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16. Abstract

The Multiple Stress Creep Recovery (MSCR) test can characterize polymer-modified asphalt binders and correlates well with the mixture rutting parameters. The MSCR is able to complement a suite of additional binder tests, namely Dynamic Modulus, Phase Angle, and “PG-Plus” tests. A recently-completed MSCR study conducted by the LTRC recommended that the DOTD switch from the PG-plus test to AASHTO T350 (MSCR based asphalt binder specifications). The previous research study focused on mainly elastomeric polymer (SBS) and some crumb rubber and latex modified (non-SBS) binders. However, due to the limited availability of crumb rubber binders, a specification was unable to be established for the non-SBS modified binders. The objectives of this research are to further support the initial MSCR study and to characterize the elastic response of non-SBS modified binders (i.e., crumb rubber and latex) used in DOTD asphalt mixtures using the MSCR test. Additionally, this research was tasked to review current PG 70-22 binder specifications as many SBS and non-SBS binders were unable to pass current DOTD MSCR specifications. This study found that the MSCR test has the capability to characterize the performance of non-SBS modified binders used in Louisiana. Furthermore, it was concluded that PG 70-22 binder specifications were too strict. The authors recommend an adjustment of PG 70-22 binder specifications.

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Evaluation of Non-SBS Modified Binders using the Multiple Stress Creep Recovery Test

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ABSTRACT

The Multiple Stress Creep Recovery (MSCR) test can characterize polymer-modified asphalt binders and correlates well with the mixture rutting parameters. The MSCR is able to complement a suite of additional binder tests, namely Dynamic Modulus, Phase Angle, and "PG-Plus" tests. A recently-completed MSCR study conducted by the LTRC recommended that the DOTD switch from the PG-plus test to AASHTO T350 (MSCR based asphalt binder specifications). The previous research study focused on mainly elastomeric polymer (SBS) and some crumb rubber and latex modified (non-SBS) binders. However, due to the limited availability of crumb rubber binders, a specification was unable to be established for the non-SBS modified binders. The objectives of this research are to further support the initial MSCR study and to characterize the elastic response of non-SBS modified binders (i.e., crumb rubber and latex) used in DOTD asphalt mixtures using the MSCR test. Additionally, this research was tasked to review current PG 70-22 binder specifications as many SBS and non-SBS binders were unable to pass current DOTD MSCR specifications. This study found that the MSCR test has the capability to characterize the performance of non-SBS modified binders used in Louisiana. Furthermore, it was concluded that PG 70-22 binder specifications were too strict. The authors recommend an adjustment of PG 70-22 binder specifications.

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IMPLEMENTATION STATEMENT

The MSCR test utilizes the same Dynamic Shear Rheometer (DSR) device required to perform to the current Performance grade testing. MSCR testing has the ability to replace current "PG Plus" test (force ductility and elastic recovery) which require the use of a ductilometer. Preparation and testing time for force ductility and elastic recovery demands an entire day, while MSCR preparation and testing can be completed in 15 minutes. DOTD and contractors can eliminate specific testing equipment which will save cost and time.

From the initial MSCR research (11-1B), PG 70-22m (SBS) material was evaluated and the MSCR criteria was implemented into the Louisiana Standard Specification for Roads and Bridges. However, concerns relative to how non-SBS modified binders would perform in the MSCR test were quickly realized. The results of this study present a recommended MSCR specification for PG 70-22 binders modified with both SBS and non-SBS modifiers.

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INTRODUCTION

Asphalt binders are modified to increase the durability and reliability of asphalt pavements. Numerous research studies have proved that modifiers improve the strength and durability of the asphalt binders by raising the stiffness at high temperatures, lowering the stiffness at low temperatures, and increasing adhesion properties *[1] [2] [3]*.

In the initial Superpave mix design procedures, the Dynamic Shearer Rheometer (DSR) was used to characterize the viscous and elastic behavior of asphalt binders at medium to high temperatures. While the DSR has shown to be successful in characterizing neat (un-modified) binders, it has been less reliable with modified binder results. Due to this issue, many state agencies adopted the "PG-Plus" tests to identify the presence of polymer modified binders. PG-Plus tests include the force ductility, elastic recovery, and separation of polymer tests. These tests were able to determine the presence of a modifier though unable to evaluate the performance of the binders. The Multiple Stress Creep Recovery (MSCR) test was the latest improvement to the Superpave Performance Graded (PG) Asphalt Binder specification and was developed to more accurately indicate the performance of the asphalt binders. MSCR is a creep and recovery test that is "blind" to modification type. MSCR differs from DSR and the PG Plus test by applying higher stresses and strains on the binder which "activates" the binder's polymer network *[3] [4] [5]*. A non-recoverable creep compliance (J_{nr}) and MSCR percent recovery (R) is computed from this test and characterizes the stress dependency of polymer-modified asphalt binders. J_{nr} represents the stiffness of asphalt binders, lower J_{nr} equals more stiffness; while MSCR recovery represents the elasticity of the binder, higher recovery equals more elastic.

A MSCR validation study was completed by the Louisiana Transportation Research Center (LTRC) in 2016. Styrene-Butadiene-Styrene (SBS), crumb rubber (CRM) and latex modified asphalt binders were evaluated to assess the suitability of the MSCR test to be included into the Louisiana Department of Transportation and Development's (DOTD) asphalt binder specifications in addition to identifying the potential of replacement of current PG Plus tests with MSCR percent recovery. The researchers determined it was possible to replace the currently used PG-Plus tests with the MSCR percent recovery and phase angle criteria. While CRM and latex modified binders were similarly tested, due to limited availability of these binders, a specification was unable to be established for PG 82-22rm binders. From the recommendations of the initial MSCR study, DOTD has implemented the MSCR for PG 70-22m and PG 76-22m (SBS modified) binders in the new DOTD specifications. However, CRM and latex modified binders were not included to these new specifications *[6]*.

Additionally, since the new MSCR specifications were implemented, there have been issues with producers passing the MSCR curve with PG 70-22m binders in the updated specifications.

SBS, crumb rubber and latex modifiers are the major modifiers for Louisiana binders. Previous research, including the initial LTRC's initial MSCR study, has shown that SBS modifiers performed better on the MSCR test than crumb rubber and latex modified binders *[6] [7]*. Early test trials with crumb rubber modified binders did not show promising results on the MSCR *[6]*. However, transportation agencies, asphalt contractors and binder producers are continually experimenting with different binder combinations to meet the MSCR criteria. Although SBS polymers tend to have better MSCR performance, there has been little observed performance issues in the field. CRM and latex modifiers are viable alternatives for a more economical asphalt mixture.

OBJECTIVE

The original objectives of this research project were to evaluate Non-SBS modified binders (i.e., crumb rubber and latex) used in DOTD asphalt mixtures by means of the MSCR test and to fine tune the replacement of PG Plus tests with the MSCR. An additional objective was added during the course of the research project to review PG 70-22m asphalt binder specifications due to issues of binders being unable to pass MSCR curve requirements.

SCOPE

This study evaluated a total of 17 non-SBS modified asphalt binders. Binders included in this study were modified with CRM, latex, or a hybrid mixture (i.e., CRM and SBS polymer blend). Different modification rates were evaluated for performance characteristics on each binder test. The high performance grades (PG) of binders ranged from PG 64 to PG 88 and were blended either in a refinery, an asphalt plant or in the LTRC asphalt laboratory. Modified binders mixed at LTRC asphalt lab started as a PG 67-22 base binder before modification. LTRC followed manufacturer mixing protocols and procedures throughout the study. All DSR, MSCR, elastic recovery, and force ductility testing was conducted at the LTRC asphalt laboratory.

Binders evaluated in this study are labeled according to their modification in the report for confidentiality. For example, L, AMB, CRY, and HYB stand for latex, ambient CRM, cryogenic CRM, and hybrid modified binders, respectively, followed by the binders' high performance grade and listed in order from lowest to highest, according to their high temperature continuous grade (also known as the binders' true grade). Additionally, DOTD specifications label SBS as PG 76-22m and non-SBS modified binders as PG 76-22rm respectively, and may be identified similarly in the report.

This research project concentrated primarily on crumb rubber, latex, and hybrid modified asphalt binders characterized by the MSCR test, which was conducted on Rolling Thin Film Oven (RTFO) aged asphalt samples at 67°C. MSCR gap heights of 1- and 2-mm were also evaluated. Additionally, Force Ductility, Elastic Recovery, and DSR (G* and Phase angle) tests were conducted to perform a comprehensive evaluation of the asphalt binders included in this study. Three replicates per binder specimen were tested for all tests and an average value was used as the final result. Historical data from the initial MSCR study by LTRC was used to compare PG 70-22 SBS and non-SBS modified binders in order to determine better MSCR parameters.

METHODOLOGY

A suite of asphalt binder characterization tests was conducted to evaluate the high temperature performance of binders investigated under the scope of this study. Table 1 summarizes the binder tests that were included.

Table 1
List of binder tests

Name of the Test	*Test Protocol*	*Test Temperature*	*Binder Condition*	*Measured Criteria*
MSCR	AASHTO T 350	67°C	RTFO Aged	$J_{nr0.1}$, $J_{nr3.2}$, $R_{0.1}$ and $R_{3.2}$
DSR	AASHTO T 315	64°C to 88°C	Both Unaged and RTFO Aged, PAV Aged	G*, δ, and G*/Sinδ
Elastic Recovery	AASHTO T 301	25°C	RTFO Aged	% elastic recovery
Force Ductility	AASHTO T 300	4°C	Unaged	Force ductility and force ductility ratio

Multiple Stress Creep Recovery

The multiple stress creep recovery (MSCR) test was performed in accordance with AASHTO T350. Testing was conducted at 67°C using the rolling thin film oven (RTFO) aged material in accordance to Louisiana DOTD specifications and tested at two stress levels, 100 and 3200 Pa. The same (RTFO) aged specimen used in the DSR was used for MSCR testing. The MSCR results measure the non-recoverable creep compliance (J_{nr}) and percent recoveries (R) to characterize the stress dependency and temperature sensitivity of polymer-modified binders. Gap heights of 1-and 2-mm were tested to check if crumb rubber particles interfered with testing results. Current 2016 DOTD specifications require PG 70-22m and PG 76-22m binders to have a maximum $J_{nr3.2}$ of 2.0 and 0.5, respectively, and to pass MSCR curve.

Dynamic Shear Rheometer

The dynamic shear rheometer (DSR) is used to characterize the viscous and elastic behavior of asphalt binders at medium to high temperatures. DSR testing was done on original, RTFO and PAV aged binder samples following AASHTO T315 procedures. Binders from this study are tested at temperatures starting at 64°C increasing every 6°C increments until specification failure, where it is assigned a performance grade (PG). The DSR also gives the continuous grade, where the device calculates exact temperature at specification failure. DOTD specifications for DSR require test results, G* sin delta, of original binders to be a minimum of 1 kPa, RTFO aged binders to be a minimum of 2.2 kPa, and PAV aged binders to be a maximum of 5000 kPa.

Force Ductility

The forced ductility test involves measuring the tensile properties of polymer-modified asphalt binders by determining the force required to maintain a specific elongation rate of a test specimen at a certain elongation and a specified temperature, therefore characterizing the toughness of a binder sample. It is a modified ductility test generally used as an indicator of the presence of polymer in an asphalt material. Procedure was followed in accordance with AASHTO T300. Previously, in 2006 DOTD specifications, the force ductility at 30 cm elongation and force ductility ratio (ratio of the force at the second peak to the force at initial peak, f_2/f_1) to be reported for PG 70-22m and PG 76-22m binders, respectively *[8]*. Force Ductility was eliminated from the 2016 DOTD specifications. For the computation of force ductility ratio, f_2 is taken as the force at the 30-cm elongation.

Elastic Recovery

Elastic recovery test measures the tensile property of polymer-modified asphalt using the same ductilometer used for Ductility and Force Ductility. The AASHTO T301 method was followed in this study to conduct elastic recovery tests on RTFO aged binders at 25°C with 10 cm elongation. The elastic recovery of a binder is computed as the percentage of recoverable strain measured after the binder sample is elongated to 10 cm at a certain speed, held in that stretched position for five minutes, and then cut into halves. A higher recovery value is preferable as it indicates a more elastic binder. 2006 DOTD asphalt binder specification required minimum elastic recoveries of 40% and 60% for PG 70-22m and PG 76-22m binders respectively *[8]*. The current 2016 DOTD specification requires minimum elastic recoveries of 60% for PG 82-22rm binders only *[9]*.

DISCUSSION OF RESULTS

Binder Modification and Performance Grades

In Table 2 below, the 17 non-SBS modified asphalt binders evaluated in this study are listed in order of their high continuous grade (CG), from lowest to highest. The research looked into various modification rates and base binder sources to compare performance characteristics of different types of non-SBS modified binders. Some binders have an unknown binder source and modification percentages in which the authors were unable to obtain this information from the respective contractors or producers. All of the binders started out as a base binder of PG 67-22 before modification. Modification by the addition of CRM, latex, or a hybrid mixture increased the PG of each binder with the L64 binder being the exception. CRM and latex modifiers increased the viscosity and stiffness of asphalt binders resulting in an increased CG. Latex modified binders inclined to have lower CG, while CRM and hybrid binders graded at PG 76-22rm and higher.

Table 2
Non-SBS modified asphalt binders

ID	*PG*	*CG*	*Binder Source*	*Blended by*	*Modification*
L64	64	69.6	A	Contractor	1.8% Latex
L70(1)	70	74.2		Contractor	2% Latex
L70(2)	70	74.4	C	Contractor	2.8% Latex
L70(3)	70	75.9	C	Contractor	3.8% Latex
HYB76(1)	76	78.3	A	Contractor	10% CRM (ambient), 0.60% polymer
L76(1)	76	78.8	B	Contractor	3.5% Latex
L76(2)	76	79.4	B	Contractor	3.6% Latex
HYB76(2)	76	79.5	A	LTRC	5.0% CRM (ambient), 2.4% polymer
L76(3)	76	79.6	B	Contractor	3.7% Latex
HYB82(1)	82	82.0	A	LTRC	7.0% CRM (ambient), 2.4% polymer
AMB82(1)	82	82.7		Contractor	8% CRM (ambient)
CRY82	82	84.8	A	LTRC	10% CRM (cryogenic), 0.60% polymer
AMB82(2)	82	84.9		Contractor	12% CRM (ambient)
HYB82(2)	82	85.9	A	Contractor	10% CRM (ambient), 0.60% polymer
HYB82(3)	82	86.9	A	Contractor	12% CRM (ambient), 0.60% polymer
HYB88(1)	88	89.5	D	Producer	CRM (ambient), polymer
HYB88(2)	88	89.8	H	LTRC	7.0% CRM (ambient), 2.4% polymer

MSCR Results

The average MSCR recovery at 3.2 kPa ($R_{3.2}$) and average MSCR non-recoverable creep at

3.2 kPa ($J_{nr3.2}$) are presented in Table 3. All binders were tested at 67°C according to DOTD MSCR specifications.

Table 3
MSCR average results

ID	$R_{0.1}$	$R_{3.2}$	R_{diff}	$J_{nr0.1}$	$J_{nr3.2}$	J_{nrdiff}	MSCR Curve
L64	5%	1%	80.0%	2.58	2.96	14.7%	Fail
L70(1)	36%	21%	41.7%	1.28	1.78	39.1%	Fail
L70(2)	46%	28%	39.1%	0.62	0.96	54.8%	Fail
L70(3)	50%	31%	38.0%	0.58	0.92	58.6%	Pass
HYB76(1)	52%	21%	59.6%	0.53	0.97	83.0%	Fail
L76(1)	47%	23%	51.1%	0.70	1.14	62.9%	Fail
L76(2)	67%	51%	23.9%	0.36	0.58	61.1%	Pass
HYB76(2)	61%	45%	26.2%	0.32	0.49	53.1%	Pass
L76(3)	76%	60%	21.1%	0.24	0.43	79.2%	Pass
HYB82(1)	47%	26%	44.7%	0.43	0.67	55.8%	Fail
AMB82(1)	71%	37%	47.9%	0.12	0.29	141.7%	Fail
CRY82	58%	38%	34.5%	0.29	0.47	62.1%	Pass
AMB82(2)	71%	39%	45.1%	0.12	0.29	141.7%	Fail
HYB82(2)	71%	42%	40.8%	0.16	0.35	118.8%	Pass
HYB82(3)	74%	46%	37.8%	0.13	0.30	130.8%	Pass
HYB88(1)	91%	83%	8.8%	0.05	0.10	100.0%	Pass
HYB88(2)	72%	60%	16.7%	0.09	0.13	44.4%	Pass

Each binder's high continuous grade was plotted alongside the $R_{3.2}$ and $J_{nr3.2}$ values in Figure 1 and Figure 2. It is evident from both figures that the higher graded binders showed higher average $R_{3.2}$ and lower average $J_{nr3.2}$ values in comparison to their lower continuous graded counterparts. $J_{nr3.2}$ values appeared to correlate better than $R_{3.2}$ values. Generally, a PG 82-22rm binder contains a higher percentage of modifiers when compared to a PG 76-22rm or PG 70-22rm binders, which explains the above-mentioned trend. It is noticeable based on these figures that the MSCR test results are capable of distinguishing between the different PG grades on the basis of $J_{nr3.2}$ and $R_{3.2}$ results.

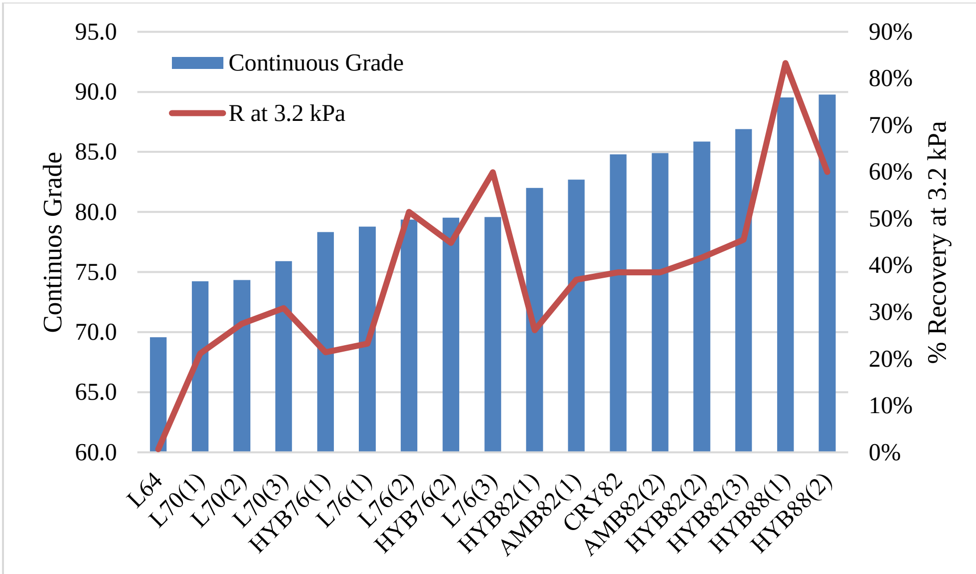

Figure 1

Continuous grade & average MSCR recovery @ 3.2 kPa ($R_{3.2}$)

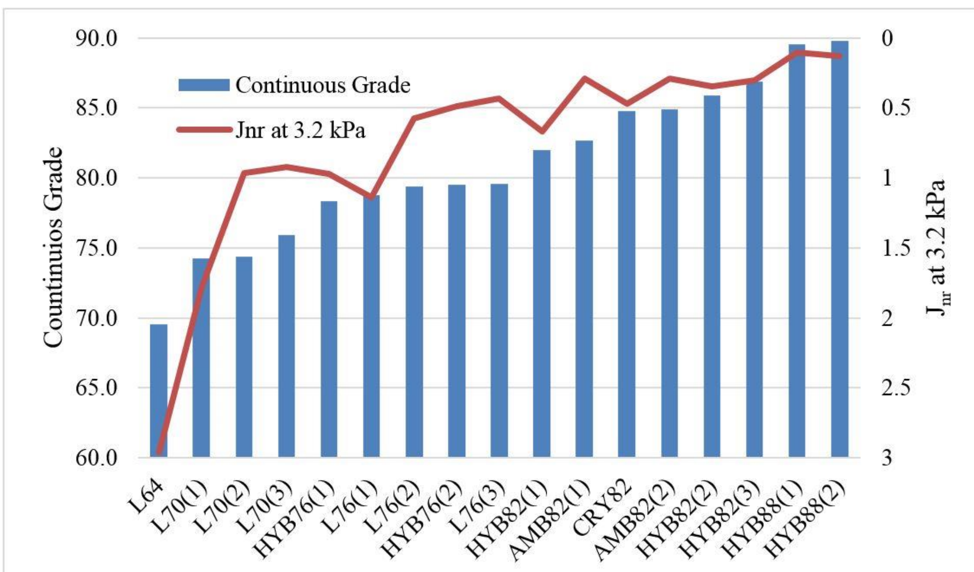

Figure 2

Continuous grade & average non-recoverable creep compliance @ 3.2 kPa ($J_{nr3.2}$)

According to AASHTO T350, the average MSCR Recovery at 3.2 kPa result is to be plotted against the average J_{nr} at 3.2 kPa result for a specific binder at a certain test temperature and compared with a line defined by the equation, y = 29.371(x)-0.2633 to measure the elastic behavior. Any plotted point falling above the line indicates the corresponding binder to be modified with an acceptable modifier to possess sufficient delayed elastic response while any point falling below the line contains insufficient modifier.

Figure 3 shows all 17 binders plotted with the MSCR elastic response curve. Solid-filled shapes denote the 13 PG 76-22rm and higher graded binders and the non-filled shapes represent the one PG 64-22rm and three PG 70-22rm binders. The different shapes identify the type of modification, squares are hybrids, triangles are CRM, and circles are latex. Out of the 17 binders tested with MSCR, nine binders passed and eight failed. 2016 DOTD specifications require PG 70-22m and PG 76-22m binders a maximum $J_{nr3.2}$ values of 2.0 and 0.5, and to pass the MSCR curve.

From the observations presented in Figure 3, two of the three PG 70-22rm binders failed to pass the curve. It appears the increase of latex percentages did deliver better performance on the MSCR curve with gradual increase in the percentage of latex modifier improved the binders' placement on the curve. The 3.8% latex binder, L70(3), was capable of passing the MSCR curve. Binder L64 graded similar to a neat binder of PG 64, showing that the 1.8% latex modification attributed negligible performance advantages. Hybrid binders did perform better than the CRM and latex modified binders which indicates the addition of SBS polymers may be necessary for crumb rubber modifiers to pass MSCR criteria.

Another interesting correlation was how the different binder sources with similar modifications reacted according to the MSCR. HYB88(2) and HYB82(1) contained the same exact modifiers and percentages, but their respective base binder came from different binder producers. HYB88(2) revealed superior MSCR results and passed the MSCR curve while the other did not. This may show that binder source can have a large impact on the performance of binders with the MSCR test.

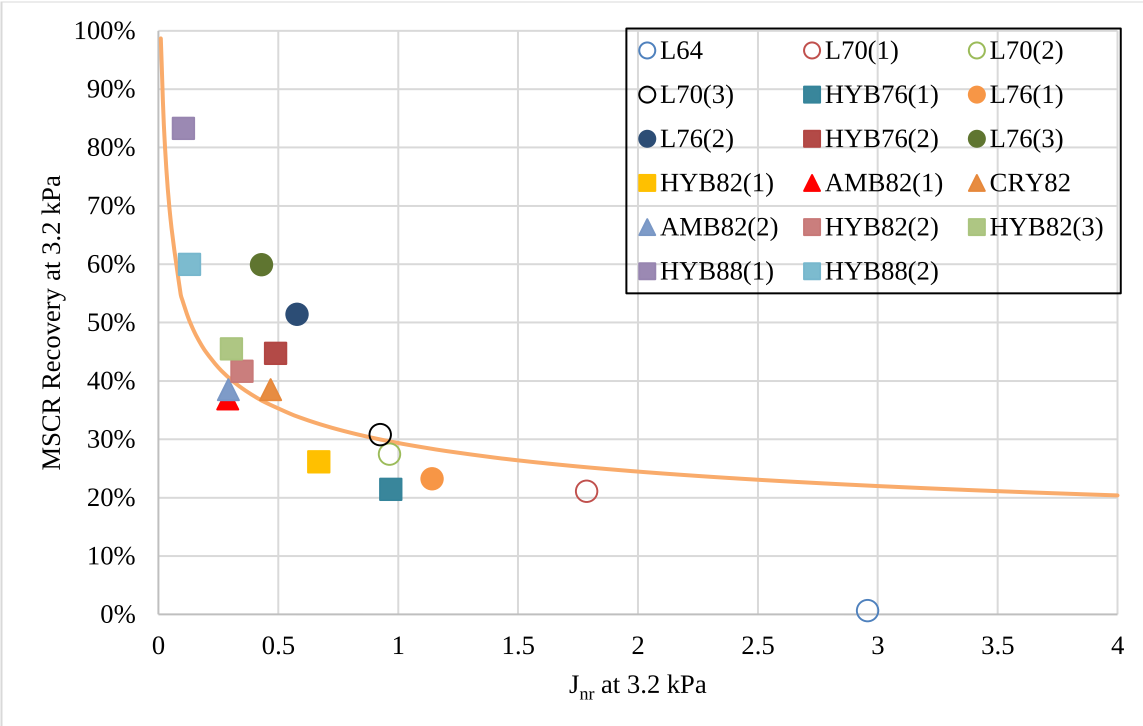

Figure 3
MSCR elastic response of non-SBS modified binders at 67°C

The non-recoverable creep compliance (J_{nr}) was developed based on the non-recovered strain at the end of the recovery portion of the test divided by the initial stress applied during creep. The J_{nr} value normalizes the strain response of binder to stress that was able to categorize polymer-modified binders. Current DOTD specifications require PG 70-22m and PG 76-22m binders to have $J_{nr3.2}$ of less than or equal to 2.0 and 0.5 respectively.

Figure 4 displays J_{nr} values and the respective maximum J_{nr} specification for PG 70-22m and PG 76-22m. All PG 70-22rm successfully meet PG 70-22m specifications of J_{nr} of less than or equal to 2.0. Binder L64 did not meet, but since the binder graded at a PG 64-22, it did not need to meet PG 70-22m specification. PG 76-22rm and PG 82-22rm were similarly plotted. Current DOTD specifications require only PG 76-22m binders to have a J_{nr} to be less than or equal to 0.5, but from the figure, three PG 76-22rm binders and one PG 82-22rm binder resulted in $J_{nr3.2}$ values greater than 0.5. The PG 82-22rm and higher graded binders appear to effectively meet a $J_{nr3.2}$ specification of less than or equal to 0.5. According to AASHTO M332, binders resulting in a $J_{nr3.2}$ less than or equal to 0.5 can withstand 30 million (equivalent single axle loads) ESALs.

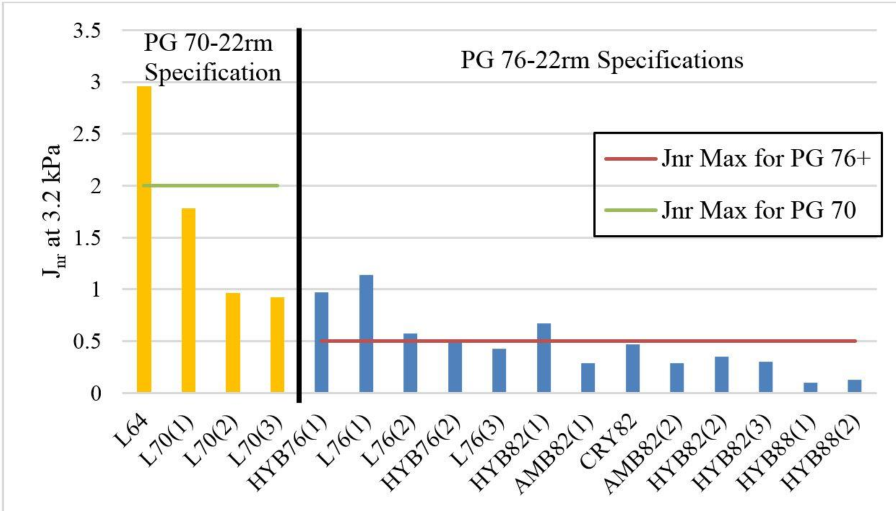

Figure 4

J_{nr} specification for PG 70-22m and PG 76-22m binders

According to AASHTO M332, the J_{nr} difference (J_{nrdiff}) values should be less than 75% to show that the binders are not stress sensitive to test temperatures. CRM and Hybrid binders tested on in this study tended to be more stress sensitive at test temperature of 67°C as seen in Figure 5. The higher graded binders were more likely of receiving a high J_{nrdiff} than the lower graded binders. Latex binders, except for one binder L76, delivered results lower than 75% J_{nrdiff}. This may be a crumb rubber modifier issue as several other research studies have seen this similar situation *[10]*.

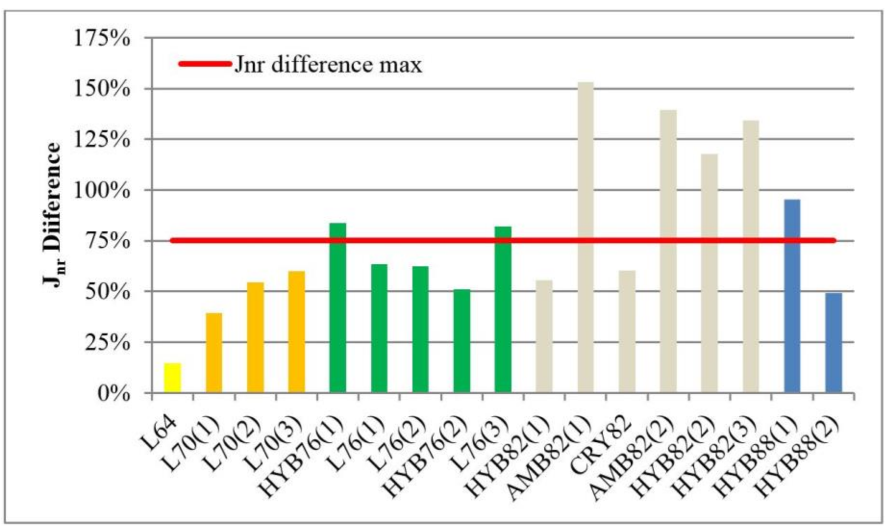

Figure 5

J_{nr} difference maximum value Elastic Recovery Comparisons

Table 4 displays the percent elastic recovery, MSCR percent recovery ($R_{3.2}$) and MSCR curve results. Elastic Recovery was conducted at 25°C and MSCR testing was held at 67°C. Current 2016 DOTD Specifications require PG 82-22rm binders to pass a minimum of 60% on the elastic recovery test. PG 70-22m and PG 76-22m are required to meet MSCR curve.

Table 4
Average elastic recovery results

ID	*ER*	*R3.2*	*MSCR Curve*
L64	71%	1%	Fail
L70(1)	65%	21%	Fail
L70(2)	47%	28%	Fail
L70(3)	43%	31%	Pass
HYB76(1)	50%	21%	Fail
L76(1)	42%	23%	Fail
L76(2)	66%	51%	Pass
HYB76(2)	80%	45%	Pass
L76(3)	82%	60%	Pass
HYB82(1)	74%	26%	Fail
AMB82(1)	79%	37%	Fail
CRY82	80%	38%	Pass
AMB82(2)	78%	39%	Fail
HYB82(2)	62%	42%	Pass
HYB82(3)	68%	46%	Pass
HYB88(1)	95%	83%	Pass
HYB88(2)	81%	60%	Pass

The average percent elastic recoveries were plotted against the average MSCR $R_{3.2}$ results as displayed in Figure 6. Poor correlation was observed as the R-squared value was 0.3585. However, the Asphalt Institute mentions a very strong correlation between these two test results was unlikely due to the difference in test conditions and test methodologies *[5]*.

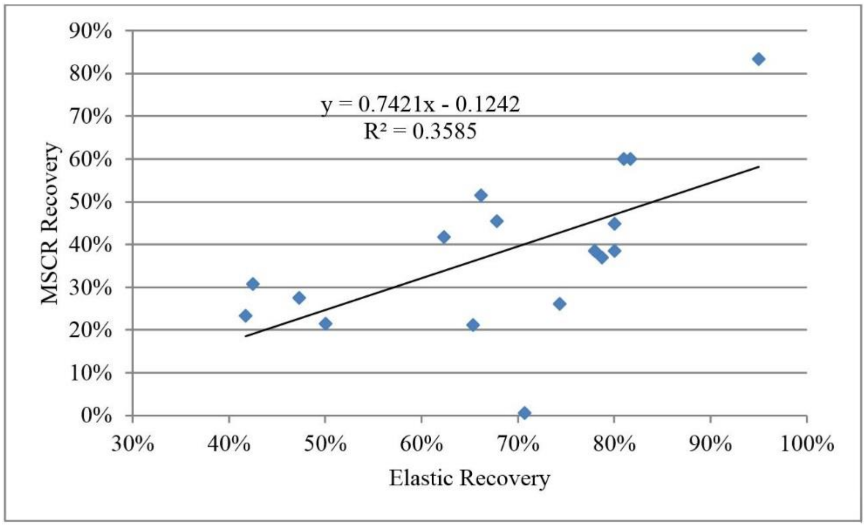

Figure 6
Elastic recovery & MSCR recovery correlation

The Asphalt Institute recommended that state transportation agencies use their current minimum elastic recovery specification and to subtract 15% for the minimum MSCR percent recovery value *[5]*. According to this recommendation, all PG 70-22rm binders in Louisiana shall require a minimum $R_{3.2}$ value of 25% and all PG 76-22rm and higher graded binders shall require a minimum of 45% respectively as the previous DOTD binder specification required a minimum elastic recovery values of 40% and 60% for the PG 70-22rm and PG 76-22rm binders.

To assess the above hypothesis, the MSCR percent recovery and percent elastic recovery results are plotted as presented in Figure 7 and Figure 8. For the PG 70-22rm binders, only two binders passed both MSCR percent recovery and Elastic Recovery. For the PG 76-22rm and higher graded binders, five binders pass minimum elastic recovery of 60%, but do not pass the 45% minimum MSCR recovery. It is worth noting that none of the binders could meet the minimum MSCR $R_{3.2}$ target value of 25% or 45% without passing the minimum elastic recovery of 40% or 60%. This indicates that MSCR test is capable of capturing a limitation existed in the current binder specifications. Also, the MSCR recovery specification is the strictest among the two recovery (elastic recovery and MSCR recovery) specification criteria discussed here. Asphalt Institute recommends when evaluating the data graphically, the minimum MSCR recovery requirement should be established in a manner where the user risk is approximately equal to the supplier risk.

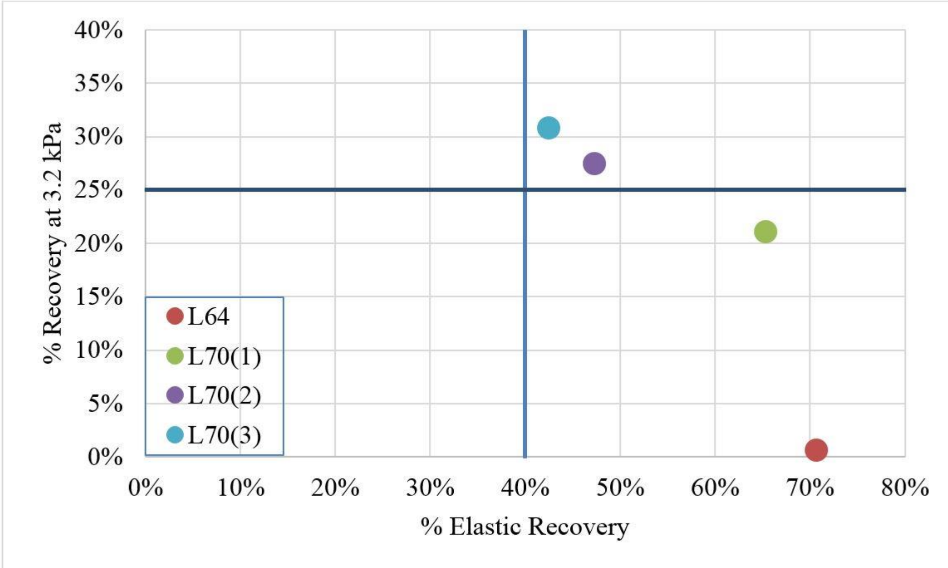

Figure 7

Elastic Recovery vs. MSCR Recovery for PG 64-22 and PG 70-22rm Binders

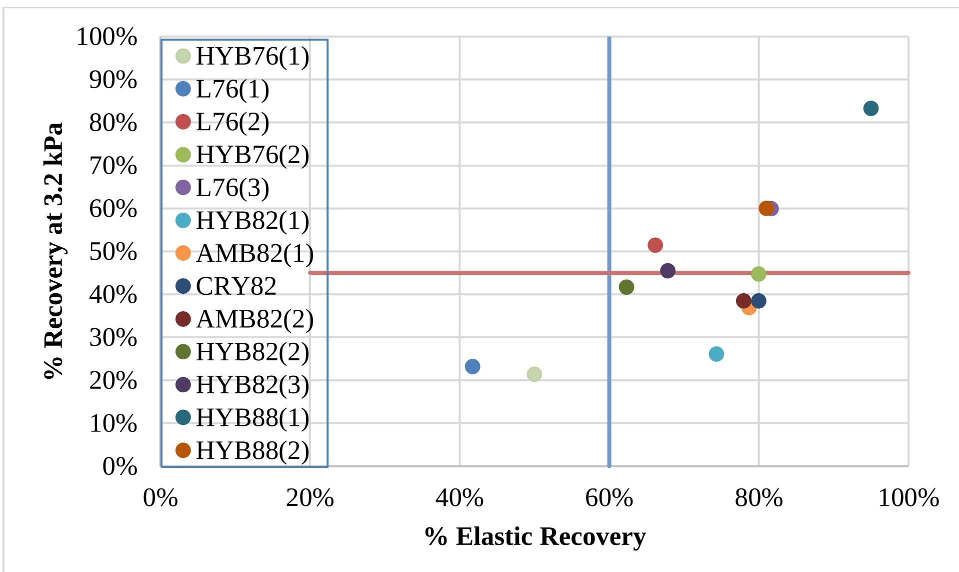

Figure 8

Elastic recovery vs. MSCR recovery for PG 76-22rm & higher graded binders

Force Ductility Replacement

In LTRC's initial MSCR research project, the authors found both phase angle and MSCR recovery ($R_{3.2}$) correlated well with force ductility results, though they concluded maximum phase angle from the DSR to replace force ductility testing due to better correlation *[6]*. From their data, they found a max phase angle of 75° could successfully replace force ductility ratio for PG 76-22m binders. PG 70-22m binders were similarly tested for a max phase angle of 78° to replace force ductility at 30 cm elongation; however, due to poor correlations, a solid conclusion could not be determined. One of the major objectives of this study was to continue collection of phase angle and MSCR recovery data of PG 70-22 binders in order to further conclude replacing force ductility test. However, due to the nature of CRM and latex modified binders grading at higher temperatures, only three PG 70-22rm binders could be examined for this study. Force ductility was run on seven binders and tested for force ductility ratio and force ductility at 30 cm elongation, as seen in Table 5.

Table 5
Average force ductility and phase angle results

ID	*FD Ratio*	*FD @ 30 cm*	$R_{3.2}$	*Phase Angle*
L64	0.30	0.02	1%	85.0
L70(1)	0.41	0.18	21%	76.7
L70(2)	0.36	2.45	28%	77.9
L70(3)	0.29	3.56	31%	75.5
HYB76(2)	0.35	12.13	45%	74.3
HYB82(1)	0.41	16.22	26%	76.9
HYB88(1)	0.86	9.94	83%	63.2

Figure 9 and Figure 10 show good correlations of MSCR percent recovery and phase angle results versus force ductility results with R squared values of 0.7542 and 0.7541; however, Figure 11 and Figure 12 show poor correlations with force ductility at 30 cm with R squared values of 0.1561 and 0.2124, similar to the initial MSCR study *[6]*. It can be understood from these figures that force ductility ratio better correlates with phase angle and MSCR percent recovery. Force ductility at 30 cm does not show good correlations with any other test. Additional PG 70-22 binders will need to be collected to solidify a max phase angle of 78° for PG 70-22 binders. Although technologists will no doubt conduct comparative testing between MSCR Recovery and other PG Plus tests, they should not necessarily expect strong correlations. Test conditions are sufficiently different between the MSCR and "PG Plus" tests that strong relationship would be unlikely.

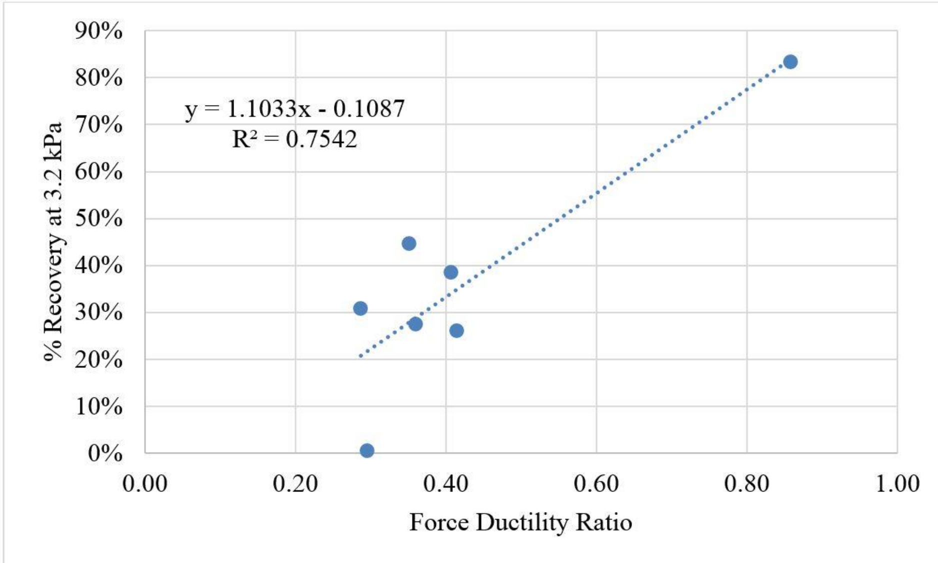

Figure 9
Force ductility ratio versus MSCR recovery

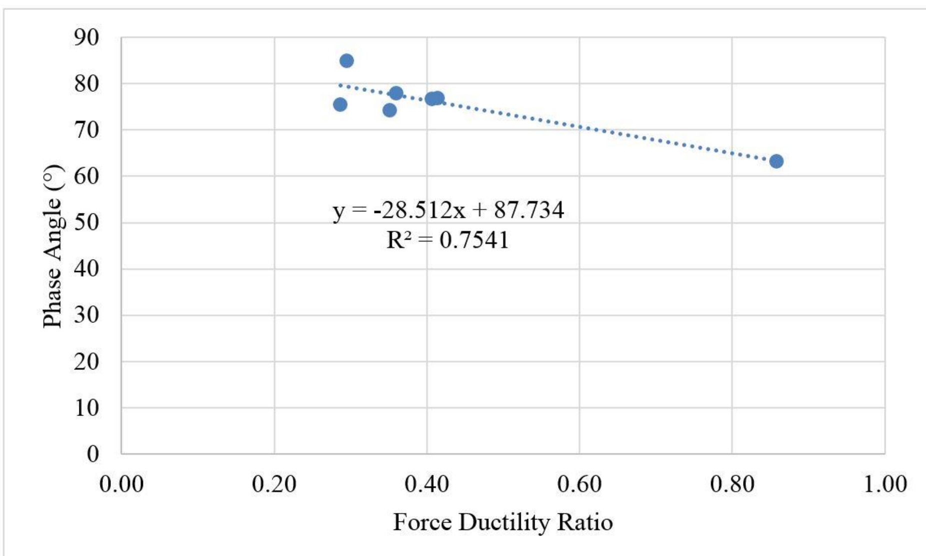

Figure 10
Force ductility ratio versus phase angle

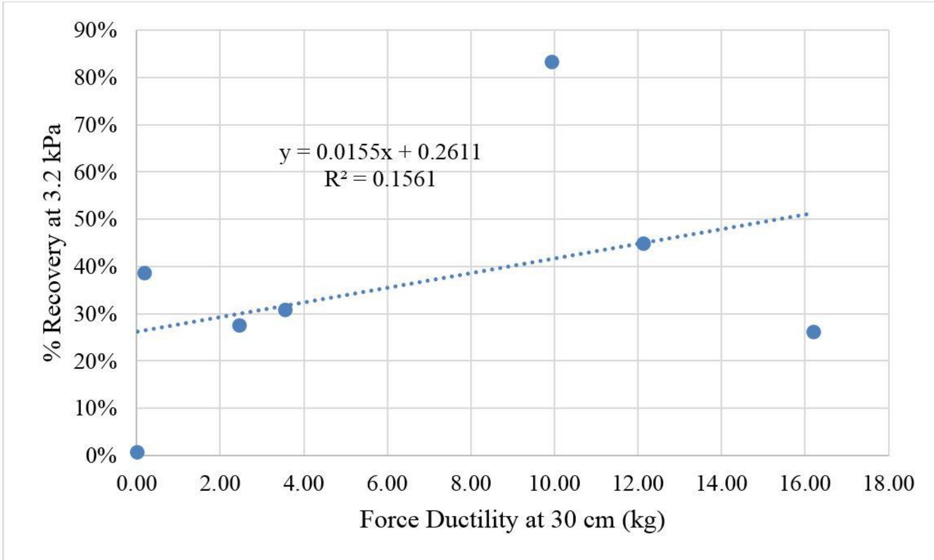

Figure 11

Force ductility at 30 cm versus MSCR percent recovery

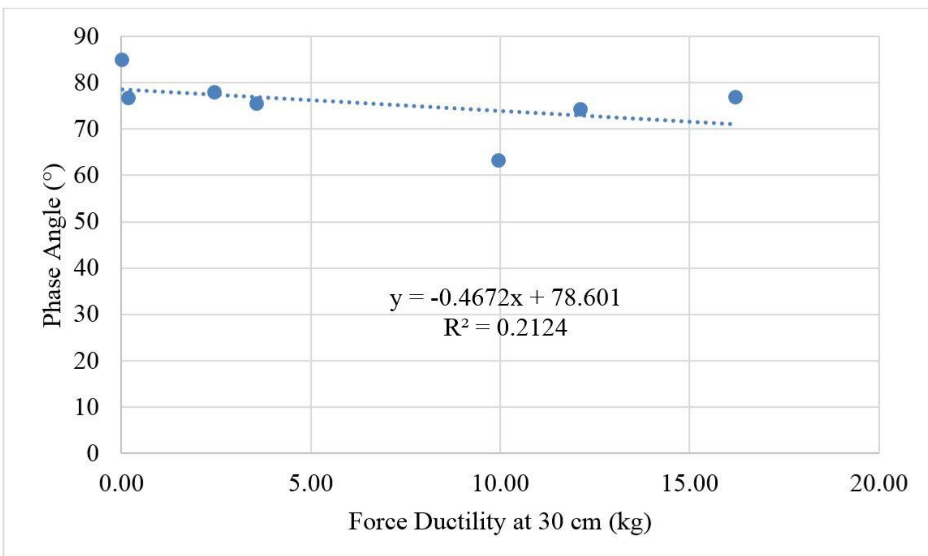

Figure 12

Force ductility at 30 cm versus phase angle

Gap Height Evaluation

One issue with rubber modified binders is the size of the rubber particles in the binder. The rubber particles in crumb rubber binders may interfere with the MSCR test configurations, and can raise potential issues during asphalt binder testing. Evaluation of gap heights were evaluated in this study briefly. Using the 25-mm plate, 1- and 2-mm gap heights were tested on binders, HYB76(2) and HYB82(3). Table 6 below shows the results of the testing. From this evaluation, the binders displayed no discernable differences meaning the rubber particles had no effect on test results.

Table 6
1-mm and 2-mm MSCR Results

ID	Gap	$R_{0.1}$	$R_{3.2}$	R_{diff}	$J_{nr0.1}$	$J_{nr3.2}$	J_{nrdiff}	MSCR Curve
HYB76(2)	2-mm	67%	48%	28.4%	0.26	0.44	69.2%	Pass
HYB76(2)	1-mm	67%	51%	23.9%	0.36	0.58	61.1%	Pass
HYB82(3)	2-mm	72%	46%	36.1%	0.10	0.22	120.0%	Pass
HYB82(3)	1-mm	74%	46%	37.8%	0.13	0.30	130.8%	Pass

Issues with PG 70-22 modified binders

Through meetings with DOTD and asphalt industry personnel over the course of this study, the authors found that modified PG 70-22 binders (SBS and non-SBS) were having difficulties meeting the recently implemented MSCR curve specification. This was effectively eliminating the use of PG 70-22 binders and making it more expensive to build roads, as only a PG 76-22 binder could meet the MSCR specification. It was proposed, with approval from DOTD and asphalt industry personnel to update the PG 70-22 MSCR specifications to pass a minimum MSCR recovery ($R_{3.2}$) and minimum and maximum $J_{nr3.2}$ parameters. LTRC was given the task to determine the minimum MSCR recovery and $J_{nr3.2}$ parameters which was incorporated into this study.

Historical data from the initial MSCR project (11-1B) along with the PG 70-22rm binders in this study were evaluated to determine more realistic MSCR parameters for PG 70-22 binders *[6]*. Results are listed in Table 7. Most PG 70-22 binders were unable to pass the MSCR curve as can be seen in Figure 13. Standard deviation for MSCR recovery and $J_{nr3.2}$ values was 11% and 0.58 respectively and were plotted alongside the MSCR curve in order to provide a better idea of where most of the binders were plotting. PG 70-22 binders had no issues meeting required maximum $J_{nr3.2}$ of 2.0 with the average being 1.60; however, binders were having trouble meeting MSCR recovery with the average being 17%. Normally, binders would need to have a minimum of 25 to 30% MSCR recovery in order to pass the MSCR curve.

Table 7
PG 70-22 modified binder results

ID	$R_{3.2}$	$J_{nr3.2}$
L70(1)	21%	1.78
L70(2)	28%	0.96
L70(3)	31%	0.92
PG 70-22m binders (From 11-1B) [6]	17%	1.43
	33%	0.73
	11%	1.87
	14%	1.8
	5%	1.39
	1%	2.91
	11%	1.73
	5%	1.95
	14%	1.42
	23%	1.52
	34%	0.93
	3%	2.58
Average	17%	1.60

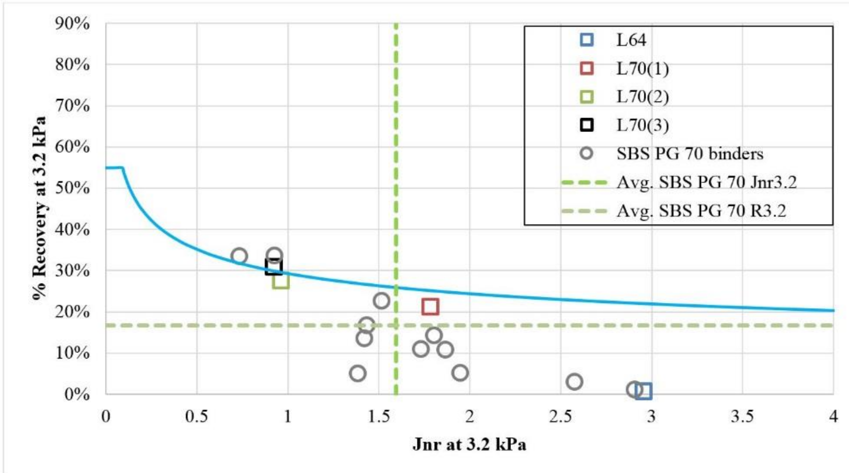

Figure 13
MSCR elastic response of PG 70-22 (SBS and non-SBS) binders

To further support lowering the MSCR recovery specifications, a Loaded Wheel Tracking (LWT) test was conducted on mixture samples containing the latex binders L70(2) and L70(3).

The mixtures easily passed the required LWT maximum of 6-mm rut depth at 20,000 passes as displayed in Figure 14and Figure 15. This test demonstrated that the latex binders provided sufficient recovery and stiffness capabilities and that the current MSCR specifications may be too severe for PG 70-22 binders.

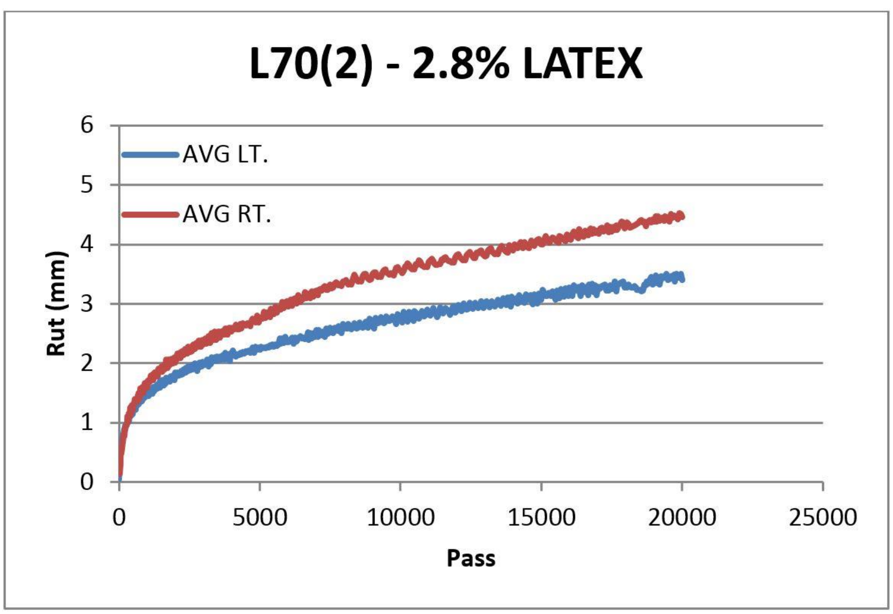

Figure 14
LWT result for L70(2) mixture

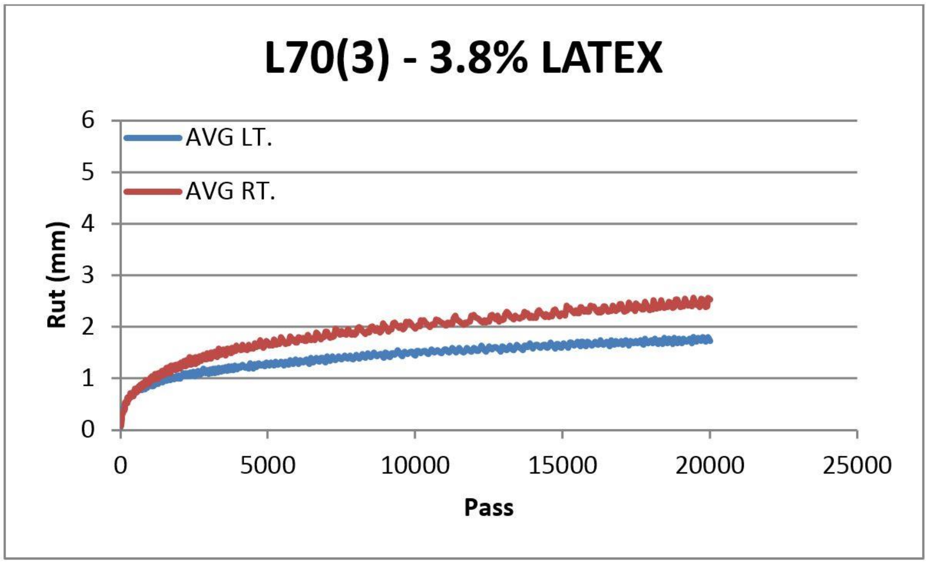

Figure 15
LWT result for L70(3) mixture

Figure 16 displays the proposed PG 70-22 specification alongside the current MSCR curve. From the data collected in this report, a minimum $J_{nr3.2}$ of 1.0 was determined necessary to reduce cracking probabilities by making the binder less stiff. The current maximum $J_{nr3.2}$ of 2.0 was kept to require sufficient loading strength. MSCR recovery was lowered to a minimum of 15%.

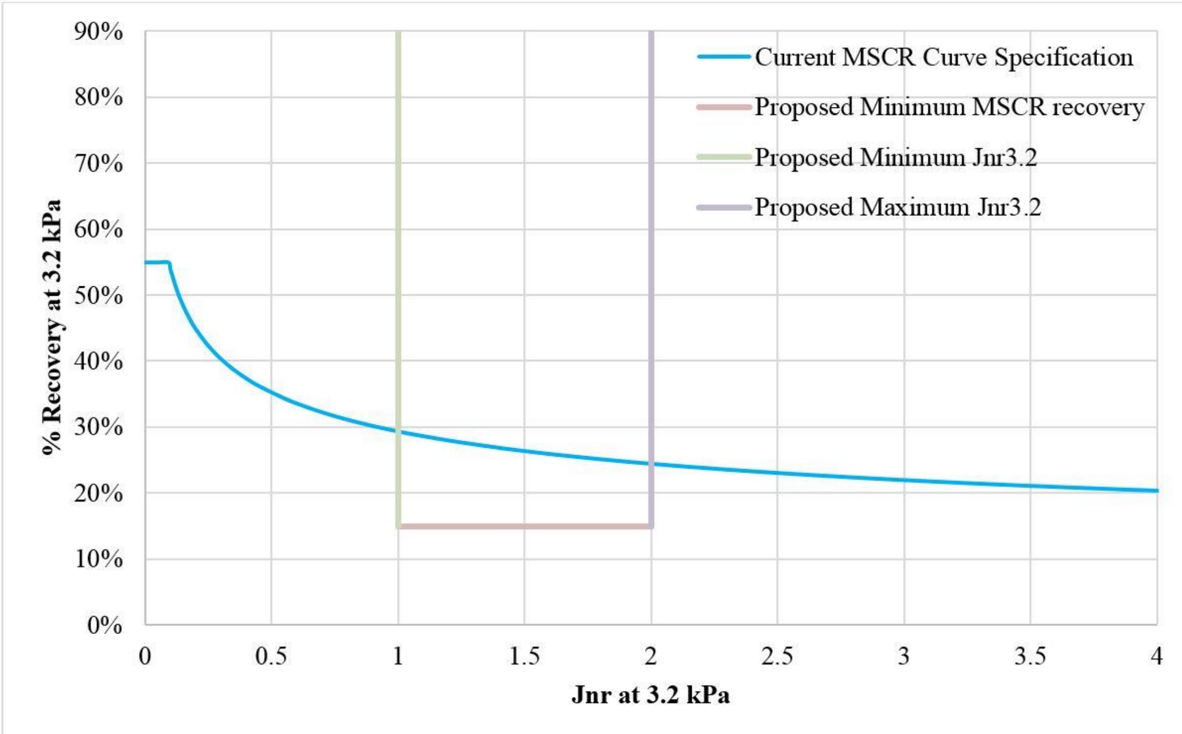

Figure 16
Proposed PG 70-22 specification

CONCLUSIONS

Based on the experimental results of 17 non-SBS modified asphalt binders under the scope of this study, the following conclusions can be drawn:

- The MSCR test is capable of evaluating the performance of non-SBS modified binders (i.e., CRM, latex, and hybrid mixes). Non-SBS binders graded as PG 82-22rm are able to meet MSCR curve and maximum J_{nr} parameters that can withstand extreme traffic loadings.

- Test results indicated that a greater sensitivity to elastomeric response was found using the MSCR percent recovery test as opposed to Elastic Recovery, showing that MSCR percent recovery is capable of capturing a limitation that existed in the elastic recovery test.

- The base binder source of modified binders can have significant impact on MSCR results based on the MSCR curve. Also hybrid binders, comprised of rubber and polymer mixtures, performed better than binders with just crumb rubber or latex.

- Due to the nature of CRM and latex modified binders grading at higher temperatures, the research team was unable to obtain enough PG 70-22rm binders to make a solid conclusion for a max phase angle of 78° to replace force ductility at 30 cm.

- Phase angle and MSCR percent recovery correlated well with force ductility ratio, while they both correlated poorly with force ductility at 30 cm. The initial MSCR study by LTRC had this same issue.

- Gap height testing showed no significant differences. The testing indicated that the rubber particles contained in the binders were not interfering with MSCR testing.

- Modified binders graded at PG 70-22 (SBS and non-SBS) have trouble meeting current DOTD MSCR specifications. LWT latex mixture results show acceptable performance of latex binders when in mixture form.

RECOMMENDATIONS

From the outcomes of this study, the authors recommend the following:

- Non-SBS modified (i.e., crumb rubber, latex, and hybrid) asphalt binders to be included into DOTD specifications utilizing MSCR specifications. Three out of the six PG 82-22rm binders are capable of meeting maximum $J_{nr3.2}$ of 0.5 and MSCR curve requirements.

- PG 70-22 modified binders (SBS and non-SBS) specifications should be updated to require a minimum MSCR Recovery of 15% and to require a non-recoverable creep ($J_{nr3.2}$) value to be between 1.0 and 2.0.

- LTRC should continue collecting PG 70-22 binders (SBS and non-SBS) to further support updated MSCR parameters and also to determine if a 78° max phase angle should be implemented for PG 70-22 binders.

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

AASHTO	American Association of State Highway and Transportation Officials
cm	centimeter(s)
CG	Continuous Grade
CRM	Crumb Rubber Modifier
DOTD	Louisiana Department of Transportation and Development
DSR	Dynamic Shear Rheometer
ER	Elastic Recovery
FHWA	Federal Highway Administration
FD	Force Ductility
$J_{nr0.1}$	Non-Recoverable creep Compliance at 0.1 kPa
$J_{nr3.2}$	Non-Recoverable creep Compliance at 3.2 kPa
kg	kilogram(s)
kPa	kilo-Pascal (1000 Pascal)
LTRC	Louisiana Transportation Research Center
MSCR	Multiple Stress Creep Recovery
mm	mili-meter(s)
PG	Performance Grade
$R_{0.1}$	MSCR Percent Recovery at 0.1 kPa
$R_{3.2}$	MSCR Percent Recovery at 3.2 kPa
SBS	Styrene-Butadiene-Styrene

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APPENDIX

MSCR Test

The MSCR test is a creep and recovery test that uses a haversine load for 1 second followed by a 9-second rest period in each cycle. During the 9-second rest period, the specimen recovers a portion of the strain that is developed in the 1-second loading period. In this study, the MSCR test was conducted as per AASHTO T 350 method. Two stress levels, 100 Pa and 3200 Pa, were used with the application of a controlled shear stress. This was accomplished by applying a 100 Pa shear stress for 10 consecutive creep-recovery cycles and immediately followed by another 10 cycles of a 3200 Pa shear stress. Figure 17 illustrates the stress application and the subsequent strains recorded from a typical MSCR test.

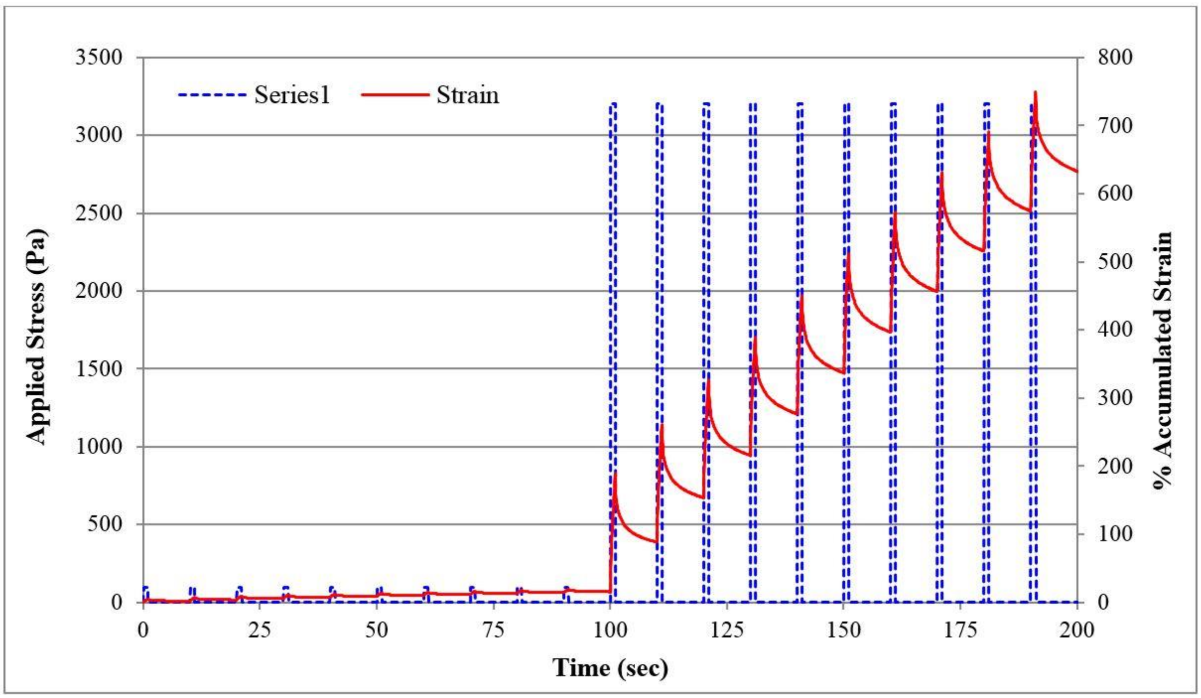

Figure 17
Typical MSCR test output

An Anton Paar MCR 302 DSR (as shown in Figure 18) with a 25-mm parallel plate geometry set-up was employed in this study. For each binder sample, the same operator tested three replicates to establish the consistency of testing. The non-recoverable creep compliances (J_{nr}) and percent recoveries were computed at each stress levels and temperatures to characterize the stress dependency and temperature sensitivity of polymer-modified binders. For a particular stress cycle, J_{nr} is computed by dividing the non-recoverable strain with the stress applied for that cycle. Therefore, J_{nr} for a particular loading cycle under 100 Pa stress application is:

$$J_{nr} = \frac{\gamma_{nr}}{\sigma} = \frac{\gamma_{nr}}{0.1} \qquad (3)$$

The J_{nr} for each of the 10 loading cycles at 100 Pa creep stresses were calculated individually and then averaged to find the average non-recoverable creep compliance at 100 Pa ($J_{nr0.1}$). In a similar approach, the average non-recoverable creep compliances at 3200 Pa ($J_{nr3.2}$) were also computed. Alternatively, the percent recovery was computed by taking the difference between the peak strain and the final strain and dividing by the peak strain for each individual loading cycle (Figure 19). Mathematically,

$$\text{Percent Recovery} = \frac{\gamma_p - \gamma_u}{\gamma_p} \times 100 = \frac{\gamma_r}{\gamma_p} \times 100 \qquad (4)$$

The average percentage of recoveries at the 100 Pa and 3200 Pa stress levels are represented as $R_{0.1}$ and $R_{3.2}$, respectively, for the remainder of this report. In addition, the stress sensitivity parameter, J_{nrdiff} was calculated using the following equation:

$$J_{nrdiff} = \left(\frac{J_{nr3.2} - J_{nr0.1}}{J_{nr0.1}}\right) \times 100 \qquad (5)$$

Figure 18
Anton Paar MCR 302 DSR

The AASHTO T 350 method also included a simple method to identify the presence of an elastomeric polymer in a binder on the basis of $R_{3.2}$ and $J_{nr3.2}$ measured at the same temperature. It is stated that if the $R_{3.2}$ value falls above the line presented by equation $y = 29.371(x)^{-0.2633}$, (where x = average $J_{nr3.2}$ and $y = R_{3.2}$) the asphalt binder is considered as modified with an acceptable elastomeric polymer (Figure 20).

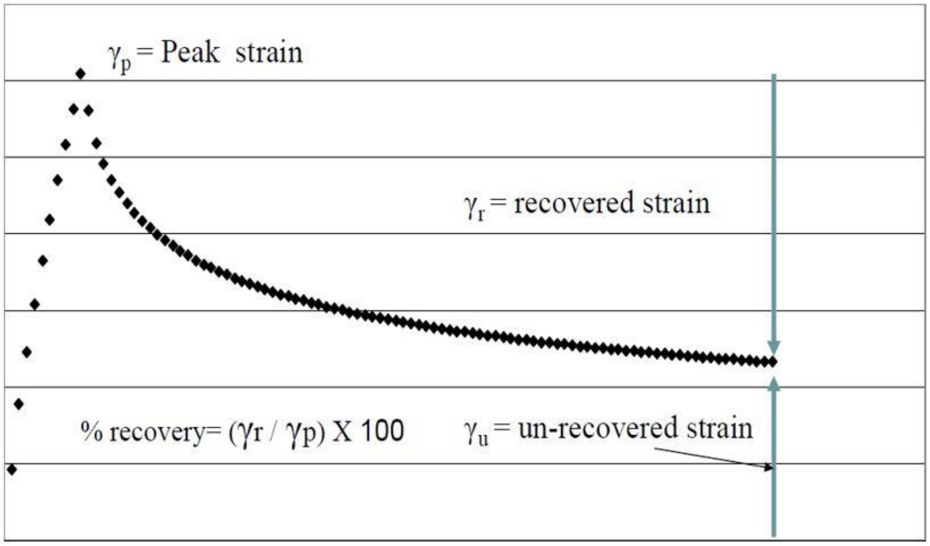

Figure 19
Details of MSCR loading cycle

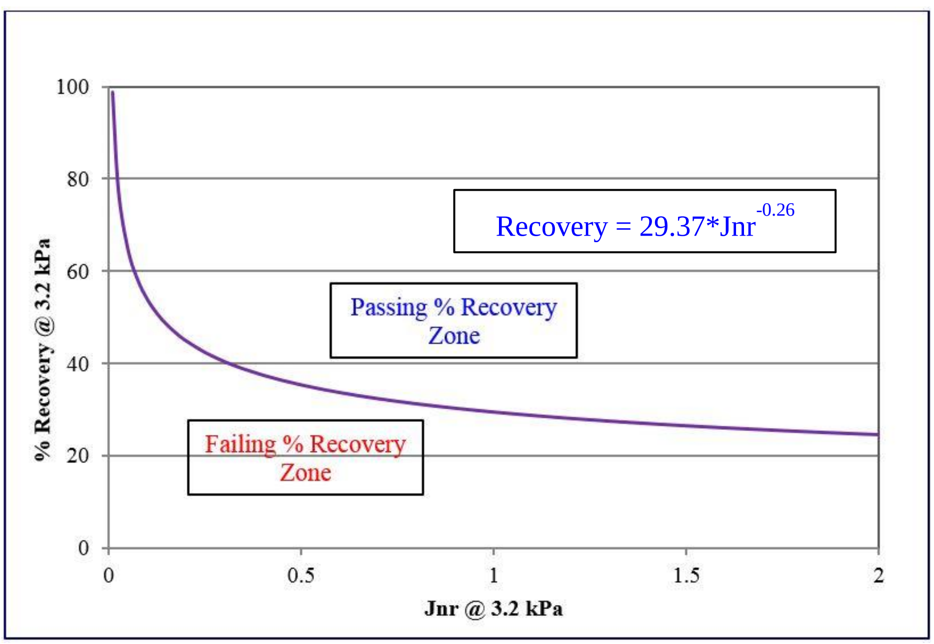

Figure 20
AASHTO elasticity curve

Force Ductility and Elastic Recovery Test

The forced ductility test involves measuring the tensile properties of polymer-modified asphalt binders by determining the force required to maintain a specific elongation rate of a test specimen at a certain elongation and a specified temperature, therefore, characterizing the toughness of a binder sample. It is a modified ductility test generally used as an indicator of the presence of polymer in an asphalt material. In this study, the AASHTO T 300 method was utilized to measure the force ductility of unaged original binders at 4°C and a deformation rate of 5 cm/min as directed in the current Louisiana asphalt binder specifications. A typical ductilometer test setup (as shown in Figure 21) was utilized in conjunction with a load cell that continuously recorded the force required to pull the specimens. The resulting output can be used to create a load-deformation (stress-strain) curve; however, the interpretation of data has been found to be different for different agencies. Currently, DOTD specifies the force ductility at 30 cm elongation and force ductility ratio (ratio of the force at the second peak to the force at initial peak, f_2/f_1) to be reported for PG 70-22m and PG 76-22m binders, respectively. For the computation of force ductility ratio, f_2 is taken as the force at the 30 cm elongation.

Figure 21
Typical ductilometer test setup

As the inherent strength and toughness of an asphalt binder improves with the polymer modification, a greater tensile stress is required to break the molecular bonds of modified binders when compared to the conventional ones. Figure 22 illustrates a typical stress-strain curve plotted from a force ductility test output. For an unmodified binder, the stress-strain curve appears like the left half (represented with a dotted line) of the stress-strain curve of a polymer-modified binder. As can be seen, typically there are two loading regions: primary and secondary in the stress-strain plot. The initial slope of the curve in the linear region under primary loading is denoted as the "Asphalt Modulus," whereas, the second slope identified in the secondary loading is termed as "Asphalt-Polymer Modulus". Generally, it is observed that after peak stress, when the unloading occurs, both modified and unmodified asphalt binders unload to the point where the polymer-modified binder demonstrates a secondary loading but the unmodified binder keeps unloading. Shuler et al. attributed this secondary reloading as the presence of polymer where the polymer starts to carry the applied load. The initial peak in force ductility test defines the strength of the base asphalt; whereas, the second peak explains the strength of the polymer network. Note that the strength of a particular binder at a certain elongation can be increased either by adding more polymer or by increasing the stiffness of the base asphalt. However, in Louisiana the force ductility ratio has been found to remain fairly constant for a given amount of SBS and the same crude asphalt. Interestingly, the plastomeric modification seldom retains the cohesiveness and often shows brittleness under tensile load even though it generally produces stiffness to the binders. This is why the force ductility requirement has been waived for the rubber modified binders in the DOTD asphalt binder specifications.

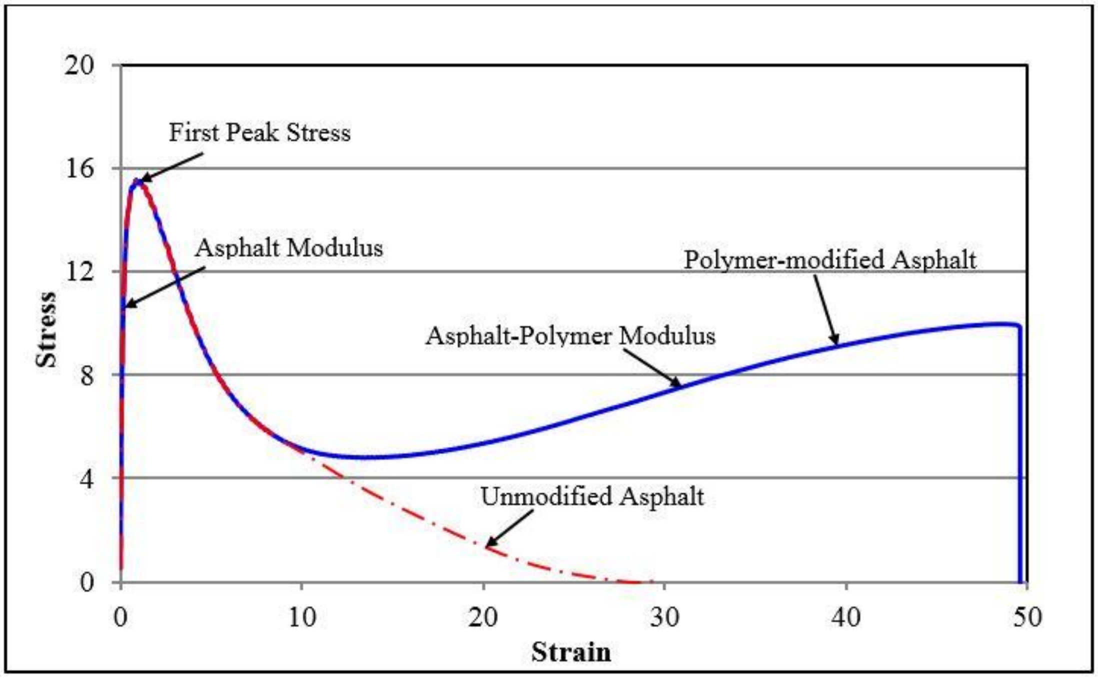

Figure 22
Typical stress-strain curve from a force ductility test

Elastic recovery tests measure the tensile property of polymer-modified asphalt using a ductilometer, as shown in Figure 21. The AASHTO T 301 method was followed in this study to conduct elastic recovery tests on RTFO aged binders at 25°C with 10 cm elongation. The elastic recovery of a binder was computed as the percentage of recoverable strain measured after the binder sample is elongated to 10 cm at a certain speed, held in that stretched position for five minutes, and then cut into halves. A higher recovery value is preferable as it indicates a more elastic binder. The 2006 DOTD asphalt binder specification requires minimum elastic recoveries of 40% and 60% for PG 70-22m and PG 76-22m binders respectively. The 2016 DOTD specifications have eliminated force ductility from specifications, but still requre PG 82-22rm binders to have a minimum elastic recovery of 60%.