Final Report

EVALUATION OF NEW BINDERS USING NEWLY DEVELOPED FRACTURE ENERGY TEST

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DISCLAIMER

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	ml
gal	gallons	3.785	liters	l
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 l shall be shown in m^3.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	l
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
psi	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
ml	milliliters	0.034	fluid ounces	fl oz
l	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg	megagrams	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	psi

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

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16. Abstract

This study evaluated a total of seven asphalt binders with various additives using the newly developed binder fracture energy test. The researchers prepared and tested PAV-aged and RTFO-plus-PAV-aged specimens. This study confirmed previous research findings that fracture energy is unaffected by loading rates. This research outlines the characteristics of true stress-true strain curves for asphalt binders with various additives. The results indicate that SBS polymer-modified asphalt binder exhibits a true stress-true strain curve with a distinct second stress peak at all loading rates, and has high fracture energy. Four binders exhibited comparable fracture energy with and without RTFO testing, while the fracture energy of other three increased significantly after RTFO testing. Limited information is available regarding the additives in the tested binders and their relative contents; however, the BFE test appears to clearly identify the presence of SBS polymer modifier and rank the cracking resistance of tested binders in terms of fracture energy. The BFE test successfully identified three binders which failed to meet the Superpave PG 76-22 grading requirements and clearly distinguished between the remaining four qualified binders.

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EXECUTIVE SUMMARY

In this study, seven binders with various additives were provided by Florida Department of Transportation (FDOT) and evaluated at University of Florida using the newly developed Binder Fracture Energy (BFE) test. The BFE test was found to be capable of providing accurate determination of fracture energy of binder at intermediate temperatures. By consistently locating the fracture plane at the center of the specimen, the new specimen geometry assured accurate measurements of the stress and strain on the fracture plane, which in turn assures accurate determination of fracture energy.

A testing temperature of 15˚C was recommended in FDOT Research Project BDK75 977-27, "Development of a Binder Fracture Test to Determine Fracture Energy" and used in current study, as the least variance in measured fracture energy occurred at this temperature. To verify previous findings, specimens of PAV residue only were prepared and tested at a various loading rates from 500 to 900 mm/min. For a better evaluation of the selected binders, RTFO-plus-PAV-aged specimens were also prepared and tested.

Testing results of PAV residue confirmed previous finding that the fracture energy of binder is unaffected by the loading rates and the true stress-true strain curve for SBS polymer-modified binder and non-SBS polymer-modified binder are distinguishable. The loading rate of 500 mm/min was found to be appropriate as the start point of the BFE test. The seven asphalt binders in this study can be ranked into three groups based on fracture energy values: binders with average fracture energy 1) above 400 psi (Binder-G, Binder-B, and Binder-F), 2) above 800 psi (Binder-A and Binder-D), and 3) above 1200 psi (Binder-C and Binder-E).

Comparing to PAV residue only, similar conclusions (i.e. loading rates independent characteristic) can be made based on testing results of RTFO-plus-PAV-aged specimens. However, for all binders, higher fracture energy results were obtained from specimens experienced RTFO-plus-PAV aging tests than the ones from PAV residue only. SBS polymer-modified binders had greater increases in fracture energy than non-SBS polymer-modified binders. Also, the second stress peak on the true stress-true strain curve of SBS polymer-modified binder, which indicates the existence of SBS polymer, became more pronounced after the RTFO test. The RTFO test was found to be difficult to perform on the Binder-C, as it kept leaking out of the glass bottles during the rotation. Based on fracture energy values of RTFO-plus-PAV-aged specimens, the new ranking of seven binders generally agreed with previous grouping results.

In conclusion, the new BFE test and data interpretation system provides accurate and repeatable measurements of fracture energy of binders. The presence of SBS polymer modifier can be identified from the true stress-true strain curves of either PAV residue specimen or RTFO-plus-PAV-aged specimen. Several recommendations were made regarding implementation of this work, including performing BFE tests on rubber-modified asphalt binders and hybrid asphalt binders (rubber and polymer), and further use and evaluation of the test to determine binder damage rates and fracture properties of mastic and mixture.

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CHAPTER 1 INTRODUCTION

1.1 Background

Research by Roque et al (1) revealed that existing methods of testing asphalt binders used nationally under the current specifications—including Dynamic Shear Rheometer (DSR) ($G^*\sin\delta$), Elastic Recovery, and Force-Ductility—fail to provide parameters that consistently correlate with the relative cracking performance of mixtures in the field at intermediate temperatures (i.e., 0–30˚C). The presence of coarse rubber in rubber-modified binder and hybrid binder may yield suspicious DSR and Multiple Stress Creep Recovery test results. Fracture energy is reputed to have a strong correlation with the fracture resistance of asphalt mixtures, which is strongly influenced by the fatigue resistance of asphalt binder.

Fracture energy analysis can be used to predict cracking performance, but Direct Tension (DT) testing is deficient in terms of obtaining fracture energy accurately. Specifically, the relatively long middle section of a DT specimen makes it not only difficult to apply a high enough strain rate to reduce ductility, but also impossible to ensure the location of the failure plane and determine the corresponding failure strain. Researchers (2) at the University of Florida developed a new binder test to determine Binder Fracture Energy (BFE) as part of FDOT Research Project BDK75 977-27, "Development of a Binder Fracture Test to Determine Fracture Energy". The new specimen geometry successfully overcomes the deficiencies of DT tests by consistently locating the failure plane at the center of the specimen. This geometry also eliminated the sharp corners that were causing stress concentrations and premature cracking.

The resulting BFE test clearly distinguished various binder types using the measured fracture energy density and unique characteristics of true stress-true strain curves. In addition, BFE test results indicate that the presence—and to some extent, the content—of SBS polymer in the binder can be identified from the characteristics of the true stress-true strain curve. The BFE test provides an economical alternative to mixture fracture tests for evaluating the relative effects of various modifiers on cracking performance, which is the main purpose of this study.

1.2 Objectives

The overall objective of this research was to use the newly developed BFE test to measure the fracture energy density of asphalt binders with various additives. It should be noted that "fracture energy" is short form of the full term "fracture energy density". Both were used interchangeably throughout the report. In consultation with FDOT, the researchers selected seven types of asphalt binder with different additives, all of which were intended to meet the current specification requirements for PG 76-22 (PMA). Detailed objectives of this research are as follows:

- Perform BFE tests on selected binders at 15˚C using the protocol established in BDK75 977-27.
- Evaluate and compare the test results of various binders to characterize their respective true stress-true strain curves, and evaluate the cracking performance from the point view of fracture energy.
- Develop a testing standard protocol that can be used by the FDOT to perform and analyze BFE tests.

1.3 Scope

The FDOT delivered the seven selected asphalt binders to University of Florida. Two types of aged specimens were prepared and tested including PAV residue only and RTFO-plus-PAV-aged specimens. This study tested all binders at 15˚C using an MTS servo-hydraulic testing machine.

CHAPTER 2 SPECIMEN PREPARATION AND TESTING PROGRAM

2.1 Specimen Preparation

2.1.1 Material

Seven asphalt binders were provided by the FDOT and delivered to University of Florida for the BFE test, as listed in Table 1.

Table 1 Material Inventory

Binder ID	Weight (g)
A	710
B	740
C	700
D	650
E	690
F	860
G	790

2.1.2 Specimen Preparation

The specimens preparation follows the previous developed testing protocol in BDK75 977-27. The asphalt binders were preheated in an oven until sufficiently fluid to pour. The first step in creating the specimens was to clean the mold assemblies (i.e., bottom plate, two side plates, piece of Mylar, two end tabs, two paper clamps) and create a complete testing mold set (Figure 1). The next steps were to place the asphalt binder in the oven at the appropriate temperature, and then stir the asphalt binder using a hot glass bar before pouring it into the mold. The third step was rapidly and continuously pouring the asphalt binder into the mold from one side to the other, ensuring excess sample extended over the top of the mold (Figure 2). The researchers then trimmed the specimen surface with a hot spatula after the specimen reached room temperature (Figure 3). The final step was to place the specimen into the MTS chamber to reach testing temperature.

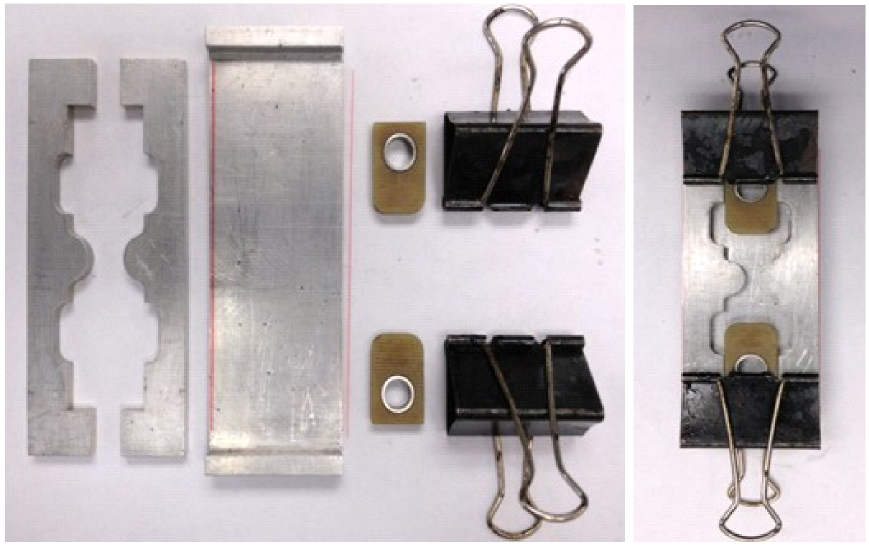

Figure 1 Mold assembly and complete mold set

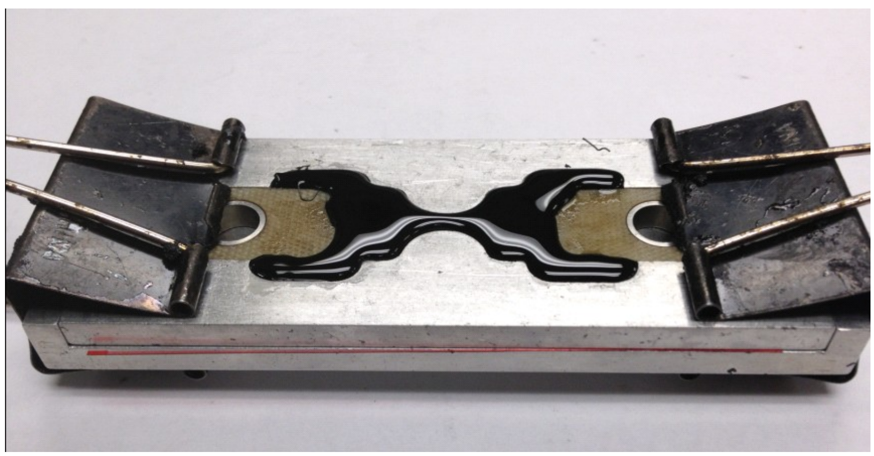

Figure 2 Overpouring binder into mold

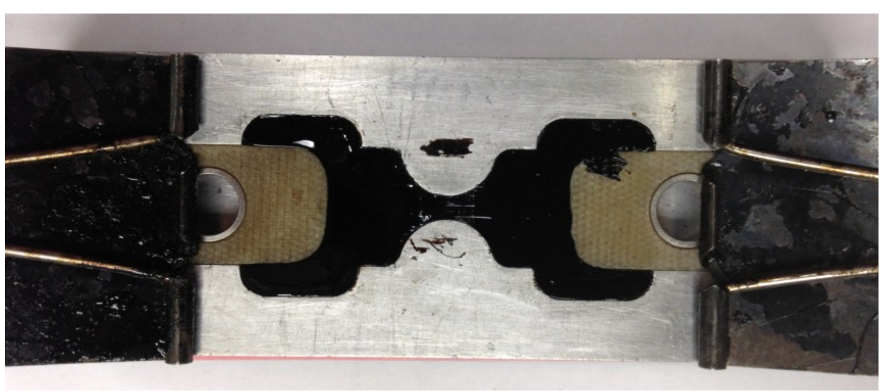

Figure 3 Specimen after trimming surface

2.2 Testing Program

2.2.1 Testing Method

The BFE tests were performed at 15˚C, using an MTS closed-loop servo-hydraulic loading system, and conditioned the specimens inside an MTS environmental chamber that provides a suitable and stable testing environment (Figure 4). A temperature controller monitored the temperature of the chamber, ensuring it remains within ±0.5˚C. The specimen was fixed to the lower loading head and pulled from the upper loading head at a selected loading rate until rupture occurred (Figures 5-A and 5-B). The distance between the upper and lower loading heads was calibrated before performing any BFE tests to allow the two press fit pins to be easily and smoothly inserted into the cavities of the de-molding gauge. The specimen was vertically suspended between the upper and lower loading heads, as any bending or twisting will deform the specimen, causing it to become unusable.

Figure 4 Conditioning specimen in the MTS Chamber

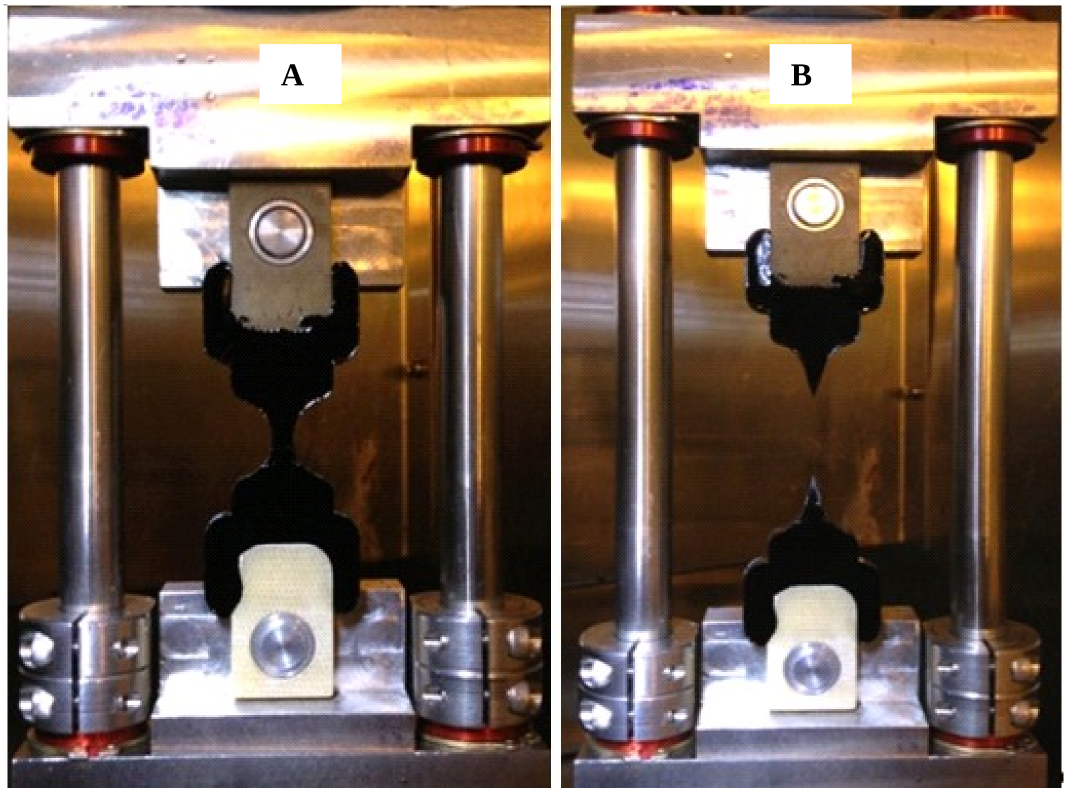

Figure 5 Specimen configurations before (A) and after (B) BFE test

2.2.2 Testing Plan

The testing program included two aging conditions for the binders: PAV aging only and RTFO-plus-PAV aging. The RTFO test was conducted following AASHTO T240, “Standard Method of Test for Effect of Heat and Air on a Moving Film of Asphalt Binder (Rolling Thin-Film Oven Test)” and the PAV test was performed following AASHTO R28, “Standard Practice for Accelerated Aging of Asphalt Binder Using a Pressurized Aging Vessel (PAV)” (Figures 6-A and 6-B). BFE tests were conducted on PAV residue, in order to compare the results with BDK 75 977-27, measure fracture energy, characterize true stress-true strain curves, and evaluate and modify the previously established testing protocol.

The FDOT BDK75 977-27 recommended testing at 15˚C, as the least variance in measured fracture energy occurred at this temperature; therefore, in present study all tests were conducted at this temperature. The researchers used loading rates of 500–900 mm/min to verify the independent loading characteristics of the BFE test and to determine the appropriate loading rate for testing on RTFO-plus-PAV-aged specimens. Friction tests were conducted at the same testing temperature with various loading rates to obtain the pulling resistance between bearings and metal bars.

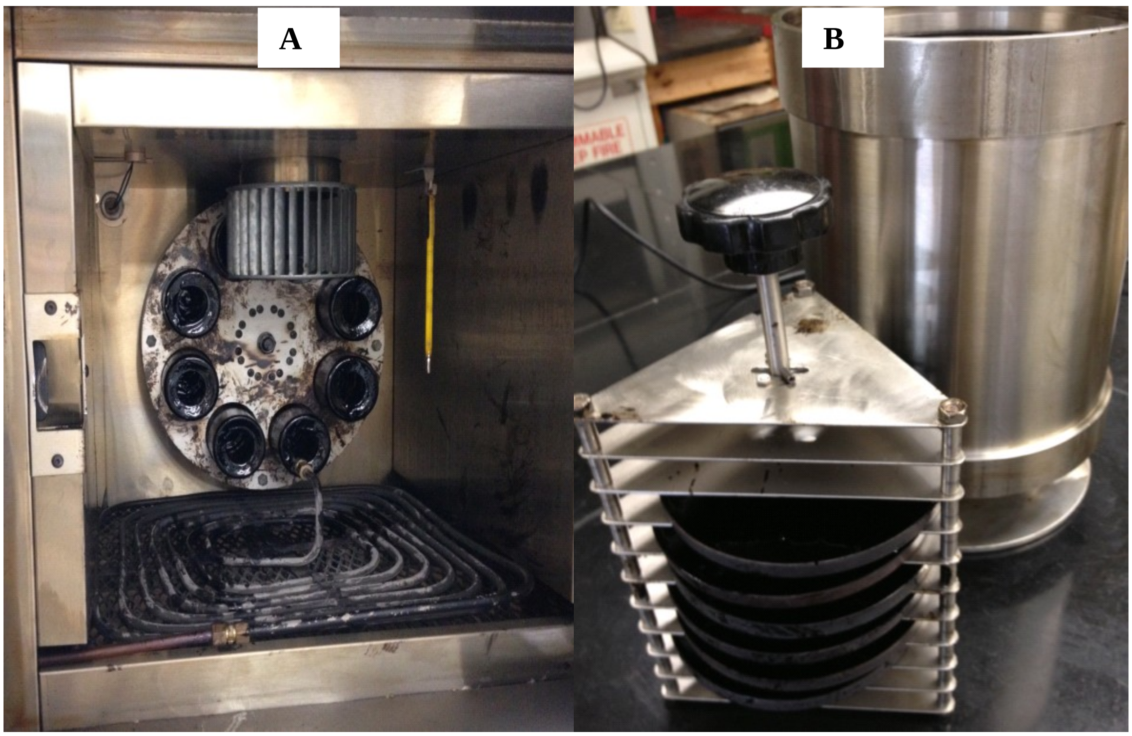

Figure 6 Performing RTFO test (A) and PAV test (B)

CHAPTER 3 TEST RESULTS

3.1 Friction Test Results

Comparing to previous project, a new loading frame was manufactured which provides more accurate stress data by eliminating mechanical noise to large extents. The MTS machine output data were consistent over various loading rates, and an average friction value of 1.1496 pounds was used in the data analysis (Figure 7).

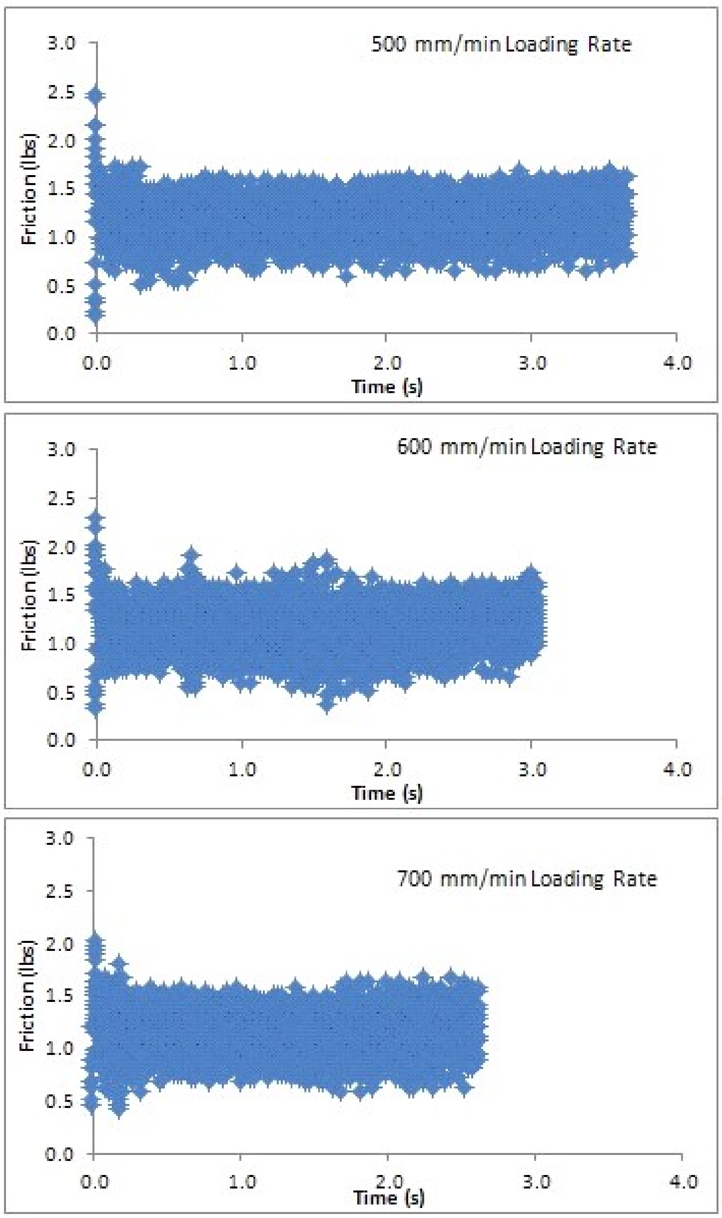

Figure 7 Friction test results at 500, 600, and 700 mm/min loading rates

3.2 PAV Residue Only

The researchers prepared and tested the PAV residue of seven asphalt binders at 15˚C using loading rates of 500–900 mm/min. Testing results are listed in Table 2.

Table 2 Testing Results for PAV Residue Only

Binders	**Loading Rate (mm/min)**	**Extension to Fracture (in)**	**Fracture Energy (psi)**
Binder-B	500	0.9932	448.28
	600	0.9829	383.52
	700	0.9576	393.11
	800	0.8739	449.83
	900	0.8949	421.77
Binder-C	500	2.1562	1204.68
	600	2.0800	1417.26
	700	2.1006	1014.63
	800	1.7506	1230.76
	900	2.5037	1154.25
Binder-A	500	1.7829	865.09
	600	1.7854	833.49
	700	1.7410	910.99
	800	1.6413	945.96
	900	0.9597	397.17
Binder-D	500	1.6475	874.07
	600	1.6787	835.07
	700	1.6834	846.19
	800	1.5253	875.55
	900	1.5476	856.48
Binder-E	500	2.1957	1269.51
	600	2.1966	1316.06
	700	2.1577	1228.71
	800	2.1169	1353.44
	900	2.0266	1348.63
Binder-F	500	0.9913	436.53
	600	1.0268	430.61
	700	1.0467	499.73
	800	0.9939	369.99
	900	0.9928	511.16
Binder-G	500	0.9438	337.97
	600	0.9432	391.25
	700	0.9873	402.95
	800	0.9667	415.77
	900	0.9002	439.52

3.2.1 Binder-A

The fracture energy of Binder-A was generally consistent at various loading rates, except for at 900 mm/min, when the fracture energy was clearly lower than at the other loading rates (Figure 8). A second specimen was prepared and tested but ended in premature fracture failure, indicating that the polymer could not function well at this high loading rate.

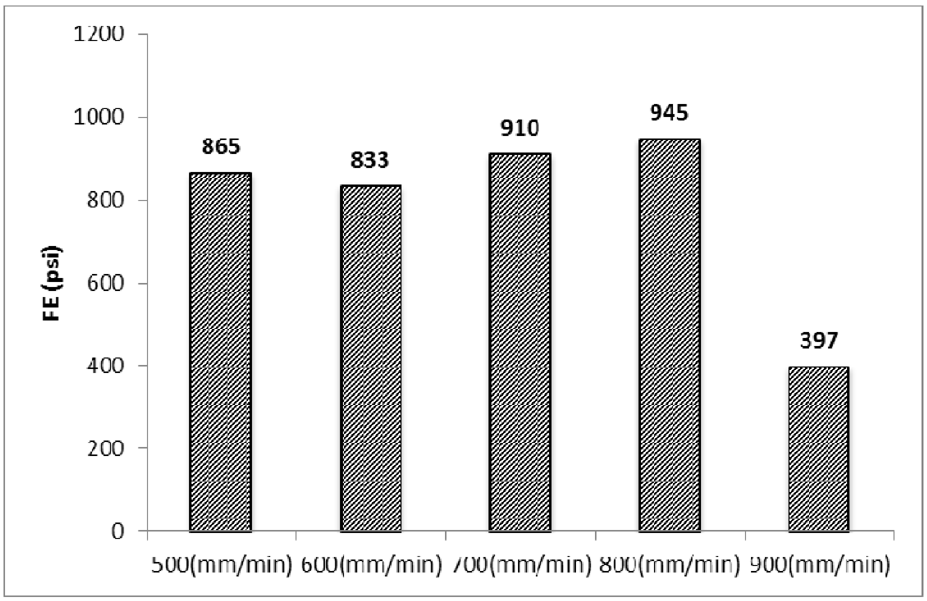

Figure 8 Binder-A, fracture energy vs. loading rates

The true stress-true strain curves of Binder-A, except that of the specimen tested at 900 mm/min, exhibited similar patterns and shapes with a clear second peak at various loading rates (Figure 9). The specimen tested at 500 mm/min exhibited a more pronounced second stress peak than the others, which indicates that this loading rate was appropriate for identifying the existence of SBS polymer in Binder-A. The true stress-true stain curves for specimens tested at the loading rates from 600 mm/min to 800 mm/min look similar to that of rubber-modified binders. As described in BDK75 977-27, the term “inflection” is attributed to an obviously lower second stress peak which indicates the existence of rubber in the asphalt binder. However, the fracture energy of rubber-modified asphalt binder was found in the range of 400 to 500 psi. In this case, the higher average fracture energy of Binder-A excluded the possibility that this binder was rubber-modified. Also, the second stress peak becomes more pronounced as RTFO test was added which will be discussed in section 3.3.1.

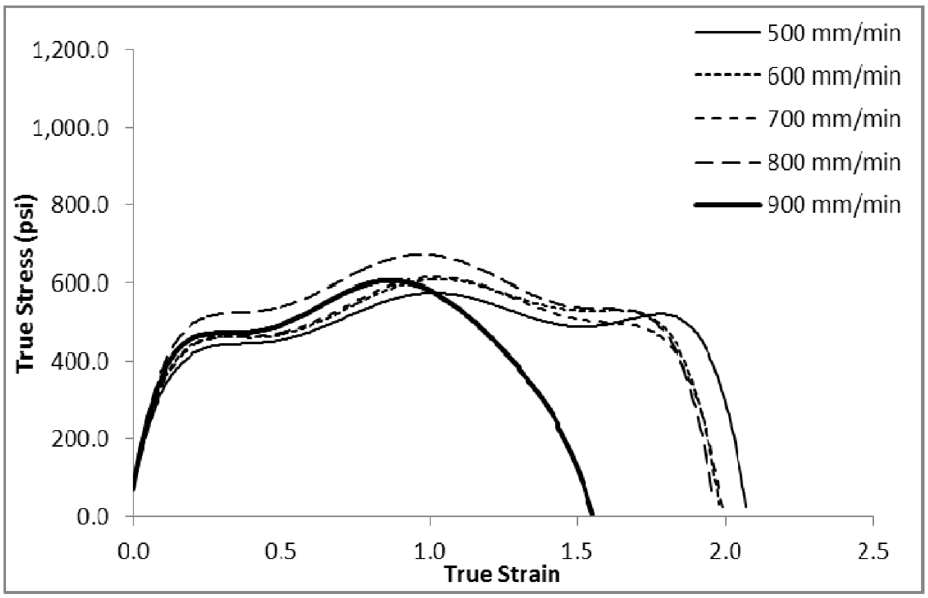

Figure 9 Binder-A, true stress-true strain

3.2.2 Binder-C

The specimen tested at 600 mm/min exhibited the largest fracture energy value (Figure 10), but the fracture energy for the ones at 700 mm/min, 800 mm/min and 900 mm/min were consistent, with a difference of less than 10% (15% tolerance was defined in BDK75 977-27). The true stress-true strain curves of Binder-C at various loading rates all exhibited an obvious second stress peak (Figure 11). Specimens tested at 700 mm/min and 800 mm/min had higher stress value than the one tested at 600 mm/min before hitting the second stress peak. The second stress peak and high fracture energy identified the existence of SBS polymer in the binder.

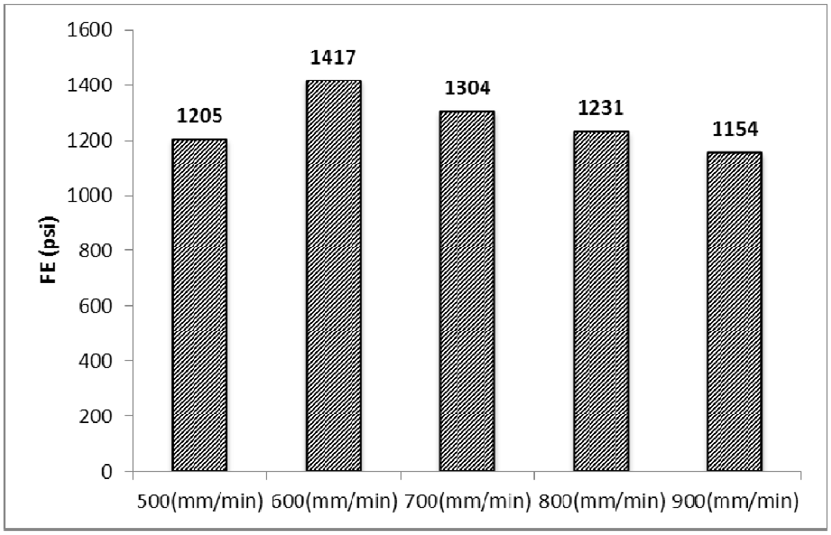

Figure 10 Binder-C, fracture energy vs. loading rates

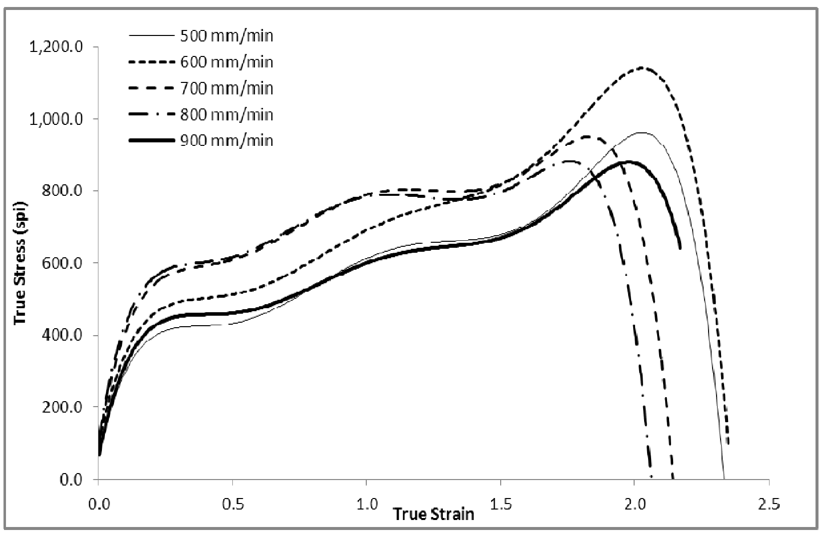

Figure 11 Binder-C, true stress-true strain

3.2.3 Binder-B

The fracture energy results were consistent for Binder-B at various loading rates (Figure 12). The loading rates had no influence on the fracture energy. It is clear that the fracture energy of Binder-B is lower than Binder-C and Binder-A. None of the curves exhibited a second stress peak (Figure 13), which is characteristic of SBS polymer-modified binder. The BFE test effectively distinguished between non-SBS polymer modified and SBS-polymer-modified binder.

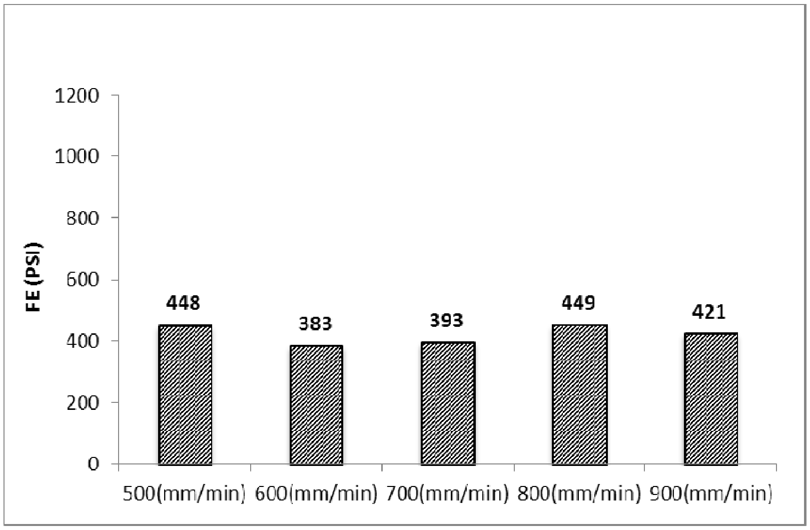

Figure 12 Binder-B, fracture energy vs. loading rates

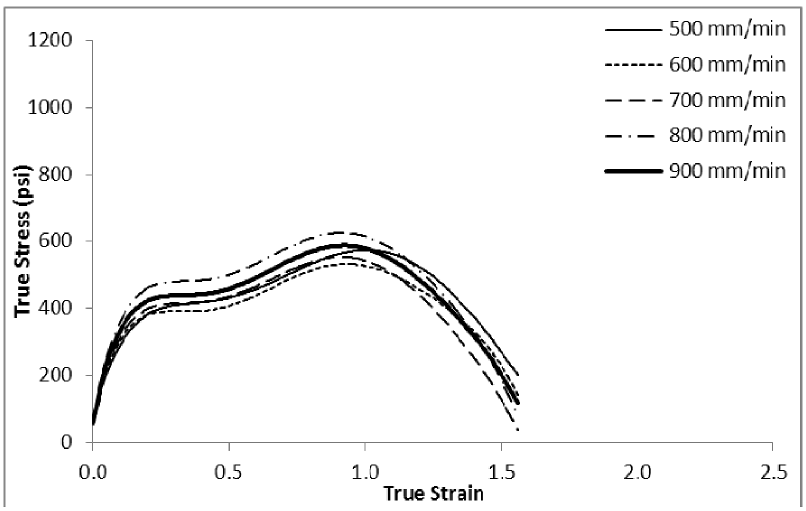

Figure 13 Binder-B, true stress-true strain

3.2.4 Binder-G

The fracture energy results for Binder-G were similar at various loading rates (Figure 14); however, unlike other tested binders, the fracture energy increased as the loading rate increased. The fact that the differences between the fracture energies of specimens tested at 600, 700, and 800 mm/min were much smaller than the previously established tolerance (15%), it is unlikely that fracture energy is dependent on loading rates. The true stress-true strain curve for tests conducted at 500 mm/min exhibited a lower stress value, and curves identical to those of the other four specimens at the same strain level (Figure 15). The true stress-true strain curve for Binder-G exhibited only one stress peak, regardless of loading rate, and the fracture energy was much lower than SBS-polymer-modified binder, which confirmed the feasibility of using the BFE test to identify the existence of SBS polymer in asphalt binder.

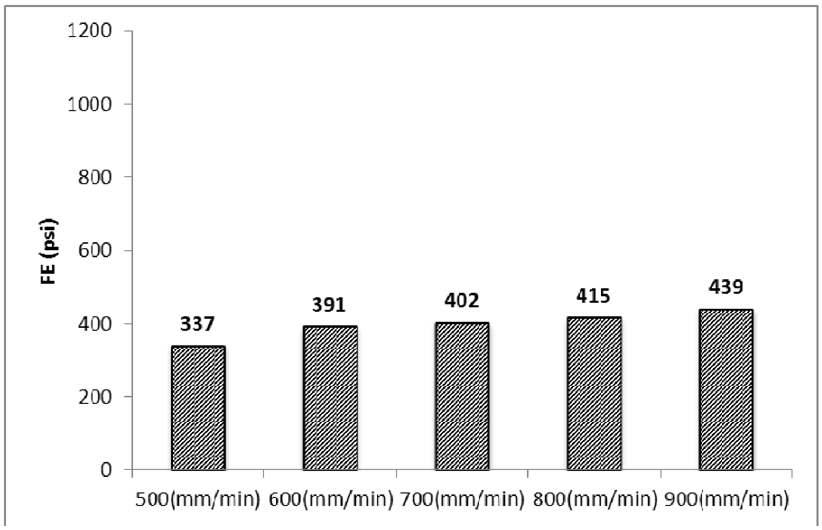

Figure 14 Binder-G, fracture energy vs. loading rates

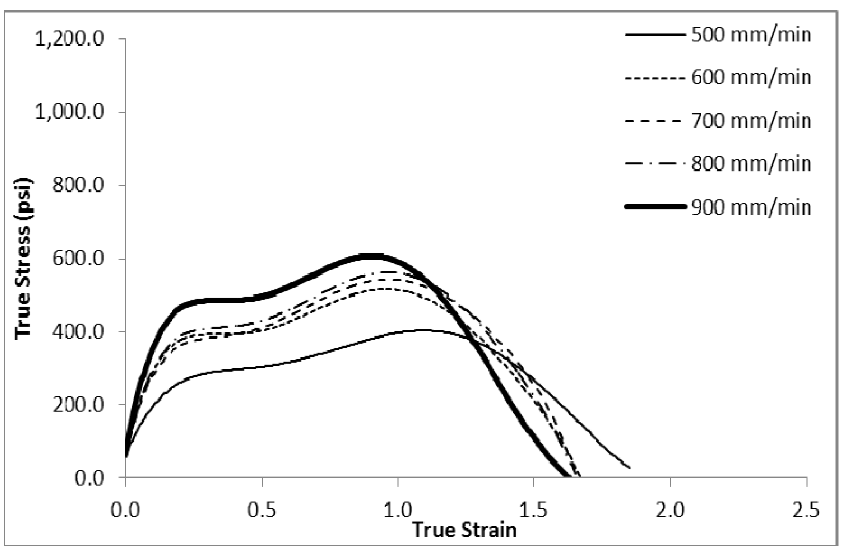

Figure 15 Binder-G, true stress-true strain

3.2.5 Binder-E

The fracture energy densities of Binder-E were consistent at various loading rates, with a difference of less than 10% (Figure 16). The fracture energy of Binder-E was clearly higher than any of the other tested binders, which suggests that Binder-E would perform better in terms of cracking resistance at intermediate temperature. The true stress-true strain curves for Binder-E at various loading rates exhibited clear second stress peaks that were higher than the first stress peaks (Figure 17). At 900 mm/min, the strain value at the second peak was lower than that of other specimens, but since it exhibited a larger stress value at the corresponding strain level, the fracture energy value itself was comparable to the others.

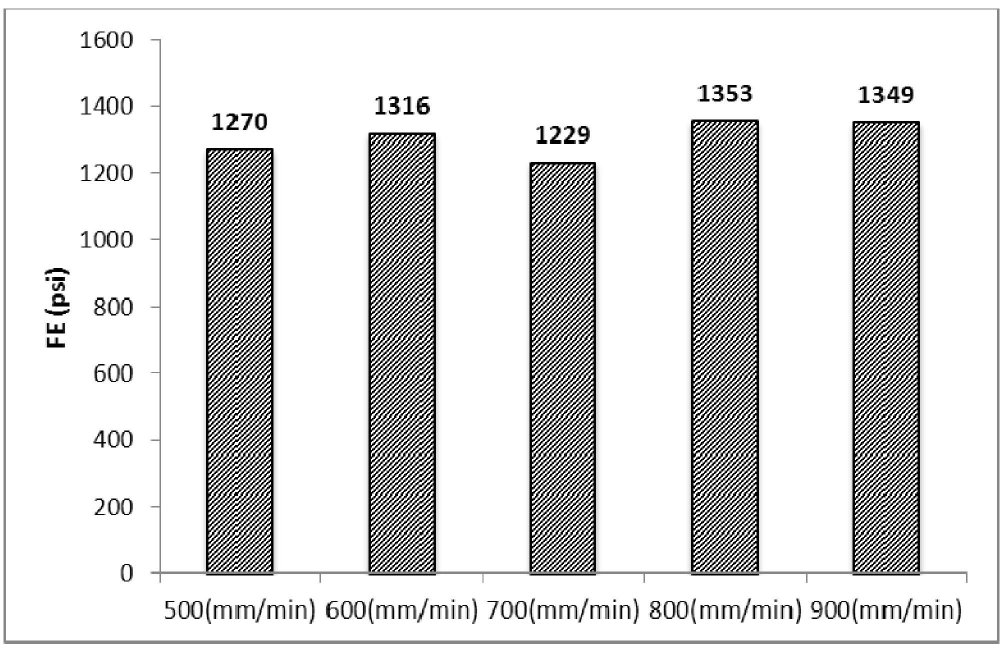

Figure 16 Binder-E, fracture energy vs. loading rates

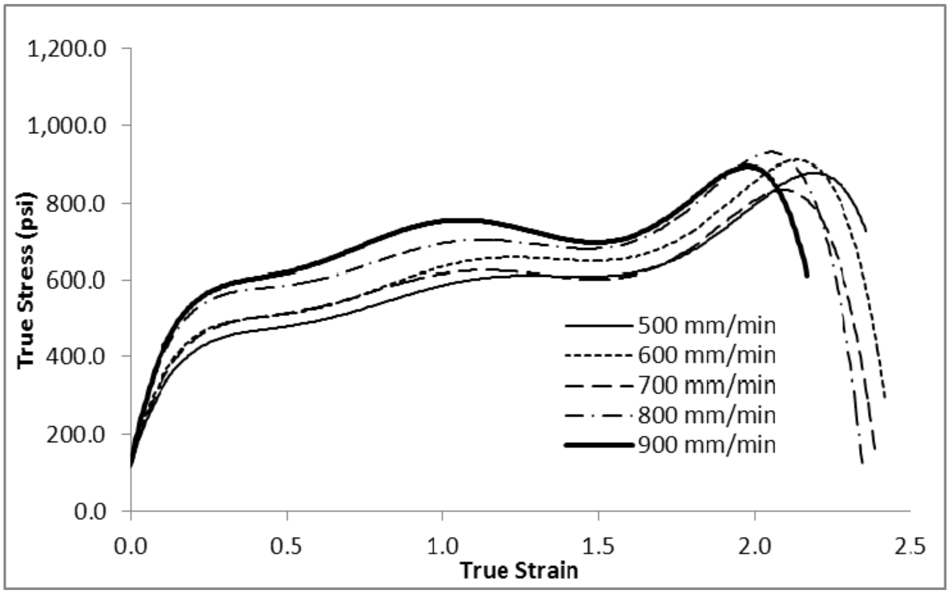

Figure 17 Binder-E, true stress-true strain

3.2.6 Binder-F

Binder-F exhibited consistent fracture energy results at various loading rates (Figure 18), except for the specimen tested at 800 mm/min. A second specimen was prepared and tested at this loading rate, but encountered premature fracture failure (Figure 19); similar to what occurred when Binder-A was tested at 900 mm/min. The true stress-true strain curve for the specimen tested at 800 mm/min exhibited a clearly lower stress value compared to other specimens at the same strain levels (Figure 20). The Binder-F curves did not exhibit a second stress peak, which suggests that it may not be a SBS-polymer-modified binder. Therefore, the researchers concluded that Binder-F had similar fracture energy to Binder-B and Binder-G, and expected that the three performed similarly in terms of cracking resistance at intermediate temperature.

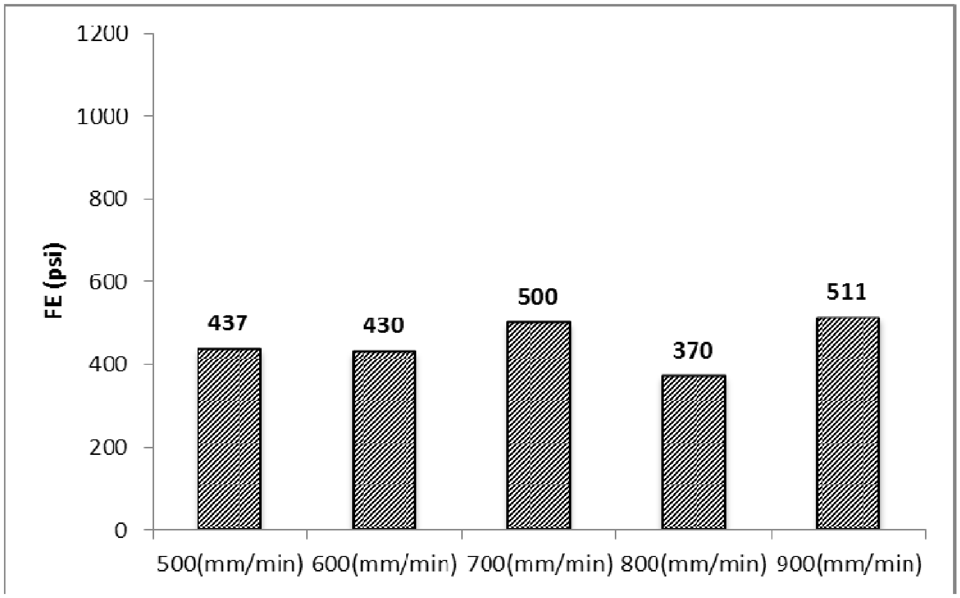

Figure 18 Binder-F, fracture energy vs. loading rates

Figure 19 Premature fracture failure of Binder-F PAV residue at 800 mm/min

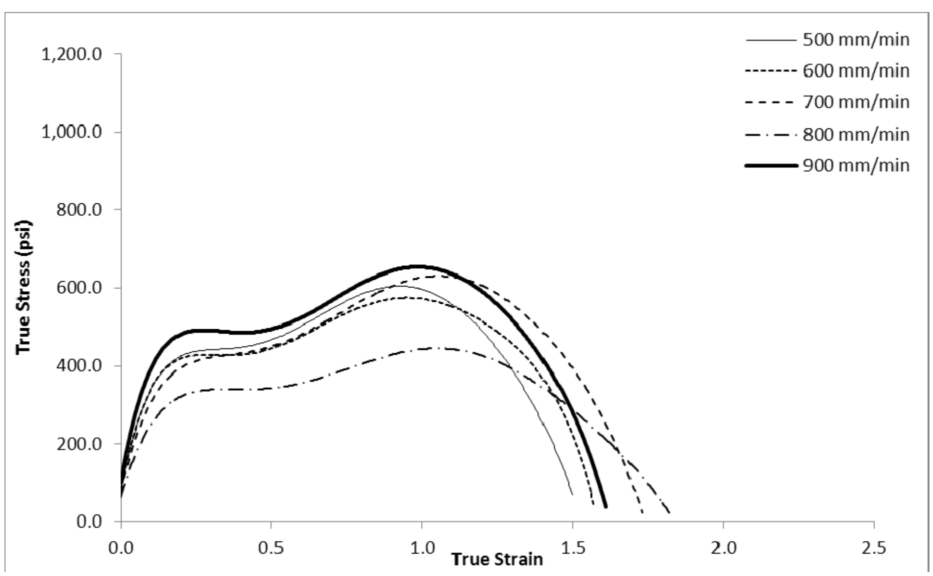

Figure 20 Binder-F, true stress-true strain

3.2.7 Binder-D

Binder-D exhibited consistent fracture energy results at various loading rates (Figure 21). The second stress peak values at 500, 600, and 700 mm/min were close to the first stress peak; however, at 800 and 900 mm/min, the second stress peak was lower than the first stress peak. This observation indicates the loading rates of 800 mm/min and 900 mm/min may be too fast for this binder, and SBS polymer could not function well.

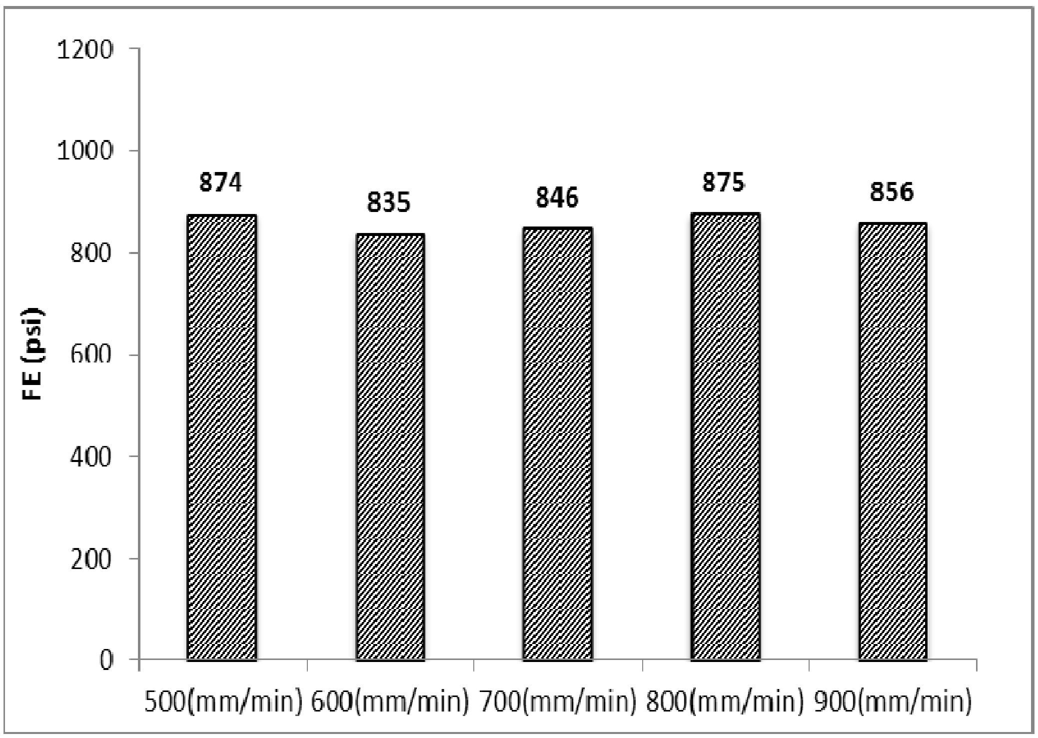

Figure 21 Binder-D, fracture energy vs. loading rates

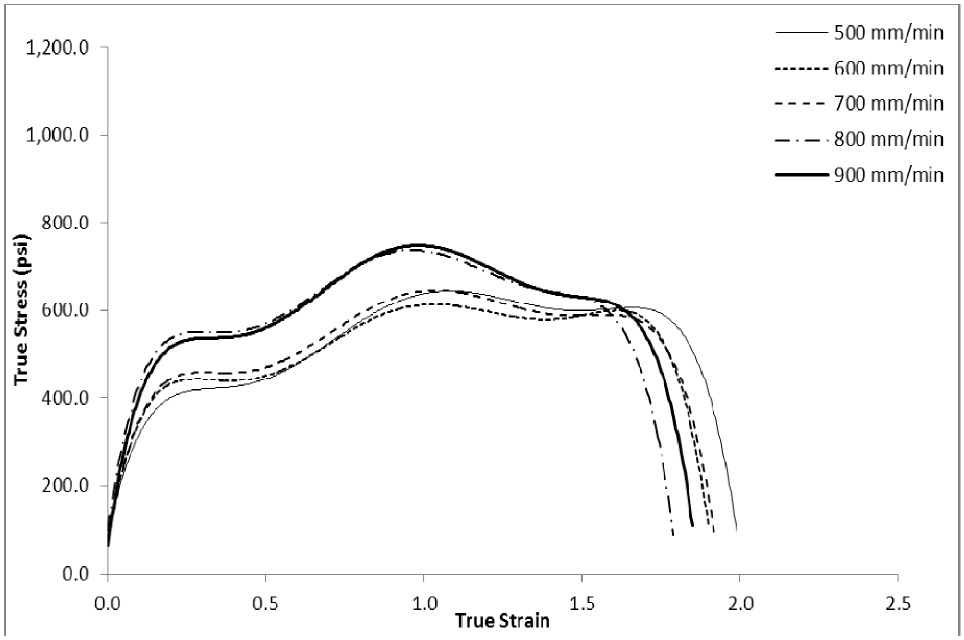

Figure 22 Binder-D, true stress-true strain

3.2.8 Overall Analysis on PAV Residue

As discussed above, PAV residue specimens exhibited consistent fracture energy at various loading rates. This research confirmed true stress-true strain curve characteristics identified in BDK75 977-27 for non-SBS polymer-modified and SBS polymer-modified binder. The researchers averaged, ranked, and plotted the fracture energy data based on material type, in order compare the seven tested asphalt binders (Figure 23). The fracture energies of Binder-G, Binder-B, and Binder-F were clearly similar, and they were much lower than those of the other four binders. In terms of fracture energy, the testing results indicates that binders with various additives can exhibit varied cracking resistance, even were all intended to meet the same Superpave PG 76-22 (PMA) requirements.

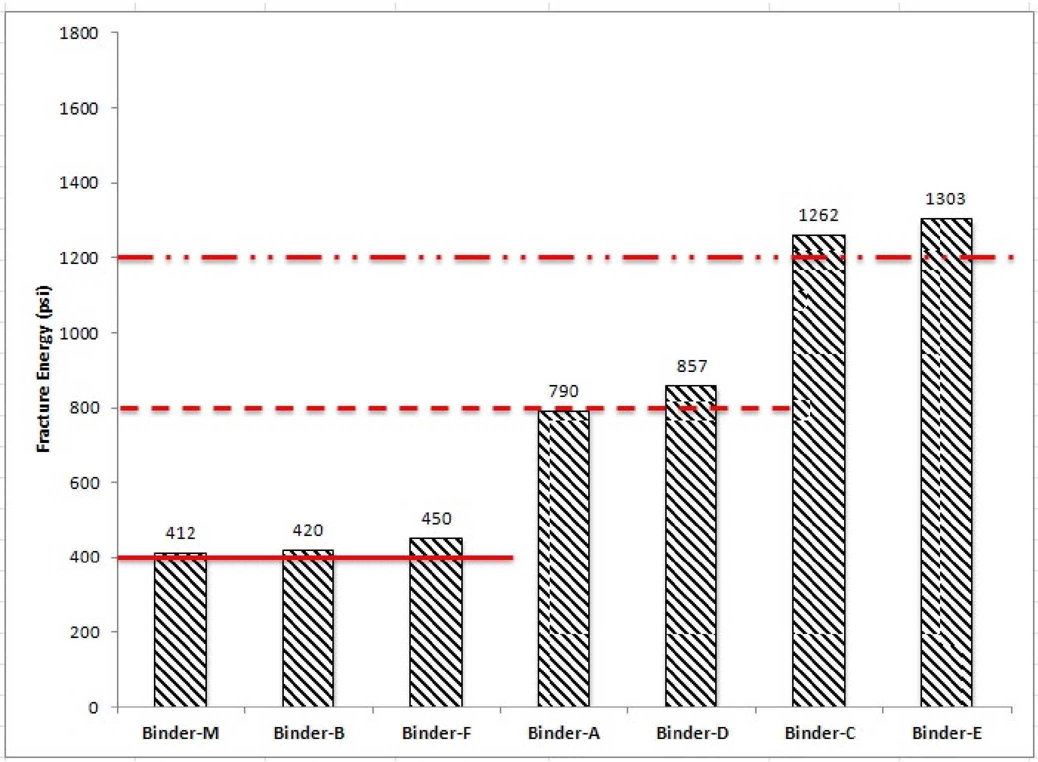

Figure 23 Average fracture energy densities for all PAV residue binders

The researchers ranked the fracture energy of all binders tested as per below:

- ✓ Binder-E and Binder-C exhibited fracture energy with average values greater than 1200 psi, which was significantly higher than the fracture energy of the other five binders. Binder-E exhibited the greatest fracture energy.
- ✓ Binder-A and Binder-D exhibited similar average fracture energy with average values close to 800 psi, which was lower than the two above binders. The true stress-true strain curves of these two binders exhibited first stress peak strain values similar to the above two binders; however, the second stress peak was less pronounced in Binder-A and Binder-D, which indicates that they may have contained less amounts of SBS polymer than Binder-E and Binder-C.
- ✓ Binder-G, Binder-B, and Binder-F exhibited the lowest average fracture energy value (approximately 400 psi). All three true stress-true strain curves exhibited neither a second stress peak nor an inflection. According to BDK75 977-27, unmodified PG 76-22 asphalt binder normally exhibits fracture energy of 200–

300 psi and the true stress-true strain curve of non-SBS-modified binder exhibits neither a second stress peak nor an inflection. However, binders in this category have similar true stress-true strain curve with non-SBS polymer-modified binder, but relatively higher fracture energy than unmodified binder.

3.3 RTFO-plus-PAV Residue

As discussed above, all specimens exhibited consistent fracture energy at 15°C, regardless of loading rate; therefore, the researchers selected this temperature for all BFE tests on RTFO-plus-PAV-aged specimens. The researchers conducted two tests on each specimen with a starting loading rate of 500 mm/min. If premature failure occurred at 500 mm/min, a reduction in loading rate by 100 mm/min should be made. If elongation occurred, the researchers increased the loading rate by 100 mm/min. Figure 24 presents the overall fracture energy data obtained for all specimens at 500 mm/min and testing results are listed in Table 3.

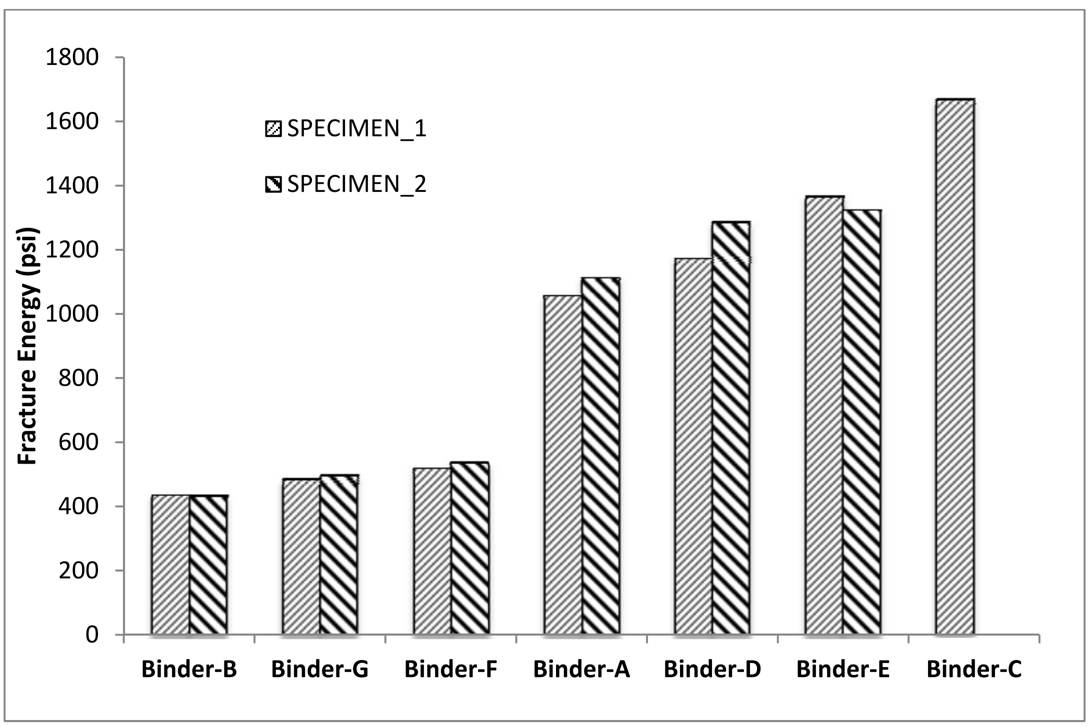

Figure 24 Fracture energy data for all tested specimens at 500 mm/min.

Table 3 Testing Results for RTFO-plus-PAV-Aged Specimen

Binders	Loading Rate (mm/min)	Extension to Fracture (in)	Fracture Energy (psi)
Binder-B	500	461.8	1.0642
	500	512.01	0.9714
Binder-C	500	1667.49	1.9875
	NA	NA	NA
Binder-A	500	1055.54	1.7274
	500	1112.31	1.6706
Binder-D	500	1171.67	1.5479
	500	1284.44	1.6139
Binder-E	500	1365.62	1.8317
	500	1323.03	1.8873
Binder-F	500	518.01	0.9717
	500	536.15	0.967
Binder-G	500	483.67	1.0032
	500	495.14	0.9991

3.3.1 Binder-A

The true stress-true strain curves for two specimens of Binder-A exhibited clear second stress peaks and corresponding true strain value of approximately 1.6 (Figure 25). Specimen 1 exhibited a slightly higher stress peak than Specimen 2, but a lower true strain value at the second stress peak, which resulted in the two specimens exhibiting comparable fracture energy. The second peak stress increased and became greater than the first stress peak value after RTFO testing. This binder likely contained SBS polymer, based on the true stress-true strain curve characteristics and fracture energy magnitude.

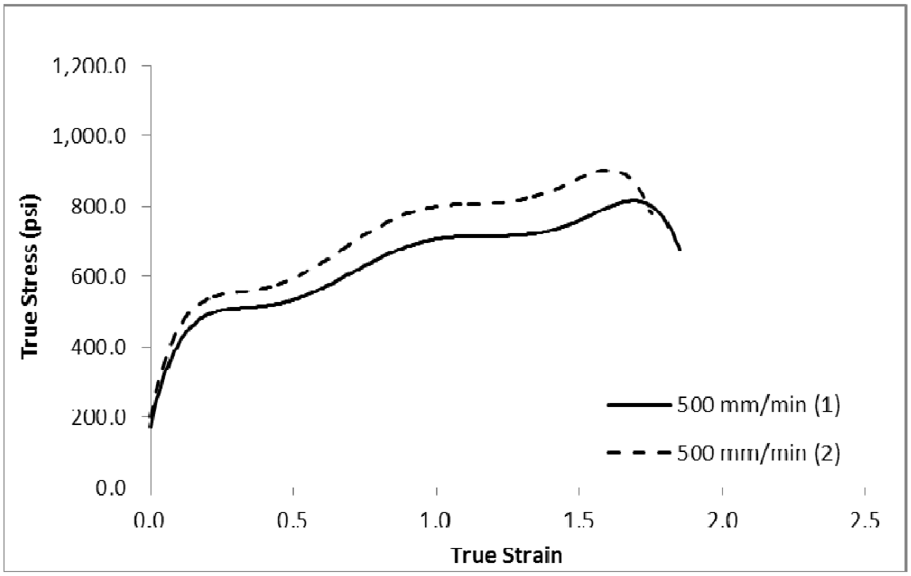

Figure 25 Binder-A, RTFO-plus-PAV, true stress-true strain

3.3.2 Binder-C

Only one test of Binder-C succeeded at 500 mm/min (Figure 26). A second test at this loading rate ended in premature fracture failure. Further attempts failed to produce additional RTFO-plus-PAV-aged material of this binder. During the RTFO test, the binder did not roll inside the bottles with the carriage very well, but continually leaked out of the opening. One possible explanation for this phenomenon is that the viscosity of the Binder-C specimen remained high during testing and did not reduce enough to flow at the RTFO testing temperature. As the testing temperature reduced, the polymer quickly became rigid and the viscosity quickly increased, causing difficulties while pouring the binder into the mold. Therefore, an understanding of the viscosity-temperature relationship is necessary for this binder. Despite only one test succeeding, it was clear that that RTFO significantly increased the fracture energy of Binder-A. In this case, the second stress peak was so high that it caused the first stress peak to be nearly indistinguishable.

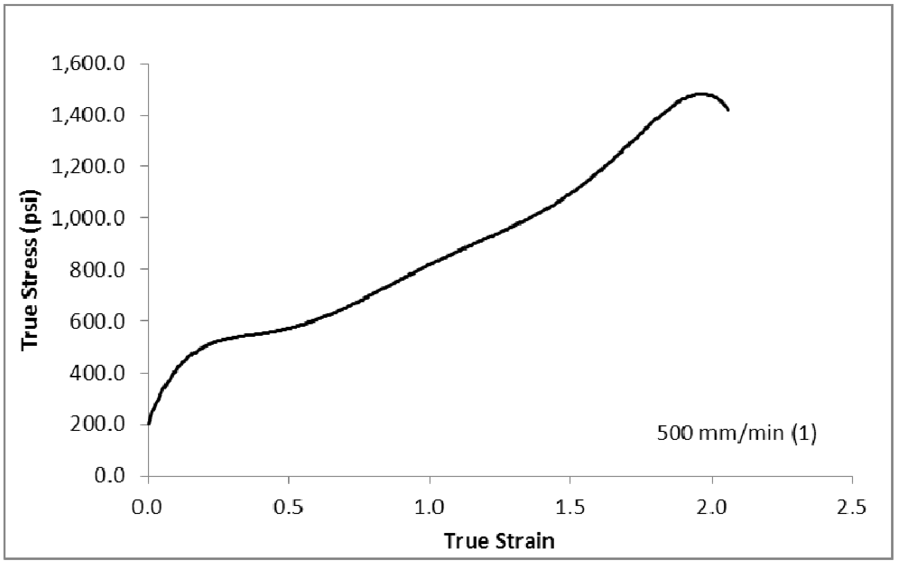

Figure 26 Binder-C, RTFO-plus-PAV, true stress-true strain

3.3.3 Binder-B

Two specimens of Binder-B exhibited similar fracture energy at 500 mm/min (Figure 27). The true stress-true strain curves exhibited one stress peak, indicating that the RTFO test does not cause a second stress peak for non-SBS polymer-modified asphalt binder. The average fracture energy was slightly higher than that of the specimens of PAV residue only.

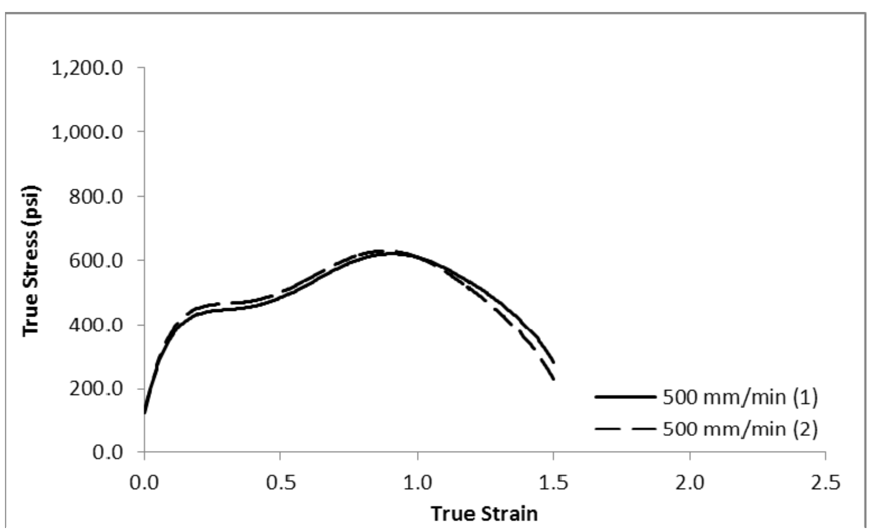

Figure 27 Binder-B, RTFO-plus-PAV, true stress-true strain

3.3.4 Binder-G

Binder-G exhibited two similar true stress-true strain curves (Figure 28).

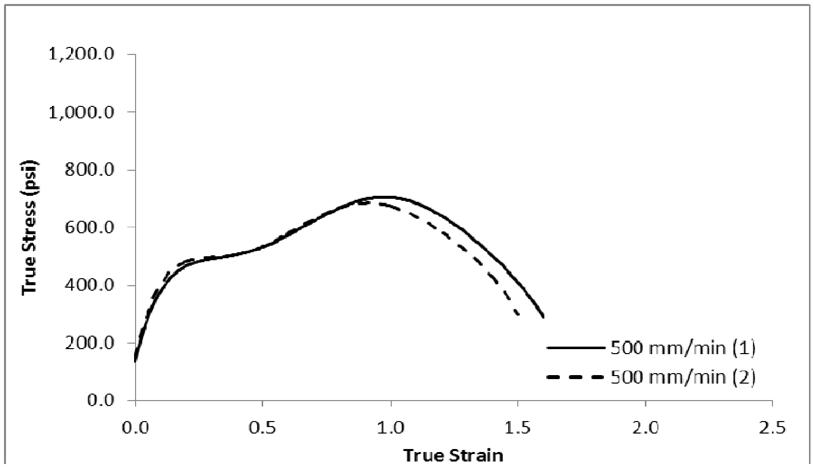

Figure 28 Binder-G, RTFO-plus-PAV, true stress-true strain

3.3.5 Binder-E

Both BFE tests were successful at 500 mm/min loading rate. The true stress-true strain curves were similar, with one specimen exhibiting a slightly higher stress value than the other (Figure 29). The difference between two fracture energies was 3%, which is insignificant, since the specimen with the lower second stress peak compensated with a larger strain value. The difference between the first stress peak and the second stress peak was significant enough to indicate the presence of SBS polymer.

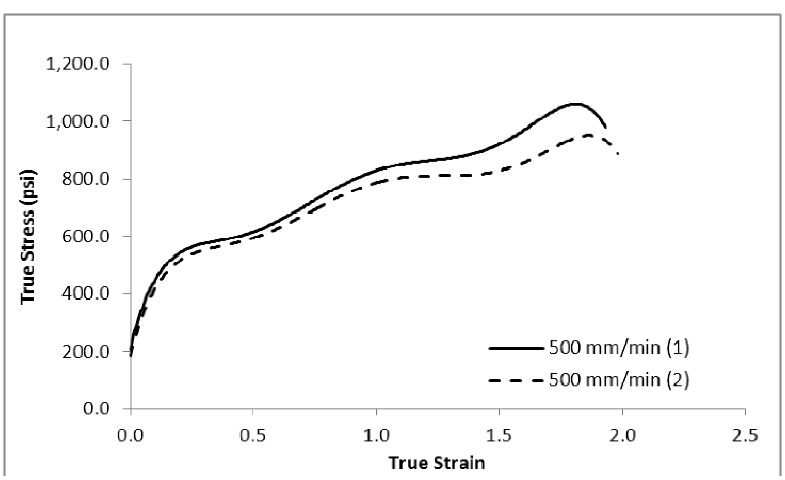

Figure 29 Binder-E, RTFO-plus-PAV, true stress-true strain

3.3.6 Binder-F

The true stress-true strain curves were consistent for two specimens of Binder-F tested at 500 mm/min, with almost identical second peak stress values (Figure 30). The patterns and shapes of the curves remained the same after RTFO testing. The fracture energy was slightly higher than PAV residue only, which confirms the trend that RTFO leads to higher binder fracture energy.

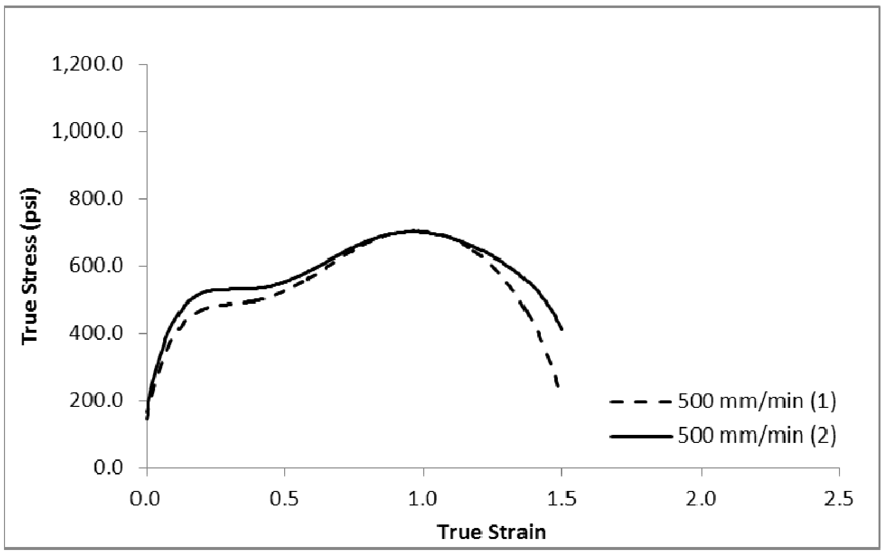

Figure 30 Binder-F, RTFO-plus-PAV, true stress-true strain

3.3.7 Binder-D

The true stress-true strain curves were consistent for two specimens of Binder-D tested at 500 mm/min (Figure 31). Specimen 1 exhibited a lower second peak stress and a lower corresponding strain value than Specimen 2. The difference in fracture energy between two specimens was within 10%, which is acceptable. The second stress peak was clear enough to indicate high polymer content.

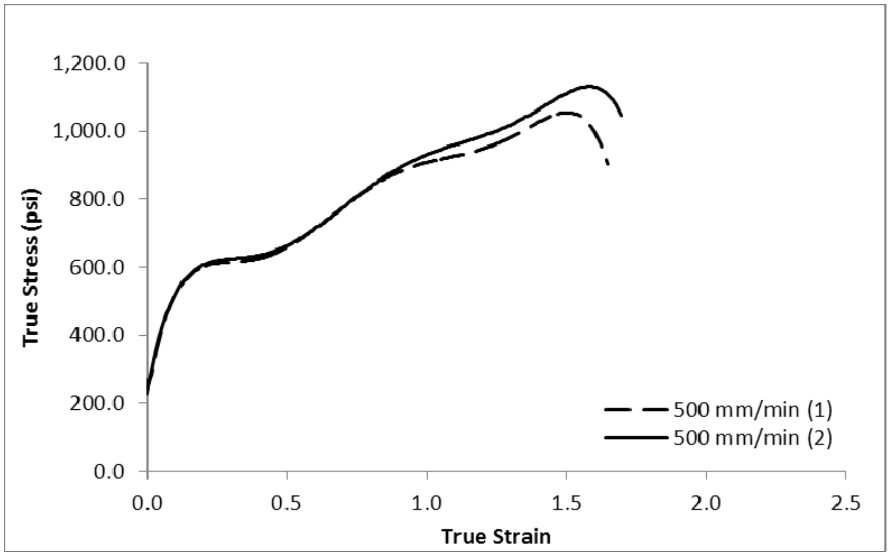

Figure 31 Binder-D, RTFO-plus-PAV, true stress-true strain

3.3.8 Overall Analysis on RTFO-plus-PAV Specimens

The researchers prepared and tested specimens of each binder at 500 mm/min loading rate until two tests were successful. The researchers then calculated and plotted the average fracture energy for all binders (Figure 32).

Discussions about the BFE testing results on RTFO-plus-PAV-aged specimens were listed below:

- ✓ After RTFO testing, Binder-C exhibited the greatest fracture energy value (1667 psi); however, the researchers were uncertain regarding this single value, as only one test was successful, and attempts failed to collect RTFO tested binder material to continue BFE testing. The fracture energy of Binder-E did not increase significantly, but was higher than all other binders, except Binder-C.
- ✓ The average fracture energy of Binder-A and Binder-D increased greatly after RTFO testing. As shown in Figure 32, the fracture energy of Binder-D reached 1200 psi after adding the RTFO test.

- ✓ The average fracture energy of Binder-B, Binder-G, and Binder-F increased slightly after RTFO testing.
- ✓ Overall, RTFO testing did not significantly change the fracture energy for non-SBS polymer-modified asphalt binder; however, it clearly affected the SBS polymer-modified binders.
- ✓ Therefore, RTFO testing can be eliminated when performing BFE tests only to identify the presence of SBS polymer, since the BFE test on PAV residue only could successfully achieve this purpose.

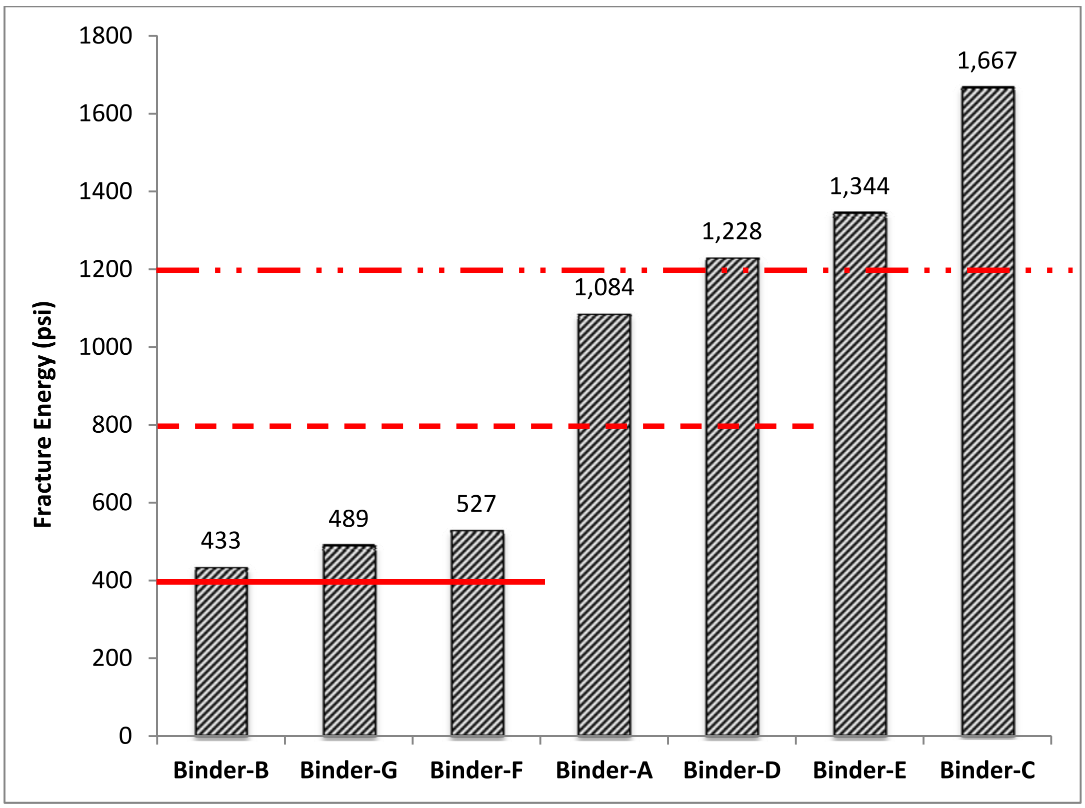

Figure 32 Fracture energy densities for all RTFO-plus-PAV Specimens

3.4 Comparison between PAV residue only and RTFO-plus-PAV Material

RTFO testing is known to simulate manufacturing and placement aging, and PAV tests are known to simulate in-service aging over a 7–10 year period. The specified testing time for RTFO testing is 85 minutes, and 20 hours for PAV testing. The RTFO test increased the fracture energy of all binders tested in this study. This increase was clearer in polymer-modified binders than in non-SBS polymer modified binders. The RTFO test results confirmed the presence of SBS polymer in binders by making the second stress peak to be more pronounced. However, difficulties were encountered when preparing the RTFO-aged SBS polymer-modified asphalt binder specimens for the BFE test. Therefore, further research is needed to determine the necessity of adding RTFO test or not when performing the BFE test to evaluate the cracking performance of SBS polymer-modified asphalt binders at intermediate temperature.

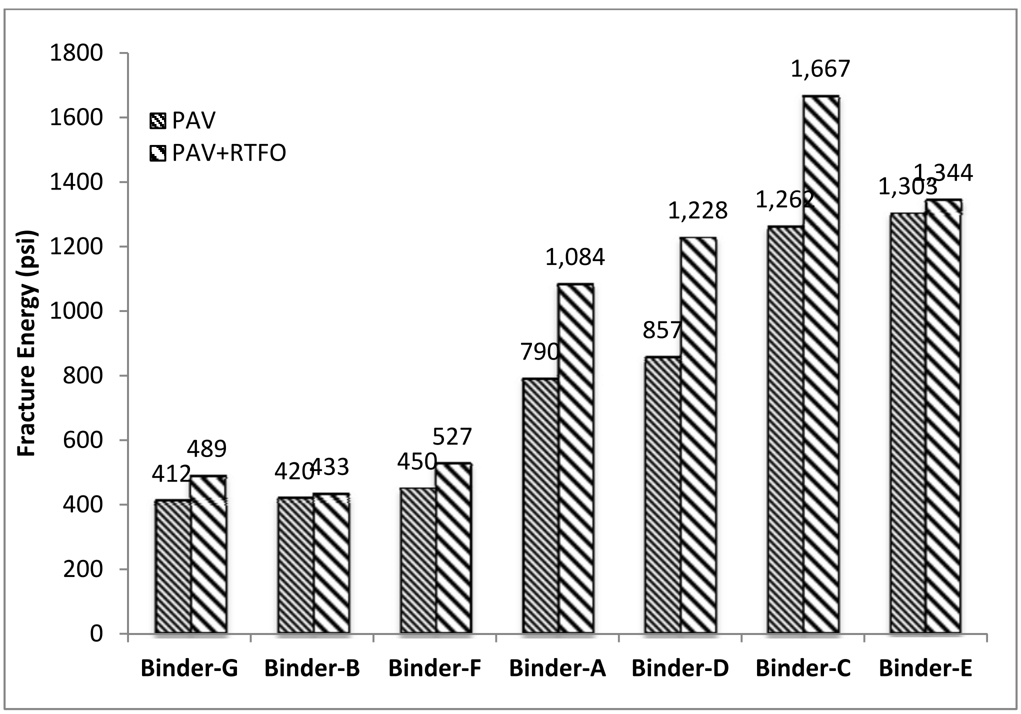

Figure 33 Comparison of fracture energy between PAV residue only and RTFO-plus-PAV specimens

CHAPTER 4 CONCLUSIONS

4.1 Summary and Findings

This study evaluated the cracking performance of asphalt binders with various additives in terms of fracture energy, which can be measured at intermediate temperatures using the newly developed BFE test. The work involved three main tasks: 1) evaluate the new BFE test system by verifying that fracture energy is independent of loading rate, and that each binder exhibits a unique true stress-true strain curve shape based on modifiers added; 2) evaluate the cracking resistance of the selected asphalt binders with various modifiers in terms of fracture energy at intermediate temperatures; and 3) verify the original testing procedure and formulate a standard testing protocol.

The work conducted in this study and associated findings are listed below.

TASK I:

- At intermediate temperatures (15˚C in this study), the newly developed BFE test produced consistent and repeatable fracture energy for seven binders tested at loading rates of 500–900 mm/min. All fracture planes of successful tests occurred at the center of the specimen, ensuring accurate determination of stress and strain, which in turns ensured the determination of fracture energy on the fracture plane.
- This study, as well as BDK75 977-27, concluded that the characteristic shape of the true stress-true strain curve from the BFE test was closely related to binder type. Specifically, the existence of a second stress peak on the true stress-true strain curve indicated the existence of SBS polymer in asphalt binders. The corresponding strain for the first stress peak (the only peak stress peak for non-SBS polymer binder) was found to be approximately 1.0 for all tested binders.

TASK II:

- The seven asphalt binders in this study can be ranked into three groups based on average fracture energy values: binders with average fracture energy 1) above 400 psi (Binder-G, Binder-B, and Binder-F), 2) above 800 psi (Binder-A and Binder-D), and 3) above 1200 psi (Binder-C and Binder-E).
- The average fracture energy for all tested binders increased slightly after RTFO testing. Binder-D exhibited average fracture energy that increased from 857 to 1228 psi.

TASK III:

- This study confirmed that fracture energy is independent of loading rate, and that each binder exhibits a unique true stress-true strain curve shape based on modifiers added. The researchers determined 500 mm/min at 15˚C to be appropriate starting loading rate value for BFE test.

After binder testing was completed, FDOT disclosed additional binder information. Three of the seven binders in this study failed to meet PG 76-22 requirements, and none of the remaining binders are formulated exclusively with an SBS modifier. Based on the fracture energy results, the BFE test ranked the seven binders, and successfully matched the information provided by FDOT, as can be seen in Table 4.

Table 4 BFE Test Results and PG grading Tests Results

Binder ID	Fracture Energy* (psi)	PG grading Requirements
Binder-G	>400	Fail
Binder-B	>400	Fail
Binder-F	>400	Fail
Binder-A	>800	Pass
Binder-D	>800	Pass
Binder-C	>1200	Pass
Binder-E	>1200	Pass
* Note: The fracture energy testing results are from PAV residue only.		

4.2 Recommendations and Future Work

After extensive testing, the researchers established the following recommendations for further implementation of this work:

- A small loading cell should be used to avoid the mechanic noise encountered, as the peak force value in this study was around 20 lbs.
- Rubber-modified asphalt binders and hybrid binders should be tested using the new testing frame and new standard testing protocol.
- This study identified the effects of different additives on fracture energy of asphalt binders; however, how that relates to fracture resistance of mastic and mixture, although important, have yet to be established.

LIST OF REFERENCES

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(2) Roque, R., Niu, Y., Lopp, G., and Zou, J.,” Development of a binder fracture test to determine fracture energy” Final report for FDOT BDK 75 977-27 Contract, University of Florida, Gainesville, FL, 2012.