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Validity of Multiple Stress Creep Recovery (MSCR) Test for DOTD Asphalt Binder Specification

by

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16. Abstract

Numerous studies have shown that G*/Sinδ, the high temperature specification parameter for current Performance Graded (PG) asphalt binder is not adequate to reflect the rutting characteristics of polymer-modified binders. Consequently, many state Department of Transportation (DOT)s have added supplemental specifications, also known as “PG-Plus” tests, to identify the presence of polymer-modified binders. Louisiana Department of Transportation and Development (DOTD) is one among those state agencies that require force ductility, elastic recovery, and separation of polymer tests as the “PG-Plus” requirements. However, most of these PG-Plus tests are unable to evaluate the performance of the polymer-enhanced binders and only determine the presence of a modifier. In this study, 44 Styrene-Butadiene-Styrene (SBS) polymer-modified asphalt binders currently graded as PG 70-22m and PG 76-22m and commonly used in the state of Louisiana were investigated. Those binders were collected from seven local asphalt binder suppliers. A suite of asphalt binder characterization tests namely: MSCR, G*/Sinδ, elastic recovery, and Force Ductility were conducted to assess the suitability of MSCR test to be included in Louisiana DOT’s asphalt binder specifications in addition to identifying the potential of replacing elastic recovery and force ductility tests with MSCR recovery. Based on the findings of this study, DOTD is recommended to make the transition to AASHTO MP 19, the new J_{nr}-based asphalt binder specifications. Recommendations are also provided to replace the currently used elastic recovery and force ductility tests with the MSCR recovery results.

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ABSTRACT

Numerous studies have shown that G*/Sinδ, the high temperature specification parameter for current Performance Graded (PG) asphalt binder, is not adequate to reflect the rutting characteristics of polymer-modified binders. Consequently, many state departments of transportation (DOTs) have added supplemental specifications, also known as “PG-Plus” tests to identify the presence of polymer-modified binders. Louisiana Department of Transportation and Development (DOTD) is one among those state agencies that require force ductility, elastic recovery, and separation of polymer tests as the “PG-Plus” requirements. However, most of these PG-Plus tests are unable to evaluate the performance of the polymer-enhanced binders and only determine the presence of a modifier. In this study, 44 Styrene-Butadiene-Styrene (SBS) polymer-modified asphalt binders currently graded as PG 70-22m and PG 76-22m and commonly used in the state of Louisiana were investigated. Those binders were collected from seven local asphalt binder suppliers. A suite of asphalt binder characterization tests (MSCR, G*/Sinδ, elastic recovery, and Force Ductility) were conducted to assess the suitability of the MSCR test to be included in DOTD’s asphalt binder specifications in addition to identifying the potential of replacing elastic recovery and force ductility tests with MSCR recovery. Based on the findings of this study, DOTD is recommended to make the transition to AASHTO MP 19, the new J_{nr}-based asphalt binder specifications. Recommendations are also provided to replace the currently used elastic recovery and force ductility tests with the MSCR recovery results.

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IMPLEMENTATION STATEMENT

The experience obtained from this research study has led to the development of a revision to the current DOTD asphalt binder specifications to implement the new AASHTO MP 19 specifications for the testing of liquid asphalt binders.

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INTRODUCTION

Higher traffic coupled with heavier loads lead the asphalt industry to introduce polymer-modified binders to enhance the durability and strength of hot mix asphalt (HMA) pavements. When the Superpave Performance Graded (PG) binder specification (AASHTO M 320) was introduced, it was expected that all asphalt binders with the same "Performance Grade" would function the same under a similar climate and traffic condition regardless of how those binders are produced. Since then, numerous research studies have shown that G*/Sinδ, the high temperature specification parameter for current PG asphalt binder, is not adequate to reflect the rutting characteristics of modified binders *[1-3]*. It was observed that G*/Sinδ is derived from the linear viscoelastic response measured from cyclic reversible loading that does not allow a direct measurement of the accumulation of permanent deformation with load repetition. Although the parameter G*/Sinδ can capture the viscous and elastic effects of neat binders, it is limited to adequately capture the benefits of elastomeric modification of asphalt binders.

The rheological character of modified asphalt binders has been found to depend on: the distribution of polymer in a binder, amount of polymer, cross–linking agent amount, and other additives such as polyphosphoric acid (PPA) *[4]*. Also, asphalt modified with different polymer types can perform differently even though they fall under the same PG group as designated in the current binder specification system. Interestingly, the AASHTO M 320 binder specifications was developed primarily on the basis of studies conducted on unmodified asphalt binders, and therefore, its applicability for polymer-modified binders has always been questioned *[5]*. As such, many state DOTs have adopted supplemental specifications, also known as "PG-Plus" tests in addition to the conventional PG specifications. However, in most cases, the PG-Plus tests do not reflect the performance and rather identify the presence of polymer in polymer-modified binders. Moreover, differences have been found to exist between the test protocols, test conditions, and their corresponding specification requirements. Unavailability of bias and repeatability statements adds further difficulties in utilizing these PG-Plus test results for quality control and quality assurance purposes with high confidence.

DOTD is one among those state agencies that require force ductility, elastic recovery, and separation of polymer tests as the PG-Plus requirement. However, both force ductility and elastic recovery tests have been found to be inadequate to evaluate the performance of the polymer-enhanced binders *[3]*. More specifically, these tests can determine the presence of a modifier in a binder only. It is beyond the competency of these tests to measure the enhanced-performance that binders achieve through polymer-modification *[5]*.

Multiple Stress Creep Recovery (MSCR) test, which has already been included in the latest AASHTO specifications for PG asphalt binder (AASHTO MP 19), showed every potential to resolve the previously mentioned issues. This test was developed on the basis of findings from various internal studies conducted by FHWA *[3]*. Conceptually, MSCR test is capable of providing the state agencies with an asphalt binder specification that is related better to field performance. Basically, MSCR is a creep and recovery test that uses a single test protocol and is quick and easy to perform. A non-recoverable creep compliance (J_{nr}) computed from this test is exercised to characterize the stress dependency of polymer-modified asphalt binders. J_{nr} is also reported to correlate well with the mixture rutting parameter *[1]*.

MSCR percent recovery, another parameter computed from the MSCR test can provide an indication of delayed elastic response of asphalt binder. It is anticipated that an asphalt binder with a high delayed elastic response is designated to possess significant elastic component at the test temperature. Currently in the AASHTO MP 19, no requirement was set for MSCR percent recovery. However, recent findings by the Asphalt Institute indicated that MSCR percent recovery results can possibly replace elastic recovery and force ductility test results *[6]*. Moreover, the J_{nr} and percent recovery can be used to characterize the microstructural aspects of polymer-modified binders as like as the dispersion of SBS polymer and other commonly used additives in asphalt binders *[4]*.

Louisiana has been using polymer modified binders since 1993 and crumb rubber modified binders since 2008. With the inclusion of MSCR test in the AASHTO MP 19 and an anticipation of its wide spread utilization, there has been a need for DOTD to verify whether the parameters such as: J_{nr} and MSCR percent recovery are sensitive to polymer and crumb rubber modified binders commonly used in Louisiana. Consequently, this study was initiated to identify the feasibility of DOTD to make a transition to the latest MSCR based AASHTO asphalt binder specifications.

Background and Literature Review

Asphalt binder is a petroleum product that sometimes occurs naturally but is usually obtained as a by-product during the distillation of refining crude oil *[7]*. At ambient temperature asphalt is a black, sticky, semisolid, and highly viscous material that softens as it is heated and hardens when cooled. Being a viscoelastic-thermoplastic material, the response of asphalt binder to load application is highly dependent on loading time, surrounding temperature, and stress levels. With low temperature and faster loading, asphalt shows stiffer and more elastic behavior whereas, at higher temperatures and longer loading times, it becomes softer and acts like a viscous fluid. For many years, asphalt binders were most commonly characterized by their physical properties determined using empirical tests namely: penetration, softening point, viscosity, ductility and so on *[8]*.

The ASTM D 946 specification, established in the late 1940s, has been recognized to be the oldest practice to control the quality of asphalt binder *[7]*. The specification solely relied on the penetration test that measures the depth of a sewing needle pushed into an asphalt binder sample under a specific loading time and temperature condition (generally 25°C). In the 1970s, the viscosity test began to be used extensively to grade asphalt binders on the basis of viscosities measured as the time required by an asphalt sample to flow through a calibrated glass tube at specific temperatures. As per ASTM D 3381 and AASHTO M 226 methods, absolute viscosities measured at 60°C and 135°C were used as the key physical properties of asphalt grading *[7]*. However, both penetration and viscosity are empirical measures that failed to capture binder performances under different loading and temperature regimes. Test results at 25°C, 60°C, and 135°C are never appropriate to represent a binder's performance at a wide spectrum of loading and temperatures that an asphalt pavement normally experience in field service *[9]*.

The well-acknowledged limitations in penetration and viscosity grading system directed the asphalt binder research community to develop a new binder specification that relates well with their field performance. In so doing, the Strategic Highway Research Program (SHRP) conducted a 5-year (1987 to 1992) research effort and consequently, the Superpave PG binder specification (AASHTO M 320) and the supporting test procedures were developed. The SHRP researchers designed a generic, performance-based, and climate-driven binder specification to address three major distresses found in asphalt pavements: rutting, fatigue, and thermal cracking. A suite of performance tests were developed or adapted, considering distresses are primarily related to the climate in which the roadway exists. Under this system, the Dynamic Shear Rheometer (DSR) has become the most commonly used equipment for measuring the rheological properties of asphalt binder at high and intermediate temperatures. The AASHTO T 315 test method is extensively used to measure the two important parameters: Complex modulus (G*) and the Phase angle (δ) to characterize the viscoelastic behavior of asphalt binders at different age periods of the binder life. G* is considered as the total resistance of a material to deformation under a sinusoidal shear stress load; whereas, δ measures the relative amounts of viscous and elastic components. At maximum pavement temperature, higher G* and low δ are desirable as each contributes to a reduced tendency for the binder to deform under load, and consequently, better rut resistance of a binder. Based on the above hypothesis, the SHRP researchers introduced a parameter namely, rutting factor: G*/Sinδ to measure the stiffness of a binder. Theoretically, the higher the G*/Sinδ, the stiffer the binder is, and therefore, shows more resistance to the permanent deformation.

Although G*/Sinδ has been used for many years to characterize the rutting resistance of asphalt binders, it has been fallen short in explaining the rutting performance of certain binders, especially the polymer-modified ones. While investigating the limitation of the AASHTO T 315 test method, Bahia et al. identified four problematic areas as follows: (1) the use of fully reversible cyclic loading in testing, (2) characterization of rutting parameter based on total dissipated energy, (3) fewer numbers of loading cycles, and (4) the grade bumping for traffic speed and volume *[10]*. The authors further elaborated that the current practice of fully reverse loading to be misleading as it does not allow to separate the energy dissipated in viscous flow and the energy spent temporarily (not dissipated) in delayed elasticity. In actuality, the load that causes rutting in real pavement is not fully reversed and starts from zero, rises to a maximum value and then eventually returns to zero again. Under the SHRP study, Anderson et al. anticipated a direct relationship between rutting and total energy dissipated per cycle as described in the following equation *[11]*:

$$W_i = \pi \times \tau_0^2 \times \frac{Sin\delta}{G^*} \qquad (1)$$

where,

W_i = total energy dissipated per cycle

τ_o = maximum stress applied

Unfortunately, this concept is not very appropriate for modified binders and is mostly validated for conventional or unmodified neat binders. The total energy dissipated (W_i) can be divided into three components: elastic, delayed elastic, and viscoelastic. Both elastic and delayed elastic energies are recoverable and, therefore, do not contribute to permanent deformation. Alternatively, only the non-recoverable viscous energy portion contributes to permanent deformation. For unmodified binders, the elastic and delayed elastic components are very small, which makes W_i almost equal to viscous components. Thus W_i becomes a good indicator of permanent deformation for conventional binders. On the other hand, modified binders contain more elastic and viscoelastic components at high pavement temperatures and consequently, W_i is not directly related to the energy dissipated in viscous flow that causes permanent deformation *[10]*.

The lack of a reliable performance related binder test, especially for elevated temperatures, has led to research into the development of new test methods. During a creep and recovery test, Shenoy estimated a new parameter: |G*|/ {1-(1/tanδ Sinδ)} that found to describe the unrecovered strain for polymer-modified binders more accurately *[12]*. In the NCHRP 9-10 study, Bahia et al. identified that rutting of asphalt binders depends on elasticity, delayed elasticity, and viscous flow properties *[1]*. It was further observed that the AASHTO T 315 method does not allow a direct measurement of accumulation permanent deformation with load repetition especially for polymer-modified binders that often show nonlinear elastic responses. In order to solve this deficiency, researchers offered the Repeated Creep and Recovery (RCR) test to measure the damage behavior of binder both in the linear and non-linear range. With an intelligent selection of the loading-unloading cycles and applied stress range, different traffic conditions can be simulated in this test successfully. The test was also designed to calculate the accumulated permanent deformation during each cycle that can be used to evaluate the rutting resistance of binder. The Burgers four-element model was utilized to determine the viscous creep stiffness of binder. Subsequently, the researchers recommended the replacement of the parameter G*/Sinδ with another parameter, namely the viscous component of the creep stiffness G_v, defined as:

$$G_v(t) = \frac{\eta o}{t} = \frac{1}{J_v(t)} \quad (2)$$

where,

η^o = the zero shear viscosity

J_v = Viscous compliance

Delgadillo et al. initiated another study to determine the stress dependency of binders in the RCR test and the relationship with mixture performance *[4]*. The recommended stress level of 25 Pa by Bahia et al. was thought to be very low in comparison to the real life stresses a binder is subjected to. Subsequently, a higher stress level was proposed. The results indicated that the binder stress sensitivity relied upon the type of binder, how those were modified, and the testing temperatures. It was also noticed that binders that withstood higher stress in the RCR test was able to produce mixture with lesser permanent deformation.

As a potential replacement of high temperature binder tests, the FHWA kept evaluating the RCR test (originated from NCHRP 9-10) at various stress levels and temperatures and eventually introduced a new asphalt binder test: the MSCR test *[3]*. The RCR test was performed at one stress level and repeated for 100 cycles; whereas, the MSCR test conducted by FHWA consisted of 11 stress levels each with 10 cycles of loading and relaxation. The test started with the lowest stress level and then proceeded to the next stress level after finishing every 10 cycles. There was no rest period between the creep and recovery cycles or the stress levels. The results indicated that the MSCR test can successfully characterize the stress dependency of polymer-modified binders. Moreover, it was able to differentiate the characteristics of various modifiers. For simplification, two stress levels: 0.1 kPa and 3.2 kPa were finally selected on the basis of a better correlation between MSCR based binder rutting criteria and corresponding mixture rutting results. 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.

In 2009, AASHTO introduced several J_{nr} based binder specification requirements, as an alternative to the current high temperature PG specifications. The new specification specifies the numerical grades of binder considering the environment the binders are intended to be used. In addition, a letter (i.e., S/H/V/E) is assigned to designate the suitable traffic levels such as: standard, heavy, very heavy, and extreme. For example, when the intended traffic level is estimated to be standard traffic (i.e., < 10 million ESALs) an "S" is placed at the end of the numerical grade of the binder (i.e., PG 64-XXS). Table 1 provides a snap shot of the new MSCR based specification as mentioned above.

Table 1
Summary of new MSCR based specifications for PG 64-XX grade

Design Traffic Level (ESALs, millions)	New PG Designation	Original Binder (AASHTO T 315) @ 64°C	RTFO Aged Binder MSCR (AASHTO TP 70) @ 64°C		PAV Aged Binder (AASHTO T 315) @ 25°C
			$J_{nr3.2}$ (kPa^{-1})	% J_{nrdiff}	
Standard (<10 m)	PG 64-22S	G*/Sinδ≥ 1.0 (kPa)	≤ 4.0	≤ 75 %	G*xSinδ ≤ 5000 (kPa)
Heavy (10~30 m)	PG 64-22H	G*/Sinδ≥ 1.0 (kPa)	≤ 2.0	≤ 75 %	G*xSinδ ≤ 6000 (kPa)
Very Heavy (>30 m)	PG 64-22V	G*/Sinδ≥ 1.0 (kPa)	≤ 1.0	≤ 75 %	G*xSinδ ≤ 6000 (kPa)
Extreme (>30 m + Standing Traffic)	PG 64-22E	G*/Sinδ≥ 1.0 (kPa)	≤ 0.5	≤ 75 %	G*xSinδ ≤ 6000 (kPa)

Recently, D'Angelo and Dongre completed another study to determine the applicability of the MSCR test to characterize the dispersion of SBS and other commonly used polymers in asphalt binders *[4]*. The authors observed that the MSCR test is useful to optimize the blending of SBS polymer in asphalt binder and can be more effective than the G*/Sinδ and the Elastic Recovery test currently used by most highway agencies.

Limitations of Elastic Recovery and Force Ductility Tests

The two most widely used PG-Plus tests are the elastic recovery and force ductility tests that are conducted with the use of a ductilometer. As illustrated in Figure 1, the data collected from the Asphalt Institute website indicated that 37 states in the country currently use elastic recovery/force ductility/Phase Angle or other type of tests or a combination as their PG-Plus specification requirement. Conversely, the remaining 13 states prefer not to employ any PG-Plus test *[13]*. However, the Asphalt Institute's data also show the existence of a wide variation in the testing criteria and specification requirements among the various state agencies in the U.S. For example, Louisiana, Oklahoma, and Colorado, among others, currently require the elastic recovery test to be conducted at 25°C on the RTFO aged binder; Alabama requires it to be done at 10°C on the RTFO aged binder; whereas, Texas requires the test to be conducted at 10°C but on an unaged original binder. Likewise, all these abovementioned states set different percentage recovery requirements as the "passing" criteria in their respective binder specifications. Other major disadvantages of elastic recovery and force ductility tests have been found to be the manual data collection, inconsistencies in sample preparation, and time consuming sample preparation, conditioning, and testing.

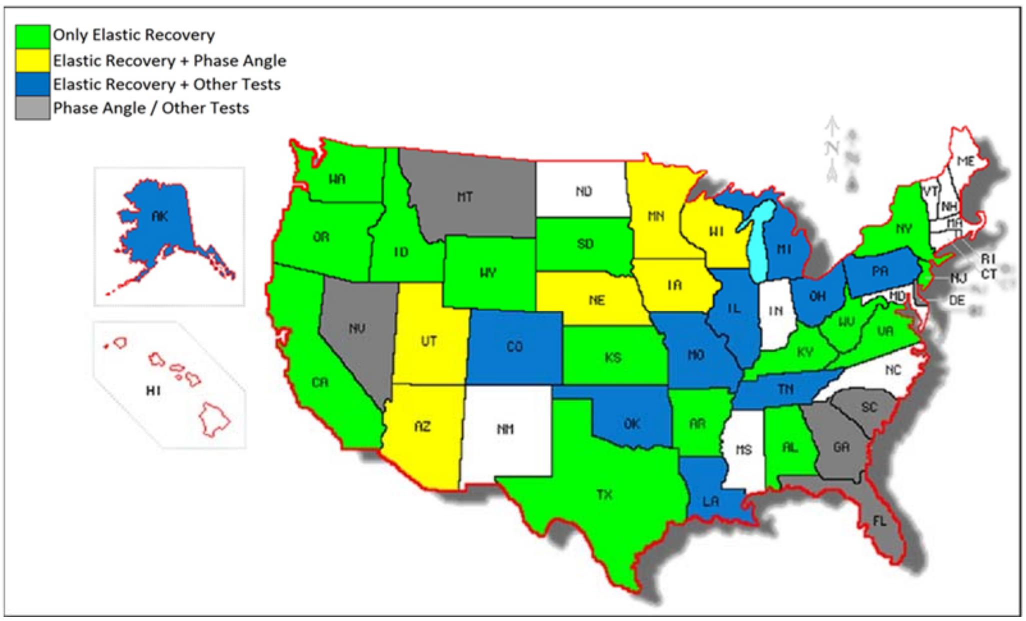


Figure 1
PG-Plus tests around the U.S.

Recently, Tabatabaee et al. expressed concern regarding the continuous change in sample geometry during the elongation phase in a ductility test *[14]*. The researchers observed that the stress in a binder sample is influenced by the stiffness and rate of relaxation in addition to the continuous cross-sectional change. The change in cross-section can also affect the elastomeric three dimensional network of polymers, which may affect both the overall Poisson ratio and the rate of stress relaxation of asphalt binder as the sample elongates at a constant rate. Therefore, the comparison of the ductility between different modified and unmodified binders would be significantly affected by the varying stress states between samples.

OBJECTIVE

The major goal of this study was to characterize the elastic behavior of various asphalt binders (mainly PG 76-22m and PG 70-22m), which are listed in the Qualified Products List of DOTD, on the basis of MSCR test results. It was anticipated that the outcome of this study would eventually lead to identifying the suitability of the MSCR parameters to be included in the current DOTD asphalt binder specifications. Additional analyses were conducted to find possible correlations between MSCR percent recovery and currently utilized PG-plus (i.e., elastic recovery and force ductility) test results with an aim to replace the later tests with MSCR. Finally, several recommendations have been proposed to revise the current asphalt binder specifications for the state of Louisiana.

SCOPE

A wide spectrum of styrene-butadiene-styrene (SBS) polymer-modified PG 70-22m and PG 76-22m binders commonly used in the state of Louisiana were investigated under the scope of this study. Testing of Crumb Rubber Modified (CRM) binders were also included in the original proposal; however, only nine CRM modified PG 82-22rm and two PG 76-22rm binders could be tested due to their unavailability during the course of the study.

A total of 44 SBS modified asphalt binders from seven asphalt binder suppliers were evaluated. Among those, 21 binders were PG 76-22m, and the remainder were PG 70-22m as per the current DOTD asphalt binder specifications. To maintain confidentiality, the binder suppliers are randomly labeled as A, B, C, and so forth for the remainder of this paper. From each supplier, numerous deliveries of binder samples were received periodically during the two-and-a-half-year span of this study. This approach was to check the consistency of the asphaltic properties of the same PG graded binder (i.e., PG 76-22m) from the same supplier over a longer period of time. However, due to certain limitations, an equal number of sampling-deliveries could not be maintained for every binder supplier. Binders received from a specific supplier but in different deliveries were labeled as a sequential number placed next to the supplier's ID. For example, binders collected from supplier "A" in consecutive deliveries were labeled sequentially as: A1, A2, A3, and so forth.

This research initially concentrated on MSCR tests conducted on both original and Rolling Thin Film Oven (RTFO) aged asphalt samples at 64 and 70°C. Afterwards, a limited factorial of binders was experimented at 67°C, which was not in the original scope of this research. Additionally, Force Ductility, Elastic Recovery, Gel Permeation Chromatography (GPC), and regular 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 MSCR and DSR tests; whereas, two replicates were tested for force ductility and elastic recovery tests.

METHODOLOGY

A suite of asphalt binder characterization tests were conducted to evaluate the high temperature performance of binders investigated under the scope of this study. Table 2 summarizes the binder tests that were included. It should be noted that both unaged and RTFO aged binder samples were examined in this study. The AASHTO T 240 method was followed whenever a binder was needed to be RTFO aged. Since temperature is one of the most influential factors for asphalt binder characterization, the testing temperatures were selected carefully on the basis of the local Louisiana environment.

Table 2
List of binder tests

Name of the Test	Test Protocol	Test Temperature	Binder Condition	Measured Criteria
MSCR	AASHTO TP 70	64°C, 67°C[1], and 70°C	Both Unaged and RTFO Aged	$J_{nr0.1}$, $J_{nr3.2}$, $R_{0.1}$ and $R_{3.2}$
Shear Modulus and Phase Angle	AASHTO T 315	64°C, 67°C, 70°C, and 76°C	Both Unaged and RTFO 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
GPC	Daly et al. (17)	-	Both Unaged and RTFO Aged	Polymer content

[1] DOTD minimum allowable grade

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 TP 70 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 2 illustrates the stress application and the subsequent strains recorded from a typical MSCR test.

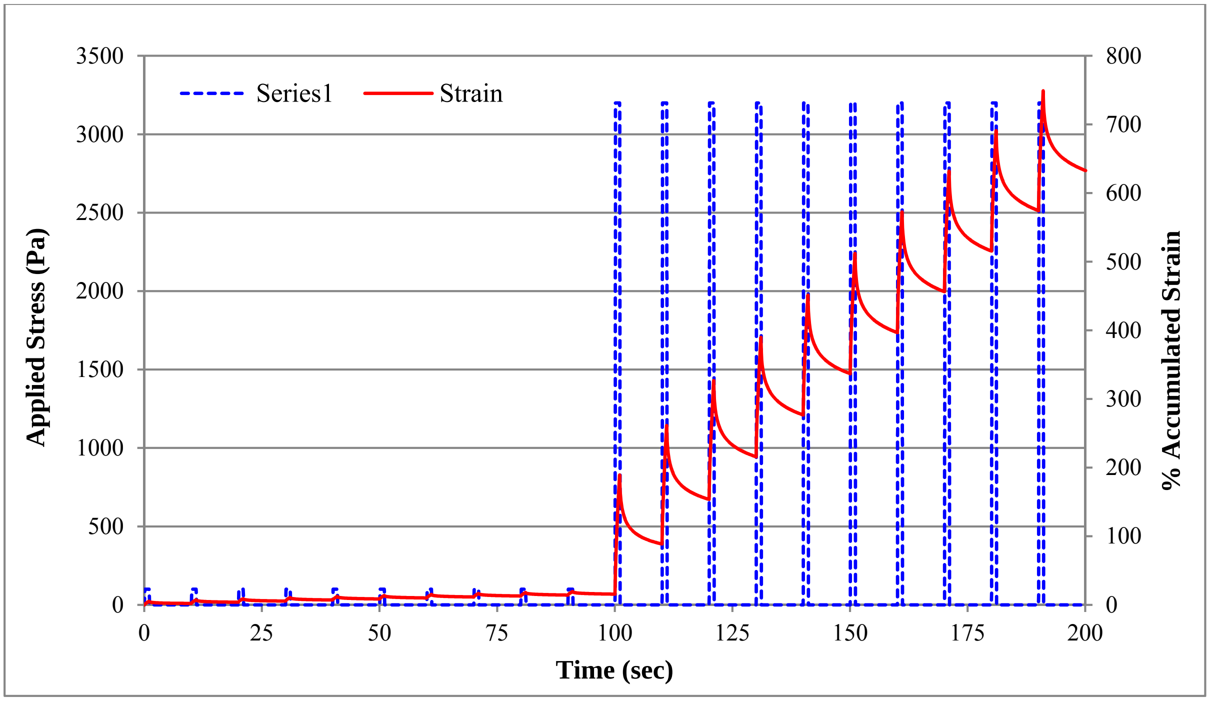


Figure 2
Typical MSCR test output

An Anton Paar MCR 302 DSR (as shown in Figure 3) 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 4). 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 3
Anton Paar MCR 302 DSR

The AASHTO TP 70 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 5).

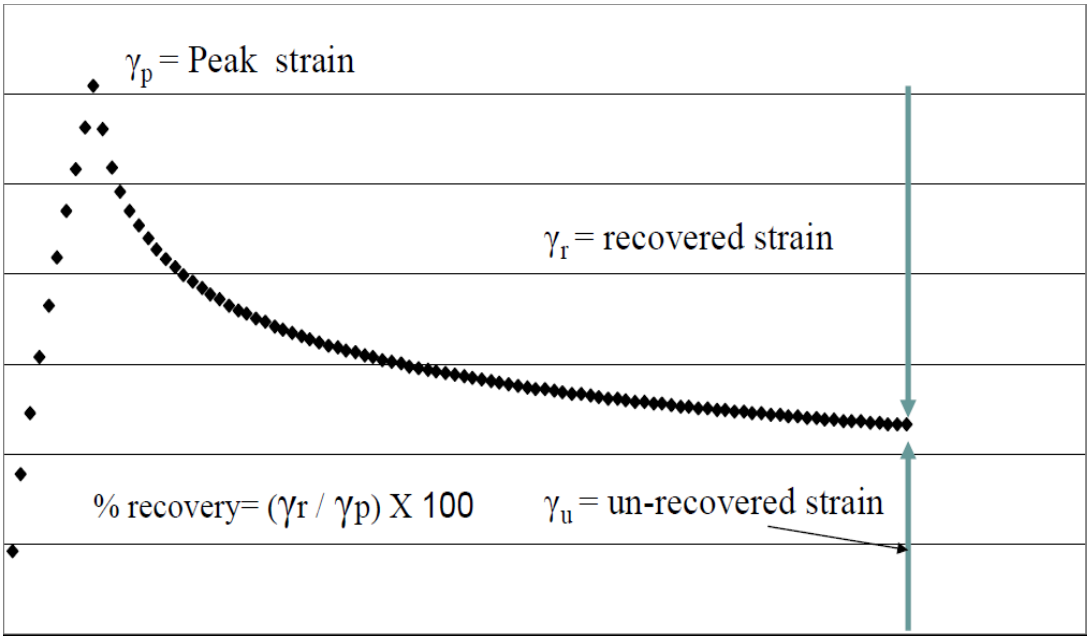


Figure 4
Details of MSCR loading cycle

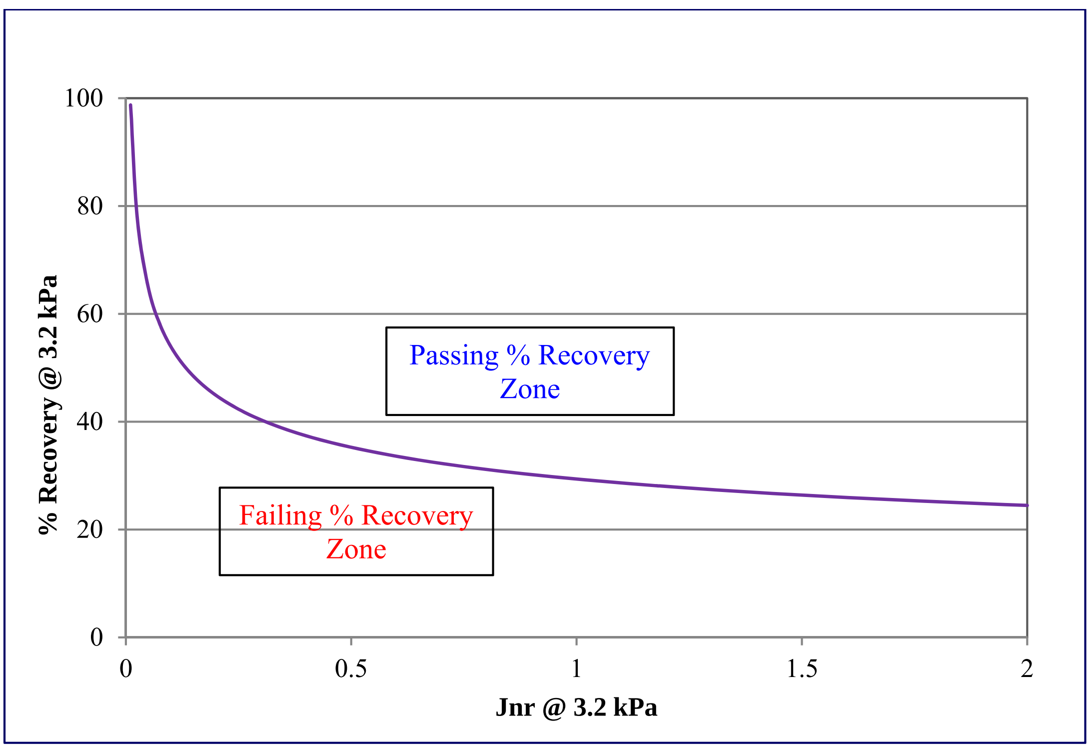


Figure 5
AASHTO elasticity curve

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 6) 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, f2/f1) to be reported for PG 70-22m and PG 76-22m binders, respectively *[15]*. For the computation of force ductility ratio, f2 is taken as the force at the 30 cm elongation.

Figure 6
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 7 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" *[16]*. 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 *[16]*. 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 current DOTD asphalt binder specifications.

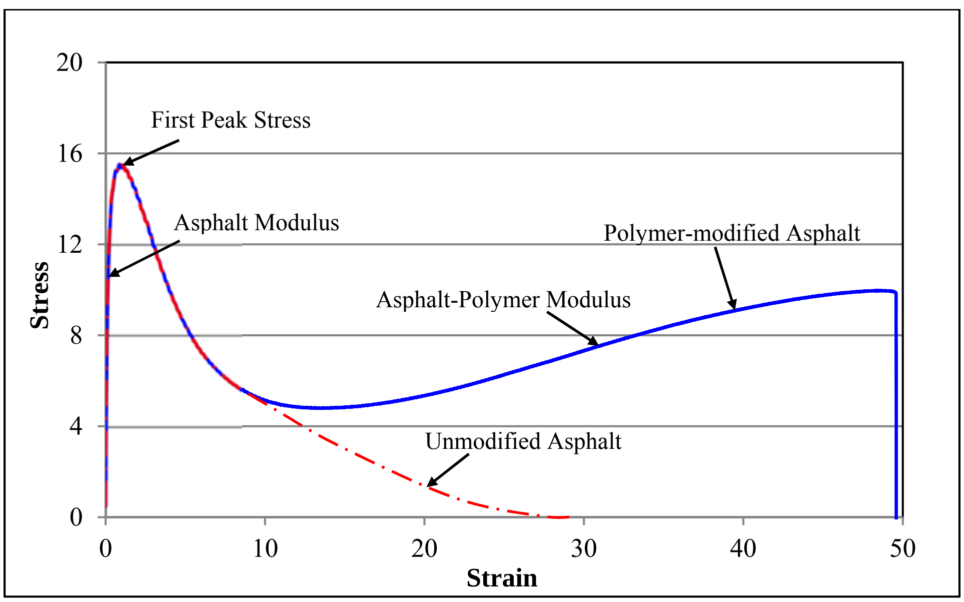


Figure 7
Typical stress-strain curve from a force ductility test

Elastic recovery test measures the tensile property of polymer-modified asphalt using a ductilometer as shown in Figure 6. 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 current DOTD asphalt binder specification requires minimum elastic recoveries of 40 percent and 60 percent for PG 70-22m and PG 76-22m binders respectively.

GPC Test

GPC is a chromatographic method in which the molecules are separated on the basis of their sizes in a solution of a particular solvent. In this study, the GPC test was performed following the method described in another LTRC study conducted by Daly et al. *[17]*. An EcoSec high performance GPC system (HLC-8320 GPC) as shown in Figure 8 was used for GPC testing. During the GPC analysis, a Tetrahydrofuran (THF) solution of asphalt binder were injected into a set of porous columns and eluted. The components with high molecular weight elute first followed by the components with lower molecular weights.

Figure 8
EcoSec high performance GPC system

Chemically, asphalt is a mixture of complex organic molecules that range in molecular weight from several hundred to several thousand. It is mainly comprised of two major components: 80 percent of asphaltenes and 20 percent maltenes approximately. Asphaltenes, the stable part of asphalt binder possess the higher molecular weights whereas, maltenes have the lower molecular weights. Basically, maltenes are the light oils that are easily affected by the exposure to environment. During polymer modification, generally a high molecular weight polymer is added to the neat asphalt binder to enhance the performance. However, due to a large difference in molecular mass, the polymer and the asphalt components of a polymer-modified asphalt can be separated using a GPC technology. As shown in Figure 9, the SBS polymer with a molecular weight greater than 19,000 daltons elutes first and then followed by the asphaltenes and maltenes with molecular weights 3000-19000 dalton, and below 3000 dalotons respectively *[17]*.

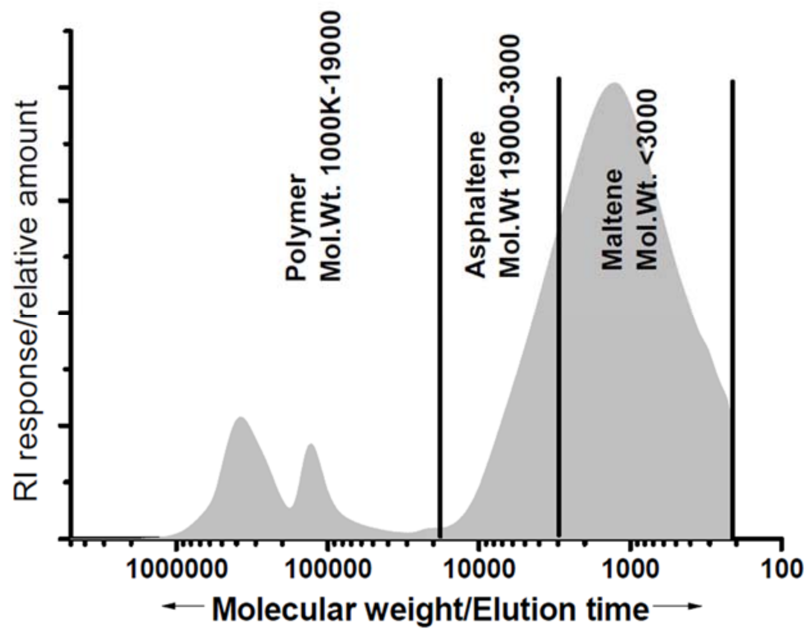


Figure 9
Polymer separation using GPC

DISCUSSION OF RESULTS

MSCR Test Results

Figures 10 and 11 respectively present the snapshots of MSCR based test results for both the unaged and the RTFO aged SBS polymer-modified binders included in this study. The detailed test results for individual binders are presented in Tables 3 and 4 of Appendix A. Each vertical bar illustrated in Figures 10 and 11 is a representation of the average $J_{nr3.2}$ and $R_{3.2}$ respectively, resulting from three replicates prepared from the same binder supply. The error bars on top of each vertical bar indicate the ±1 standard deviation of the mean $J_{nr3.2}$ and $R_{3.2}$ results. In general, standard deviations for MSCR $J_{nr3.2}$ and percent $R_{3.2}$ were found to be very consistent. The standard deviations for unaged binders were slightly greater in comparison to the aged ones but nothing was significant. Theoretically, a lower $J_{nr3.2}$ and higher $R_{3.2}$ results for RTFO aged binders are desirable as those indicate lower rut susceptibility and higher elastic behavior respectively. It is evident from Figures 10 and 11 that the PG 76-22m binders showed lower average $J_{nr3.2}$ and higher average $R_{3.2}$ values in comparison to their PG 70-22m counterparts. Generally, a PG 76-22m binder contains a higher percentage of SBS polymer when compared to a PG 70-22m binder produced from the same supplier, which explains the above-mentioned trend. It is also noticable that the MSCR test results are capable of distinguishing between the PG 76-22m and PG 70-22m grades on the basis of $J_{nr3.2}$ and $R_{3.2}$ results when binder samples were collected from the same supplier.

To assess the consistencies of those test results further, the “d2s” values for each binder supply were calculated and compared with the results of an inter-laboratory study conducted by the Asphalt Institute *[18]*. It should be noted that the precision and bias measures are yet to be included in the current AASHTO TP 70 test method; therefore, the study conducted by the Asphalt Institute may be taken as a valid reference to date. Statistically, “d2s” stands for “difference 2 standard deviation,” which represents the maximum expected difference between two independent measurements for a single operator or multilaboratory test scenario. In this study, the d2s was computed from three individual binder specimens tested by a single operator within a single laboratory. As mentioned in ASTM C670-13, the d2s precision values were calculated as $1.96\sqrt{2} \times$ Standard deviations (for 95 percent confidence level). Figures 12 and 13 present the d2s precision values for J_{nr} and percent recovery at 3.2 kPa, respectively. Besides a few exceptions, most of the binders (more than 85 percent) were able to meet the d2s limit for J_{nr} at 3.2 kPa documented in the Southeast Asphalt User-Producer Group (SEAUPG) and Northeast Asphalt User-Producer Group (NEAUPG) interlaboratory studies conducted by Asphalt Institute *[18]*. However, the d2s results for percent recoveries were more scattered and often failed to meet the Asphalt Institute’s threshold of 3.9 percent for SEAUPG and 7.7 percent for NEAUPG respectively. A closer look indicated that results exceeded the limits mostly when binders were tested at 70°C. Perhaps, conducting MSCR test at 70°C was too severe a condition for the binders that are originally meant to perform at the average Louisiana climatic temperature of 64°C. Over all, the computed d2s results provide confidence that the consistency of testing and computations were well maintained in this study.

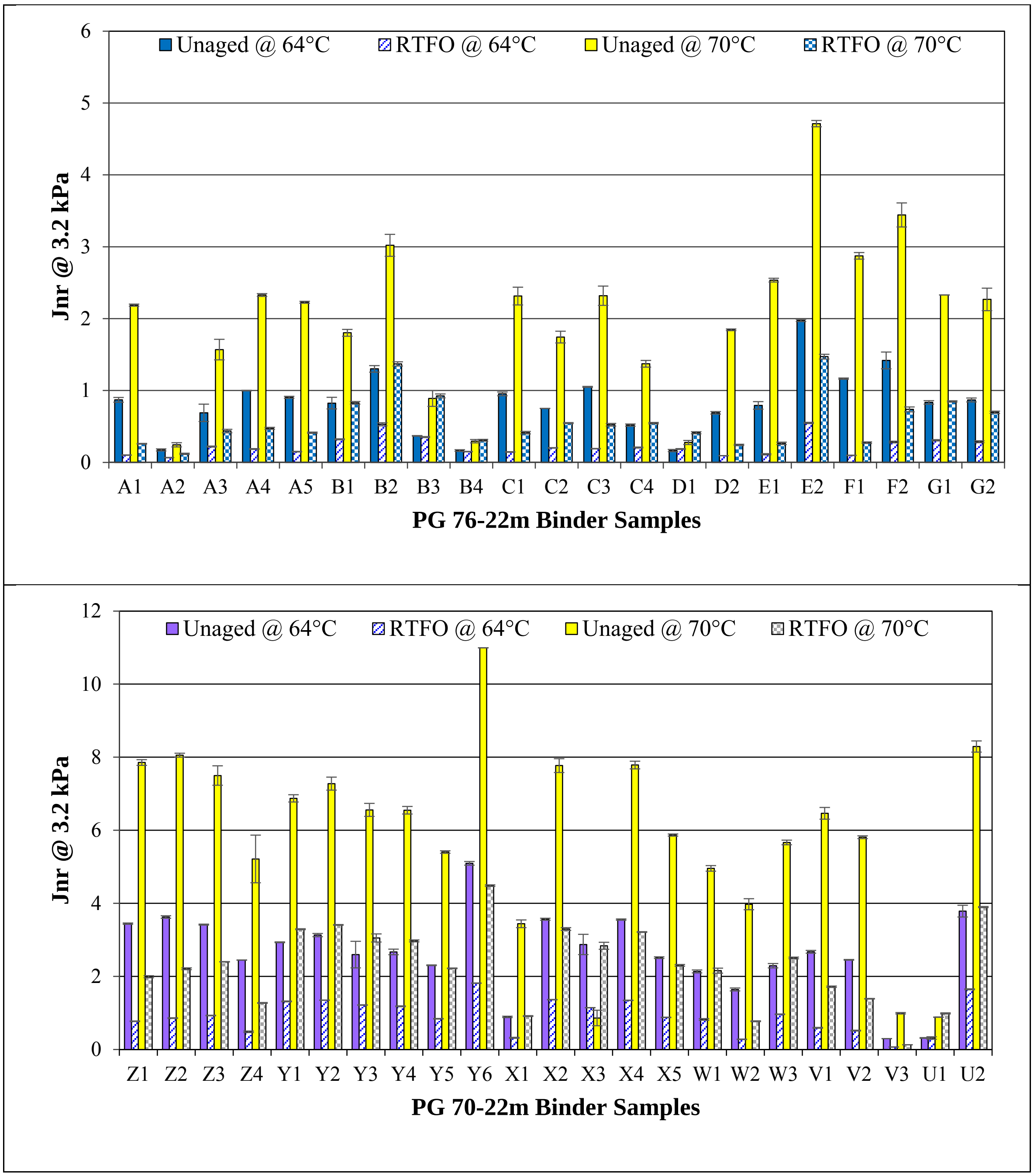


Figure 10
Average J_{nr}s @ 3.2 kPa

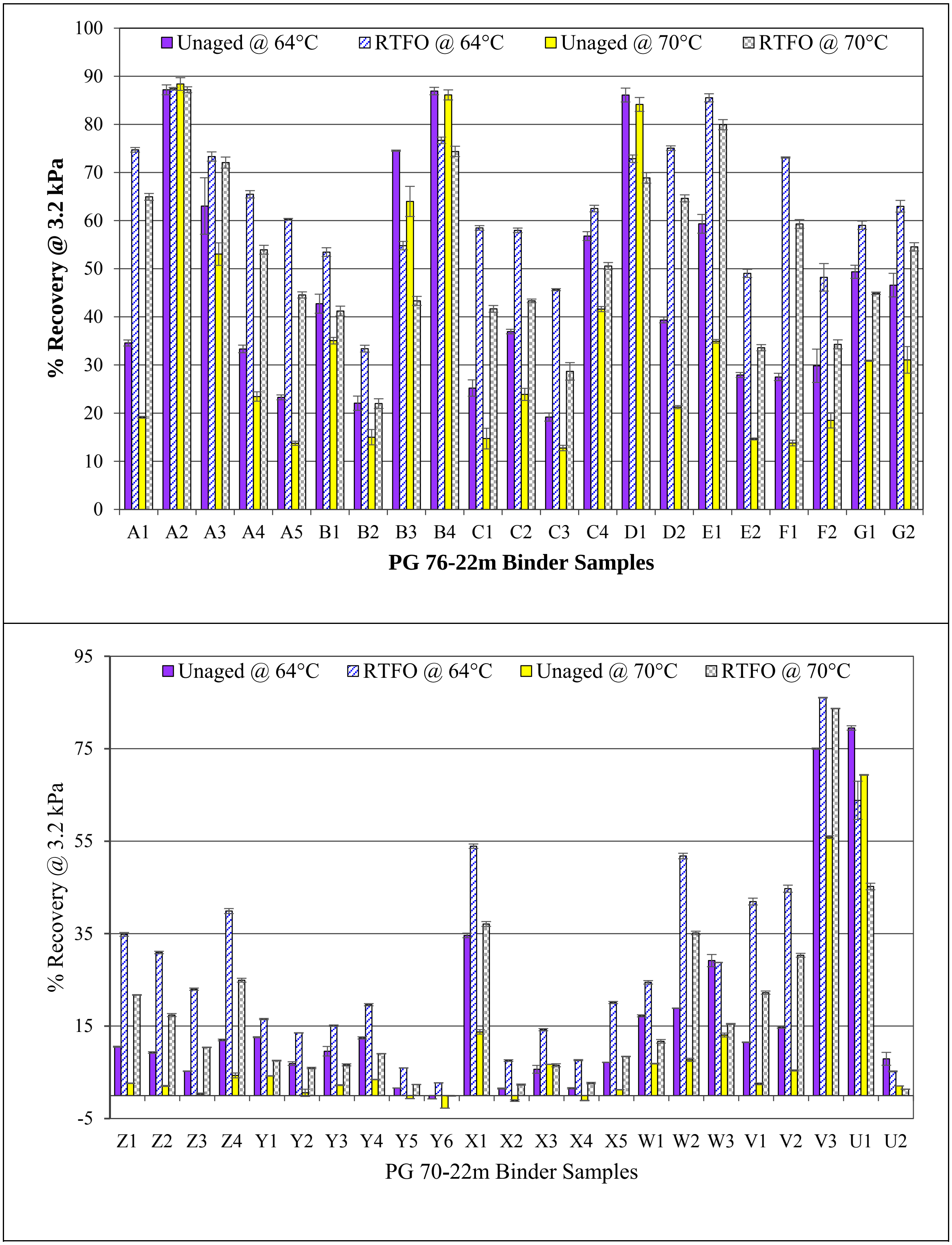
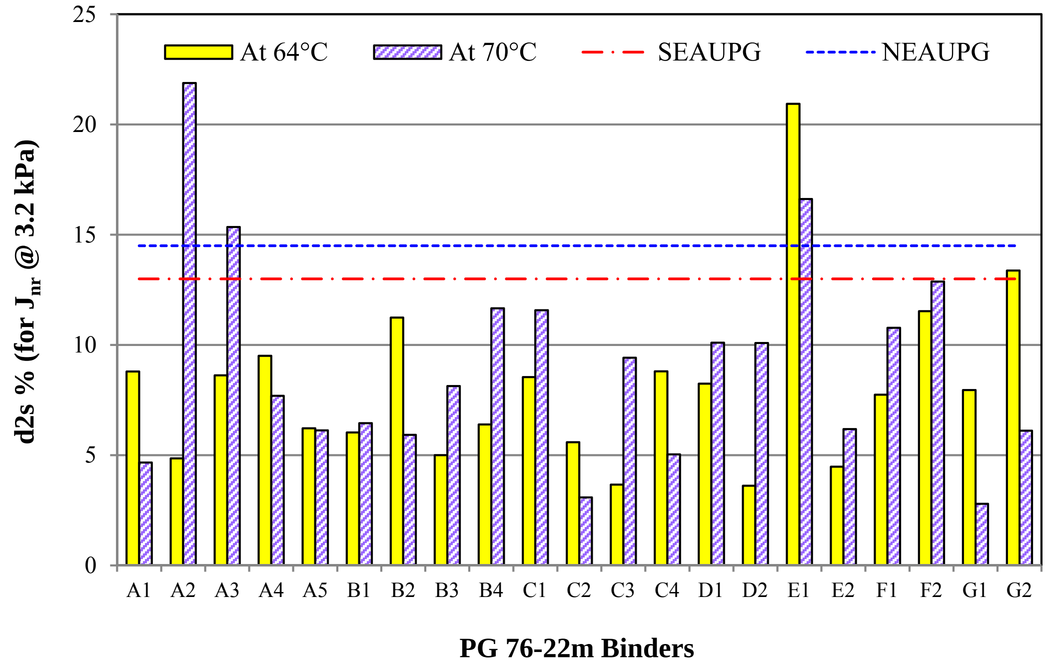


Figure 11
Average percent recoveries @ 3.2 kPa



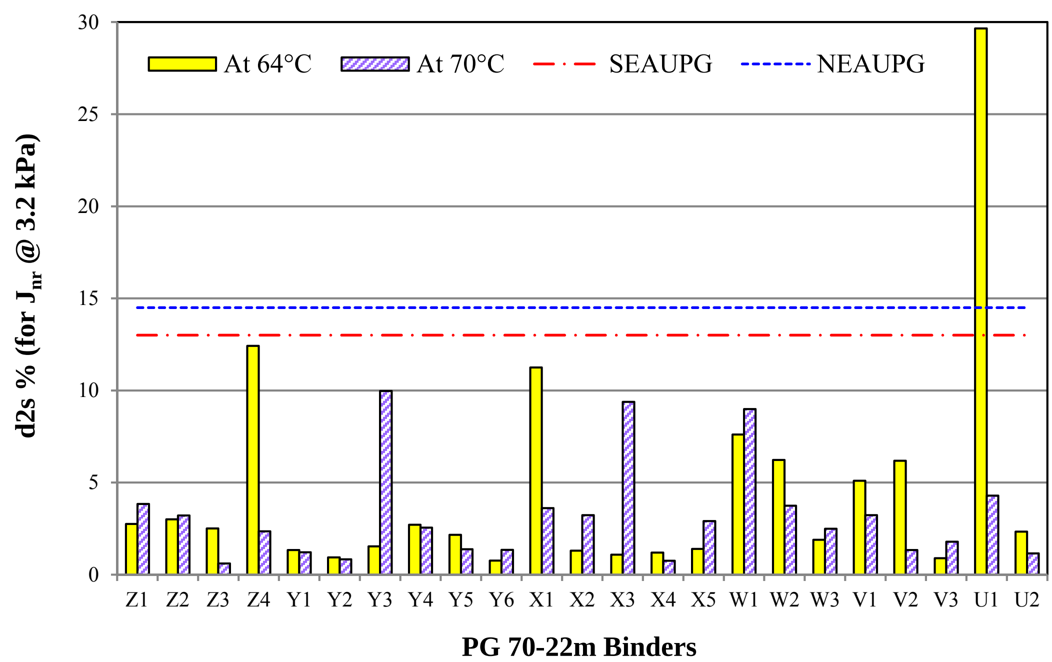


Figure 12
Comparison of d2s for J_{nr} @ 3.2 kPa

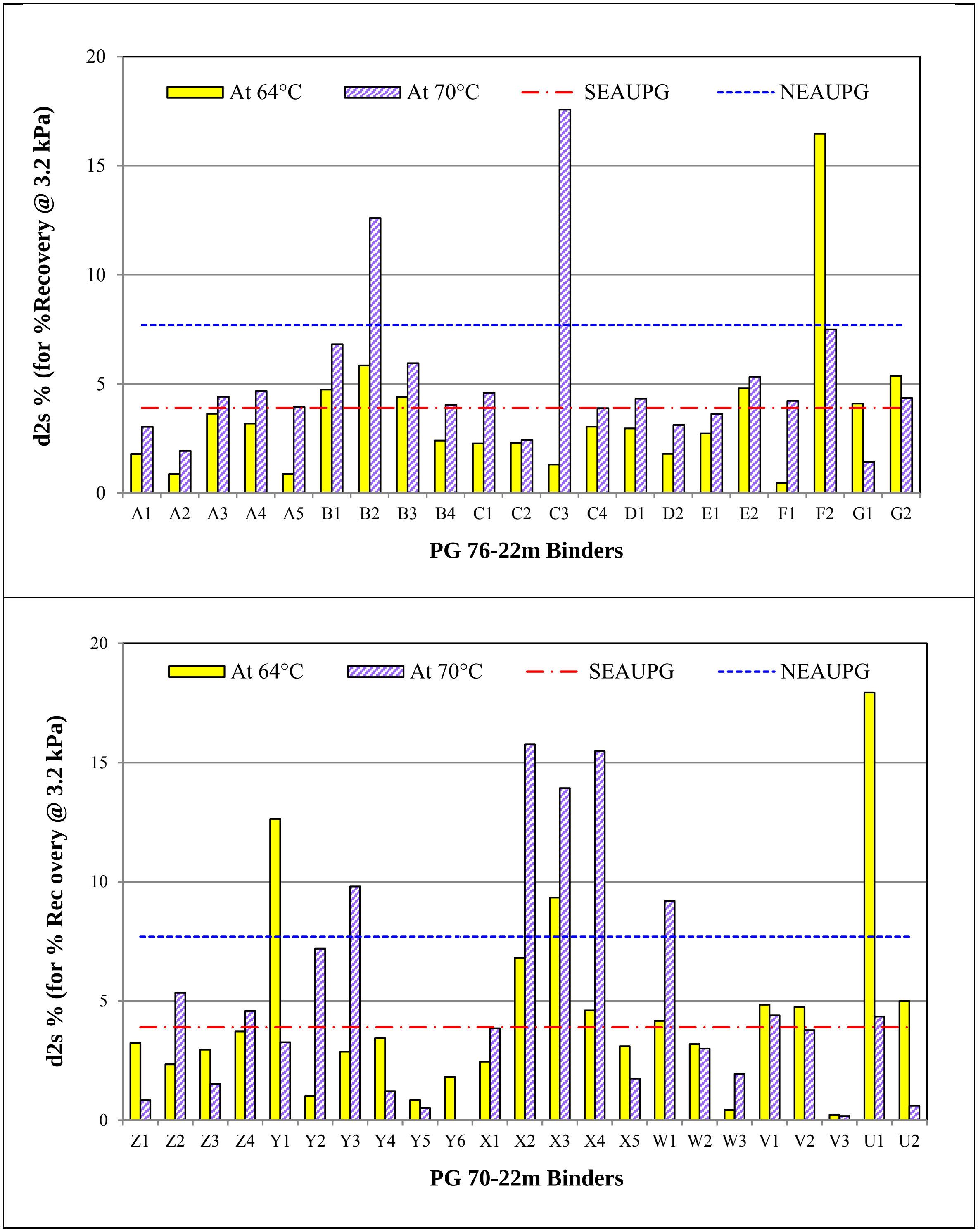


Figure 13
Comparison of d2s for percent recovery @ 3.2 kPa

As can be seen from Table 1, the current AASHTO MP 19 specification is regulated by two MSCR based parameters: $J_{nr3.2}$ and J_{nrdiff}. First, every binder is checked against a maximum

J_{nrdiff} of 75 percent to ensure that binder is not stress sensitive at the testing temperature. Then the binder is graded as operational for a specific traffic level (i.e., S/H/V/E) for a certain environmental temperature on the basis of $J_{nr3.2}$ results. Figure 14 represents the J_{nrdiff} for every binder included in this study, which clearly indicates that none of those binders were stress sensitive.

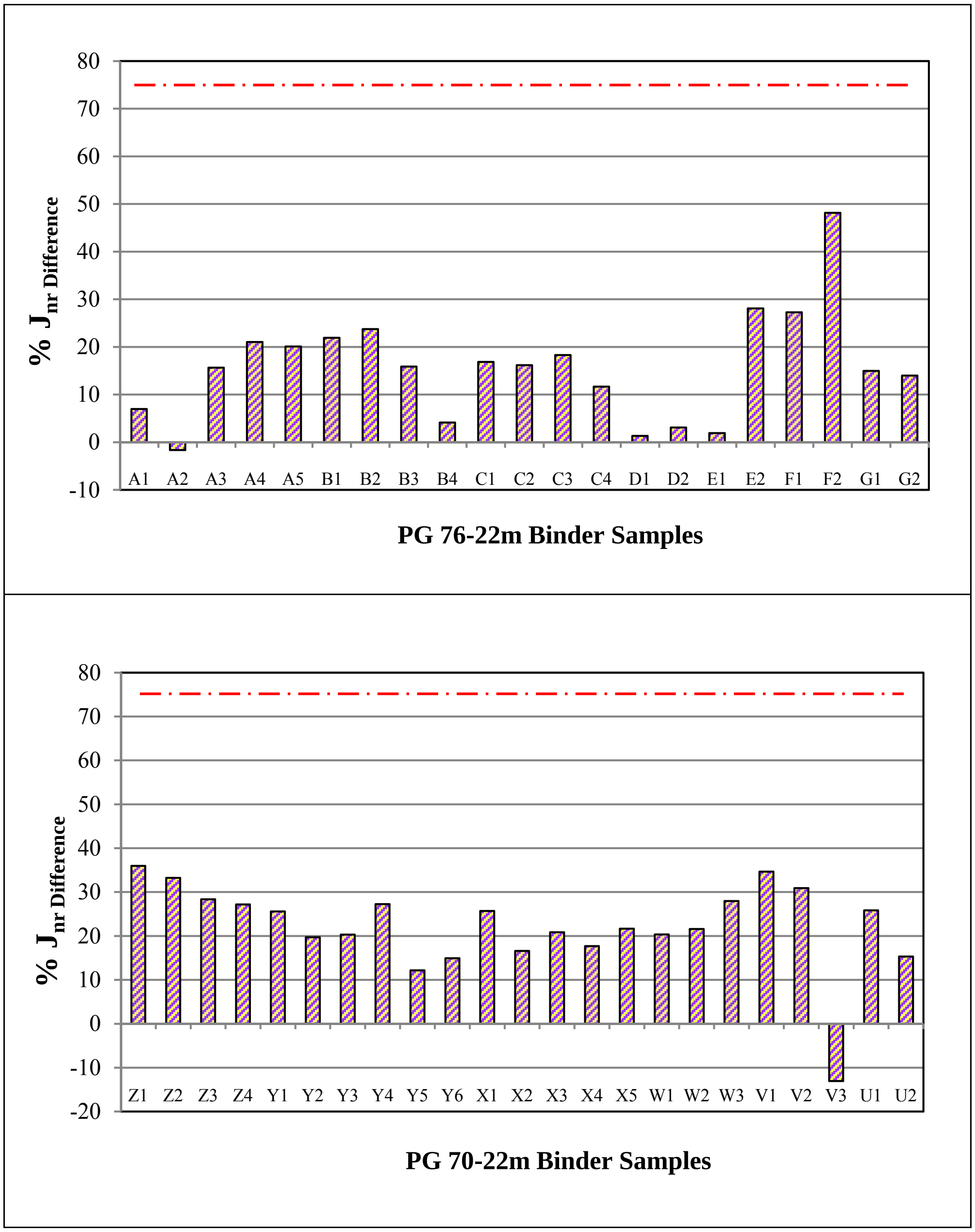


Figure 14
Stress sensitivity check for binders

Figures 15 and 16 illustrate the average J_{nr} results and the corresponding J_{nr}-based performance grades for PG 76-22m and PG 70-22m binders at 64°C and 70°C temperatures, respectively. It can be seen that the binders commonly achieved a higher MSCR grade at 64°C in comparison to 70°C. Generally, the stiffness of an asphalt binder is found to be a function of loading time and testing temperature. As the loading time in the MSCR tests remained constant, a decrease in stiffness (resulted in a higher J_{nr} values) was ensured with a rise in testing temperature.

As expected, the PG 76-22m binders achieved higher MSCR grades when compared to their PG 70-22m counterparts at both testing temperatures. Further investigation shows that all but two PG 76-22m binders (specimen B2 and E2) can be graded as the highest possible grade according to AASHTO MP 19, PG 64-22E at 64°C. Even though B2 and E2 failed to meet the minimum $J_{nr3.2}$ required for class "E" at 64°C, their respective $J_{nr3.2}$ values of 0.530 kPa^{-1} and 0.549 kPa^{-1} are very marginal with the specification limit of 0.5 kPa^{-1}. When specimens from individual suppliers are compared visually, binders A, C, D, and G showed better consistencies in test results than others. Perhaps this is an indication that the quality of PG 76-22m binders supplied by A, C, D, and G were equally maintained during the period of this study. Over all, the MSCR results indicate that the binders currently graded as PG 76-22m were found to be very capable of handling the severe traffic condition at 64°C climatic condition.

Unlike PG 76-22m binders, the results for PG 70-22m binders showed comparatively higher variability. At 64°C, five of the PG 70-22m binders performed similar to PG 76-22m and fell in the category of 64-22E (Figure 15). However, 50 percent of the remaining 18 binders was graded as 64-22V and the other half was 64-22H. It is expected that the PG 70-22m binders may show inferior J_{nr} based grade in comparison to PG 76-22m binders, as PG 70-22m binders contain lesser amount of SBS polymer. However, achieving three different grades (i.e., 64-22E, 64-22V, and 64-22H) clearly indicates that these PG 70-22m binders possibly perform differently even under similar traffic and climatic conditions. Interestingly, the current AASHTO T 315-based specification fails to capture this variation in performance and all PG 70-22m binders considered in this study were labeled with the same PG grade.

Testing at 70°C showed higher variability in results as presented in Figures 16. For PG 76-22m category, all samples from suppliers A and D were able to meet the "E" category. Binder Cs and Gs were fairly consistent but failed to meet the "E" category and obtained PG 70-22V grade with an exception of binder C1. Alternatively, binder Bs and Es showed the highest variability among the PG 76-22m group and fell in three different classes: H, V, and E. For PG 70-22m binders, the variability in J_{nr} results was even wider at 70°C in comparison test results at 64°C. About 65 percent of the PG 70-22m binders obtained a grade of PG 70-22S and the solitary binder Y6 failed to meet even the minimum J_{nr} requirement (J_{nr} = 4.0 max) for AASHTO MP 19 specification. This raises a point of concern when testing MSCR at 70°C, whether it is too destructive to represent their true field performance for the PG 70-22m binders experimented in this study. In Louisiana, similar binders have been used in the roadway construction for more than a decade, and field data warrant a better performance than the PG 70-22S class indicates. It is also worth knowing that none of the south-eastern states validated 70°C as the MSCR testing temperature for their respective binder specifications. Considering these facts, the MSCR test at 70°C is not recommended for the adoption of AASHTO MP 19 for the state of Louisiana.

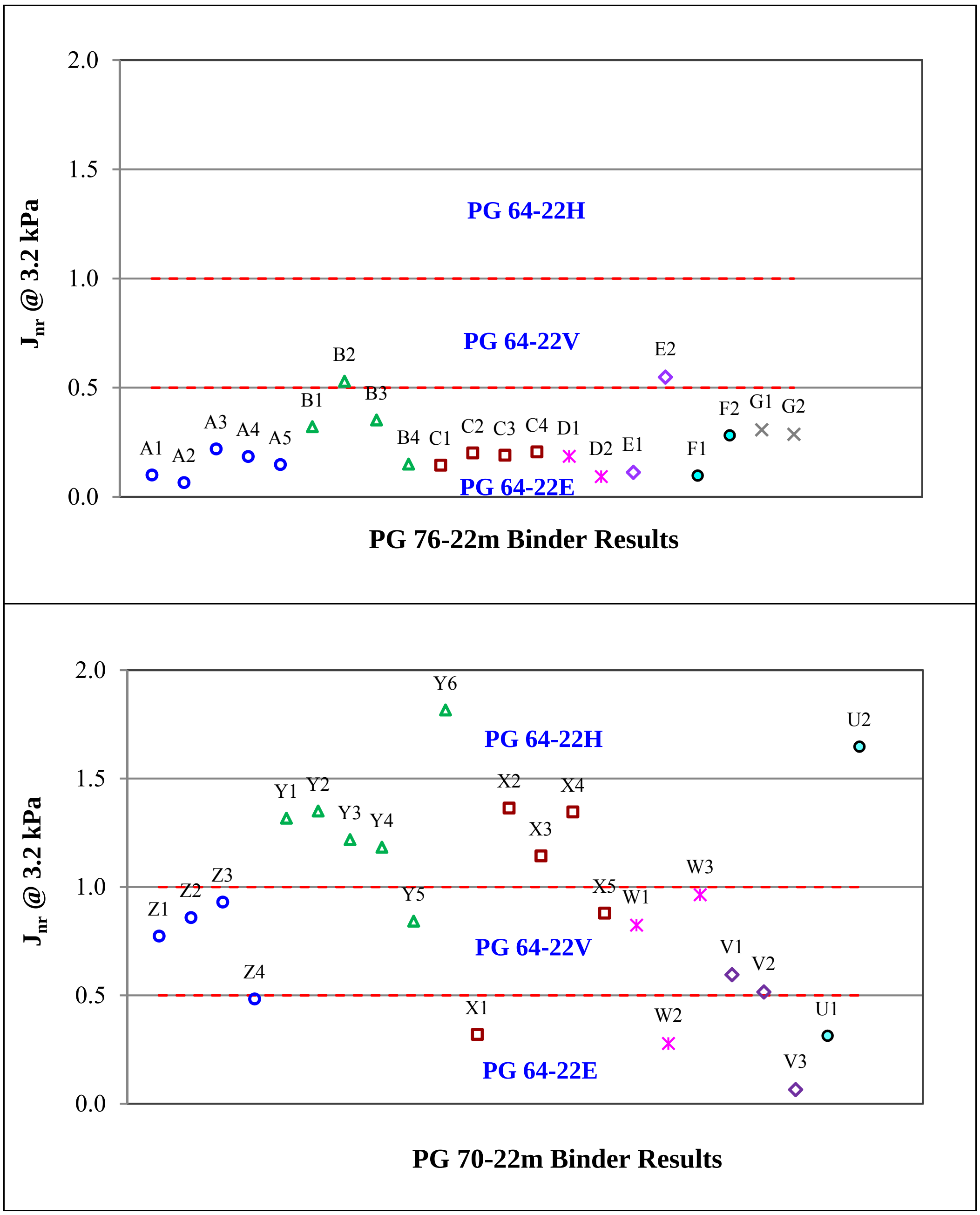


Figure 15
J_{nr}-based performance grades at 64°C

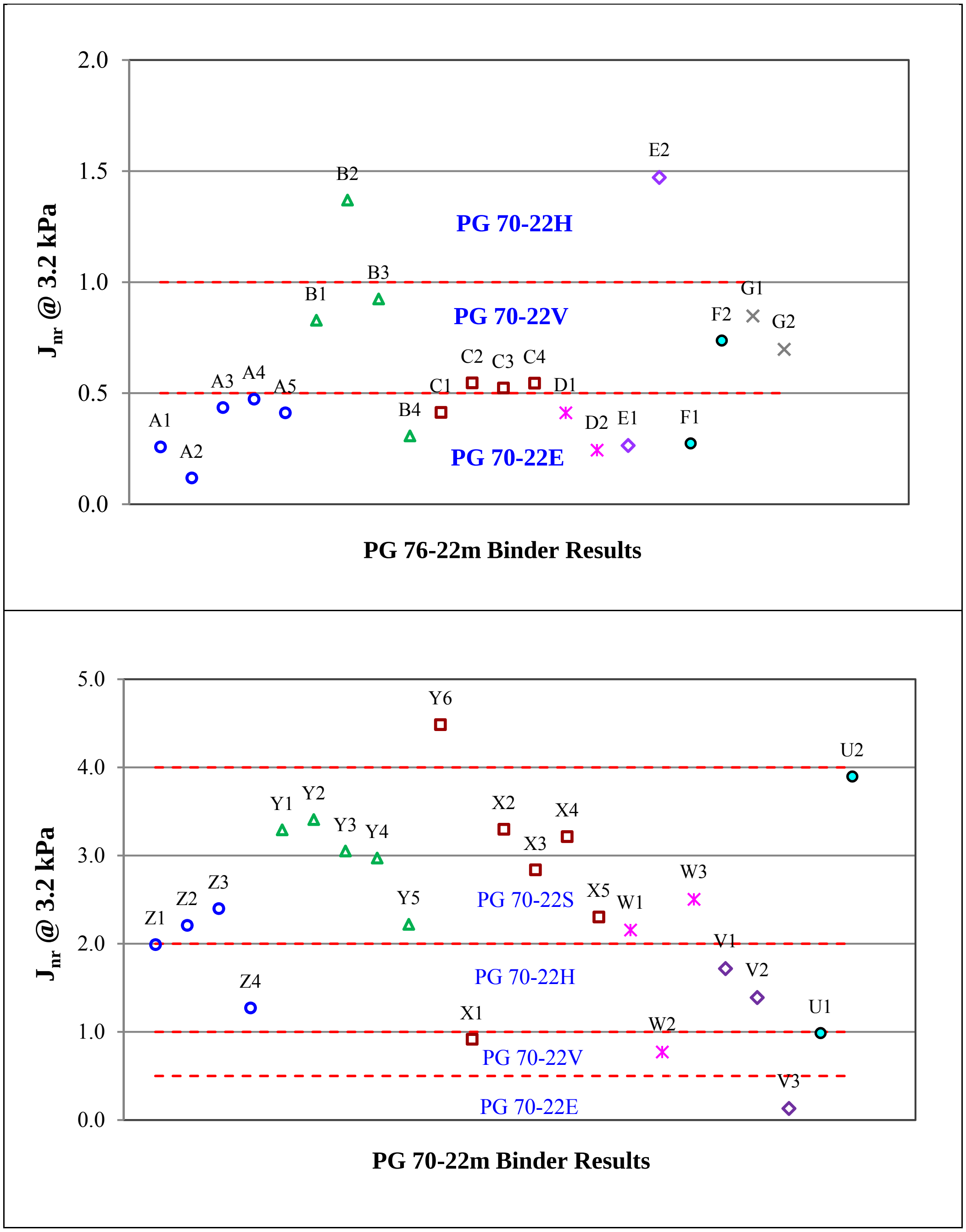


Figure 16
J_{nr}-based performance grades at 70°C

The MSCR $R_{3.2}$ in combination with $J_{nr3.2}$ is capable of identifying whether an asphalt binder has sufficient elastic components. According to AASHTO TP 70, the average $R_{3.2}$ results can be plotted against the average $J_{nr3.2}$ results 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 elastomeric polymer to possess sufficient delayed elastic response and vice versa. To evaluate the elastic response of all binders considered in this study, the average $J_{nr3.2}$ and $R_{3.2}$ results at 64°C are plotted against one another as shown in Figure 17. It is evident that PG 76-22m binders showed superior elastic response in comparison to PG 70-22m binders. Except B2, all PG 76-22m binder samples passed the delayed elastic criteria reported in AASHTO TP 70. Alternatively, the elastic behavior for PG 70-22m binder group, in general, do not look very promising and only 39 percent of these binders meets the acceptable delayed elastic response criteria as discussed above. Noticeably, none (except X1) of the PG 70-22m binders from suppliers B and C managed to pass the recovery curve described in AASHTO TP 70.

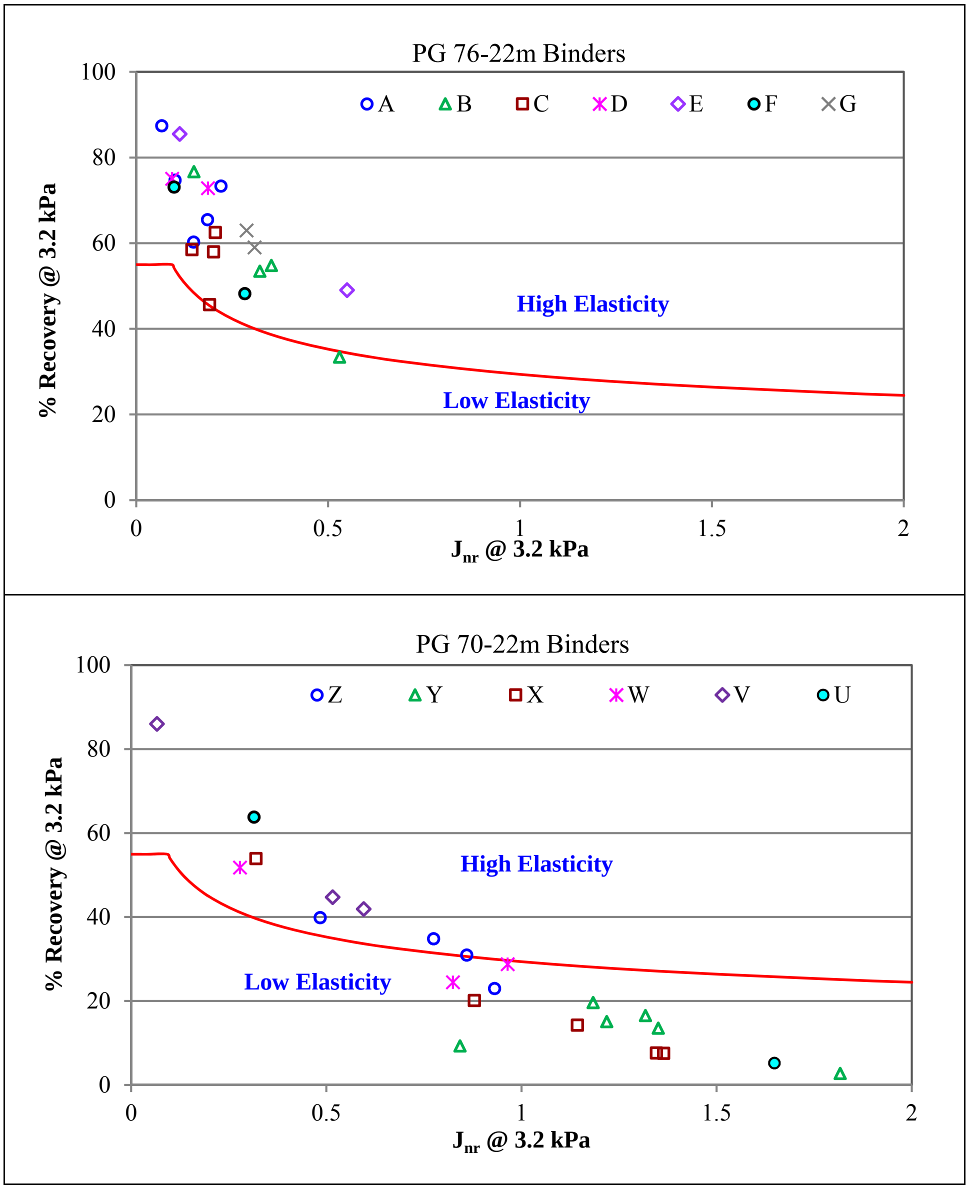


Figure 17
MSCR based elastic response of binders at 64°C

Elastic Recovery Test Results

Figure 18 presents the elastic recovery test results for binders included in this study. As can be seen, all PG 76-22m binders convincingly met the current DOTD elastic recovery specification requirements of 60 percent minimum. On the other hand, four PG 70-22m binders (Y5, Y6, X2, and X4), failed to achieve the current DOTD minimum elastic recovery requirements of 40 percent for their PG binder category. Two samples each of the four binders were obtained from suppliers B and C. Interestingly, all binder samples (except sample X1) collected from these two suppliers failed to meet the MSCR recovery curve as presented earlier in Figure 17. It should also be noted that binders Y6, X2, and X4 showed the inferior J_{nr} performance in their respective groups as shown earlier in Figures 15 and 16.

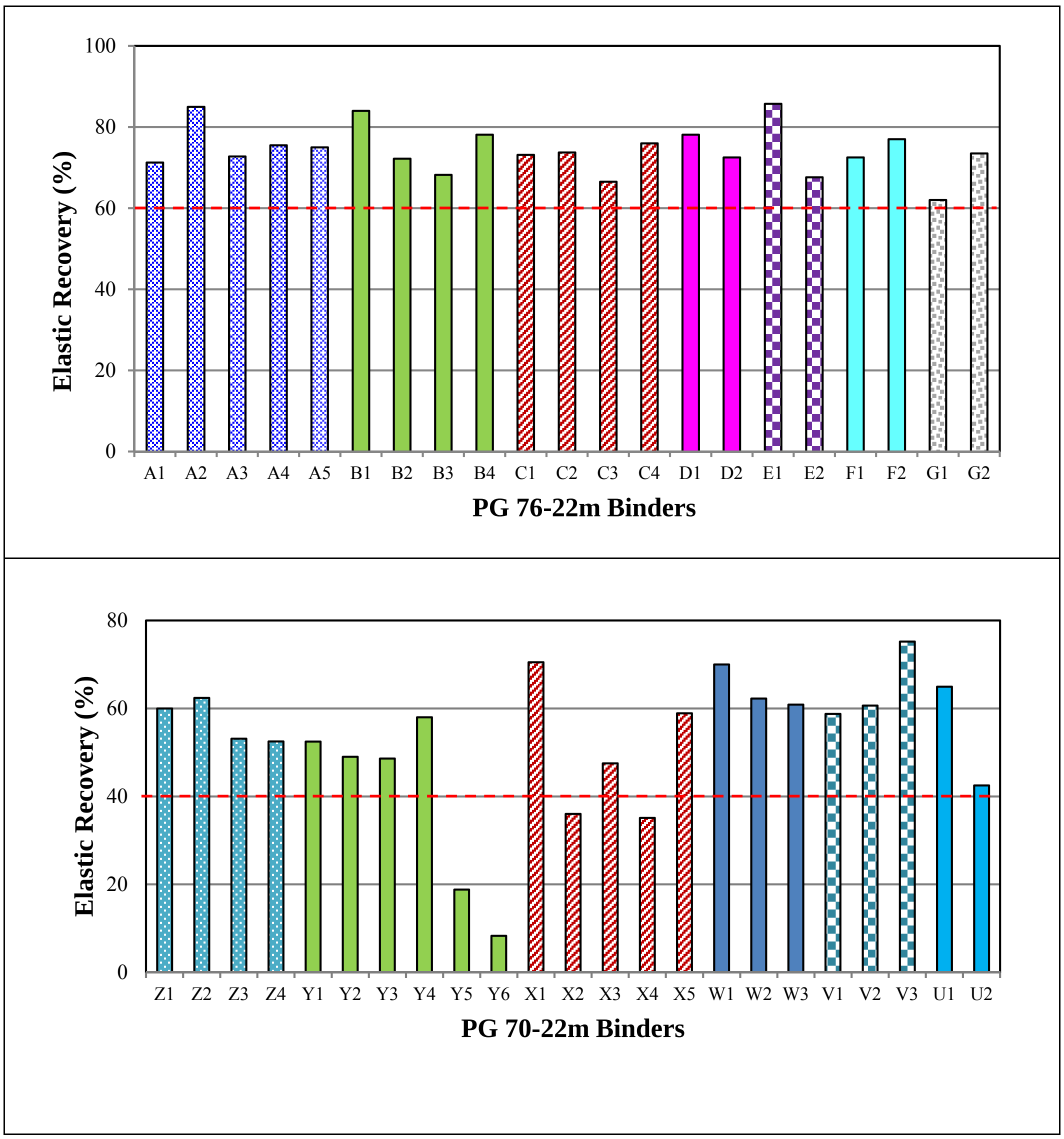


Figure 18
Elastic recovery test results

Correlation between Elastic Recovery and MSCR Recovery

To verify a direct relationship between elastic recovery and MSCR recovery results, the average percent elastic recoveries for all binders tested at 25°C were plotted against the average MSCR $R_{3.2}$ results tested at 64°C as shown in Figure 19. A fair correlation was observed with a R^2 value of 0.69. Even though both these parameters seem to measure the elastic behavior of binders tested, a very strong correlation between these two test results was unlikely due to the difference in test conditions and test methodologies.

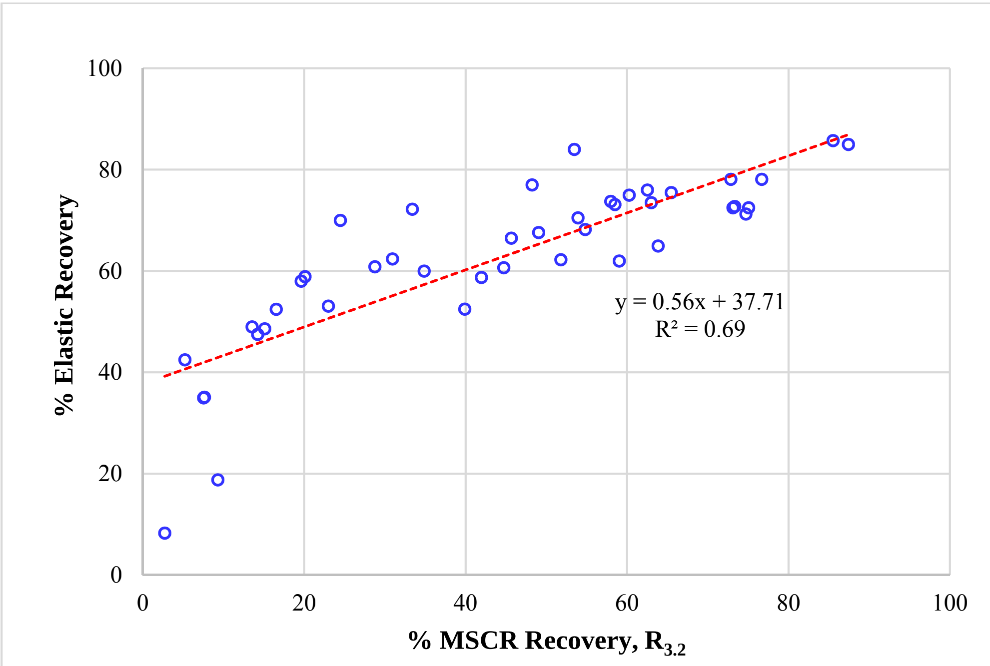


Figure 19
Correlation between elastic recovery and MSCR recovery

In a recent Southeast Asphalt User-Producer Group (SEAUPG) MSCR Task Force WebEx meeting, researchers from Asphalt Institute suggested, "If using the elastic recovery value at 25°C, an appropriate MSCR $R_{3.2}$ criterion at 64°C is 15 percentage points less than the current elastic recovery criterion." According to this recommendation, all PG 76-22m and PG 70-22m binders in Louisiana shall require a minimum $R_{3.2}$ value of 45 percent and 25 percent respectively as the current DOTD binder specification requires minimum elastic recovery values of 60 and 40 percent for the aforementioned binder classes. To assess the above hypothesis, the percent elastic recovery and MSCR $R_{3.2}$ results are plotted along "X" and "Y" axis, respectively, as shown in Figure 20. Except for one binder B2, all PG 76-22m binder samples met both the current elastic recovery specification and the proposed minimum MSCR $R_{3.2}$ of 45 percent. The sample B2 met the elastic recovery specification, however, failed to meet the MSCR $R_{3.2}$ requirement with a $R_{3.2}$ value of 33.4 percent. Interestingly, this same B2 binder previously failed to meet the J_{nr} requirement of PG 64-22E category and was downgraded to PG 64-22V class (Figure 15).

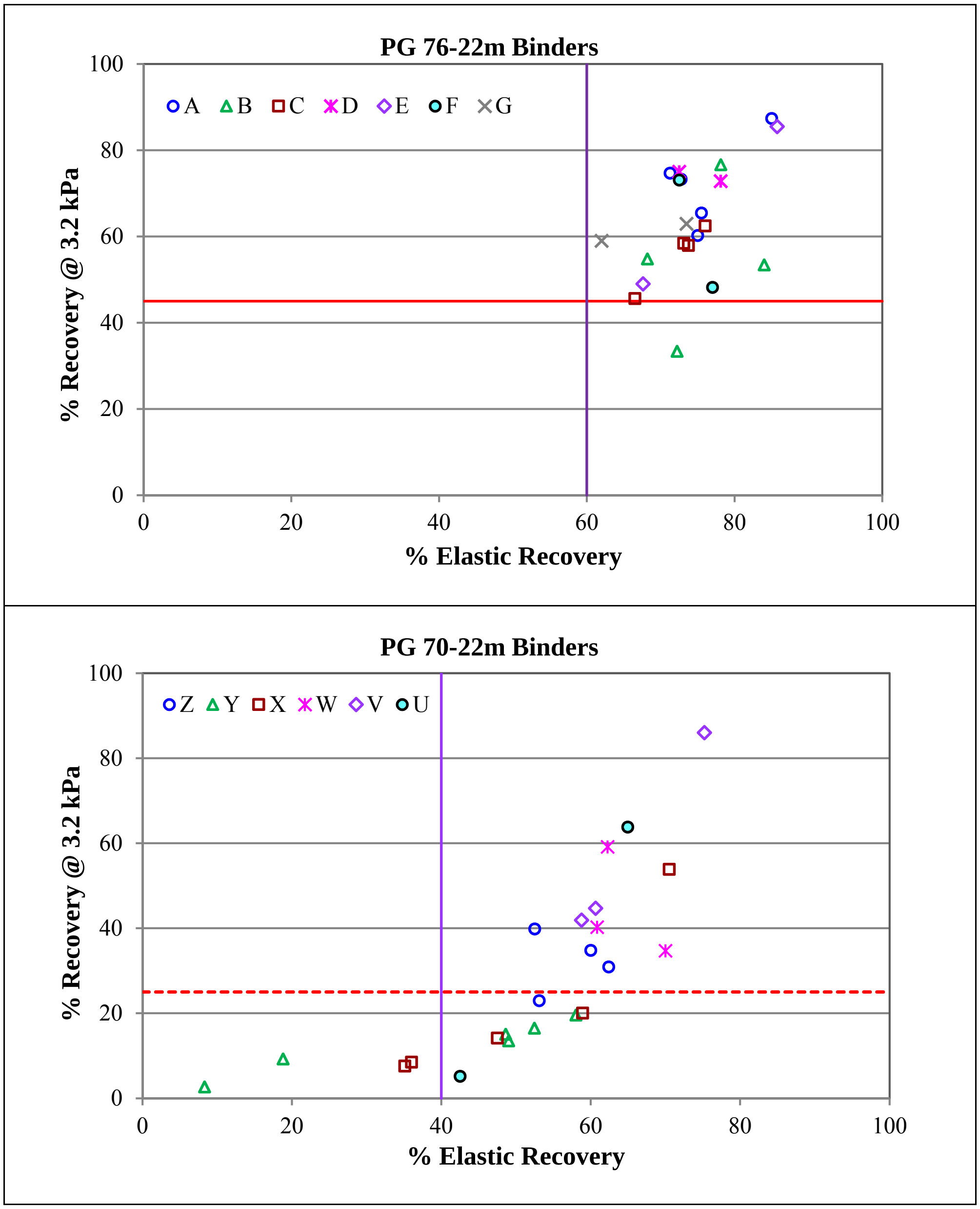


Figure 20
Possible replacement of elastic recovery with MSCR recovery

For the PG 70-22m binder group, all samples from suppliers B and C (except sample X1) failed to meet the MSCR $R_{3.2}$ target of 25 percent. Additionally, one sample each from A and F suppliers were also found to fall in the failing group. This analysis showed an almost identical pattern when binder $R_{3.2}$ results were compared against the AASHTO TP 70 elastic response curve as illustrated in Figure 17. It is worth noticing that none of the binders could meet the minimum MSCR $R_{3.2}$ target value of 25 percent without passing the current minimum elastic recovery of 40 percent. This clearly 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. However, judging both AASHTO TP 70 and the Asphalt Institutes proposed specifications (Figures 17 and 20), it seems optional for DOTD to choose either one for the forthcoming asphalt binder specifications for the state of Louisiana.

Force Ductility Test Results

As required by the current DOTD asphalt binder specification, Figure 21 presents the force ductility ratio (f2/f1) for all PG 76-22m asphalt binders at 4°C and 5 cm/min elongation rate as measured by force ductility test. Alternatively, the force ductility in kg at 30 cm elongation is measured and reported for all PG 70-22m binders (Figure 22). From Figure 21, it is evident all PG 76-22m binders successfully met the current specification of a minimum force ductility ratio of 0.30. However, the PG 70-22m binders in general, met the force ductility specification of 0.23 kg except samples Y5, Y6, and X2. Due to the data unavailability, the results for samples C1, X1, W1, and Z2 could not be included in Figures 21 and 22.

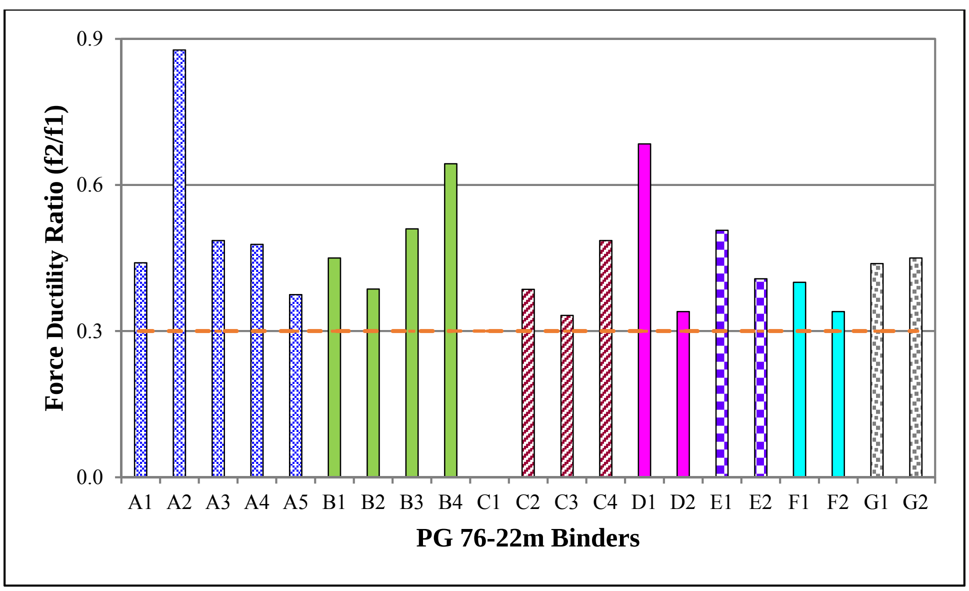


Figure 21
Force ductility ratio results for PG 76-22m binders

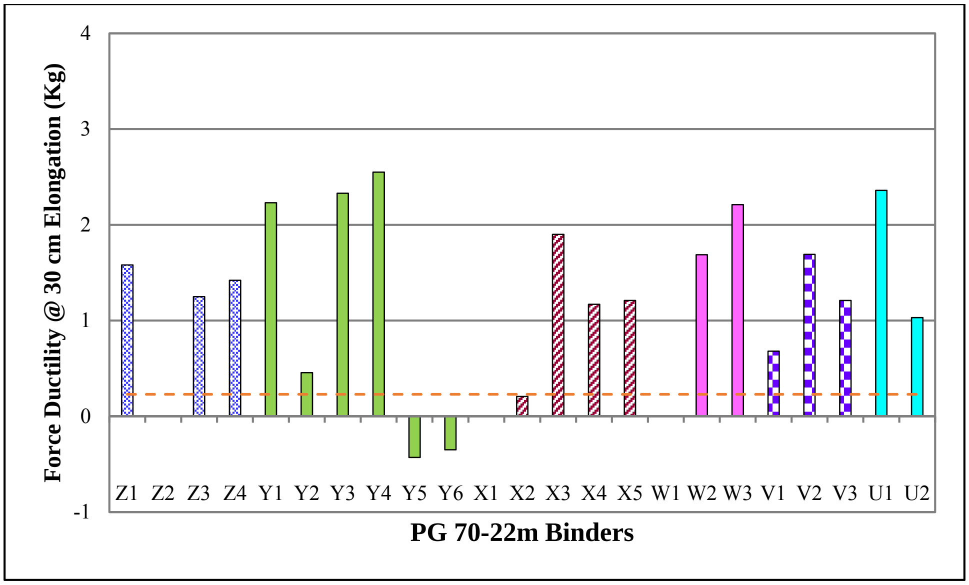


Figure 22
Force ductility results for PG 70-22m binders

A more in-depth investigation was exercised using the data generated from the force ductility tests conducted in this study. The continously applied load and their corresponding elongation for individual binders were plotted in terms of load displacement curves as presented in Figures 23 and 24. As can be seen from Figure 23, each individual PG 76-22m binder acted uniquely to the same load application even though those were collected from the same supplier, labeled as the same PG asphalt. It is also noticable that most of the binders reached the first peak at similar elongation; however, their second peak did not follow any type of pattern. The PG 70-22m binders as presented in Figure 24 showed better consistencies in comparison to their PG 76-22m counterparts; however, the inconsistencies are still evident. This is an indication that the current force ductility test may only be able determine the presence of polymer but it definitely lacks in capturing the complete performance of the binder over the whole duration of the test. Instead, the current force ductility ratio of a binder solely depends on the performance of that binder at a specific point (at 30 cm elongation) or at the second peak, rather considering the binder's performance for the whole test span. Perhaps this is not presenting a true characterization of the binder.

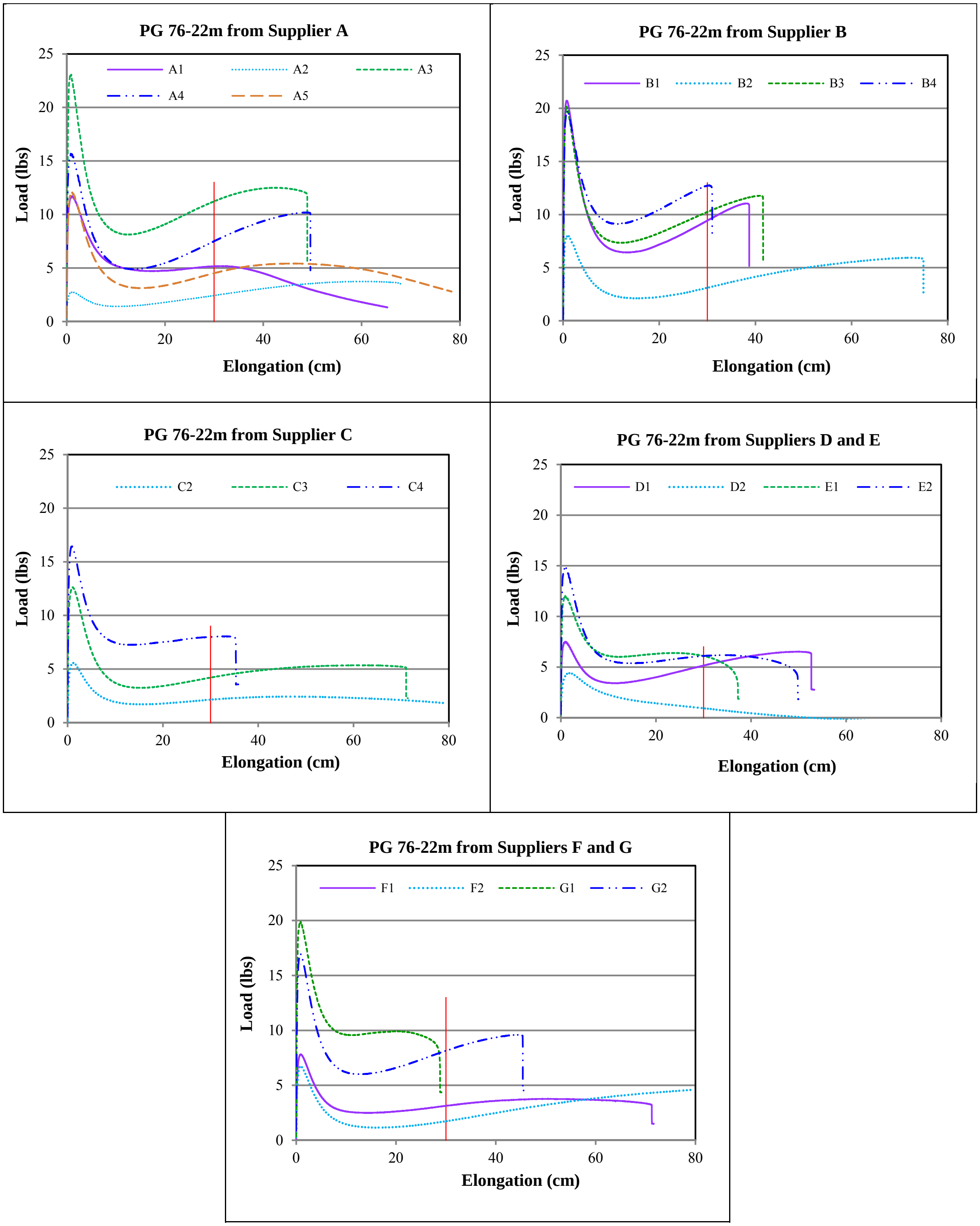


Figure 23
Comparison of PG 76-22m binder responses in force ductility tests

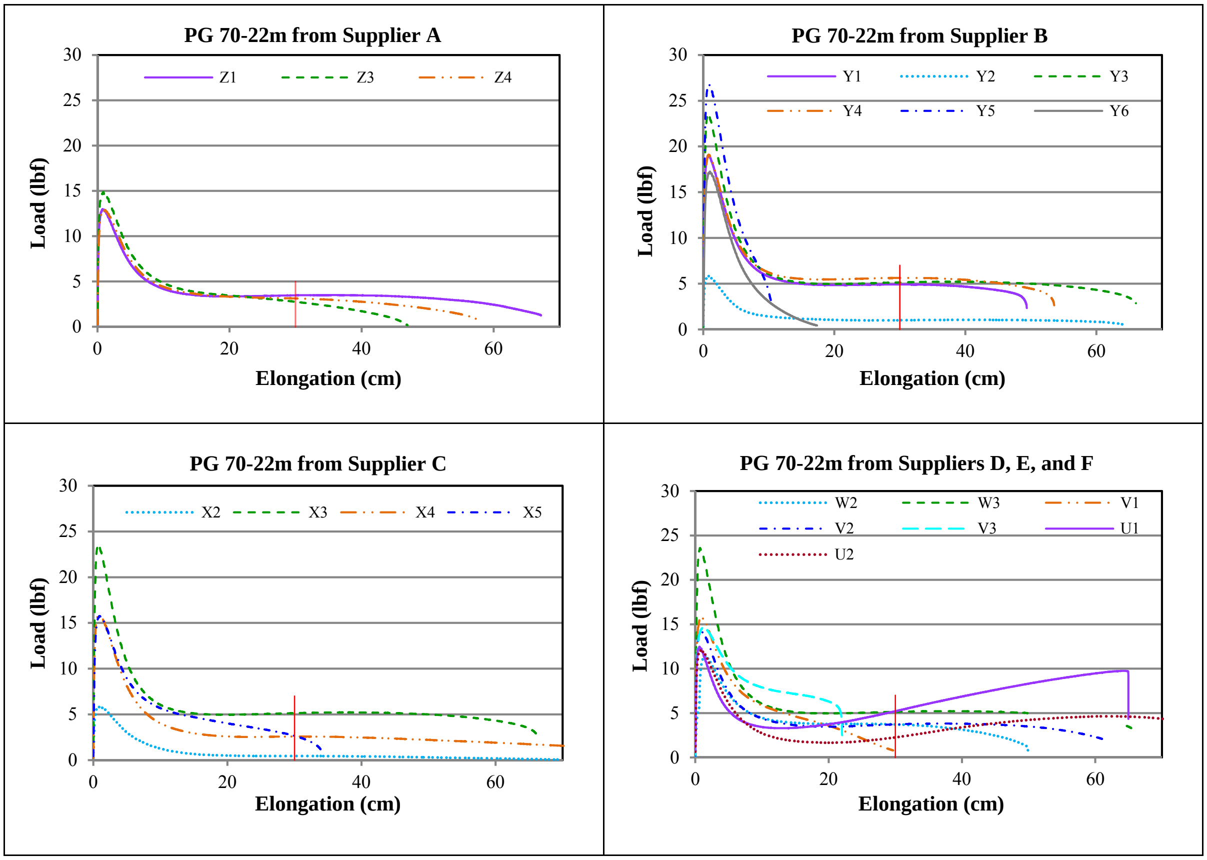


Figure 24
Comparison of PG 70-22m binder responses in force ductility tests

Correlation between Force Ductility Ratio and Phase Angle

Figures 25 and 26 illustrate a relative comparison of force ductility test results with MSCR $R_{3.2}$ and phase angle results, respectively. Each bar represents the force ductility ratio (for PG 76-22m binders) and force ductility at 30 cm (for PG 70-22m binders) for individual binders; whereas, the MSCR $R_{3.2}$ and phase angles are presented with the line graphs. It is clearly noticeable that the force ductilitiy and MSCR $R_{3.2}$ results followed a similar trend. More specifically, whenever a binder obtained a greater force ductility value (represented with a taller bar graph), it also achieved a greater MSCR $R_{3.2}$ value (represented with a a high point on the line graph). Alternatively, an oppossite trend was seen for force ductility and phase angles results (Figure 26). For example, sample A2 had a higher force ductility ratio in comparison to samples A1 and A3. As mentioned above, the MSCR $R_{3.2}$ for sample A2 is the highest and the phase angle is the lowest among the group of A1, A2, and A3 binders. However, the relative changes in magnitude of test results for those binders were not always constant. From Figures 25 and 26, it is also noticable that the force ductility ratios (for PG

76-22m binders) followed the trends more closely in relation to force ductily (for PG 70-22m binders).

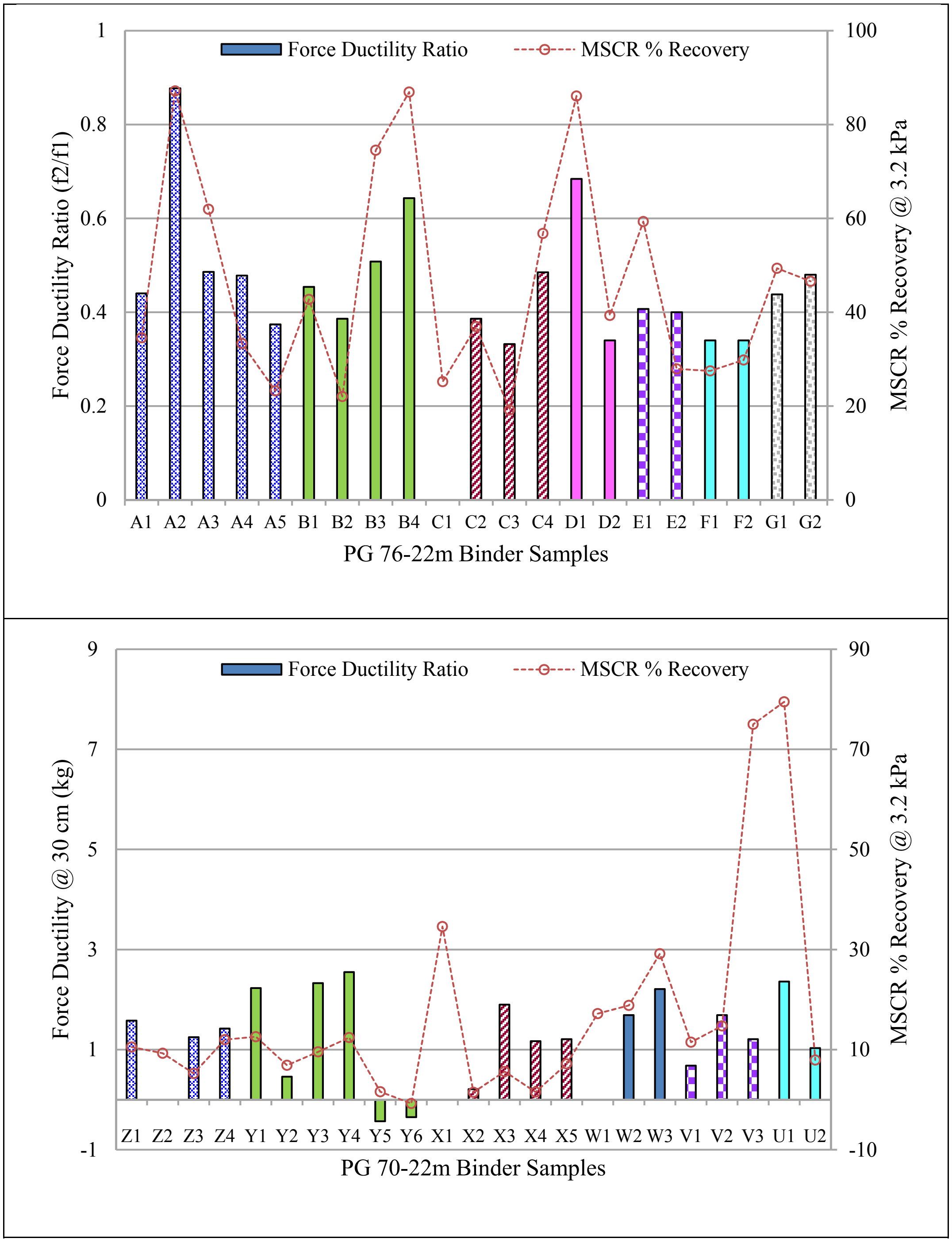


Figure 25
Comparison of force ductility and MSCR $R_{3.2}$

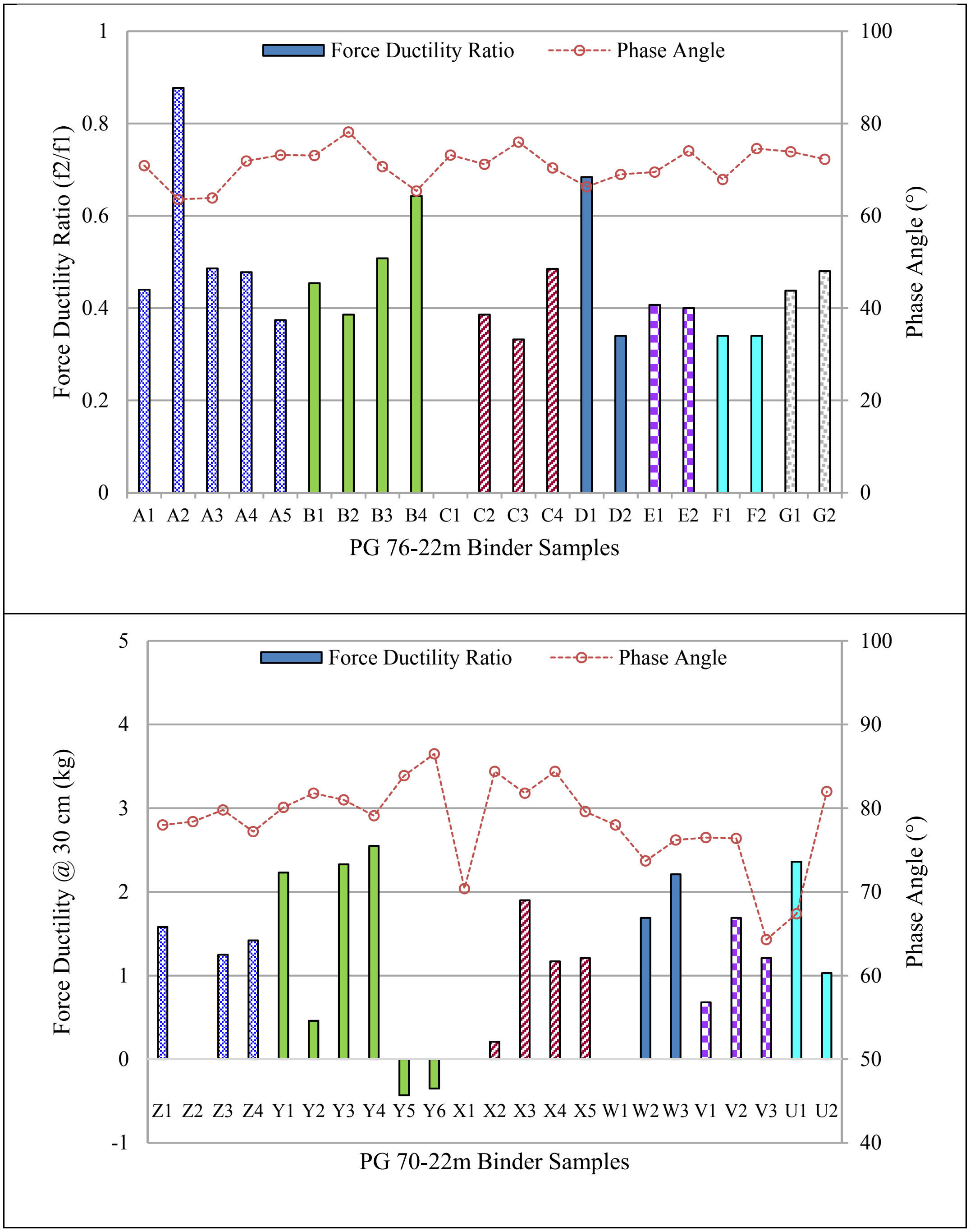


Figure 26
Comparison of force ductility and phase angle

Figure 27 presents a scatter plot of average MSCR percent recovery and force ductility ratio results for all PG 76-22m binders included in this study. The linear regression line, its equation, and the co-efficient of variance are also included in Figure 27. Similarly, a scatter plot and corresponding regression properties of average phase angle and force ductility ratio results for unaged PG 76-22m binders at 76°C are illustrated in Figure 28. As can be seen, both plots in general, showed good correlations with R^2 values of 0.70 and 0.75, respectively; however, the phase angle seemed to have a better correlation (higher R^2) with force ductility ratio.

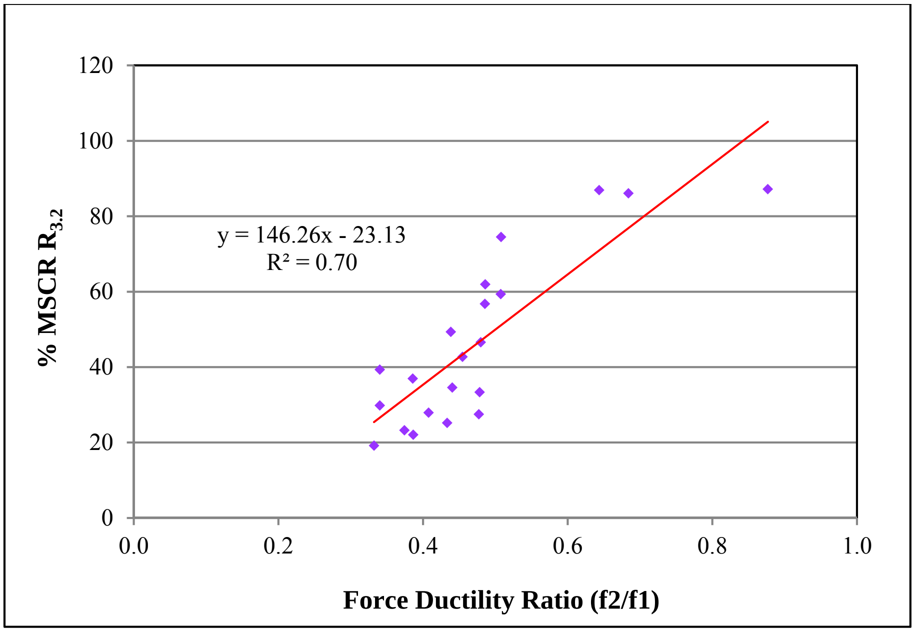


Figure 27
Correlation between MSCR percent recovery and force ductility ratio

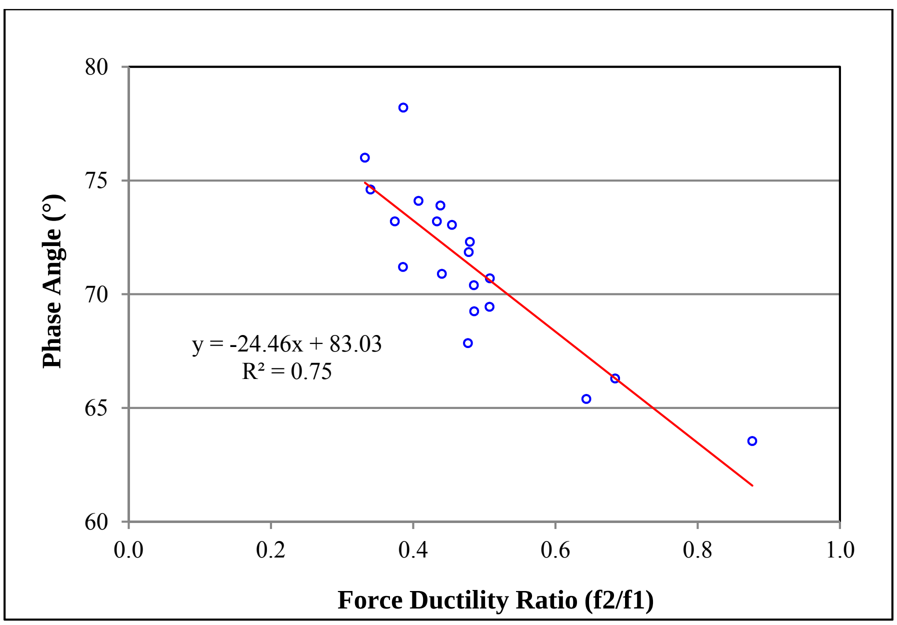


Figure 28
Correlation between DSR phase angle and force ductility ratio

One of the major objectives of this study was to investigate the possibility of replacing force ductility test and the average force ductility ratio. The MSCR percent recovery and phase angle results were investigated further to satisfy this objective and the results are presented in Figures 29 and 30. It is worth noting that several state agencies (Georgia, Florida, Arizona, Wisconsin, Minnesota, etc.) require the phase angle of the original PG 76-22m binder to be 75° or less at a temperature of 76°C in order to ensure binder's elastic properties. In both Figures 29 and 30, the vertical lines represent the minimum force ductility ratio requirement 0.3 as per the current DOTD asphalt binder specification. Therefore, any data point falling to the right of this line indicates the binder meeting the current specification. On the other hand, in Figure 29, the horizontal line drawn along the phase angle value of 75° represents the maximum allowable phase angle value as specified by various state agencies. The results indicate that all PG 76-22m binders included in this study passed the force ductility ratio specification; however, a couple of binders (B2 and C3) failed to meet the phase angle specification (Figure 29). Interestingly, both these binders showed inferior elastic behaviors (sample B2 failed and sample C3 marginally met) when compared to the AASHTO TP 70 elasticity curve as shown in Figure 17 before. A recent study by the New Jersey DOT (NJDOT) also indicated that the phase angle specification is stricter than an elastic recovery specification *[19]*. The results from this current study is found to be in total agreement with the findings of NJDOTD. This provides confidence with the introduction of a phase angle specification requirement of 75° maximum for unaged PG 76-22m binders for the state of Louisiana.

A similar approach was taken to compare the MSCR percent recovery and force ductility ratio of unaged PG 76-22m binders as shown in Figure 30. Currently, there is no reference specification value available for MSCR percent recovery for unaged binders; therefore, the regression equation found in Figure 27 was utilized to establish a minimum MSCR percent recovery value of 21 percent as a possible replacement of the force ductility ratio of 0.3. As can be seen from Figure 30, the only binder that failed is sample C3, which in fact also failed to meet the phase angle (Figure 29) and marginally passed AASHTO TP 70 specifications (Figure 17). This provides additional confidence that MSCR percent recovery for unaged binders has similar potential to phase angles, or both phase angle and MSCR percent recovery together, or both and can be considered as a possible replacement of the current force ductility ratio specifications for the state of Louisiana.

Figure 31 illustrates the scatter plots of force ductility and MSCR percent recovery and force ductility and phase angle for unaged PG 70-22m binders. Unlike PG 76-22m binders, poor correlations were observed for both scenarios with very low R^2 values. It is worth noting that the force ductility ratio was used in the analyses for PG 76-22m binders; whereas, a different parameter: the force ductility at 30 cm elongation, which is currently being used in the specifications, was used for PG 70-22m binders. This could possibly be the reason for the poor correlations; however, further research is needed to confirm this approach.

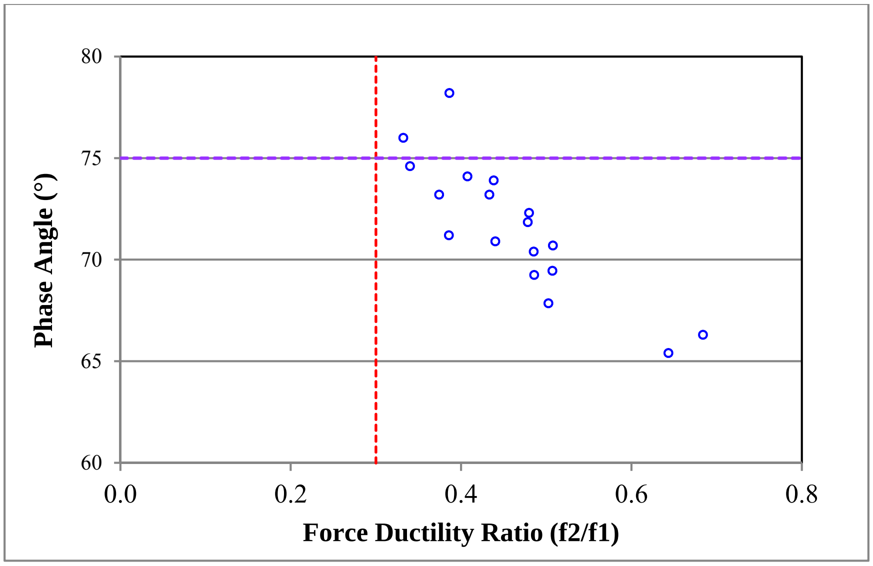


Figure 29
Replacement of force ductility ratio with phase angle for PG 76-22m

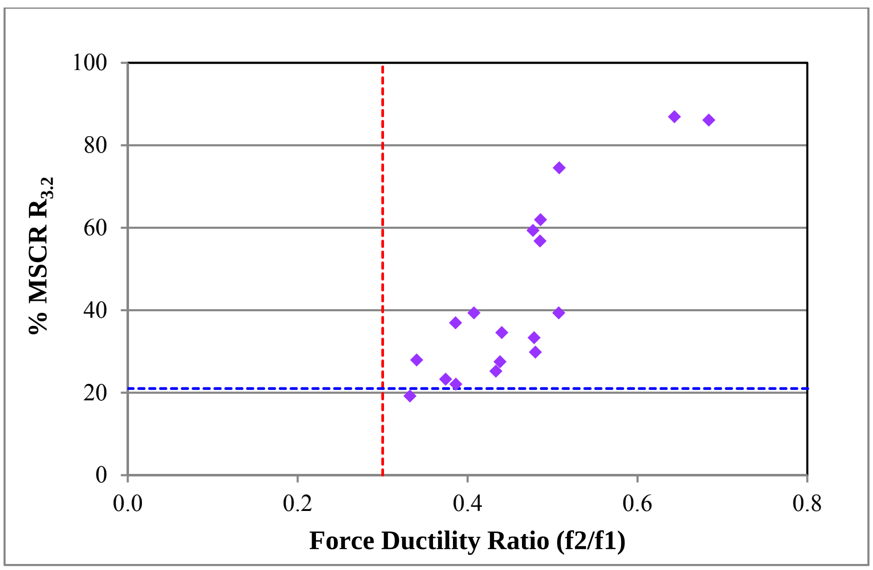


Figure 30
Replacement of force ductility ratio with MSCR recovery for PG 76-22m

Figure 32 presents the histograms and corresponding normal distribution curve for the phase angle results for unaged PG 70-22m binders tested at 70°C. Despite slight leftside skewness, the phase angle data showed decent normal distribution pattern with minimum and maximum phase angle values of 64.3° and 86.5°, respectively. The highest frequency of phase angles was recorded for the 79°-81° range. The statistical median for this entire phase angle dataset, 79.1°, belongs to the same group. However, the mathematical mean for the phase angle dataset, as represented by the red vertical line, was found to be 78.3°, which belongs to the 77°-79° group. It is worth noting that numerous states such as: Wisconsin, Arizona, Minnesota, Nebraska, etc. specified a maximum phase angle value of 77° for their unaged PG 70-22m binders *[13]*. To replace the current force ductility specification for DOTD, a maximum phase angle value of 78° for unaged PG 70-22m binders at 70°C is recommended as a provisional specification. LTRC and DOTD shall collect more phase anlge data over the time and conduct appropriate data analysis to solidify this reommendation.

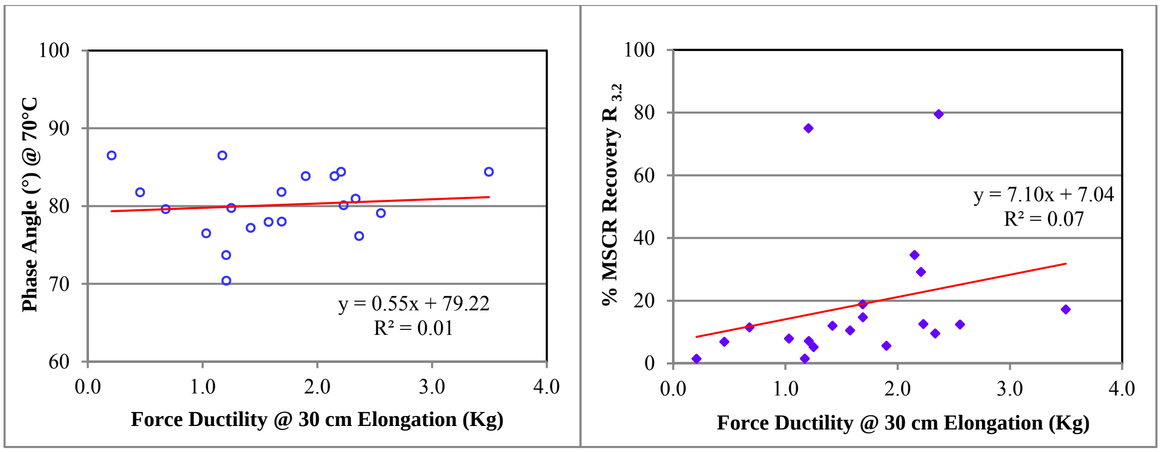


Figure 31
Correlations: force ductility-phase angle, force ductility-MSCR Recovery

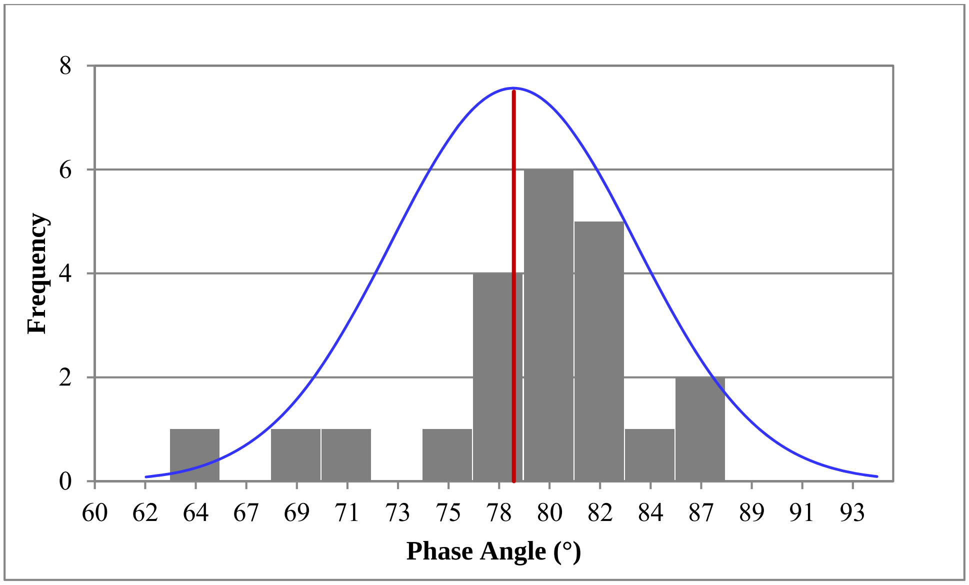


Figure 32
Histogram and Normal distribution of phase angles

GPC Test Results

The percentage of polymer contents of various binders included in this study are presented in Figure 33. Due to the time limitation and availability of binder samples several binders could not be included in the GPC testing scheme. In general, the PG 70-22m binders contained about 2 percent polymer, whereas, the PG 76-22m binders contained 3 percent or more. It is also obvious that PG 76-22m binders contained at least one percent more polymer in comparison to the PG 70-22m binders collected from the same supplier. Interestingly binders labeled with the same PG but collected from a different supplier showed a significant variation in polymer content (Figure 33). For instance, the PG 76-22m samples from Supplier B contained 4 percent polymer, while the the PG 76-22m samples from Supplier A had about 3 percent of polymer on average.

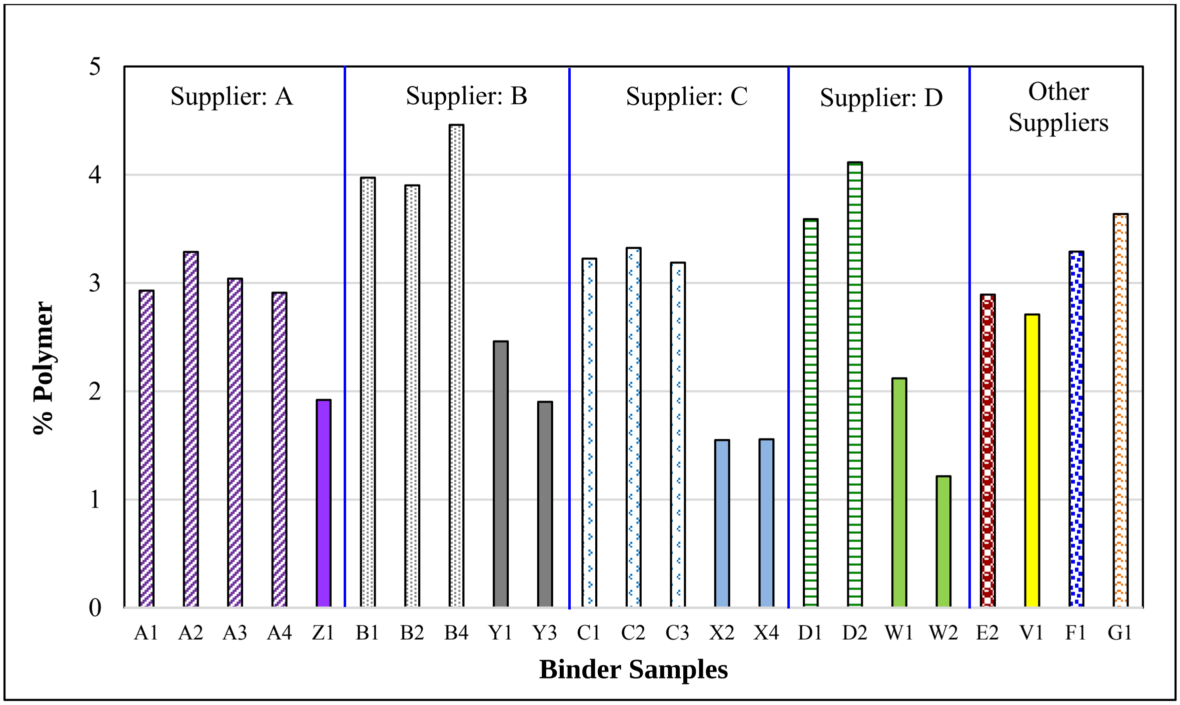


Figure 33
Polymer content for various asphalt binders

The effect of the polymer content on MSCR recovery and elastic recovery properties of PG 76-22m binders are presented in Figures 34 and 35, respectively. In both cases, very low R^2 values (0.00 and 0.08) indicate that the polymer content did not influence the MSCR recovery and elastic recovery directly even though a better elastic property is normally expected with an increase in polymer content in an asphalt binder. The impact of polymer modification is controlled generally by the chemical interaction and interlocking between a particular polymer and a specific source binder. As a different binder producer uses a different crude source, the amount of polymer usually required to produce a target PG binder varies significantly from one binder supplier to another. For further assessment, the elastic responses of individual binder samples collected from the same supplier are compared with their corresponding polymer contents as shown in Figure 36. In most of the cases, good or fair R^2 values were observed which indicate that the elastic behavior of polymer-modified binders possibly depend on the chemical interactions between a particular polymer and a specific crude binder. The results from suppliers D, E, F, G, and H could not be included in Figure 36 due to the lack of enough GPC data to validate individual correlations.

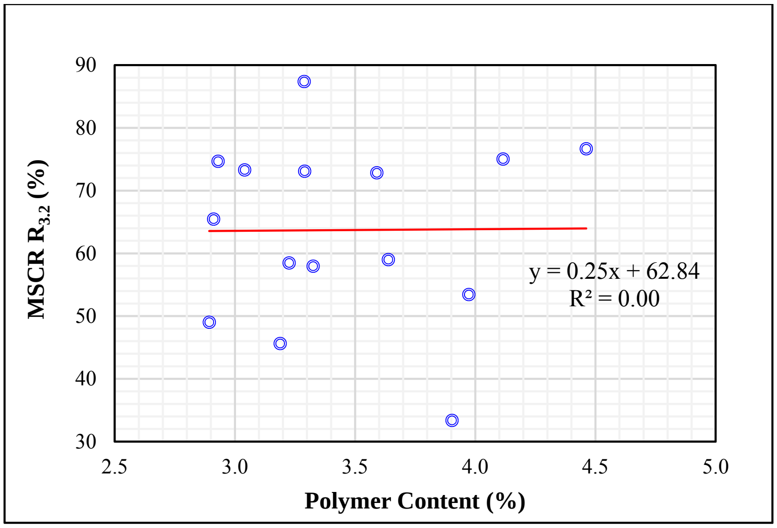


Figure 34
Correlation between MSCR $R_{3.2}$ and polymer content

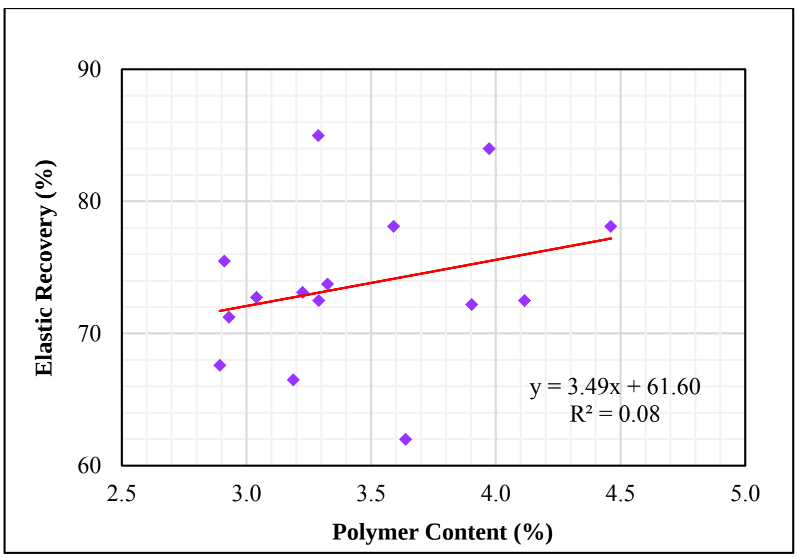


Figure 35
Correlation between elastic recovery and polymer content

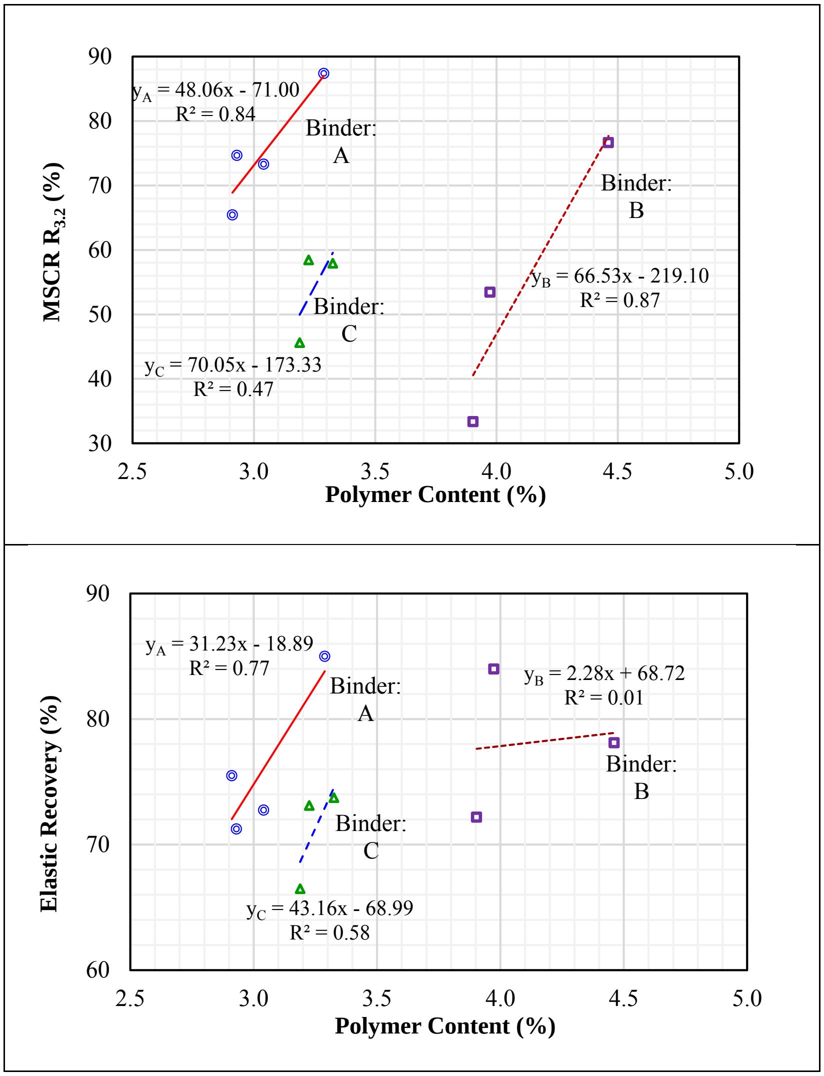


Figure 36
Elastic behavioral pattern of binders from the same supplier

CRM Binder Test Results

Figures 37 and 38 show the graphical presentation of MSCR test results for for nine rubber modified PG 82-22rm (labeled as i to ix) and two rubber modified PG 76-22rm (labeled as a and b) binders included in this study. It should be noted that only four PG 82-22rm samples could be tested at 67°C and only one PG 76-22rm sample could be tested at 70°C due to the availability of the binder samples during the testing of added factorial. Similar to the polymer-modified binders, at a specific test temperature, the binders with a higher PG grade (PG 82-22rm) obtained a higher MSCR grade when compared to binders with a lower PG grade (PG 76-22 rm). As can be seen in Figure 37, the PG 82-22rm binders showed very good rut resistance and achieved the “E” class both at 64°C and 67°C. Alternatively, both PG

76-22rm binders marginally failed to meet the J_{nr} requirement of 0.5 kPa to achieve an “E” class and eventually obtained “V” class at 64°C. At 70°C, the PG 82-22 rm and PG 76-22 rm binders in general achieved “V” and “H” classes respectively. However, the evaluation of the delayed elastic response (as measured with MSCR test) of all rubber modified binders did not look very promising. Only four PG 82-22rm binders passed the delayed elastic criteria (as shown in Figure 38) at 64°C. However, these numbers were reduced to 2 and 1 when tested at 67°C and 70°C, respectively. On the other hand, none of the PG 76-22rm binders were able to meet the elastic response curve as mentioned in AASHTO TP 70 at any test temperature.

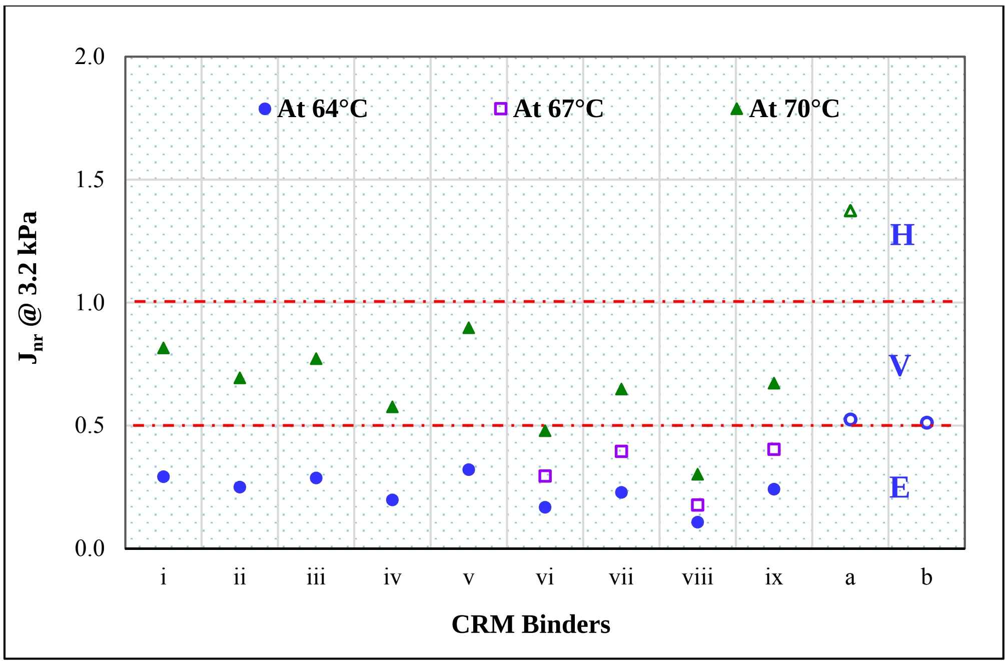


Figure 37
J_{nr}-based performance grades for CRM binders

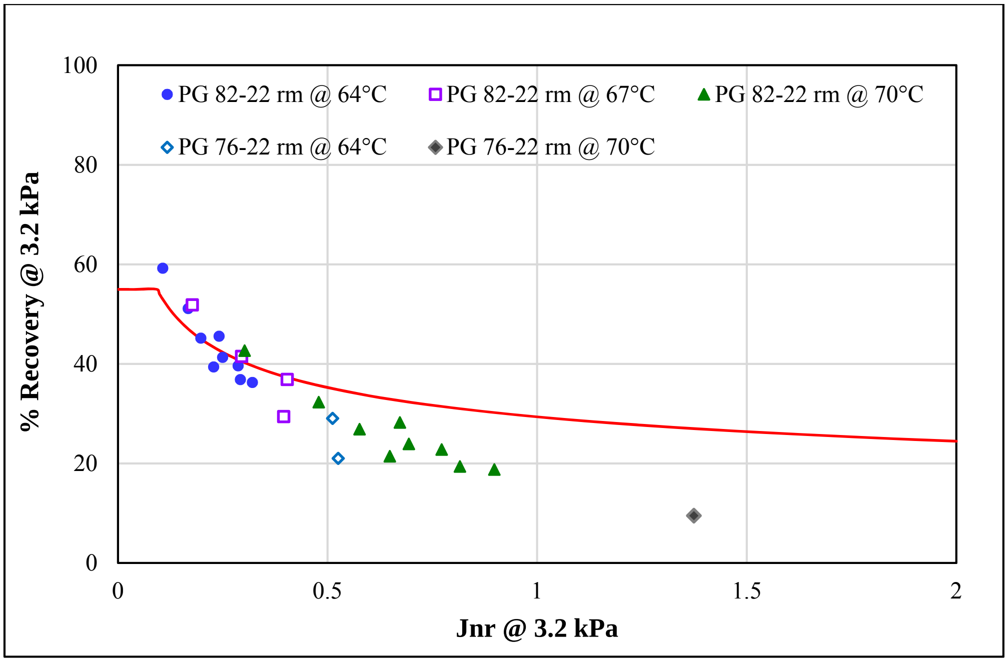


Figure 38
Elastic behavior of CRM binders

As presented before for the polymer-modified binders, Figure 39 shows the percent elastic recovery and MSCR $R_{3.2}$ results plotted along "X" and "Y" axis respectively for all rubber modified binders. Current DOTD asphalt binder specifications require a minimum elastic recovery of 60 percent for any PG 82-22 rm binder. Therefore, a minimum elastic recovery of 60 percent and a minimum MSCR $R_{3.2}$ value of 45 were taken as the criteria required for a rubber modified binder to exhibit satisfactory elastic property. It is to note that one PG 82-22 rm binder was not tested for elastic recovery due to material availability. From Figure 39, it is evident that six PG 82-22 rm binders meet the elastic recovery requirement; however, half of those binders were unable to pass the MSCR $R_{3.2}$ requirement. Once again, the PG 76-22 rm samples fell short and have yet to meet either the elastic recovery or the MSCR $R_{3.2}$ criteria set for this analysis.

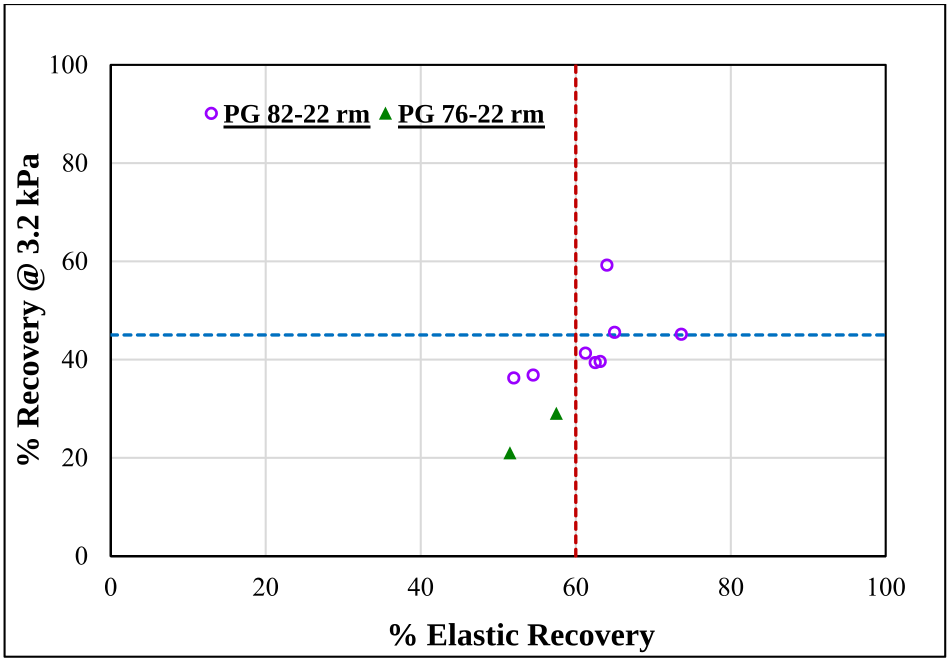


Figure 39
Comparison of elastic recovery and MSCR recovery for CRM binders

Test Results at 67°C

At the beginning, this research was aimed at evaluating the performance of Louisiana asphalt binders on the basis of MSCR tests conducted at 64°C and 70°C. However, only a few months before the completion of the study, it came to LTRC's attention that many of the southern state agencies in the U.S. had been looking to implement a common binder specification across the region. In so doing, Florida and Georgia have already included 67°C as their climatic temperature to implement MSCR characteristics (AASHTO MP 19) in their respective binder specifications. It has been realized that DOTD would benefit by embracing a similar binder specifications (introducing 67°C as the climatic temperature). Under this circumstance, LTRC has been requested to provide guidelines on the possibility of incorporating the above-mentioned common binder specifications for the southern state agencies. However, by the time the request was made, LTRC's MSCR study (11-1B) was already approaching its end, hence, a very limited factorial was experimented at 67°C for this study, which was never in the original scope. Initially it was anticipated that a linear correlation may occur among the MSCR test results at three different temperatures: 64°C, 67°C, and 70°C, which possibly lead to intrapolate the MSCR results at 67°C for the binders that were no longer available for the supplementary test factorial. However, that did not happen.

Figures 40 and 41 are the graphical comparisons of MSCR results for 13 PG 76-22m and 13 PG 70-22m binders at three different test temperatures: 64°C, 67°C, and 70°C. As was seen previously, an increase in J_{nr} and a decrease in $R_{3.2}$ were noticed with an increase in the test temperature. However, the temperature dependency for PG 70-22 m binders were found to be more prominent when compared to the PG 76-22m binders. It is noteworthy to point out, when tested at 70°C, binder sample Y6 J_{nr} value was greater than four (4.47) and is "off the charts" for both Figures 40 and 41. Interestingly, 11 among the 13 PG 76-22m binders were able to maintain the same "Class E" despite an increase in test temperature from 64°C to 67°C (Figure 40). A very similar pattern was observed for PG 70-22m binders where 11 among the 13 binders maintained the same "Class H" when tested at 67°C. For the elasticity analysis as presented in Figure 41, the binders meeting the delayed elasticity requirement at 64°C also meet the requirement at 67°C.

The results at three test temperatures were further analyzed in an auspice for any possible correlation. The $J_{nr3.2}$ and $R_{3.2}$ values at 67°C for those abovementioned 13 binders were interpolated from their corresponding test results at 64°C and 70°C. The interpolated values and the laboratory test results at 67°C were compared as presented Figures 42 and 43. From the linerar regression line, the interpolated results at 67°C can be computed and then compared with the real test data. In many cases, the test data and the interpolated values were faily close, however, it is evident that these two values did not match one another precisely. It is rather obvious that each binder behaved uniquely at individual temperatures and, therefore, a common trend (linear correlation) among the MSCR test results at 64°C, 67°C, and 70°C could not be established.

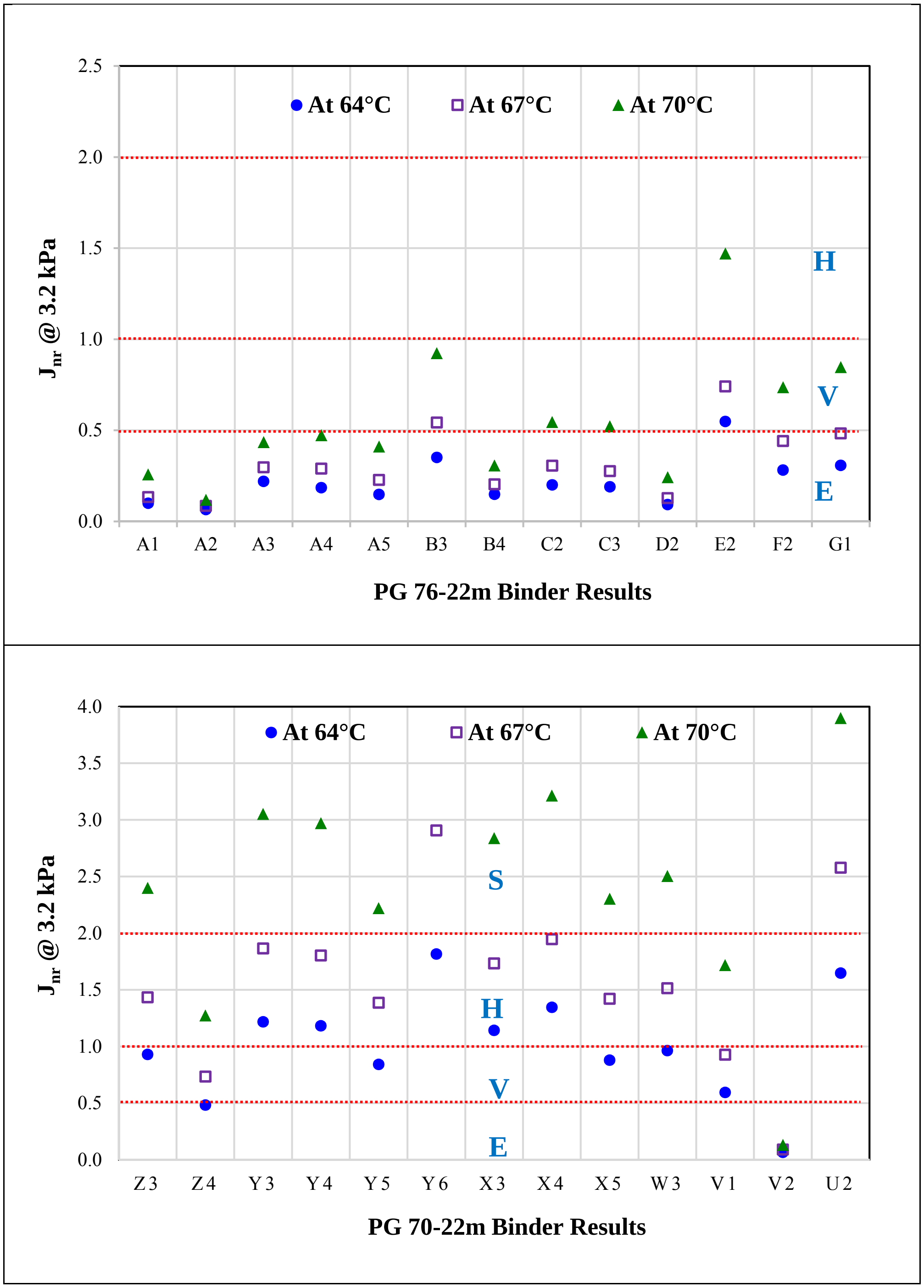
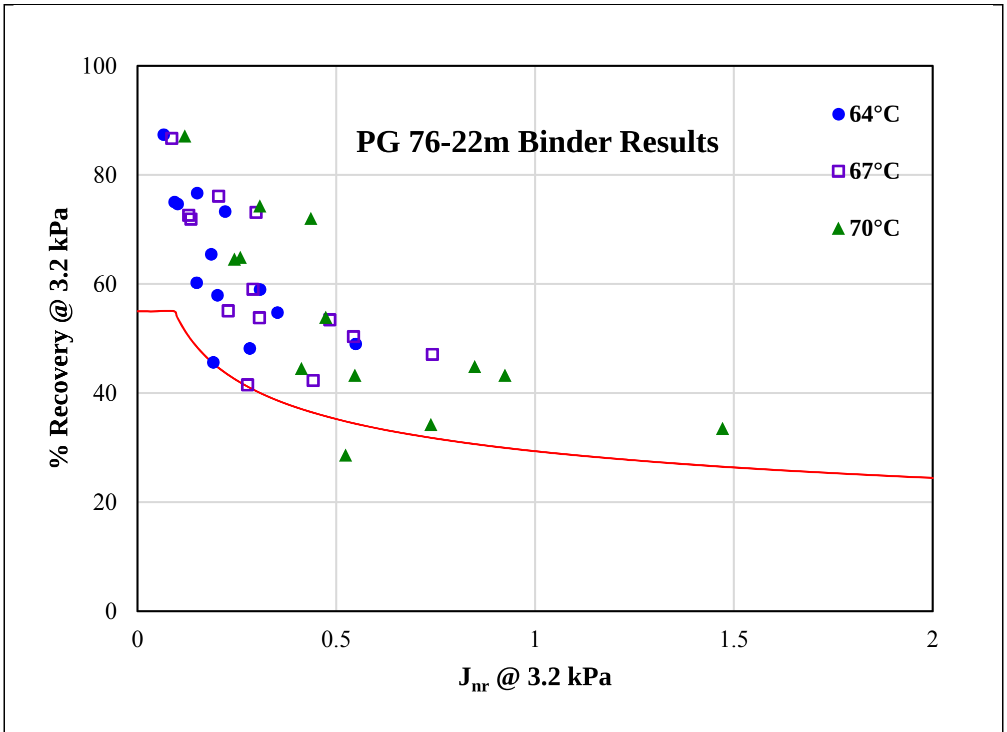


Figure 40
J_{nr}-based performance grades at 64, 67, and 70°C



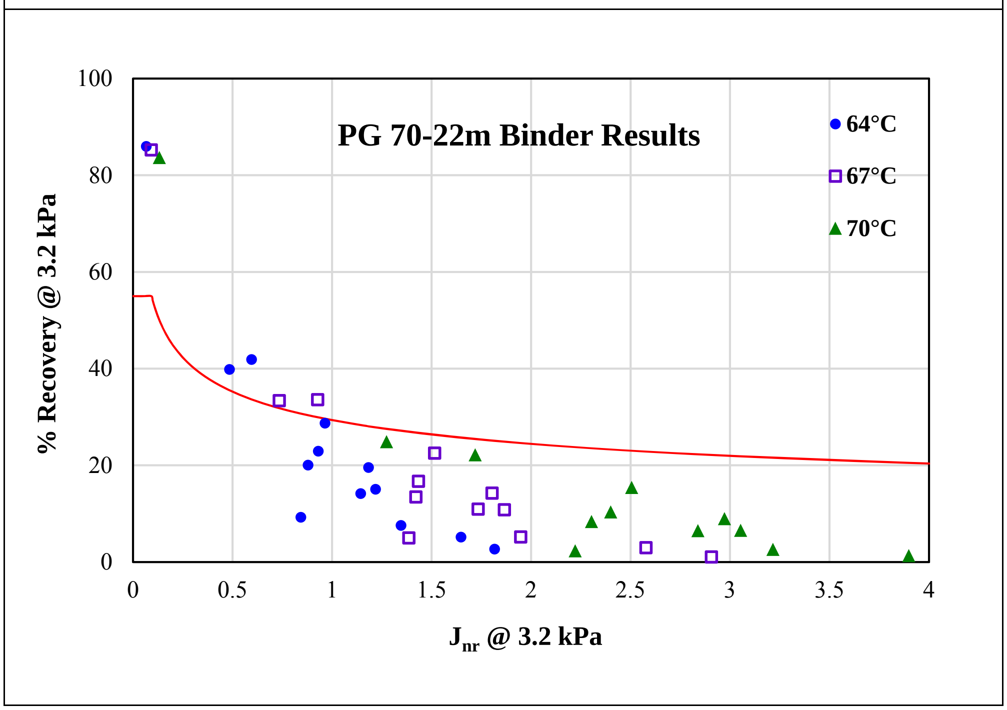


Figure 41
Elastic responses of binders at 64, 67, and 70°C

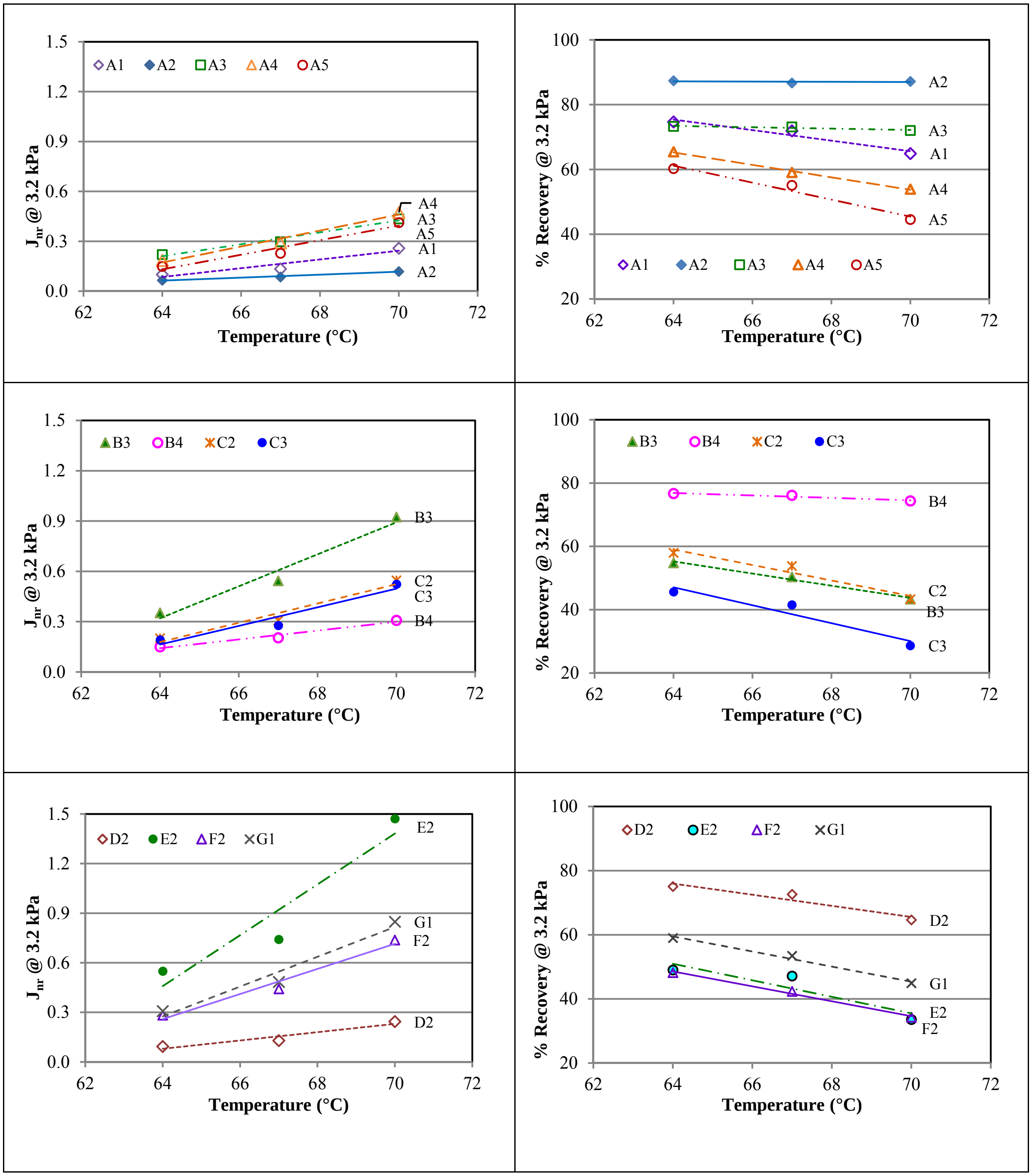


Figure 42
Comparison of interpolated results and lab-test results for PG 76-22m

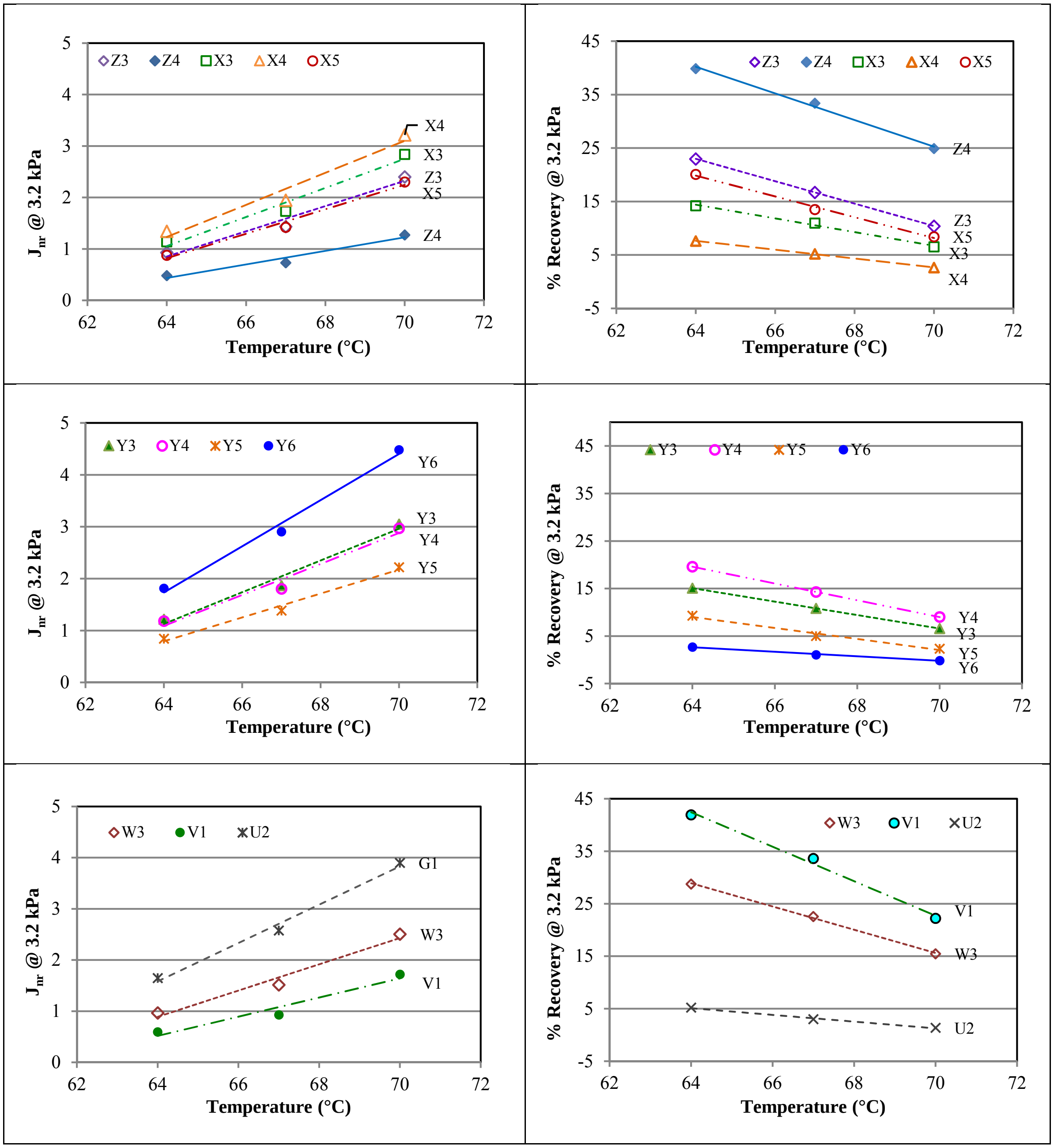


Figure 43
Comparison of interpolated results and lab-test results for PG 70-22m

CONCLUSIONS

Based on the experimental results of the 44 SBS polymer-modified and 11 rubber-modified asphalt binders under the scope of this study, it appears that DOTD is capable of making a smooth transition from its current asphalt binder specifications to AASHTO MP 19, the new MSCR based asphalt binder specifications. It is also possible to replace the currently used "PG-Plus" tests such as: elastic recovery and force ductility with the MSCR percent recovery and DSR phase angle criteria. The following specific conclusions can be drawn from the outcome of the study:

- Even though a small factorial was tested at 67°C, it is realistic for DOTD to embrace a similar MSCR-based binder specification (introducing 67°C as the climatic temperature) that other southern state agencies are currently considering.
- Binders currently graded as PG 76-22m for the state of Louisiana are very capable of handling the extreme (E) traffic condition both at 64°C and 67°C climatic conditions as measured by MSCR $J_{nr3.2}$. Considering these binders meet the delayed elastic response curve as listed in AASHTO TP 70, the current PG 76-22m binders can be classified as PG 67-22E as per AASHTO MP 19.
- Apart from few exceptions, most of the PG 70-22m binders included in this study were found capable of handling very heavy (V) and heavy (H) traffic conditions at 64°C and 67°C climatic temperatures respectively. If these binders meet the delayed elastic response curve, the current PG 70-22m binders shall be graded as PG 67-22H as per AASHTO MP 19.
- Testing at 70°C was found to be very harsh for the binders considered in this study. In most of the cases, the binders showed inferior performances at 70°C. However, similar binders in the field have been showing reasonably better performance over the years, which are comparable to MSCR results tested at 64°C and 67°C. Consequently, the MSCR test results at 70°C were not considered for further indepth analysis and the future asphalt binder specifications for DOTD.
- For unaged PG 76-22m binders, the currently used force ductility ratio can be replaced with a DSR phase angle of 75° max tested at 76°C. Similarly, a DSR phase angle of 78° max has been recommended for unaged PG 70-22m binders at 70°C instead of the force ductility at 30 cm elongation.
- MSCR percent recovery at 3.2 kPa can successfully replace the current elastic recovery test utilized by DOTD for RTFO aged binders. Binders shall meet the elastic

response curve as presented in AASHTO TP 70 in place of the current elastic recovery requirements.

- MSCR percent recovery at 3.2 kPa for unaged binders showed high potential to replace the force ductility ratio specifications currently used by DOTD. A minimum MSCR $R_{3.2}$ value of 22 percent at 64°C is recommended temporarily. However, the authors propose to collect more MSCR percent recovery data at 67°C for unaged bindrs to set a possible specification criteria.
- None of the binders included in this study were stress sensitive as measured by percent MSCR $J_{nr\text{-}diff}$.
- In general, the MSCR test and the corresponding specifications have been found to be an improvement to the current PG binder specifications for DOTD. The MSCR test was more discriminating to characterize the stress sensitivity of polymer-modified binders.
- GPC results indicate that the polymer content did not influence the MSCR recovery and elastic recovery of asphalt binders. The elastic behavior of binders rather depends on the chemical interactions between a particular polymer and a specific neat binder.
- The CRM binders showed a good performance against permanent deformation. However, their elastic responses as measured by the MSCR delayed elastic curve was not encouraging. A strong conclusion on the MSCR based performance of CRM binders cannot be made at this time due to the limited number of CRM samples in this study.

RECOMMENDATIONS

The outcome of this study clearly indicates that DOTD is ready to make a transition to the new MSCR-based AASHTO MP 19 asphalt binder specifications. The authors recommend starting a support study to establish a MSCR-based specification criterion for CRM and Latex modified binders, which could not be completed under the scope of this study due to their availability. It is also recommended that the proposed support study keep collecting the force ductility and DSR phase angle datafor unaged binders to fine tune the replacement of force ductility with DSR phase angle or MSCR recovery criteria. At this point, the authors highly recommend the implementation of AASHTO MP 19 at 67°C with the following guidelines:

- For unaged original binders: The authors recommend keeping all current PG test requirements with the exception of replacing force ductility ratio with a DSR phase angle of 75° max for unaged PG 76-22m binders tested at 76°C and a DSR phase angle of 78° max for unaged PG 70-22m binders tested at 70°C. There will be no change at all for the current PG 64-22 binders.
- For RTFO-aged binders: MSCR testing to be conducted at 67°C, with traffic level requirements designated as “E” (AASHTO MP 19) for the current PG 76-22m and “H” for the PG 70-22m binders, respectively. More specifically, the current PG 76-22m polymer-modified binders have to meet the PG 67-22E requirements as mentioned in AASHTO MP 19. Similarly, all polymer-modified binders currently specified as PG 70-22m have to meet the requirements of PG 67-22H. The requirement of regular RTFO binder DSR testing at the corresponding PG temperatures (i.e., 76°C and 70°C) will be waived for PG 76-22m and PG 70-22m binders. However, there will be no change at all for the current PG 64-22 binders.
- For RTFO-aged binders: The elastic response curve as required in AASHTO TP 70 shall be used to replace the current elastic recovery requirements.
- For PAV-aged binders: No change will be made to the current PG test requirements for PAV-aged binders.

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

AASHTO	American Association of State Highway and Transportation Officials
CRM	Crumb Rubber Modified
DOT	Department of Transportation
DOTD	Louisiana Department of Transportation and Development
DSR	Dynamic Shear Rheometer
FHWA	Federal Highway Administration
GPC	Gel Permeation Chromatography
HMA	Hot Mix Asphalt
J_{nr}	Non-recoverable Creep Compliance
LTRC	Louisiana Transportation Research Center
MSCR	Multiple Stress Creep Recovery
NCHRP	National Cooperative Highway Research Program
NEAUPG	Northeast Asphalt User-Producer Group
PG	Performance Graded
RCR	Repeated Creep and Recovery
RTFO	Rolling Thin Film Oven
SBS	Styrene-Butadiene-Styrene
SEAUPG	Southeast Asphalt User-Producer Group
SHRP	Strategic Highway Research Program

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APPENDIX

Table 3
MSCR test results for PG 76-22m binders

Binder Name	Aging Properties	Sample ID	MSCR Test Results					
			At 64°C		At 67°C		At 70°C	
			$J_{nr3.2}$	$\%R_{3.2}$	$J_{nr3.2}$	$\%R_{3.2}$	$J_{nr3.2}$	$\%R_{3.2}$
A1	Unaged	i	0.8790	34.4849			2.1968	19.2960
		ii	0.8978	34.0008			2.1710	19.1540
		iii	0.8348	35.2482			2.1936	18.9231
	Aged	i	0.1009	74.8869			0.2545	65.5569
		ii	0.0976	75.0663	0.1297	72.1035	0.2585	65.1016
		iii	0.1040	74.1593	0.1392	71.7558	0.2632	64.1605
A2	Unaged	i	0.1614	87.8347			0.2234	89.3571
		ii	0.1683	87.7171			0.2306	88.9118
		iii	0.1897	86.00			0.2774	86.8777
	Aged	i	0.0648	87.6654	0.0873	86.6828	0.1127	87.6128
		ii	0.0669	87.434	0.083	86.8859	0.1147	87.4651
		iii	0.0667	87.1192	0.0876	86.6365	0.1299	86.4911
A3	Unaged	i	0.5541	69.7017			1.4281	54.7904
		ii	0.7329	60.7082			1.564	53.9418
		iii	0.7819	58.6782			1.7142	50.3898
	Aged	i	0.2149	74.1609	0.3071	72.802	0.4205	72.838
		ii	0.2186	73.5219	0.3028	73.3504	0.4234	72.5846
		iii	0.2282	72.2685	0.2844	73.3129	0.4637	70.738
A4	Unaged	i	1.0022	33.1131			2.3389	24.4832
		ii	0.9996	34.2105			2.3064	23.3169
		iii	0.9955	32.6886			2.3407	22.5386
	Aged	i	0.1827	65.9209	0.2923	59.0493	0.4629	54.8245
		ii	0.1812	65.8896	0.2931	58.7342	0.4697	54.0122
		iii	0.1929	64.6004	0.2867	59.4487	0.4883	53.0056

A5	Unaged	i	0.921	22.694			2.2327	13.6615
		ii	0.8955	23.5563			2.2125	14.196
		iii	0.8983	23.5695			2.238	13.3576
	Aged	i	0.1477	60.4048	0.2227	55.5553	0.4054	45.1888
		ii	0.1528	60.0404	0.2303	55.0667	0.4085	44.5544
		iii	0.1465	60.3274	0.232	54.6725	0.4225	43.9229
B1	Unaged	i	0.894	40.8419			1.8559	34.6738
		ii	0.8423	42.5907			1.7638	35.8509
		iii	0.7367	44.7914			1.7884	34.6629
	Aged	i	0.3138	54.4821			0.8121	41.8339
		ii	0.3272	53.1651			0.8497	40.0435
		iii	0.324	52.724			0.8235	41.7663

Table 3
MSCR test results for PG 76-22m binders (continued)

Binder Name	Aging Properties	Sample ID	MSCR Test Results					
			At 64°C		At 67°C		At 70°C	
			$J_{nr3.2}$	$\%R_{3.2}$	$J_{nr3.2}$	$\%R_{3.2}$	$J_{nr3.2}$	$\%R_{3.2}$
B2	Unaged	i	1.2984	22.0344			3.0122	14.5313
		ii	1.3480	20.5962			2.8711	16.7656
		iii	1.2567	23.5617			3.177	13.7090
	Aged	i	0.5423	33.1703			1.3927	21.5374
		ii	0.5417	32.8264			1.3369	23.1241
		iii	0.5048	34.1817			1.3801	21.2778
B3	Unaged	i	0.3711	74.5212			0.8371	65.5508
		ii	0.3704	74.6593			0.8145	66.0310
		iii	0.3651	74.4000			1.0174	60.3900
	Aged	i	0.3473	55.3544	0.5435	50.3524	0.8990	43.9914
		ii	0.3494	55.2521	0.5405	50.3407	0.9205	43.7078
		iii	0.3592	53.7980	0.5462	50.4555	0.9529	42.2573
B4	Unaged	i	0.1566	87.4354			0.2791	86.7552

		ii	0.1601	87.3156			0.2828	86.6943
		iii	0.1769	86.0391			0.3224	84.9183
	Aged	i	0.1472	77.0824	0.2063	76.1565	0.2976	74.9346
		ii	0.1487	77.0373	0.2046	76.1335	0.3032	75.0431
		iii	0.1538	75.9085	0.2014	76.0734	0.3223	73.1111
C1	Unaged	i	0.9244	27.1527			2.3142	14.9185
		ii	0.976	24.0356			2.4377	12.4674
		iii	0.9588	24.4525			2.191	16.7612
	Aged	i	0.1421	58.8996			0.4081	42.2035
		ii	0.1503	57.9598			0.4327	40.8791
		iii	0.1431	58.5942			0.3994	41.8877
C2	Unaged	i	0.7495	37.4868			1.8359	22.7125
		ii	0.7517	36.7137			1.7101	25.2042
		iii	0.7501	36.6294			1.684	23.7667
	Aged	i	0.2009	58.111	0.3148	53.5302	0.5425	43.6274
		ii	0.1972	58.3613	0.3094	53.5389	0.5435	43.4317
		iii	0.2053	57.4355	0.2961	54.4763	0.5535	42.8929
C3	Unaged	i	1.0422	20.1255			2.3709	13.2894
		ii	1.0545	18.9439			2.4191	12.7976
		iii	1.0531	18.4811			2.1653	12.1453
	Aged	i	0.1902	45.8533	0.2854	41.1285	0.5250	27.4279
		ii	0.1937	45.6701	0.2762	41.4466	0.5050	30.7575
		iii	0.1888	45.4275	0.2689	42.0566	0.5405	27.8244

Table 3

MSCR test results for PG 76-22m binders (continued)

Binder Name	Aging Properties	Sample ID	MSCR Test Results					
			At 64°C		At 67°C		At 70°C	
			$J_{nr3.2}$	$\%R_{3.2}$	$J_{nr3.2}$	$\%R_{3.2}$	$J_{nr3.2}$	$\%R_{3.2}$
C4	Unaged	i	0.5007	57.6658			1.4227	41.4119
		ii	0.5281	56.8432			1.3317	42.2314

		iii	0.5267	55.8403			1.3603	41.2146
	Aged	i	0.1984	63.149			0.5459	50.8531
		ii	0.2089	62.5881			0.5351	51.1106
		iii	0.2104	61.7835			0.5549	49.7729
D1	Unaged	i	0.1485	87.7225			0.2984	84.8499
		ii	0.1787	85.6037			0.2873	85.0967
		iii	0.1661	84.9574			0.2448	82.4726
	Aged	i	0.1816	73.2848			0.4092	69.3983
		ii	0.1858	73.3298			0.4285	67.6325
		iii	0.1926	71.9584			0.3989	69.5743
D2	Unaged	i	0.6692	39.9988			1.8417	21.3911
		ii	0.6973	39.2138			1.8343	21.4475
		iii	0.7022	38.8303			1.8565	20.8706
	Aged	i	0.0925	75.3524	0.1320	72.2613	0.2413	64.9298
		ii	0.0927	75.3212	0.1312	72.4947	0.2365	65.1422
		iii	0.0947	74.4929	0.1236	73.1321	0.2537	63.7888
E1	Unaged	i	0.7441	61.1023			2.528	35.137
		ii	0.784	59.685			2.5144	35.1481
		iii	0.8496	57.24			2.5638	34.4907
	Aged	i	0.1075	85.9418			0.2536	80.6798
		ii	0.1084	86.0623			0.2572	80.3852
		iii	0.1227	84.5479			0.2827	78.7373
E2	Unaged	i	1.9826	28.2526			4.7079	14.8075
		ii	1.9562	28.1924			4.7578	14.6696
		iii	1.9849	27.3173			4.6707	14.4012
	Aged	i	0.5428	49.7208	0.7320	47.6474	1.4495	34.0589
		ii	0.5449	49.3002	0.7856	45.3987	1.4559	33.8496
		iii	0.5591	48.0863	0.7070	48.3223	1.5093	32.8518
F1	Unaged	i	1.1745	27.0864			2.861	14.4007
		ii	1.1594	28.3791			2.8348	13.6985
		iii	1.1607	27.0426			2.9242	13.2485

	Aged	i	0.095	73.2404			0.263	60.2086
		ii	0.0997	72.9997			0.2842	58.4012
		iii	0.0998	73.0842			0.2757	59.3322

Table 3

MSCR test results for PG 76-22m binders (continued)

Binder Name	Aging Properties	Sample ID	MSCR Test Results					
			At 64°C		At 67°C		At 70°C	
			$J_{nr3.2}$	$\%R_{3.2}$	$J_{nr3.2}$	$\%R_{3.2}$	$J_{nr3.2}$	$\%R_{3.2}$
F2	Unaged	i	1.2985	30.7499			3.5631	17.4136
		ii	1.4278	32.7539			3.2507	20.2999
		iii	1.5297	25.9997			3.5132	17.744
	Aged	i	0.283	49.3636	0.4399	42.2069	0.7083	35.0207
		ii	0.2706	50.3363	0.4571	41.9684	0.7297	33.2467
		iii	0.2941	44.9583	0.4285	42.8435	0.7754	34.6015
G1	Unaged	i	0.8147	50.285			2.3276	30.9279
		ii	0.8266	50.0153			2.3296	30.9631
		iii	0.8618	47.79			2.3294	30.7422
	Aged	i	0.3047	59.4843	0.4815	53.4918	0.8575	44.8514
		ii	0.3014	59.5634	0.4861	53.4139	0.8464	45.1523
		iii	0.3181	58.0116			0.8407	44.6944
G2	Unaged	i	0.8418	49.3408			2.3355	30.261
		ii	0.8974	45.7493			2.088	34.1461
		iii	0.8666	44.6956			2.3785	28.7931
	Aged	i	0.2788	63.8256			0.68	55.515
		ii	0.2796	63.5391			0.7078	53.8562
		iii	0.3032	61.5814			0.7053	54.3147

Table 4
MSCR test results for PG 70-22m binders

Binder Name	Aging Properties	Sample ID	MSCR Test Results					
			At 64°C		At 67°C		At 70°C	
			$J_{nr3.2}$	$\%R_{3.2}$	$J_{nr3.2}$	$\%R_{3.2}$	$J_{nr3.2}$	$\%R_{3.2}$
Z1	Unaged	i	3.4668	10.4137			7.8316	2.5563
		ii	3.4348	10.6319			7.9421	2.648
		iii	3.4368	10.5557			7.7899	2.6817
	Aged	i	0.769	34.8638			1.99	21.7859
		ii	0.7712	35.2365			2.0204	21.6648
		iii	0.7833	34.4231			1.9653	21.7686
Z2	Unaged	i	3.6487	9.2998			8.115	1.9911
		ii	3.6426	9.4514			8.0146	2.167
		iii	3.5882	9.1200			8.0378	1.9884
	Aged	i	0.8554	30.9535			2.1811	17.7549
		ii	0.853	31.1647			2.2287	17.2425
		iii	0.8702	30.645			2.2214	17.1244
Z3	Unaged	i	3.4053	5.2367			7.8005	0.0719
		ii	3.4132	5.2937			7.299	0.4633
		iii	3.4318	5.1834			7.3951	0.3839
	Aged	i	0.9314	22.9542	1.4234	16.8909	2.4045	10.4697
		ii	0.9219	23.242	1.4187	16.777	2.3944	10.3739
		iii	0.9387	22.754	1.4609	16.5059	2.4019	10.3677
Z4	Unaged	i	2.4463	11.9984			5.8509	3.7207
		ii	2.4433	12.177			4.5474	4.5474
		iii	2.4463	11.825			5.248	4.7095
	Aged	i	0.5074	39.2584	0.7383	33.4007	1.2671	25.1382
		ii	0.4798	40.1602	0.7243	33.5499	1.2686	25.1779
		iii	0.4646	40.2114	0.7402	33.3123	1.2865	24.4449
Y1	Unaged	i	2.9309	12.7097			6.8527	4.2736
		ii	2.9451	12.5906			6.9808	4.1416

		iii	2.9241	12.4706			6.7878	4.2375
	Aged	i	1.3106	16.6787			3.2793	7.5309
		ii	1.3106	16.4835			3.308	7.6145
		iii	1.3308	16.405			3.2907	7.437
Y2	Unaged	i	3.0909	7.262			7.1683	1.4745
		ii	3.1241	6.9245			7.4814	0.0652
		iii	3.1801	6.4876			7.1801	0.1813
	Aged	i	1.3465	13.5292			3.4059	6.0471
		ii	1.3488	13.58			3.421	5.9623
		iii	1.3553	13.4803			3.4016	5.7487

Table 4

MSCR test results for PG 70-22m binders (continued)

Binder Name	Aging Properties	Sample ID	MSCR Test Results					
			At 64°C		At 67°C		At 70°C	
			$J_{nr3.2}$	$\%R_{3.2}$	$J_{nr3.2}$	$\%R_{3.2}$	$J_{nr3.2}$	$\%R_{3.2}$
Y3	Unaged	i	2.8108	8.9773			6.7025	2.1211
		ii	2.802	8.9603			6.6103	2.2889
		iii	2.1766	10.7553			6.3608	2.277
	Aged	i	1.213	15.1246	1.8898	10.7900	3.1156	6.3743
		ii	1.2154	15.2239	1.8419	10.9475	3.117	6.6118
		iii	1.2257	14.9169	1.8656	10.8370	2.926	6.8419
Y4	Unaged	i	2.6264	12.4157			6.6369	3.4031
		ii	2.7606	12.2177			6.5746	3.4922
		iii	2.6287	12.6858			6.4367	3.4229
	Aged	i	1.1834	19.6626	1.8304	14.0484	2.9934	9.0394
		ii	1.1947	19.8315	1.7990	14.2660	2.9806	8.9765
		iii	1.1716	19.3513	1.7824	14.5308	2.9409	9.0494
Y5	Unaged	i	2.2991	1.609	3.4521	0.4407	5.4307	-0.6874
		ii	2.3129	1.5948	3.4511	0.4595	5.3822	-0.6489
	Aged	i	0.8378	9.3144	1.3918	4.9989	2.2136	2.3489

		ii	0.8471	9.2744	1.3806	5.0255	2.2292	2.3427
Y6	Unaged	i	5.1292	-0.766	7.6300	-1.7270	10.9921	-2.7761
		ii	5.0599	-0.7338	7.4853	-1.6746	10.9966	-2.7732
	Aged	i	1.82	2.7015	2.8959	1.0815	4.5007	-0.1353
		ii	1.8129	2.7267	2.9177	1.0767	4.47	-0.1231
X1	Unaged	i	0.9132	34.0288			3.3492	14.2873
		ii	0.8747	34.9724			3.5543	13.3593
		iii	0.894	34.8118			3.4215	13.5697
	Aged	i	0.3342	53.4536			0.9032	37.5021
		ii	0.3095	54.4065			0.9205	37.2564
		iii	0.315	53.8656			0.9261	36.5109
X2	Unaged	i	3.5723	1.5502			7.9886	-1.2502
		ii	3.5872	1.3723			7.6687	-0.912
		iii	3.5346	1.5811			7.6548	-1.1838
	Aged	i	1.3569	7.5476			3.3188	2.4948
		ii	1.3666	7.7151			3.3241	2.2549
		iii	1.369	7.3448			3.2551	2.2746
X3	Unaged	i	2.5571	6.6203			0.9769	6.7553
		ii	3.0706	5.3202			0.9921	6.7055
		iii	2.996	5.0103			0.6183	6.7242
	Aged	i	1.1452	14.4376	1.7291	11.4152	2.7516	6.9071
		ii	1.1459	14.2476	1.7432	10.6766	2.8229	6.3045
		iii	1.1386	13.9815	1.7300	10.8686	2.9418	6.3805

Table 4

MSCR test results for PG 70-22m binders (continued)

Binder Name	Aging Properties	Sample ID	MSCR Test Results					
			At 64°C		At 67°C		At 70°C	
			$J_{nr3.2}$	$\%R_{3.2}$	$J_{nr3.2}$	$\%R_{3.2}$	$J_{nr3.2}$	$\%R_{3.2}$
X4	Unaged	i	3.5469	1.6348			7.7203	-1.058
		ii	3.5762	1.6387			7.7299	-1.0636

		iii	3.5477	1.3960			7.9084	-1.1508
	Aged	i	1.3476	7.6482	1.9601	5.1983	3.2225	2.7962
		ii	1.3506	7.7377	1.9351	5.2333	3.2056	2.7045
		iii	1.3394	7.4875			3.2182	2.5048
X5	Unaged	i	2.5215	7.1152			5.8735	1.259
		ii	2.5299	7.1738			5.8392	1.2459
		iii	2.4898	7.1826			5.8941	1.1836
	Aged	i	0.8741	20.2507	1.424	13.4932	2.3315	8.3653
		ii	0.8815	20.1924	1.4219	13.4971	2.2877	8.4712
		iii	0.882	19.8347	1.417	13.5402	2.2918	8.4157
W1	Unaged	i	2.0917	17.4549			5.031	6.8377
		ii	2.166	17.0987			4.9614	6.8329
		iii	2.1508	17.0511			4.8787	6.9503
	Aged	i	0.8501	24.0527			2.1457	11.8006
		ii	0.8145	24.5764			2.0951	12.0374
		iii	0.8081	24.7625			2.2335	11.2778
W2	Unaged	i	1.6687	18.9059			4.0647	7.4036
		ii	1.6633	18.8283			4.0614	7.6514
		iii	1.5974	18.8453			3.8035	8.0626
	Aged	i	0.2766	52.0805			0.7687	35.4555
		ii	0.2737	52.1854			0.7662	35.2612
		iii	0.2857	51.1036			0.7854	34.7198
W3	Unaged	i	2.2647	29.9448			5.7296	13.0293
		ii	2.2523	29.9263			5.6037	13.5078
		iii	2.3624	27.6355			5.6636	12.6738
	Aged	i	0.9604	28.7693	1.5058	22.6451	2.5218	15.4953
		ii	0.9721	28.7061	1.5434	22.3725	2.515	15.5559
		iii	0.961	28.7921	1.4962	22.7092	2.4799	15.3456
V1	Unaged	i	2.6425	11.5377			6.6483	2.282
		ii	2.7176	11.5178			6.3736	2.6012
		iii	2.6674	11.4250			6.3689	2.6299

	Aged	i	0.5856	42.4654	0.928	33.5933	1.715	22.4888
		ii	0.5932	42.238	0.9146	33.8623	1.7014	22.3705
		iii	0.6072	41.0969	0.9404	33.3952	1.7408	21.827

Table 4
MSCR test results for PG 70-22m binders (continued)

Binder Name	Aging Properties	Sample ID	MSCR Test Results					
			At 64°C		At 67°C		At 70°C	
			$J_{nr3.2}$	$\%R_{3.2}$	$J_{nr3.2}$	$\%R_{3.2}$	$J_{nr3.2}$	$\%R_{3.2}$
V2	Unaged	i	2.4551	14.9484			5.7993	5.2625
		ii	2.4631	14.6976			5.7809	5.3927
		iii	2.4428	14.5691			5.853	5.5331
	Aged	i	0.506	45.2321			1.3833	30.5002
		ii	0.5135	45.0952			1.3899	30.6095
		iii	0.5286	43.8415			1.3967	29.8453
V3	Unaged	i	0.2974	75.1133	0.5160	67.9195	0.9783	56.0899
		ii	0.3	74.9192	0.5054	68.6295	1.0047	55.6766
	Aged	i	0.0659	85.9834	0.0913	85.2735	0.1323	83.6522
		ii	0.0656	86.0857	0.0911	85.2646	0.1311	83.7277
U1	Unaged	i	0.3115	79.1558			0.8892	69.3863
		ii	0.3252	79.8273			0.8845	69.2633
	Aged	i	0.2885	67.401			1.0056	44.6897
		ii	0.3522	59.3061			0.9846	44.8863
		iii	0.3017	64.7863			0.9758	46.0055
U2	Unaged	i	3.6743	8.9047	5.8109	4.6025	8.4004	2.0399
		ii	3.9019	6.945	5.6931	4.658	8.1852	2.0661
	Aged	i	1.6381	5.1414	2.576	2.9336	3.9101	1.3593
		ii	1.6577	5.2743	2.5796	3.0893	3.8871	1.3635

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