Impact of Multi-Scale Asphalt Thin Beams in the Bending Beam Rheometer on the Prediction of Thermal Cracking of Bituminous Material

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Abstract

Asphalt thin beams (112 mm x 12.7 mm x 6.35 mm, length x width x thickness) in a Bending Beam Rheometer (BBR) have been used in the asphalt industry as one of methods to predict low temperature cracking properties of asphalt mixtures. Given the research work dedicated to the asphalt industry, the potential benefits of testing smaller specimens (cheaper equipment, less material, faster conditioning, easier availability for quality control, etc.) are well recognized. However, the two main criticisms of using the BBR to test mixtures are raised: (a) the thickness of the beam is smaller than the maximum aggregate size; thus a single aggregate particle can affect the results of the test, and (b) such small specimens cannot represent the overall property of the mix. This paper is conducted to address the above issues by using a combination of imaging techniques, statistical analysis, and viscoelastic modeling. Three nominal maximum aggregate sizes (NMAS), 12.5 mm (1/2''), 9.5 mm (3/8'') and 6.25 mm (1/4''), were prepared in a laboratory. Each one of the three NMAS specimens was cut into a six-faced block that was then scanned and analyzed its pixels using imaging techniques. Subsequently, asphalt blocks were trimmed into thin beams and tested in a BBR to obtain their stiffness and creep compliance values.

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Analysis of variance (ANOVA) associated with viscoelastic modelling were performed to evaluate whether multi-scale asphalt thin beams could impact the prediction of thermal cracking properties of bituminous material. Based on the results, the paper concludes that the difference between the three NMAS thin beams is not significant and their relaxation modulus curves show closer agreement. Thus, using asphalt thin beams in a BBR to determine thermal cracking properties of bituminous material is valid.

1. Introduction

In cold weather climates, low temperature cracking of asphalt pavements is one of the most prevalent distresses. Currently, there are no quality control (QC) tests adopted by highway agencies for predicting thermal stresses because available standard testing methods are not adequate. The Bending Beam Rheometer (BBR) is promising because it is simple, fast, relatively inexpensive, and highly repeatable (Zofka A., Marasteanu, Li, Clyne, & McGraw, 2005) (Zofka M., 2007) (Zofka, Marasteanu, & Turos, Determination of asphalt creep compliance at low temperatures by using thin beam specimens, 2008) (Romero, Ho, & VanFrank, 2011). The problem is that this standard test method is designed for testing asphalt binder specimens not asphalt mixture beams, which doesn’t consider the effect of the aggregates in the pavement, the differences between mixtures, or the addition of recycled asphalt pavements (RAP). However, testing asphalt mixture specimens in the BBR for measuring low temperature properties of the pavement, has been widely studied and supported (Zofka A., Marasteanu, Li, Clyne, & McGraw, 2005) (Velasques, 2009) (Ho & Romero, 2011). Despite the investigations, there are two main criticisms: the thickness of the beam is smaller than the maximum aggregate size, so one aggregate may affect test results; and such small specimens may not be representative of the asphalt pavement properties. This research tends to address these issues, evaluating the impact of multi-scale asphalt thin beams in the BBR results using imaging technology, statistical methods, and viscoelasticity.

2. Methods

2.1. Image Analysis Method

The objective of the image conversion process is to evaluate the stability of ratios of asphalt binder and air voids (ABAV) occupied in specimens. Two sets of specimens for each NMAS were produced in a laboratory. After these specimens were scanned and saved as a digital file, an imaging process was implemented to obtain a number of pixels for each specimen. The number of pixels represent the volume of asphalt binder and voids occupied within a specimen. A scale factor was used for each NMAS to have equivalent samples. If the result of counting asphalt binder and air voids is statistically equivalent, we can assume that there is no significant difference among the three NMAS. The NMAS of 4.75 mm (0.25 in) was used as a reference scale, 100%. The others two, were reduced in scale by 0.25 in./0.5 in. = 50%, for NMAS of 12.5 mm (0.5 in.); and by 25% for NMAS of 9.5 mm (0.375 in.), from: 0.375 in./0.5 in. = 75%.

2.2. Statistical Analysis Method

A one-way analysis of variance (ANOVA) was performed to validate the hypothesis that the ABAV difference between three NMAS specimens is not significant. The coefficient of variance (CV) of stiffness results from the BBR at -24°C at 60 seconds was calculated to validate the number of replicates that should be tested for measuring stiffness. CV should be less than 0.2 (Romero, Ho, & VanFrank, 2011).

2.3. Viscoelastic Modeling Method

2.3.1. Sample preparation and testing

Creep compliance data were obtained from the BBR test to characterize the low temperature properties of asphalt mixtures beams. Test specimens varied with the nominal maximum aggregate size (NMAS) (12.5mm, 9.5 mm and 4.75 mm). The NMAS of 12.50 mm was selected for the standard mixture. The asphalt samples (150 mm in diameter and 110 mm in height) were produced in the laboratory using the Superpave Gyratory Compactor (SGC), and were cut into a six faced block. Then, the block was trimmed into several thin beam with dimensions suitable for the BBR
The test was run following the AASHTO T313 standard (American Association of State Highway and Transportation Officials, 2009). Before running the test, the beams were conditioned one hour in a bath for each temperature (-18 ºC, -24 ºC and -30 ºC). The initial load was 35 ± 10 mN (contact load), and then it was increased to 450-gram (4413 ± 50 mN) to obtain measurable deflections without change in the cell calibration procedure (Zofka et al. 2005). The computer program kept the data of stiffness and deflection at 0.0, 0.5, 8.0, 15.0, 30.0, 60.0, 120.0, and 240.0 s. The data from 8 to 240 seconds were the base to determine afterward the creep compliance.

2.3.2. Viscoelastic Modelling Analysis

Linear viscoelastic (LVE) modelling analysis is used to evaluate if the relaxation moduli of the three NMAS specimens are similar and all of them can be used to estimate the low temperature properties of asphalt concrete mixtures.

A power law function was used to model the responses of creep compliance, using previous research recommendations (Christensen & Bonaquist, 2004):

\[ D(t) = D_0 + D_1 t^n \] (1)

Where \( D(t) \) is creep compliance at reduced time \( t \); \( D_0 \), and \( D_1 \) and \( n \) are power function parameters. Creep compliance from each NMAS, was expressed in terms of reduced time to represent in a single curve (master curve) the creep compliance at the three different temperatures tested, thus incorporating the temperature effect in the viscoelastic analysis. This is done by applying the time-temperature superposition principle (TTPST) that considers that there is a correspondence between the temperature change on the viscoelastic properties of materials and a shift factor on the time log scale (Schwarzl & Staverman, 1952). The reduced time is calculated as:

\[ \xi = t \alpha_T(T) \] (2)

Where \( \xi \) is the reduced time, \( t \) is the time, and \( \alpha_T(T) \) is the shift factor; dependent on the temperature. The power law parameters already mentioned, are obtained such that they minimize the sum of squared errors between experimental data and fitted values (fundamental principle of nonlinear regression), which can be represented as:

\[ \text{Minimize} \sum |D_p(\xi) - D(\xi)|^2 \] (3)

Where \( D_p(\xi) \) is the fitted power law response at reduced time \( \xi \), and \( D(\xi) \) is the raw experimental data at reduced time, \( \xi \). The relaxation modulus is obtained from creep compliance applying the interconversion principle (Findley & Lai, 1982):

\[ \hat{D}(s)\hat{E}(s) = \frac{1}{s^2} \] (4)

The caret (^) over \( D(s) \) and \( E(s) \) indicates that they are function of Laplace transform, and \( s \) is the Laplace transform parameter. From (4) and applying the Laplace transform to the Power Law function of creep compliance (1), the relaxation modulus in the Laplace domain can be expressed as:

\[ \hat{E}(s) = \frac{1}{s D_0 + D_1 \Gamma(n + 1)s^{1-n}} \] (5)

Where \( \Gamma \) is defined as a gamma function. To obtain the relaxation modulus as a function of time, the direct inverse of the Laplace transform cannot be solved but an approximate method can be applied (Schapery, 1962), resulting in:

\[ E(t) = \frac{1}{D_0 + D_1 \Gamma(n + 1)(1.786)^n} \] (6)
3. Results and Discussions

2.1. Image Analysis Results

Figure 1 shows the image conversion process, in a specimen of NMAS 12.5mm: first scaled (left image) and then converted into black and white (right image). An image computer software was implemented to obtain a number of black pixels for each specimen. This number represents the content of asphalt binder and voids.

![Figure 1: Image of a NMAS 12.5 mm asphalt mixture specimen after scale conversion, and before and after converting into black and white.](image)

2.2. Statistical Analysis Results

The result from performing ANOVA in the data from the image analysis is depicted in Table 1. Based on the calculated p-value, we fail to reject the hypothesis, which means that the ABAV differences among the three NMAS specimens are not significant.

| Groups | Count | Sum  | Average | Variance |
|--------|-------|------|---------|----------|
| 12.5 mm| 3     | 0.7978 | 0.265  | 0.000932 |
| 9.5 mm | 3     | 0.8917 | 0.297  | 0.000645 |
| 4.75 mm| 3     | 0.8648 | 0.288  | 0.000321 |

ANOVA

| Source of Vari. | SS    | df  | MS    | F       | P-value | P-value | Fcrit |
|-----------------|-------|-----|-------|---------|---------|---------|-------|
| Between Groups  | 0.0015| 2   | 0.000779 | 1.231132 | 0.356446 | 5.143253 |
| Within Groups   | 0.0037| 6   | 0.000633 |         |         |         |       |
| Total           | 0.0053| 8   |         |         |         |         |       |

The results from the analysis of the CV in creep compliance results at 60 seconds and -24 °C are shown in Table 2:

| NMAS (mm) | CV   |
|-----------|------|
| 4.75      | 0.06 |
| 9.50      | 0.07 |
| 12.50     | 0.05 |

2.3. Viscoelastic Modeling Analysis Results

The creep compliance of the asphalt concrete mixture for each NMAS at the three different temperatures is shown in Figure 2. Neither of the curves for the different temperatures are crossing between them, being almost parallel curves. The master curve created fitting the data of the creep compliance overlapping the curves of the three temperatures is shown for each MNAS in Figure 3.
Figure 2: Creep compliance curves for 4.75 mm, 9.5 mm, and 12.5 mm NMAS.

Figure 3: Master curve for 4.75 mm, 9.50 mm and 12.50 mm NMAS

Drawing and comparing the relaxation modulus curves for the three NMASs was displayed in Figure 4. Clearly the three modulus curves show close agreement.

3. Conclusions

The prediction of low temperature properties of asphalt mixtures can be analysed from creep compliance and relaxation modulus characteristics, from creep stiffness and m-value results in the BBR test. Despite the advantages of this method, it has some concerns for performing the test on asphalt mixture beams. These concerns have been addressed performing multi-scale analysis on specimens with different NMAS.

Based on the results obtained, the research concludes that:

i. A series of imaging techniques was used to compare the ratio of ABAV of the three NMAS specimens. The p-value of a one-way ANOVA test is greater than 0.05, so the ABAV difference among the three NMAS specimens (12.5 mm, 9.5mm, and 4.75mm) is not significant.

ii. The statistical analysis using CV of the stiffness of the three NMAS reveals that the number of specimens tested in the BBR is representative.
iii. Based on the result of viscoelastic modeling, the relaxation modulus curves of three NMAS specimens show good agreement. The effect of aggregate sizes on low temperature cracking is not significant, thus the three NMA sizes analyzed (4.75 mm, 9.5 mm and 12.50 mm) have close viscoelastic response at low temperatures.

iv. All test data conclude that the impact of multi-scale asphalt beams in the BBR on the prediction of thermal cracking of asphalt mixtures is minimal and can be neglected.

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