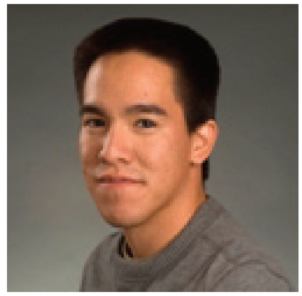
Fracture Energy Method for Determining Stiffness in Polymer Modified Asphalt Binders Using the Single Edge Notched Beam



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Abstract

Transverse cracking is a prevalent problem that occurs in asphalt pavement binders in cold climates and diminishes the integrity of the road as well as shortens the life span of the road leading to premature failure. Current specification for testing asphalt pavement binders for transverse cracking fails to accurately model the behavior of modified asphalt binders because it does not take into account the effects of physical hardening. Furthermore, current specification, which employs the use of the bending beam rheometer (BBR) and direct tension tests, was developed through the use of unmodified asphalt pavement binders and so it does not accurately model the behavior of modified asphalt pavement binders at colder temperatures. This study sought to come up with a new specification criterion for testing for transverse cracking as well as modeling the behavior of modified asphalt pavement binders at colder temperatures. This was achieved by the fracture energy method through the use of a single edge notched beam (SENB). The results showed that the fracture energy method proved to be an effective tool for modeling the behavior of modified asphalt pavement binders. However, when comparing the stiffness calculated from the SENB with that of the BBR we found that the stiffness in the SENB was much higher than that of the BBR. The increase in stiffness could very well be attributed to the differences in the way the samples are tested. Further research is necessary to come up with a way to compare the stiffness calculated from the SENB with that of the BBR before the fracture energy method can replace the BBR method.

Introduction

Transverse cracking is a serious problem that affects the longevity and performance of asphalt pavements. Transverse cracks occur due to distresses in the pavement caused by three modes of failure. The first mode of failure is called single event thermal cracking and it is characterized by a dramatic drop in temperature below a critical value that causes thermal stresses to build up in the pavement and exceed its designed capacity (2, 14). The second mode of failure is known as repetitive thermal stress which is the stress induced on a pavement caused by repetitive fluctuations in temperature below a critical value that weakens the integrity of the mix and causes it to fail without reaching a critical stress (2, 14). The third mode of failure is characterized by the repetitive loading of an asphalt pavement by regular and heavy vehicles that over time weaken the asphalt pavement's structural integrity thereby allowing for transverse cracks to form and further deteriorate the life of the road (2, 14).

One way engineers can design and prevent transverse cracking is by measuring the stiffness of the asphalt binder. Stiffness is a quantity that measures the load over the displacement of a material. It is a material property that is independent of test apparatus, sample size, or geometry (11). As such, it helps engineers to characterize the behavior of a material at low temperatures so that they can modify the material to withstand the various modes of failure that can cause transverse cracking. Current specification employs the use of the bending beam rheometer as well as the direct tension test to determine the stiffness of the material (1). The bending beam rheometer reports a value of stiffness that is taken after sixty seconds of constant loading and an m-value which is the slope of the double logarithmic graph of strain versus time (10). The m-value essentially measures the material's ability to relax stresses (10). This information is used to construct a master curve which is then used to predict how the material will behave at various temperatures (10).

Current specification however does not account for the effects of physical hardening that can occur with asphalt binders at low temperatures (2). Furthermore, when the bending beam rheometer was developed, it was developed using unmodified asphalt binders and so it does not accurately model the behavior of polymer modified asphalt binders (10). Physical hardening can have a significant effect on the validity of stiffness readings that could lead to erroneous results regarding the specification of asphalt binders. The process is characterized by free volume collapse of the material below the glass transition phase of the material (2). This hardening causes a time dependent isothermal change in the rheological behavior and specific volume of the material.

As a result, it is necessary to develop a method that takes into account the effects of physical hardening as well as the aforementioned modes of failure and create a better model for how polymer modified asphalt binders behave and resist thermal cracking.

Methodology

To conduct this study we employed the use of a Bending Beam Rheometer (BBR) and the Single Edge Notched Beam (SENB) in order to compare the stiffness for the materials selected in the study. The materials used for this study are summarized in Table 1.

Bending beam rheometer

The Bending Beam Rheometer (BBR) tests for stiffness in pavement binders by loading a beam that is placed in the apparatus between the supports at a constant load in a methanol bath where the sample is allowed to condition to the specified temperature. By measuring how much the beam has deflected over a period of five minutes, the stiffness can be calculated. Thus, the stiffness tells us how the material will behave at cold temperatures and whether or not it will fail at a certain temperature (13). Typically tests are conducted on pavement temperatures within a temperature range of -12C to -24C and a master curve is then constructed for the material. This curve then allows us to calculate the stiffness value for the material for any temperature within that temperature range. The beams are prepared by pouring hot asphalt into a mold that is allowed to cool down to room temperature which is then removed and the sample is then allowed to condition to the testing temperature for an hour.

The following equation shown below (Equation 1) is used to model the behavior of the asphalt binder and is used to calculate the stiffness of the material.

$$S(t) = A + B\,[log\,(t)] + C\,[log\,(t)]^2 \qquad (1)$$

The BBR typically reports a value for the stiffness and a value known as the m-value which is the slope of the log of stress vs log of strain (4). These two values give us an idea of how the material behaves over a range of temperatures and allows us to design pavements that meet or exceed the design criteria for a specified temperature.

Single edge notched beam

The Single Edge Notched Beam (SENB) is essentially modeled after the beams used for conducting the Bending Beam Rheometer (BBR), with the exception that the SENB requires the use of a notch that is molded using a piece of plastic that is fixed at the center of the beam. The mold is prefabricated with the notch in place and a plastic sheet is placed in the notch as shown in Figure 1. The asphalt is then poured into the mold while it is still hot and allowed to cool down to room temperature after which the mold is then removed and the corresponding beam is placed in the methanol bath to condition the sample to the specified temperature. For this study we chose to test our samples at -12C and -18C and compared the stiffness attained at these two temperatures with the stiffness attained from the BBR at those two temperatures.

The Single Edge Notched Beam is similar to the BBR in the approach used to test the beam except whereas the BBR bends the beam as it is placed horizontally, the SENB places the beam vertically with the notch facing down as shown in Figure 2. This essentially allows us to control the manner in which the beam fails through thermal cracking at low temperatures.

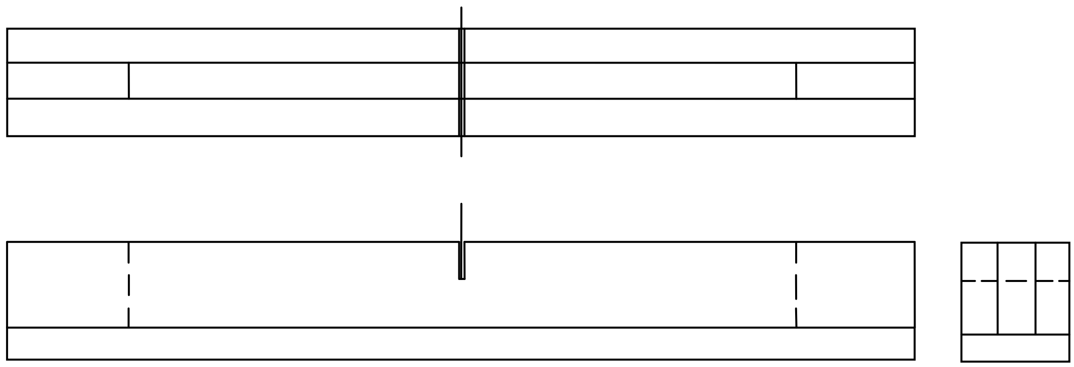

Figure 1. SENB Mold

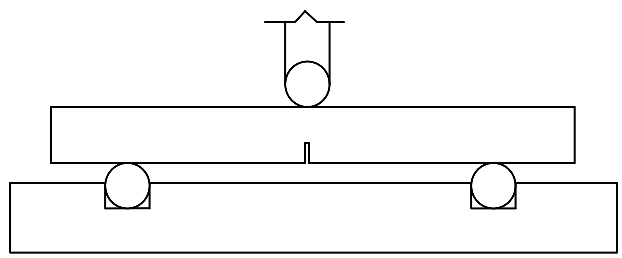

Figure 2. SENB Testing Apparatus

The mechanism for testing the notched beams is similar to that of the BBR as well except that the SENB loads the beam until the point of fracture while holding the rate of strain constant and the BBR uses a constant force on the beam and allows the strain to change over time. Essentially the SENB is measuring the energy required to propagate a crack through the material which then allows us to calculate the stiffness of the material for the specified temperature (9, 12). The fracture energy is calculated using a model developed in an excel spreadsheet and the stiffness can be calculated by equation 2:

$$S(t) = \frac{PL^3}{4bh^3\delta(t)} \tag{2}$$

Where P is the load applied in mN, L is the length of the specimen in mm, b is the width in mm, h is the height in mm and δ is the displacement at the point of fracture in mm. The equation presented above allows us to calculate the stiffness of the material up to the point of fracture. This geometric approach is independent of the type of apparatus used, geometry, or size of the sample and more discriminate in the way that it tests the material's inherent structure and ability to resist deformation.

Materials

The table shown below, Table 1, is a summary of the materials used to conduct this study. Table 2 summarizes the codes used to identify each respective material. The number scheme is used to identify whether or not the material has been modified through the addition of a polymer modifier. For example, in the sample A0, the A corresponds to the source Flint Hills and the number 0 corresponds to an unmodified binder. The samples coded with a 0 are base binders that have not been modified with a polymer additive and are used in this study to compare how the stiffness changes with the type of modifier.

Table 1. Base and Polymer Modified Asphalt Binders

Base	Modifier	Class of Modifier	Expected Grade
A0	None	None	PG 64
A1	Functionalize PE	Plastomer-Non reactive	PG 70
A2	Functionalize PE	Plastomer-Non reactive	PG 76
A3	SBS with x-linking	Elastomer-Reactive	PG 70
A4	SBS with x-linking	Elastomer-Reactive	PG 76
B0	None	None	PG 58
B1	Ter-polymer	Elastomer-Reactive	PG 64
B2	Ter-polymer	Elastomer-Reactive	PG 70
C0	None	None	PG 58
C1	PPA	Chemical Reactive	PG 64
C2	PPA+SBS+x-linking	Elastomer-Reactive	PG 70
E0	None	None	PG 64
E1	SBS with x-linking	Elastomer-Reactive	PG 70
E2	SBS with x-linking	Elastomer-Reactive	PG 76

The expected grade corresponds to the performance grade expected for the material and was confirmed using a Dynamic Shear Rheometer to confirm the true grade of the material both under the original and aged conditions (3, 8). It is important to note that the material used to conduct this study was aged material that had been aged using the Pressurized Aging Vessel (PAV) for a period of 20 hours as outlined in the performance grade criteria for grading asphalt binders (5, 6, 7).

Table 2. Source Codes for the Corresponding Materials List

Source	Code
Flint Hills	A
Mathy Construction	B
Holly Asphalt	C
Nustar	E

Since the material used in the BBR is PAV material we chose to test PAV material for the SENB as well as material that has been aged and simulates the worst conditions to which a pavement binder can be subjected (6, 7).

Results and Discussion

The figure (Figure 3) shown below is the result of the Single Edge Notched Beam on a sample B1 that has been modified with a Ter-polymer which is an elastomeric-reactive type of modifier. The fracture energy associated with the sample is displayed by the equation shown to model the recorded data. Using the value recorded for the displacement of the material up to the point of fracture it is possible to calculate the energy needed to fracture a beam with this type of polymer modifier.

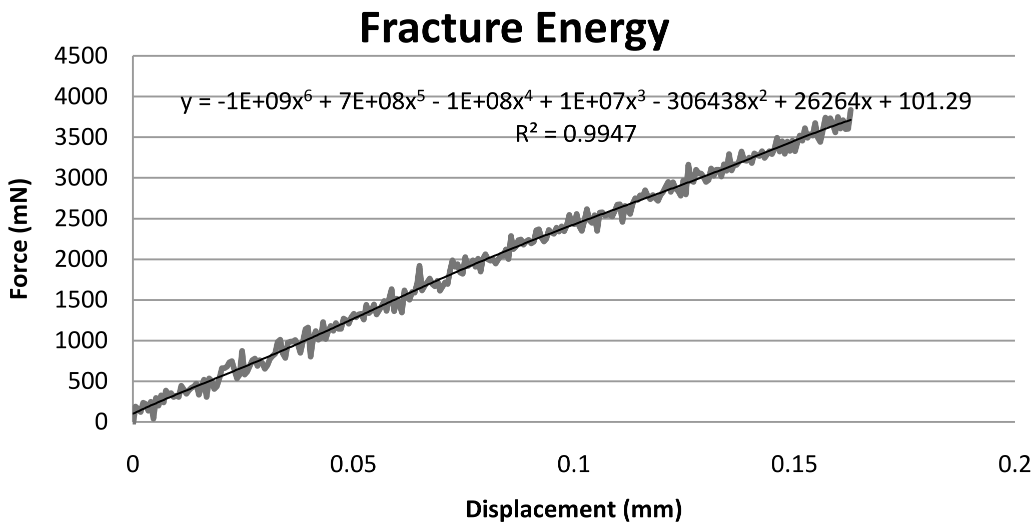

Figure 3. Fracture Energy of Sample B1

In order to ensure consistent results and repeatability, the three samples were tested on the SENB test and a test on the variability was conducted and was found to be less than 10% between samples.

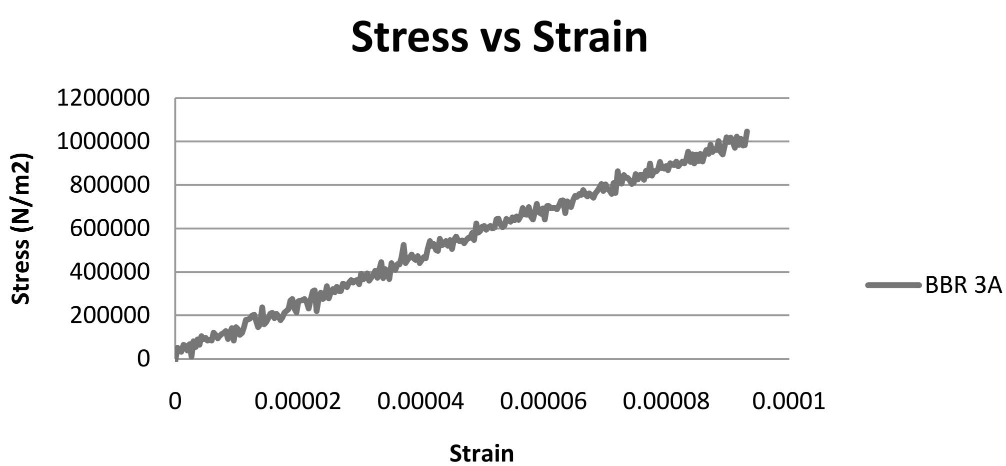

Figure 4. Stress vs. Strain Curve for Sample B1

Figure 4 is the stress vs. strain curve for sample B1 that was also derived from the data recorded by the SENB. One of the advantages that the SENB has over the BBR is the ability to calculate both the fracture energy and the stiffness as well as the stress vs. strain. The BBR is only able to yield the stiffness and the stress vs. strain. In Figure 4 the relationship shown is a linear one, which is what we had expected to observe. Noting this relationship is important when calculating the fracture energy because if a material is ductile it will not exhibit a linear relationship and thus the model used to calculate the fracture energy is not applicable.

A comparison of the fracture energy at -12C and -18C is shown in Figure 5. One of the trends that were observed was that the fracture energy tended to decrease with a drop in temperature. This observation was noted in most of the samples tested regardless of the type of modifier used when compared to their base binder.

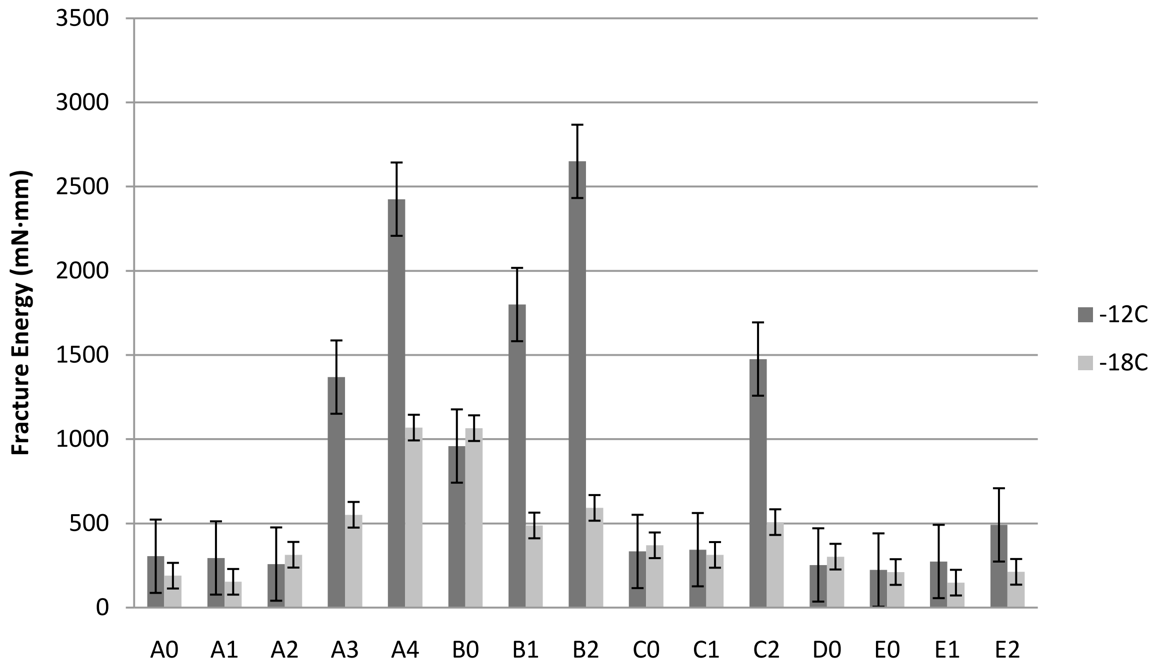

Figure 5. Comparison of Fracture Energy at -12C and -18C

This tells us that regardless of the type of modifier, the polymer modified and base binders became more brittle as the temperature dropped and thus required less energy to fracture the material. One of the important observations that can be made from this analysis is that the SBS cross linking polymer tended to fare better than the other types of polymer modifiers as displayed by samples A3 and A4.

A regression analysis conducted on the stiffness calculated from both the SENB data and the BBR data is shown in Figure 6. The figure is a graph of the stiffness vs. temperature and shows that for the most part the stiffness calculated using the SENB tends to be higher than that of the BBR.

For the most part this difference can be attributed to the difference in which the two stiffness values are calculated. The stiffness calculated using the BBR is calculated using Equation 1 which models the curve of the log of stress vs. log of strain graph. This value uses the deflection after a period of 60 seconds of loading as mentioned in the ASTM standard for flexural creep using the BBR. The stiffness calculated through the SENB is attained until the point of fracture in which case it does not have a clearly defined time period as the BBR. As a result, the stiffness values calculated with the SENB will tend to be higher than those attained with the BBR.

Conclusion

The Single Edge Notched Beam proved to be a more discriminate tool in determining how a type of pavement binder will behave with temperature, especially when modified with a polymer. The data showed that the fracture energy method is a property that is unique to the type of material as it tests the structural integrity of the material by propagating a crack through the material. Those pavement binders that tended to do better with a drop in temperature, such as the SBS cross linking polymer modifiers, could be attributed to the type of bonds generated within the microscopic structure of the material and could be a point of further research. The stiffness calculated using the data obtained through the SENB tended to be higher than that of the BBR. This difference can be attributed to the different criteria used to conduct each respective test. More research is necessary in order to come up with a way to better compare the two stiffness values so that it can be determined whether or not the SENB is a better tool attaining the stiffness of a material.

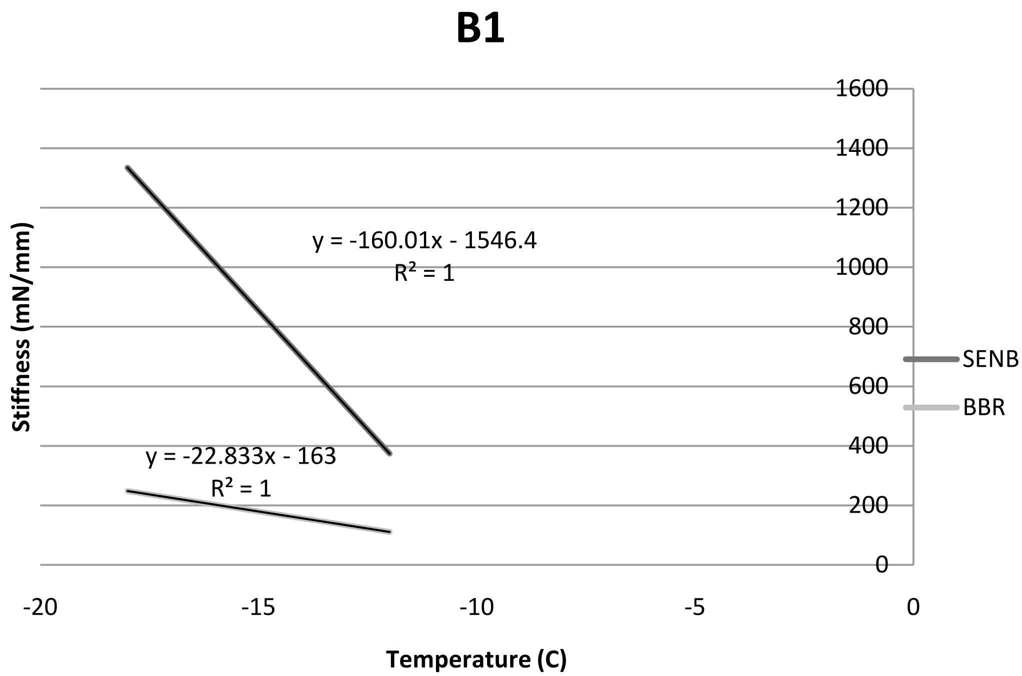

Figure 6. Linear Regression Analysis for Sample B1

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