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TPF-5 (302)

Modified Binder (PG+) Specifications and Quality Control Criteria

Task Report:

White Paper on:

Evaluation of Test Method Alternatives for Thermal Cracking Characterization of Asphalt Binders

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Executive Summary

In the current PG system (AASHTO M320) the Bending Beam Rheometer (BBR) is used to determine the low temperature grade limits based on the stiffness (S) and logarithmic creep rate (m). Both these parameters are measured at relatively low levels of load and deformation; thus there is a concern that resistance to fracture (cracking or breaking) is not really measured. For modified asphalts this concern is important as some modifiers could create a network of long-chain molecules reinforcing the binder and increasing its resistance to fracture. A number of studies have pointed out this concern and recommended implementation of a true fracture test to amend the S-m parameters. In the original PG grading system an attempt to measure cracking was proposed by using the Direct Tension Test (DTT), but only a few State Agencies use the test today because the test implementation proved to be not feasible due to variability, sample preparation issues and amount of material and replicates needed.

During the last five years a bending test has been introduced and became a standard in Europe Norms. The same bending concept was used in the US to propose a modification of the BBR to allow measuring fracture of a notched BBR specimen. The modified BBR that allows measuring fracture is called the Single Edge Notched Beam (SENB). The theory and concept of analysis is also used in testing plastics and other structural materials. The energy required to break a specimen of binder, and the strain at the maximum load, are simple-to-calculate parameters that can be derived from the SENB test. However, as of this time, the modification of the BBR could not be made simple, and there are no manufacturers of asphalt testing equipment that are willing to mass-produce the new testing system. Research works reported in the literature, including a recent Wisconsin Highway Research Program (WHRP) project, show that SENB can successfully discriminate between different materials and correlate well with pavement cracking behavior observed in the field. However, currently there is only one BBR-SENB device at the national scale that can run the test, and due to the existing challenges in manufacturing the device in large scales, there is a need to explore simpler alternatives for testing and evaluating binders at low temperatures.

Therefore the purpose of this white paper is to:

- Summarize background behind developing the (SENB) test and discuss its usage which has shown good relationship with field low temperature cracking prediction;
- Correlate the SENB parameters with asphalt mixture low temperature characterization test method (Asphalt Thermal Cracking Analyzer (ATCA)) and comment on the ability of the binder SENB testing to provide indication of mixture thermal cracking behavior;
- Compare and comment on correlations between the parameters from SENB testing to other simpler methods including the Binder Yield Energy Test (BYET) and the delta in S true grade and m true grade of binders from BBR measurements, also called (ΔT_c);
- Make recommendations for next steps to amend the S-m parameters that could be very important for modified binders and for consideration of mixtures with RAP and RAS.

The intention is to provide information on feasibility of using practice ready testing methods in characterization of low temperature behavior of asphalt binders.

The analysis of the results collected in this white paper indicates that Strength, or Failure Energy (FE) measured for binders in the SENB are very well correlated to mixture strength and FE. However strain at failure of the binders is not a good indicator of mixture cracking. Since the SENB device is not readily available, an estimate derived from BYET and BBR testing is proposed as a surrogate method to measuring binders FE. A tentative minimum value for the Failure Energy of binders equal to 40 J/m^2 estimated from BYET and BBR results is proposed for specification. It is also observed that using RAS and RAP could significantly change the relationship between binders and mixtures low temperature cracking behavior. More work is necessary to understand how best to account for using recycled materials in binders low-temperature cracking evaluation.

Development Background for Single Edge Notched Bending (SENB) Test

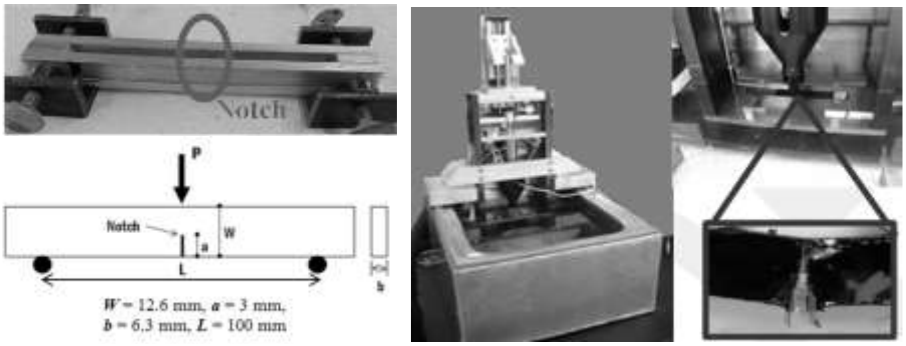
The asphalt research community has investigated thermal cracking extensively in the past two decades and yet it remains one of the most challenging pavement distresses to be evaluated and predicted. Significant progress has been made in understanding the mechanisms and factors affecting this distress. Low-temperature performance grading currently relies solely on the Bending Beam Rheometer (BBR) for determining low-temperature creep stiffness (S) and rate of modulus relaxation (m-value) at 60 s, both determined at low stress-strain levels in the pre-failure zones. This aspect raises questions with regard to applicability of properties derived from the linear viscoelastic range for prediction of binder failure properties, especially for modified binders. Therefore other important fracture and thermo-volumetric properties can be taken into account to develop a more robust and reliable specifications.

Previous research has shown the Single Edge Notched Bending (SENB) test, which is a fracture mechanics based test commonly used in metals and other materials, can be used to obtain fracture properties of asphalt binders and may be considered as an alternative test method to amend current specifications. The SENB system was developed by MARC under the Transportation Pooled Fund study on low temperature cracking sponsored by WisDOT for measuring asphalt binder, mastic, and mortar cracking resistance at low service temperatures [1, 2]. The test uses a modified Bending Beam Rheometer (BBR), with the addition of a loading motor that controls the displacement rate during testing, a load cell with a higher capacity than the regular BBR, and modified beam placement fixture, as shown in Figure 1. Tests are run at a constant displacement rate of 0.01 mm/sec on PAV aged binders.

In the BBR-SENB analysis, the failure energy, G_f is calculated instead of G_{IC} parameter defined in Linear Elastic Fracture Mechanics. Failure energy is defined as the total area under the entire load-deflection (P-u) curve, divided by the area of the ligament, as shown below.

$$G_f = \frac{U_f}{A_{lig}} = \frac{\int Pdu}{A_{lig}}$$

Where
U_f is work of failure,
G_f is failure energy
P and u are the load and displacement measured by the BBR-SENB,
A_{lig} is the area of the ligament



(a) (b)

Figure 1: (a) SENB sample mold and dimensions, and (b) BBR-SENB loading device and setup.

It has been shown that fracture properties of asphalt binders should be considered along with viscoelastic characteristics in order to truly investigate thermal cracking. Fracture properties of asphalt binders measured with SENB test show that current PG grading is not sufficient in differentiating between thermal cracking performance of asphalt binders. Binders with the same low temperature grade can have significantly different fracture energy values measured at LT grade temperature [1, 2].

Results from a recent project sponsored by the Wisconsin Highway Research Program (WHRP) showed that the SENB failure energy and displacement at maximum load can be used in binder specification for thermal cracking resistance (Figure 2) [3]. As shown in Figure 3, these parameters are shown to correlate well with observed field cracking.

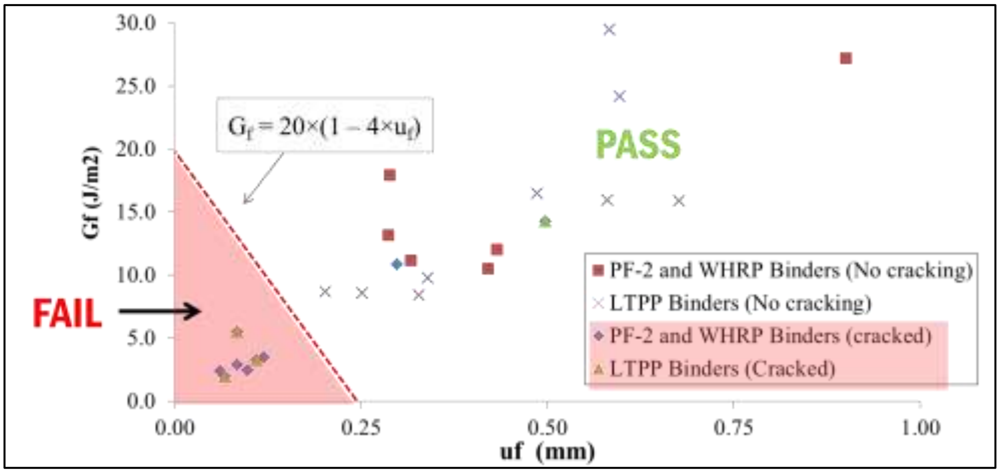


Figure 2: Proposed SENB specification based on RTFO aged conditions. Binders in the lower left triangle would fail the specification [3]

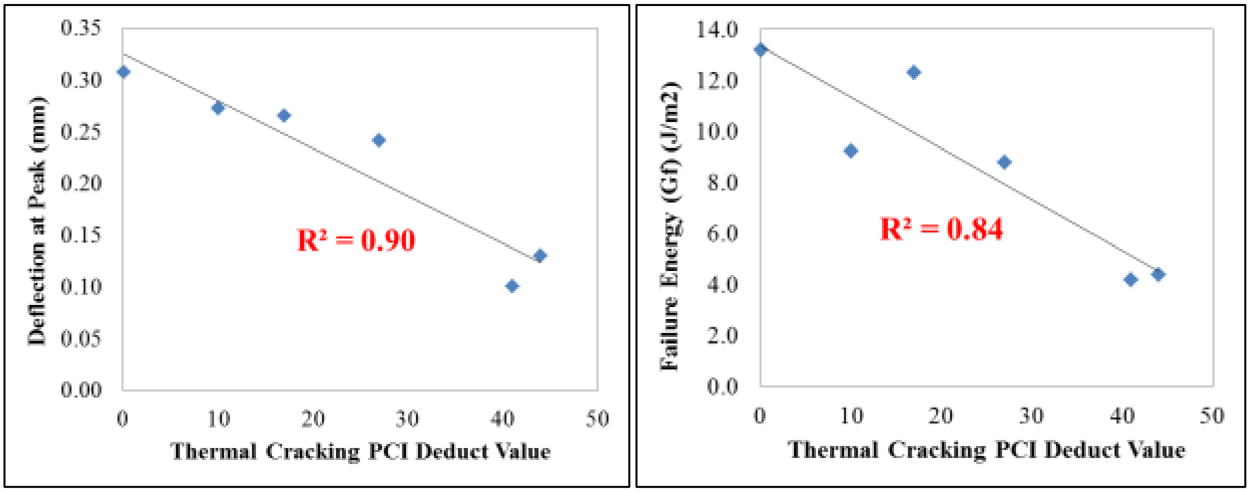


Figure 3: Correlation between displacement at maximum load (left) and failure energy (right) with field thermal cracking [3]

The binders supplied by partner states were tested in the same fashion using the SENB and the results will be presented in the following sections. In addition mixture testing using the Asphalt Cracking Tests Analyzer (ATCA) was also used to measure cracking of asphalt mixtures containing the supplier binders. The following sections discuss the correlations between SENB and mixture cracking behavior as well as applicability of other alternative tests that can replace the SENB and be included in the specifications as simpler indicators of cracking of binders.

Correlation of SENB Binder Properties to ATCA Mixture Fracture

The pooled fund binder database was used to identify correlations between binder and mixture behavior at low temperatures. Figure 4 and Figure 5 show the linear regression between binder and mixture results for strain and stress at failure parameters. Data shown in these plots and also the rest of this white paper consists of 13 different pooled fund loose mixtures and their associated binders supplied by partner states, including binders with low temperature PG grade of -22, -28 and -34. The received materials were tested using the SENB for binders and ATCA for mixture low temperature characterization.

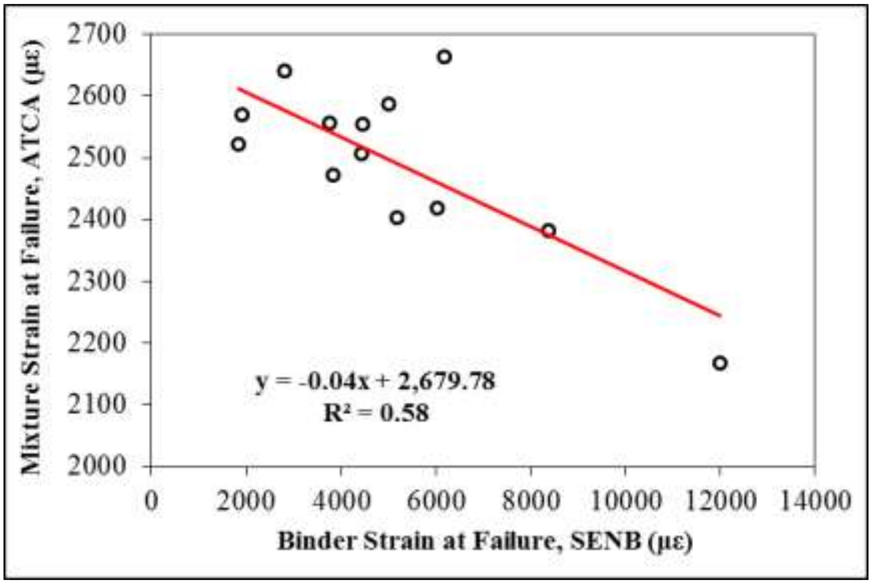


Figure 4: SENB strain at maximum load relationship with ATCA strain at failure

As shown in Figure 4, the amount of strain in mixtures at fracture stays in a narrow range of ~2100-2700 με in comparison with the wide spread (2000-12000 με) observed for tested binders. In other words, regardless of the deformation binder can show (when it is tested in the SENB at the PG LT grade of each individual binder), the mixture will show similar contraction behavior before failure. The observed trend in change in strain is not useful since higher binder strain at failure corresponds to lower strain at failure for mixture. However this negative trend can be explained based on previous work done on the relationship between binder modification, aggregate packing and low temperature behavior of asphalt mixtures [4]. The thermal shrinkage of asphalt mixtures was shown to be strongly affected by the aggregate structure since thermal strain distribution during shrinkage should be affected by packing of aggregates. It was observed that a mixture with better aggregate packing has lower coefficient of thermal contraction/expansion. Therefore strain in binders at break is less important than the aggregates packing and thus strain at break of binders from the SENB (or any other test such as the DTT) should not be considered as a reliable indicator of mixture strain at break, which is a very important factor in pavement performance.

Figure 5 shows the correlation between stress at fracture from the SENB for binders and from the ATCA for the mixtures. As shown, there is a very reasonable correlation between the two measures and the strength levels are in fact within a similar range of 0.5 to 3.5 MPa. The trend is also positive and logical (higher strength of binder=higher strength of mixture).

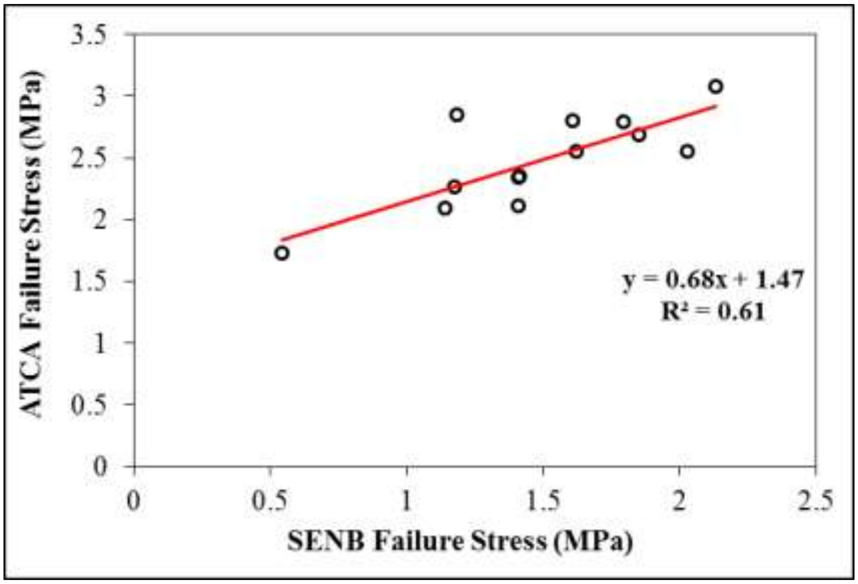
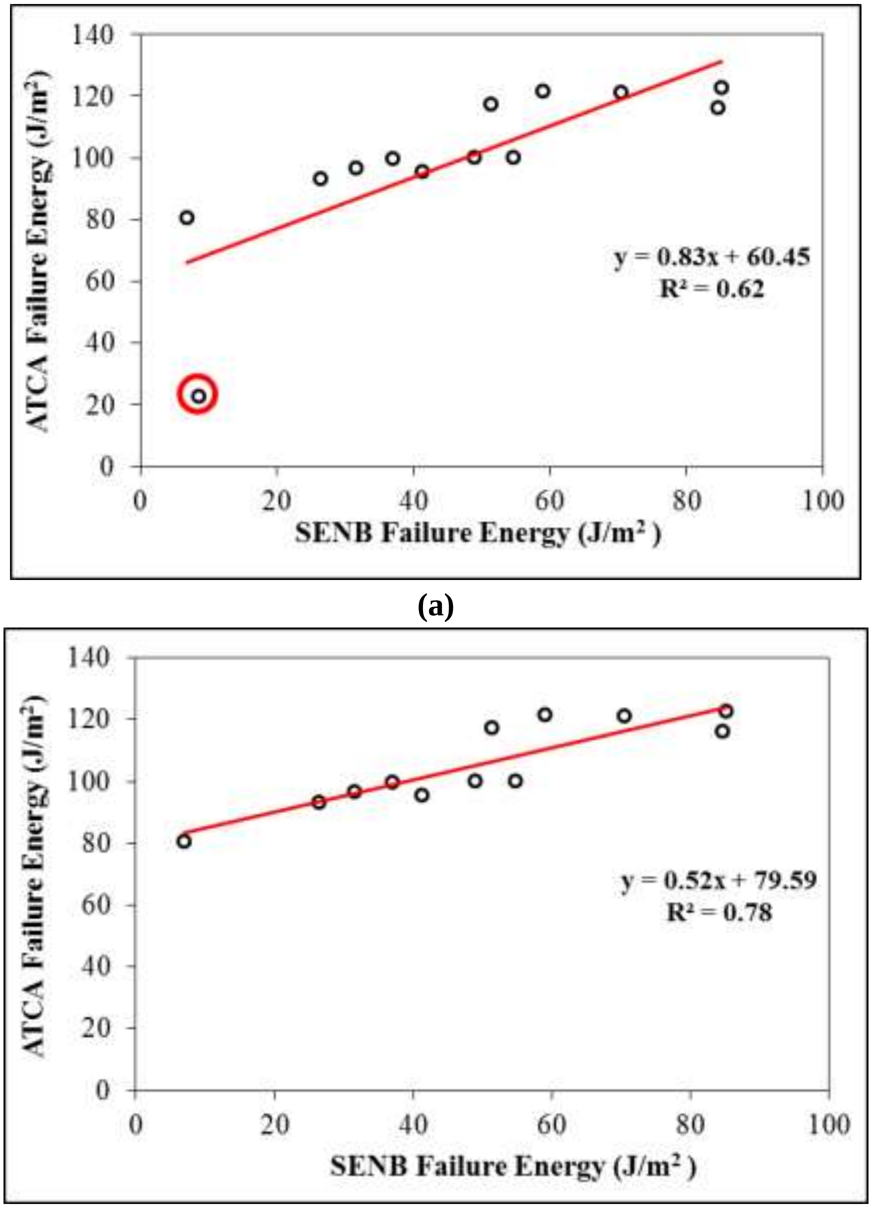


Figure 5: Correlation between binder SENB and mixture ATCA stress at failure

The general trend observed in Figure 5 clearly shows that binder fracture strength is important and it can significantly affect the maximum stress asphalt mixture can tolerate before fracture. Considering that binders and mixtures strain are not strongly dependent as shown before, the trend observed in Figure 5 prompt the idea that failure energy between binders and mixture may be comparable.

As mentioned in previous research efforts, binder failure energy indicated the potential for ranking binders significantly better than the current PG grading system when compared to the field performance data. Figure 6 shows the correlation between mixtures and binders failure energy values, which is generally linear and as the binder failure energy increases so does the mixture. It can be seen that an explained variance of 62% increases to nearly 80% when the mixture circled in red is considered as an outlier and is removed. Interestingly this particular material (binder and mixture) was also flagged in other tests performed during the current study including intermediate temperature binder characterization as an outlier. Another interesting observation about this outlier is that it fractured at very low stress level, and is the only mixture between supplied materials that has recycled shingles (RAS) in its mix design. The SENB testing was done on the binder without the RAS and thus the stiffening effect of RAS in mixtures resulting could explain the exceptionally lower tensile strength of this mixture.



(a)

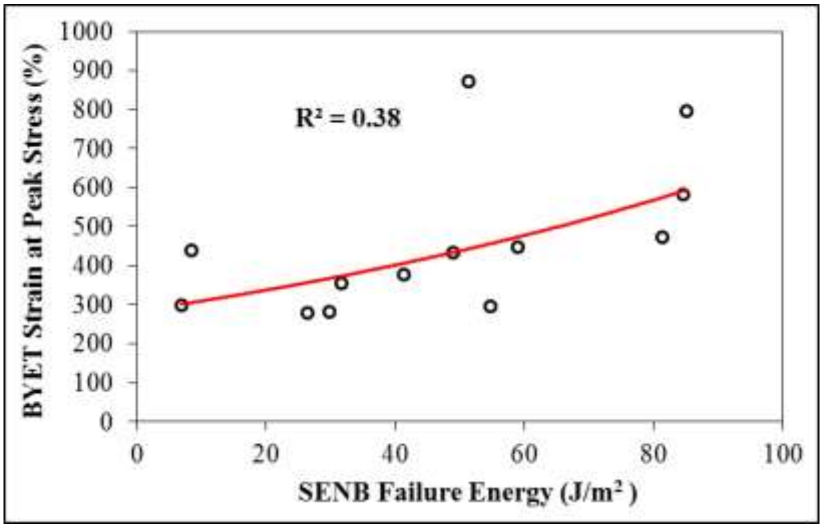
(b)

Figure 6: Correlation between mixture and binder failure energy for (a) All Mixtures prepared with RAP and RAS, (b) Mixtures Prepared only with RAP

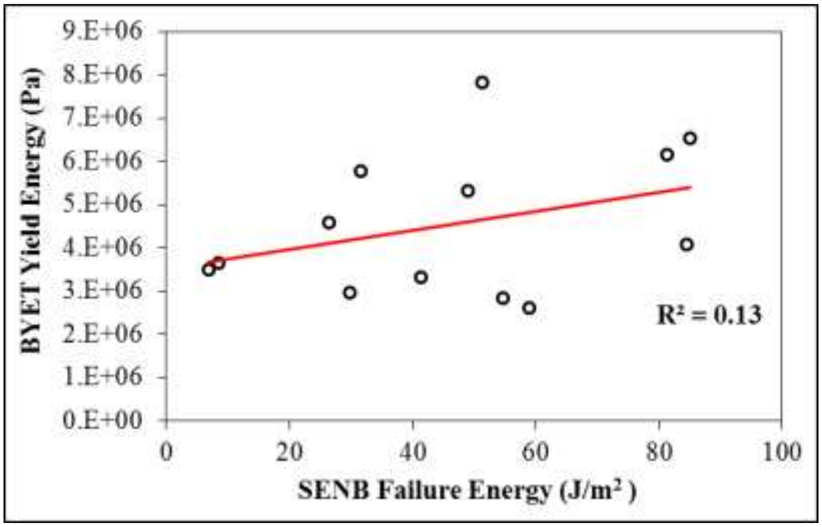
The overall spread of the results show that binder SENB parameters of stress at facture or energy at fracture correlate well with the same parameters of mixture measured with the ATCA. This promising trend suggests that the SENB failure energy may be acceptable as a quality control tool to be included in binder specification.

Feasibility of Using BYET to Replace SENB

Due to the challenges currently associated with mass producing the SENB apparatus, the research team investigated the feasibility of using easier more practice-ready test methods to replace SENB in characterizing thermal cracking potential of asphalt binders. In order to do so, the Binder Yield Energy Test (BYET) was conducted at 4°C following Method A of the AASHTO TP123 testing procedure and the two parameters of yield energy (area under stress-strain curve) and strain at peak stress were measured [5]. The relationship between the SENB failure energy and the BYET test method was investigated through linear regression and the results are shown in Figure 7.



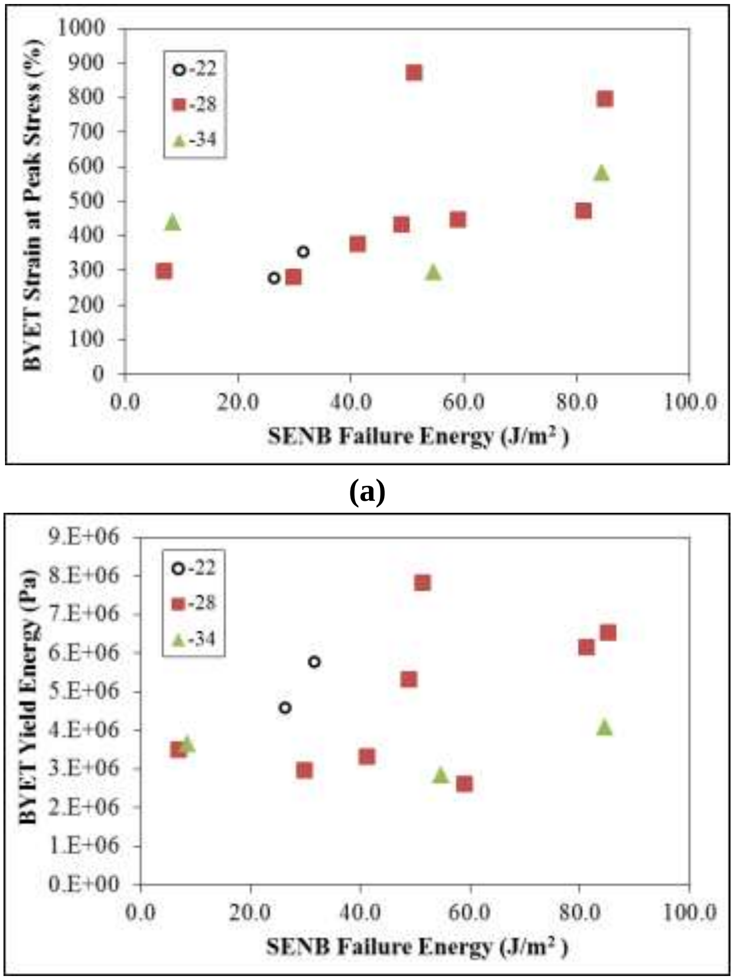
(a)



(b)

Figure 7: Correlation between SENB failure energy with (a) BYET strain at failure, (b) BYET yield energy

Considerable scatter exists in the plots shown in Figure 7 and the correlations are similarly poor, but the general trend is intuitively true where higher SENB failure energy corresponds to higher strain and yield energy in BYET. BYET yield energy and strain at peak load are indicators of the binder's resistance toward extreme load damage and ductility, respectively. Therefore it can be speculated that binder with higher ductility potential and more resistance toward larger loadings will show higher resistance toward cracking and failure. However, one explanation for the large scatter seen in the plots of Figure 7 could be the fact that these two tests (SENB vs. BYET) are fundamentally different procedures. The loading pattern changes from torsion in BYET to bending in SENB in addition to the big difference in testing temperatures (4°C comparing to low temperature PG grade). One other confounding parameter that may cause the results to be more scattered is the fact that tested binders have different PG grades and SENB failure energies are measured at different temperatures corresponding to their low temperature grades. Thus, the same data plotted in Figure 7 are categorized into three groups based on the binder's LT PG grade and the results are shown in Figure 8.



(a)

(b)

Figure 8: Comparison of SENB failure energy with (a) BYET strain at failure, (b) BYET yield energy, showing effect of binder low temperature PG grade

The trend shows slightly higher failure energies with decreasing PG LT grade of binders. Blocking the data for binder LT grade become more logical when compared to combining all the data and trend of increasing yield energy and strain at peak with increasing binder failure energy becomes clearer.

In order to further evaluate the possibility of using BYET to replace SENB, statistical analysis was conducted with an aim to develop multi-variable regression model to predict the SENB failure energy for a given asphalt binder with known Superpave and BYET parameters. Accordingly, a fairly reliable predictive model was found as it shown in the following equation due its explained variance.

$$\begin{aligned} &SENB\ Failure\ Energy \\ &\qquad = 0.054 \times Strain\ at\ Peak\ (BYET) + 2.092 \times Yield\ Enrgy(BYET) - 3.389 \\ &\qquad \times LT\ Grade - 58 \end{aligned}$$

The coefficients of selected parameters correspond to the observed trend of asphalt binders behaviors presented previously. Increasing strain at peak load and binder yield energy as well as decreasing binder LT grade showed to result in higher SENB failure strain values. Figure 9 shows the predicted versus the measured values of failure energy for the evaluated asphalt binders.

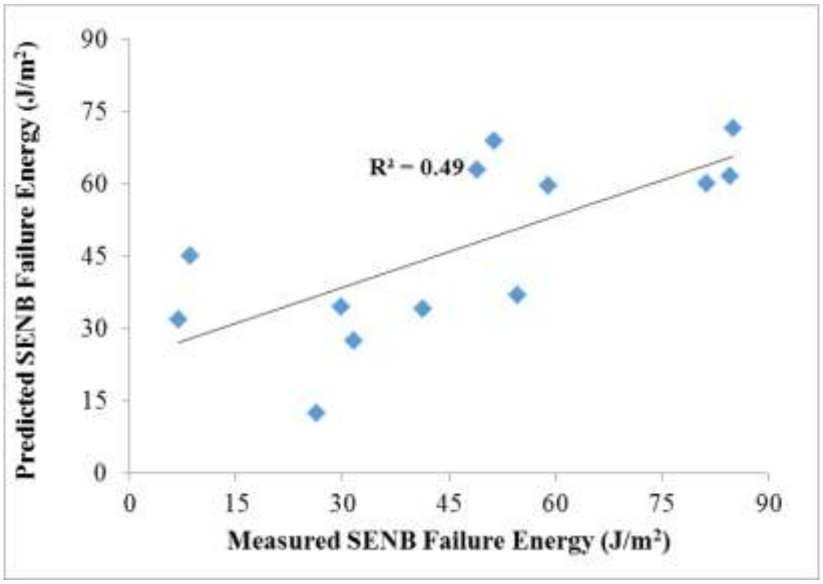


Figure 9: Comparison of predicted versus measured binder SENB failure energy using BYET and PG grading parameters

Results of the comparison between predicted and measured failure strain show a moderate correlation that once again highlights the importance of fundamental differences exists between SENB and BYET test methods. However considering multi-variable regression analysis significantly improved the correlations observed when single parameters from each test are studied individually. Given the challenges exist fundamentally between two procedures, the BYET testing method along with Superpave characteristics can likely provide some information regarding the low temperature cracking resistance of asphalt binders; however it is definitely more desirable and accurate to use SENB testing instead.

Investigating Relationship between SENB/ATCA and ΔTc

Another analysis method that has gained interest within asphalt industry recently is the difference between LT grade of binders controlled by stress relaxation (m value) and stiffness (S value) represented by a parameter know as ΔTc. The difference is negative if the binder is m-controlled and is positive if the binder is S-controlled. Previous work showed fairly good correlations between long term PAV aged ΔTc values and the pavement cracking distresses in the field [6]. The study showed ΔTc at 40 hr. PAV correlates well with cracking distress and can be used as a factor to monitor the pavements for signs of deterioration [6].

In the current study and in the search for a more practice ready testing method and analysis to replace the SENB testing, ΔTc was also evaluated and its results will be discussed in the following section. Two parameters of fracture temperature and failure energy were considered as the low temperature cracking behavior characteristics of asphalt mixtures and were compared to the ΔTc parameter. Blocking the data with binders' LT grade and percent binder replacement using recycled materials was also incorporated to better explain the relationship between mixture ATCA fracture temperature and ΔTc as depicted in Figure 10 and Figure 11.

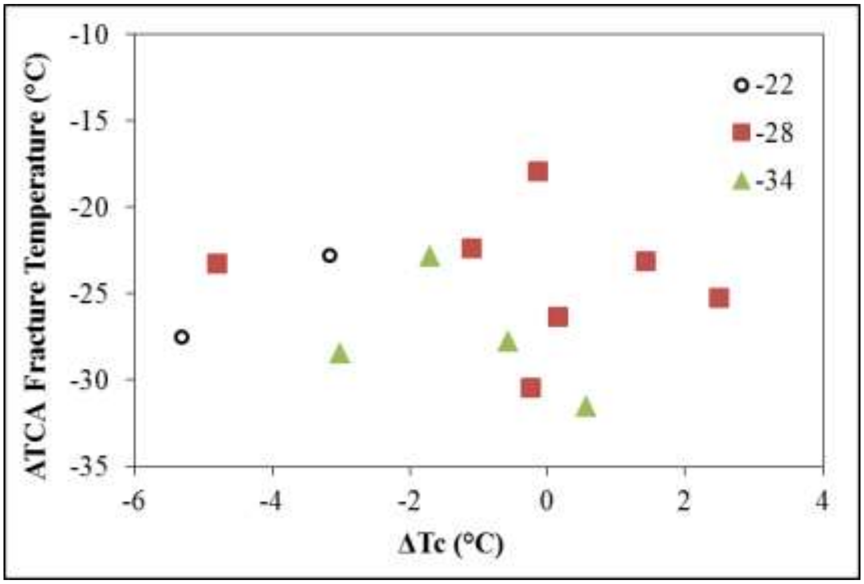


Figure 10: Comparison of ATCA testing versus ΔTc parameter-Effect of binder LT Grade

Figure 10 shows no distinct correlation between LT grade and fracture temperature or ΔTc results, even within each grade of the binders. It should be noted, however, that ΔTc in current study is calculated only at 20hr PAV while the current literature focuses on changes in ΔTc over extended aging and its correlation with mixture/field performance.

Using the mix design information provided by partner states, mixtures were categorized in three groups based on their amount of binder replacement using recycled materials (RAP and RAS), as shown in Figure 11. The groups are designated as low PBR corresponding to mixtures up to 15%, medium PBR with 15% to 30%, and high PBR for mixtures containing higher than 30% binder replacement. The overall trend in Figure 11 shows slightly higher (warmer) ATCA fracture temperature for mixtures with higher PBR which can be considered intuitive due to stiffening effect of highly aged recycled materials. Although data points are limited, lower ΔTc (more m-controlled) resulted in slightly warmer fracture temperatures. The results show there are confounding effects of mixture properties including PBR, aggregate gradation and/or structure.

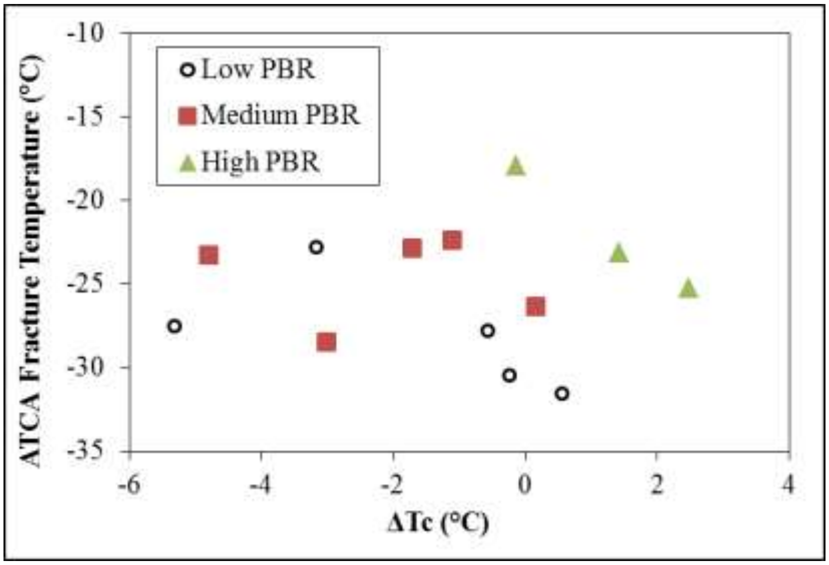
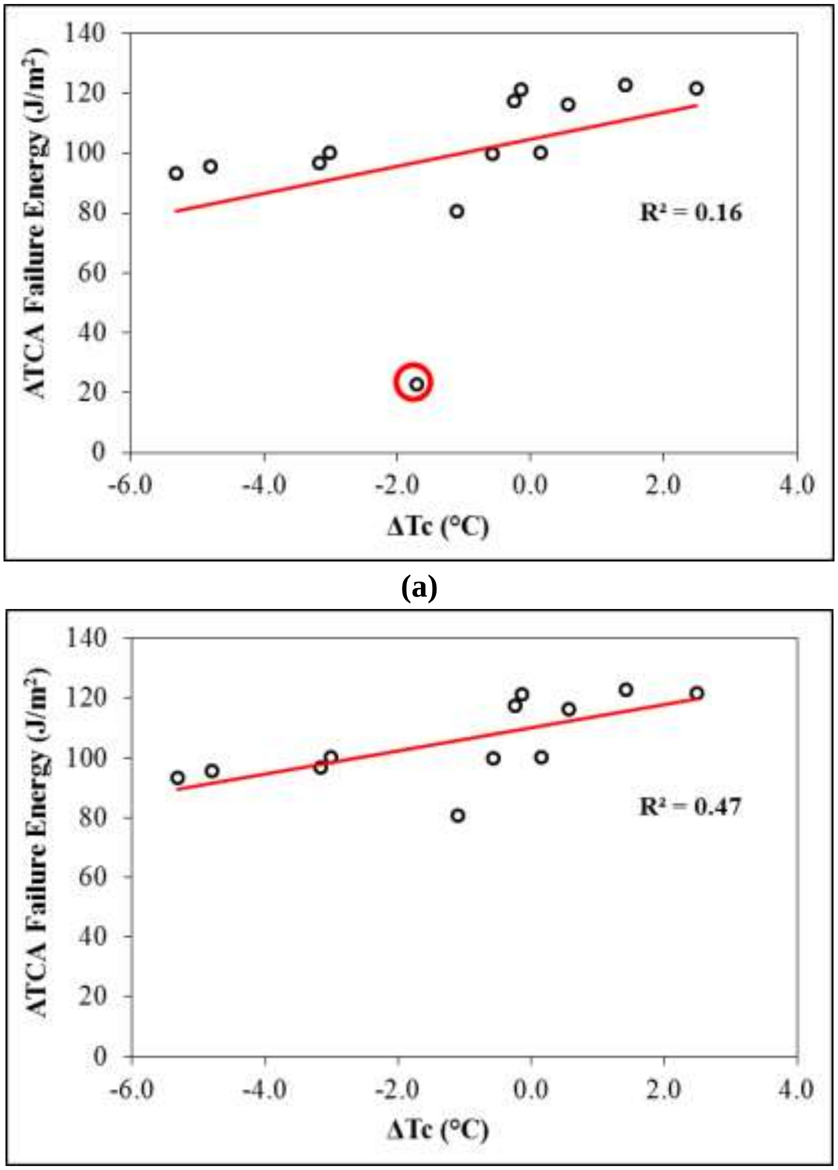


Figure 11: Comparison of ATCA testing versus ΔTc parameter-Effect of mixture PBR level

Instead of Fracture temperature, ΔTc is compared to mixture ATCA failure energy and the results are shown in Figure 12.



(b)

Figure 12: Correlation between mixture failure energy and ΔTc for (a) All Mixtures prepared with RAP and RAS, (b) Mixtures Prepared only with RAP

Similarly, the mixture with RAS material (KS 64-34) showed to behave differently than rest of the group. Once removed, the explained variance (R-square) increased from 16% to 47%, showing a general increase in failure energy and resistance toward mixture cracking once the binders become more stiffness controlled and have higher ΔTc values. However, the appropriateness of the fit was much stronger for SENB test method comparing to ΔTc relationship shown in Figure 12, which again emphasizes that for the binders supplied by partner states in the current study, SENB can be a more reliable binder testing procedure in predicting the cracking behavior of asphalt mixtures. Since ΔTc parameter showed fairly good correlation with mixture failure energy, it is also considered to be included in multi-variable regression analysis discussed earlier. The new regression model is in the following format and the relationship between its predicted values versus measured binder failure energy values is presented in Figure 13.

$$\begin{aligned}SENB\ Failure\ Energy &\\ &= 0.083 \times Strain\ at\ Peak + 0.911 \times Yield\ Enrgy - 5.122 \times LT\ Grade - 4.562\Delta T_c \\ &- 108.301\end{aligned}$$

Although the new regression model including ΔTc variable shows better predictive values for binder failure energies, the correlations is still not strong enough for users to safely replace the SENB test method. There is the possibility that investigating the trend of changes in ΔTc with extended aging as it is claimed in the literature may be more representative of the tested materials, in combination with data from BYET test at 4°C may improve the models predicting SENB results.

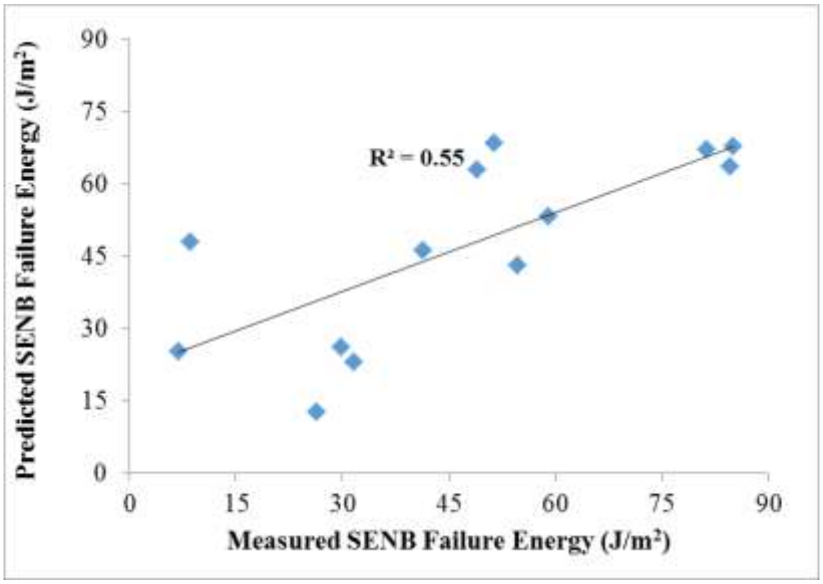


Figure 13: Comparison of predicted versus measured binder SENB failure energy using BYET, PG grading, and ΔTc parameters

Concluding Remarks and Recommendations

Based on the data presented in this white paper, the following findings and recommendations can be stated:

- The Single Edge Notched Bending (SENB) test can be used to measure binder stress and energy at failure, which have superior correlations with asphalt mixture low temperature cracking indicators.
- Since the SENB device is not readily available at this time, a combination of BYET binder properties and the ΔTc parameter measured by the BBR can provide an estimated value of the SENB Failure Energy. This estimated value can be used as a fair surrogate to the SENB test.
- More effort will be spent in the project to find a manufacturer willing to produce the SENB device. The shop drawings and operations software is ready to be shared with potential manufacturers. It will remain the partner state's choice whether the benefits from the SENB test method in more precise prediction of mixture cracking is worth the effort needed for duplicating the SENB apparatus.
- Further analysis specifically on extended aging BBR and ΔTc evaluation can help partner states better understand whether or not the practice ready procedures (BYET and ΔTc) can be further considered for specification implementation.
- It is clear in this study that RAS and RAP could significantly change the relationship between binder fracture properties and mixture fracture properties. This issue is very important and deserves further study.
- Based on data collected to date, a minimum value of Failure Energy of binders measured in the SENB (see Figure 6) or estimated from the BYET and BBR (see Figure 13) of 40 J/m^2 could be proposed for specifications.

References

[1] R. T. H. B. H. Velasquez, "Low Temperature Cracking Characterization of Asphalt Binders by Means of the Single-Edge Notch Bending (SENB) Test," *Journal of the Association of Asphalt Paving Technologists,* vol. 80, 2011.

[2] R. Velasquez, H. Tabatabaee, S. Puchalski and H. Bahia, "The Role of Asphalt Binder Fracture Properties in Thermal Cracking Performance of Mixtures and Pavements," in *Canadian Technical Asphalt Association (CTAA)*, 2012.

[3] H. Bahia, H. A. Tabatabaee, T. Mandal and A. Faheem, "Field Evaluation of Wisconsin Modified Binder Selection Guidelines-Phase II," Wisconsin Highway Research Program, 2013.

[4] P. Teymourpour and H. Bahia, "Effects of binder modification on aggregate structure and thermovolumetric properties of asphalt mixtures," *Transportation Research Record: Journal of the Transportation Research Board,* vol. 2445, pp. 21-28, 2014.

[5] AASHTO, *Measuring asphalt binder yield energy and elastic recovery using dynamic shear rheometer,* Standard Specification for Transportation Materials and Methods of Samplingand Testing, 2016.

[6] M. Ryan, D. Herlitzka, S. Engber, A. Engstler, S. Veglahn, A. Hanz and G. Reinke, "A Discussion of Some Factors Impacting Performance of Binders Blended with Additives for Reducing Low Temperature Properties of Asphalt Binders and Their Impact on Mix Performance".