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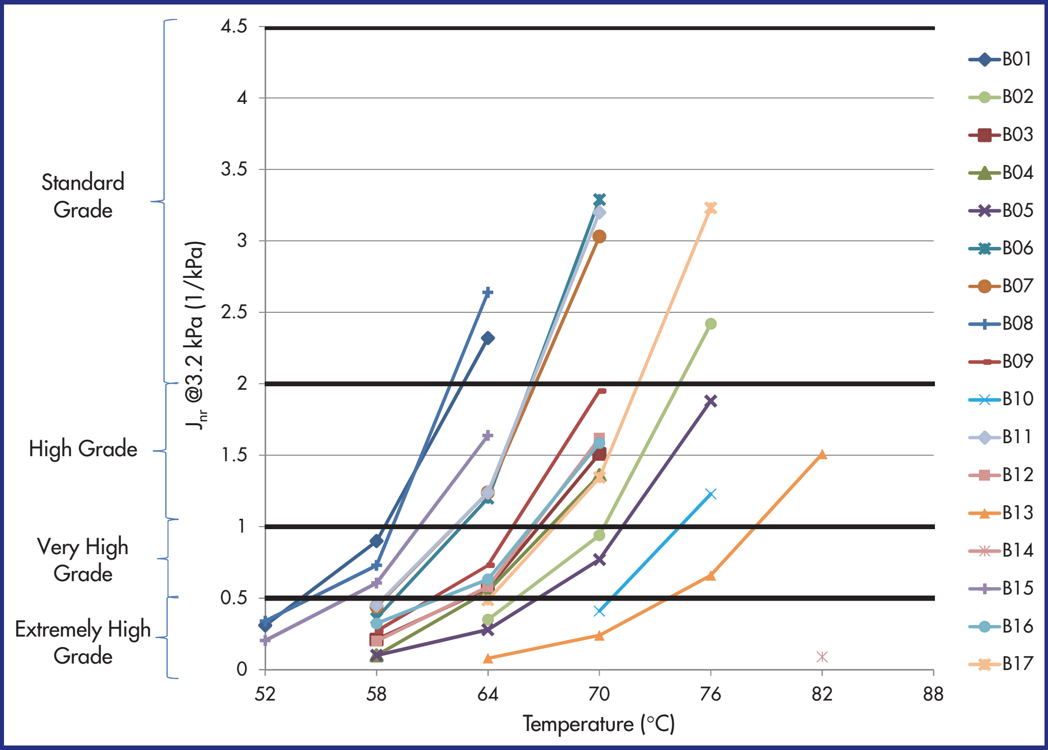
Analysis of the Multiple Stress Creep Recovery Asphalt Binder Test and Specifications for Use in Indiana



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16. Abstract

The Superpave specifications and equipment, introduced in 1993, represented a major advancement with respect to offering a better understanding of the behavior and characteristics of asphalt binders based on their rheological properties. However, the Superpave high-temperature test protocol has been shown to be inadequate for characterizing the high-temperature behavior (rutting resistance) of asphalt binders, particularly polymer modified ones. Recently, a specification based on the Multiple Stress Creep Recovery (MSCR) test has been proposed to address the shortcomings of the Superpave high-temperature binder specifications. This study aims to investigate the merits of implementing the MSCR test and specification as a replacement for the conventional high-temperature testing in the Performance Graded (PG) system. A statistical analysis was conducted on a dataset from Indiana Department of Transportation (INDOT) to see how MSCR and PG procedures differ in grading different binders used in the state. In addition, an experimental study was conducted using seventeen different modified and unmodified binders. In addition to binder tests, seven of the binders were selected to conduct asphalt mixture tests such as dynamic modulus and flow number. The results confirm that the MSCR test is a suitable replacement for the current PG high temperature test since it provides a better tool to rank modified asphalt binders as well as unmodified ones. That is, creep compliance from the MSCR test more fundamentally represents binder behavior at high temperatures compared to the PG rutting parameter. In addition, the very simplified approach, known as grade-bumping, used in the current PG system to account for high traffic levels and low speed limits can be eliminated when using the MSCR test. The MSCR test also provides a better coefficient of correlation (at both stress levels) with flow number test results than the PG rutting parameter, again indicating that it more accurately reflects binder performance at high temperatures.

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EXECUTIVE SUMMARY

ANALYSIS OF THE MULTIPLE STRESS CREEP RECOVERY ASPHALT BINDER TEST AND SPECIFICATIONS FOR USE IN INDIANA

Introduction

The Indiana Department of Transportation (INDOT) currently uses the Superpave performance grading (PG) system as standardized in AASHTO M 320. Although the Superpave PG binder specification was a significant step forward to select binders based on their performance, the test methods specified have been found to inaccurately predict the characteristics of modified asphalt binders, especially at high temperatures. In some cases, this has resulted in binders being over-engineered – using higher polymer loadings than needed to meet the climatic and traffic demands – resulting in higher material costs.

To overcome the disadvantages of M 320, especially regarding modified binders, a new test method and standard specification have been adopted by AASHTO. The new specification (M 332) uses a multiple stress creep recovery (MSCR) test, described in AASHTO T 350, to characterize binder behavior at high temperatures. The test is expected to more accurately reflect the binder contribution to rutting resistance, especially with modified binders, than the current M 320 standard.

This research was initiated to determine if implementing the new MSCR test and M 332 binder specification could lead to optimized binder properties and avoid the perceived over-engineering of modified binders. The results will allow INDOT to consider the possible benefits of implementing the MSCR test by comparing the performance of binders formulated to meet the existing M 320 specifications to those formulated to meet the M 332 specification through binder and mixture testing. Reduced cost, longer pavement service life and improved performance are potential benefits of implementation of the new standards.

Findings

- The MSCR creep compliance and Superpave rutting parameter do not correlate well to each other, especially with regard to modified binders, as shown by a comparison of paired test results on over 2400 binder samples over a six-year period. At higher concentrations of modifiers in the asphalt binders, the coefficient of determination between the creep compliance and rutting parameter decreased drastically. This is due to the fact that these two grading systems capture the viscoelastic behavior of modified asphalt binders differently.
- The MSCR can be used to test and successfully rank neat, GTR and polymer-modified binders. This means that the MSCR specification (M 332) could be implemented and applied to all binders regardless of modification.
- The MSCR test grades the binders considering both environmental and traffic conditions. That is, the expected traffic levels do not have to be addressed by so-called "grade bumping" anymore. In addition, the MSCR test is expected to optimize the binder formulation to avoid the use of over-engineered binders.
- Correlation between asphalt binder performance with asphalt mixture performance shows that the MSCR provides a better coefficient of correlation at both stress levels with flow number test results than the PG rutting parameter. That is, the MSCR grading would be expected to better reflect ultimate high temperature mixture performance, specifically resistance to rutting. Since the MSCR specification uses the same low temperature test and criteria, no changes in the low temperature mixture behavior would be expected.

Implementation

Results of the statistical and experimental approaches that were applied in the current study suggest that the MSCR test provides a better tool than the currently used PG grading system for characterizing high temperature performance properties of commonly used asphalt binders in the state of Indiana. These results suggest that INDOT could implement the MSCR test and have reasonable expectations that binders meeting the needed climatic and traffic conditions would perform well and could possibly be less expensive.

This change can be accommodated by revising Section 902 of the Standard Specifications, along with applicable design guidance. The pay items will also have to be changed to include the new binder grade designations.

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1. INTRODUCTION

Asphalt pavements play an important role in the roadway system of Indiana and other states in the U.S. Ensuring a long pavement life is beneficial for the traveling public, the agency that funds the construction and rehabilitation of pavements, and the industry that aims to create a quality pavement to remain viable. The overall performance of an asphalt pavement is highly dependent on the properties of the mixture, including the binder that holds the mixture and the pavement together.

The Indiana Department of Transportation (INDOT) currently uses the Superpave performance grading (PG) system as standardized in AASHTO M 320. This grading system is based on the idea that a binder's properties should be related to the conditions under which it is used. PG binders are selected to meet expected climatic conditions, as well as aging considerations, with a certain level of reliability. Expected traffic levels are also addressed by so-called "grade bumping" – using a stiffer binder (higher grade) than the climate demands for heavier traffic conditions. Although the Superpave PG binder specification was a significant step forward to select binders based on their performance, the test methods specified have been found to inaccurately predict the characteristics of modified asphalt binders, especially at high temperatures. Specifically, the Dynamic Shear Rheometer is used to determine the rutting parameter, $|G^*|/\sin\delta$, according to AASHTO T 315. Because of the limitations of the current M 320 specification, many states have adopted what are termed PG+ specifications, where additional tests have been added in an attempt to verify the presence of a polymer and/or to better characterize the binder performance. Indiana has not implemented any PG+ test requirements.

To overcome the disadvantages of M 320, especially regarding modified binders, a new test method and standard specification have been adopted by AASHTO. The new specification (M 332) uses a multiple stress creep recovery (MSCR) test, described in AASHTO T 350, to characterize binder behavior at high temperatures. The test is expected to more accurately reflect the binder contribution to rutting resistance, especially with modified binders, than the current M 320 standard. T 350 is used to determine both the nonrecoverable creep compliance (J_{nr}) and the percent recovery of the asphalt binder. J_{nr} is intended to replace the current rutting parameter in M 320, and percent recovery is intended to replace PG+ tests, such as elastic recovery. In addition, the standard sets a limit on the percent difference between the nonrecoverable creep compliance values at the two stress levels.

M 332 establishes binder grades (such as PG 64-22 or PG 70-22) and specification limits based on environmental factors, where the first number reflects the high pavement temperature at which the binder is expected to perform and the second number is the low temperature. Design traffic volumes (**S**tandard, **H**igh, **V**ery High or **E**xtremely High) and also accounted for in M 332, leading to grades such as PG 64S-22, PG 64H-22, etc. The intent is to replace the current, poorly supported grade bumping for traffic with a more rigorous and technically sound approach.

INDOT has been collecting data on how currently-formulated binders in the state perform in this test method since 2010. The Office of Materials Management (OMM) has been running the test for information on all binder acceptance samples alongside the conventional M 320 PG test methods. Through this testing experience, INDOT has observed that some of the higher binder grades, especially PG 76-22, may be highly over-engineered. Because ensuring compliance with the PG specifications for the higher binder grades often requires polymer modification, the material costs are increased substantially.

If the MSCR test does, in fact, better characterize the performance of modified binders, binders formulated to meet this specification may be optimized for performance. By better capturing the effects of modification, binder suppliers may be able to reduce the polymer loading, which in turn will result in lower material costs while maintaining performance.

In addition, this test and specification may provide INDOT with a means to allow the use of terminal blended, crumb rubber binders. These binders are being adopted by some states, especially those using PG+ tests, as an economical and sustainable modified binder. INDOT is willing to consider allowing crumb rubber binders to be used but currently does not have an acceptable test method to ascertain their suitability since it does not use PG+ tests. These binders fail the solubility test because of the presence of rubber particles. If the MSCR test reliably predicts which binders will perform well for Indiana's climate and traffic, one thought at the outset of this project was that the solubility test could possibly be dropped for all binders, though this is not without risk. Thus, implementation of the MSCR test might allow INDOT to adopt a permissive specification that would allow the use of economical crumb rubber binders.

1.1 Problem Statement and Objective

This research was initiated to determine if implementing the new MSCR test and M 332 binder specification will lead to optimized binder properties and avoid the perceived over-engineering of modified binders. The results will allow INDOT to consider the possible benefits of implementing the MSCR test by comparing the performance of binders formulated to meet the existing M 320 specifications to those formulated to meet the M 332 specification through binder and mixture testing. In addition, data collected by INDOT on binders used on its construction projects was analyzed to determine how currently used materials perform in the MSCR compared to the existing M 320 specification; this is reported on in Chapter 3. In Chapter 4, the results of testing additional binder testing are presented; binders from Missouri that were formulated to meet the MSCR specification are compared to conventional binders to explore the differences in behavior. Lastly, in Chapter 5, the results of testing mixtures fabricated with some of the binders tested in the laboratory phase are presented to investigate differences in mixture behavior that might be caused by the differences in the binders. Reduced cost, longer pavement service life and improved performance are potential benefits of implementation of the new standards.

For brevity in this report, the conventional T 315 high temperature test and M 320 specification will be referred to as the PG system, and the new MSCR test (T 350) and M 332 specification will be referred to as the MSCR system. It should be noted that both specifications, M 320 and M 332, use the same intermediate and low temperature tests, as well as having other similarities.

2. LITERATURE REVIEW

An asphalt mixture is a combination of coarse and fine aggregates, asphalt binder and air voids. Researchers and material scientists have made considerable advances in understanding and predicting the characteristics and behavior of asphalt paving mixtures and their constituents.

There are different types of failures that can affect the performance of an asphalt pavement. Three of the main categories are rutting, fatigue cracking and thermal cracking. Rutting is surface distortion in the wheel path induced by traffic loads; rutting mainly happens during hot weather when the binder viscosity or stiffness is reduced. Fatigue is also related to traffic and occurs when repeated deformation of the pavement under load causes longitudinal cracks in the wheel path that progressively grow into alligator cracking. Thermal cracking is related to contraction of the pavement at low temperatures and results in fairly uniformly spaced cracks, oriented transverse to the centerline.

All of these failures are directly related to the complex viscoelastic behavior of asphalt to some extent. In a dense-graded asphalt mixture, asphalt binder has an influence on the permanent deformation performance of the mixture. Several studies (Alataş, Yılmaz, Kök, & Fatih Koral, 2012; Delgadillo & Bahia, 2010; Di Benedetto, 2004; Khattak Jamal, & Kyatham, 2008; Xiao, Wenbin Zhao, & Amirkhanian, 2009) have indicated the significant effects of asphalt binder on permanent deformation characteristics in typical dense-graded asphalt mixtures. While the binder alone cannot prevent rutting, when combined with a good aggregate structure the proper binder can ensure good performance of the material under the traffic and climatic conditions for which it was designed and can provide a factor of safety if conditions exceed the design.

There have been numerous attempts to select asphalt binders based on their performance characteristics in asphalt mixtures. The introduction of Superpave's performance-based test methods and specification in 1993 was a major advancement in selecting asphalt binders based on their performance. In the Superpave specification, $|G^*|/\sin\delta$ is introduced as the rutting parameter, where G^* is the dynamic shear modulus and is the time lag in the response of viscoelastic materials. This rutting parameter is derived directly from the definition of the loss compliance, J'', which measures the energy dissipated per cycle of sinusoidal deformation (Anderson, D'Angelo, & Walker, 2010). A higher value of this rutting parameter generally indicates a stiffer binder with better rutting resistance. Since this parameter was derived for unmodified binders, the validity of its use for modified binders has been questioned. Subsequent research (Anderson & Kennedy, 1993; Bahia et al., 2001; Bouldin, Dongré, & D'Angelo, 2001; Shenoy, 2001; Tabatabaee & Tabatabaee, 2010) has indicated that this parameter does not accurately reflect the permanent strain characteristics of modified binders, nor of some conventional binders.

The Multiple Stress Creep Recovery (MSCR) test is the latest refinement of the Superpave performance graded asphalt binder specification. One advantage of the MSCR test is that it eliminates the need to run tests such as elastic recovery, toughness and tenacity, and force ductility. Although Indiana does not use these tests to characterize binders, neighboring states do, which impacts Indiana's binder suppliers as well. In addition, the results obtained from the MSCR test will provide additional information, which can be helpful in determining suitable binders to use in asphalt mixtures. Moreover, since the test reportedly better characterizes the needed high temperature binder properties, it is expected to help optimize binder formulations to avoid over-engineering and higher costs. The test uses the Dynamic Shear Rheometer (DSR), the same equipment used in the current PG specifications (with updated software), as will be described in 4.1.

A more detailed literature review is available in Appendix A of this document.

3. ANALYSIS OF INDOT DATA

Since 2010, INDOT has been collecting data on how currently formulated binders used in the state perform in the MSCR test method. The Office of Materials Management (OMM) has been running the MSCR test on all binder acceptance samples alongside the conventional AASHTO M 320 PG test methods. The data collected for a period from 2010 to 2015 were statistically analyzed to investigate the differences between the results of the performance grading (PG) system and the MSCR test-based grading. The dataset includes more than 2400 data records. MSCR testing was conducted on RTFO-aged binders as per specification; this testing was performed at 64°C for all binder grades.

Figures 3.1 to 3.4 show the correlation between the rutting parameter ($|G^*|/\sin\delta$) from the Superpave performance grading (PG) system as measured in the dynamic shear rheometer (according to AASHTO T 315) and the creep compliance (J_{nr}) from the MSCR

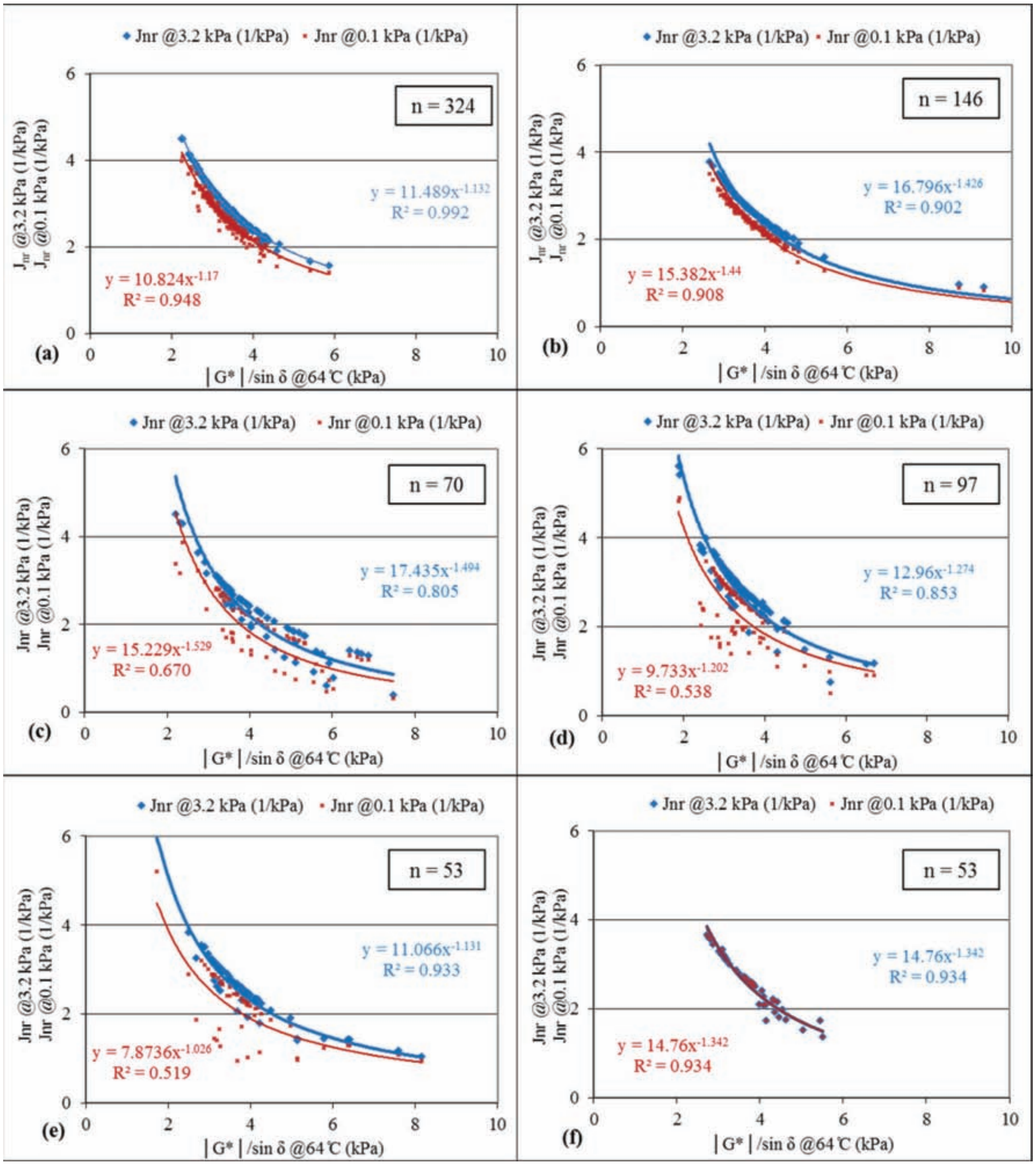

Figure 3.1 Correlation between rutting parameter from PG system and creep compliance from MSCR test for PG 64-22 binders: data for (a) 2010, (b) 2011, (c) 2012, (d) 2013, (e) 2014, (f) 2015.

test for different grades of asphalt binders. The numbers of data records (n) graphed in these figures are also shown in the legends. As a general rule-of-thumb, PG binders for which the difference between the low and high temperatures is 90°C or more are often modified. Therefore, it can be assumed, with a reasonable level of confidence, that the binders shown in Figures 3.1 and 3.2 are unmodified. It can be seen that for these binders the coefficients of determination (R^2) are statistically high for both of the stress levels used in the MSCR test (i.e., 0.1 kPa and 3.2 kPa). As the difference between the high and low temperature grades increases, the probability of having modifiers such as polymers in the asphalt binders increases. As seen in Figure 3.3, the coefficient of determination for the relationship between the rutting parameter and the creep compliance decreases for modified binders. At presumably higher levels of modification (Figure 3.4), the R^2 value decreases even more. The reduction in the R^2 value is higher at the higher stress level (i.e., 3.2 kPa). The reason for this might be related to the activation of the modification/polymer network at high stress levels. At the low stress and strain levels used in the current PG system, the modification/polymer network is never really mobilized or called upon to resist deformation (Anderson, D'Angelo, & Walker, 2010). Therefore, when tested

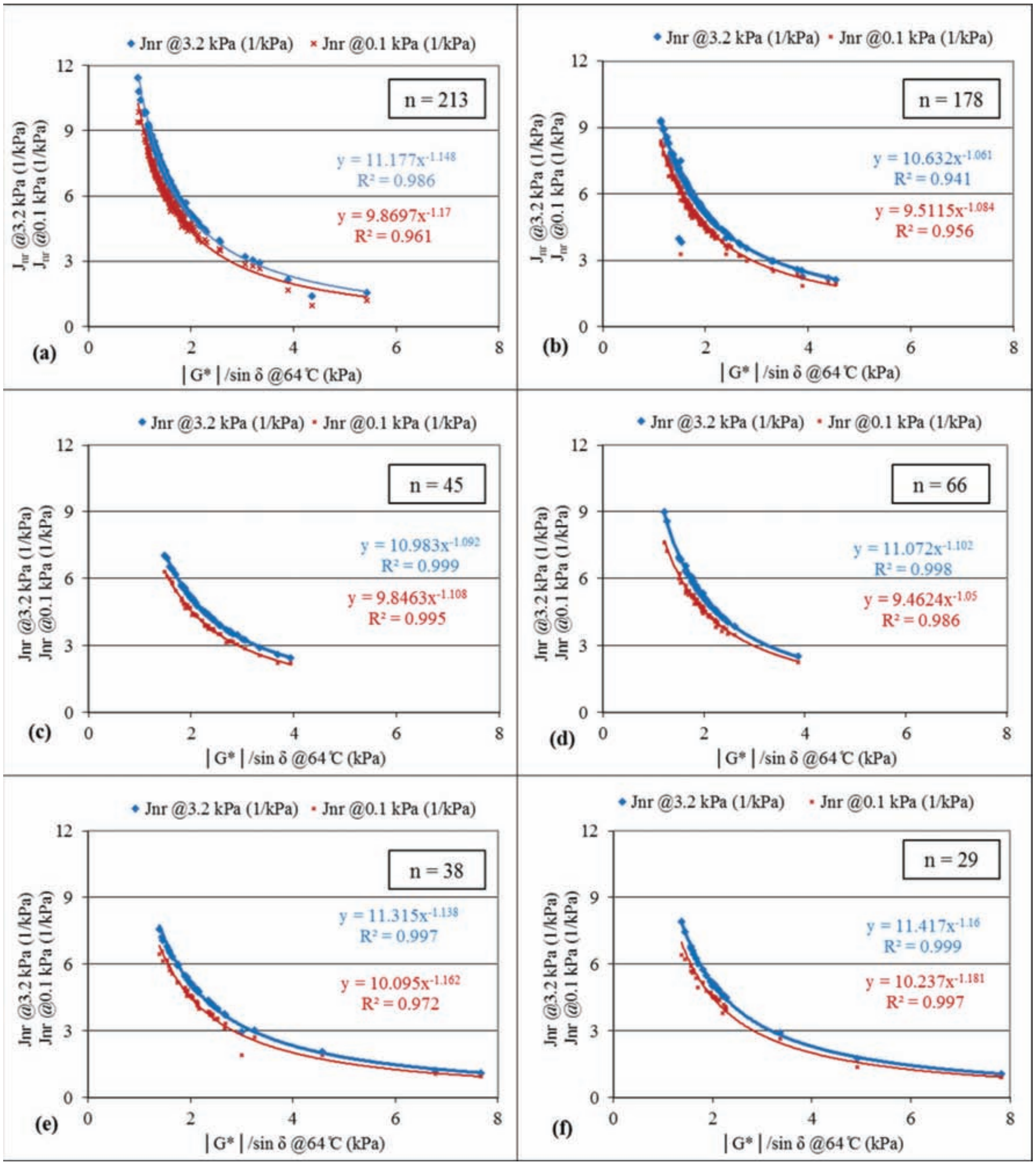

Figure 3.2 Correlation between rutting parameter from PG system and creep compliance from MSCR test for PG 58-28 binders: data for (a) 2010, (b) 2011, (c) 2012, (d) 2013, (e) 2014, (f) 2015.

using procedures utilized in the current PG system, the modifiers/polymers mainly appear to act as fillers that stiffen the asphalt. If tests used to grade binders according to the AASHTO M 320 specification were truly capturing the benefits of modification, the rutting parameter and the nonrecoverable creep compliance would be expected to be well correlated. The fact that the correlation worsens for modified binders implies that the procedures used in AASHTO T 315 are not able to fully capture the effects of modification.

Some interesting (and rather unexpected) trends observed for PG 70-22 binders are shown in Figures 3.3 and 3.4. It can be seen that the R^2 value of the correlation between the rutting parameter from the PG system and J_{nr} from the MSCR test is 0.425 for the 2015 data for PG 70-22 (Figure 3.3f). However, this value is 0.713 for the 2010 data (Figure 3.3a); the R^2 values for the unmodified binders are much more consistent from year to year (Figures 3.1 and 3.2). In Figure 3.4, the results are highly varied, especially in 2014 and 2015, and do not appear to follow the same patterns as in previous years. There appear to be distinctly different “families” of data points.

One possible explanation for these changes in the correlations might be related to the presence of different modifiers in the asphalt binders. Many binder providers,

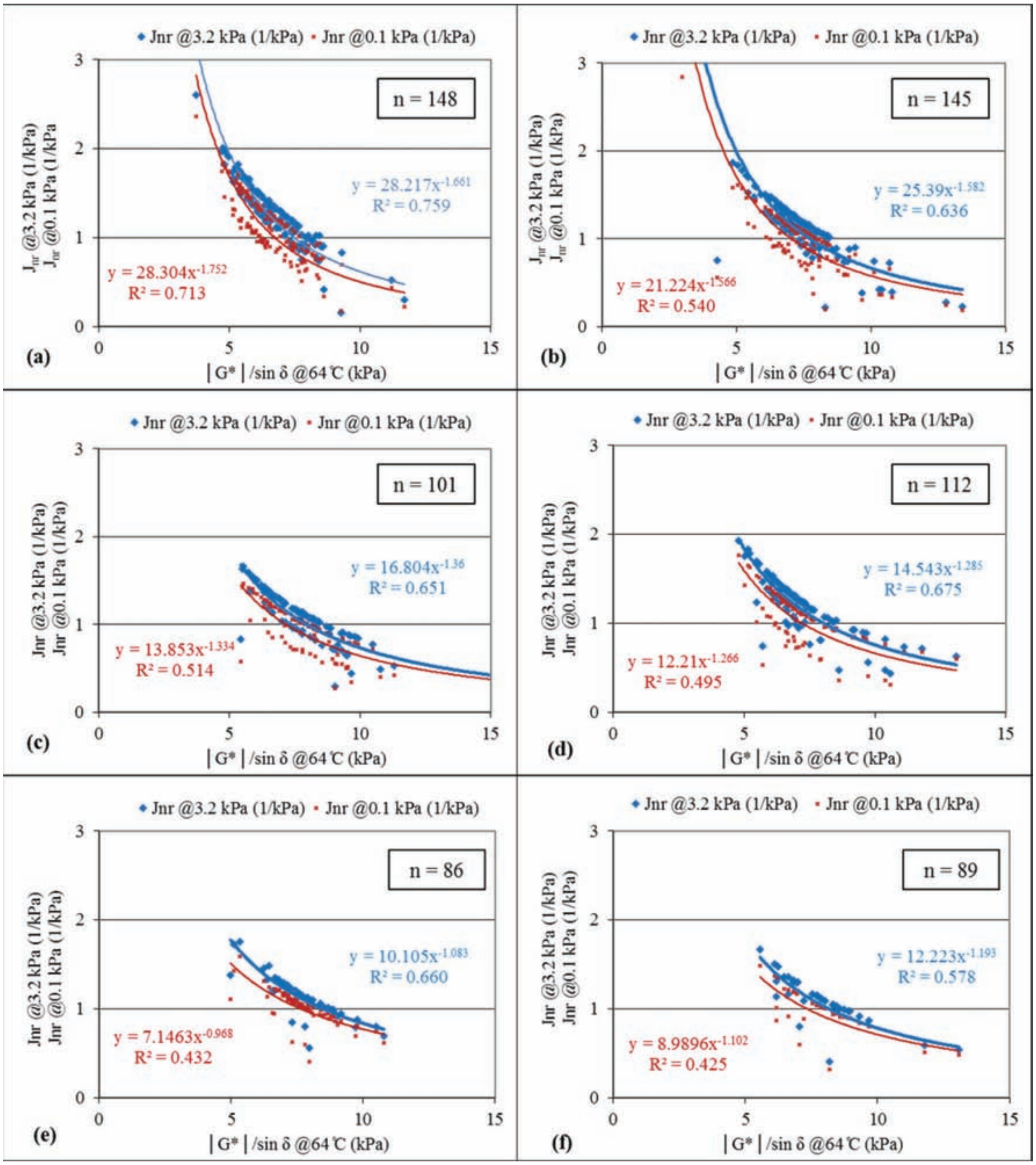

Figure 3.3 Correlation between rutting parameter from PG system and creep compliance from MSCR test for PG 70-22 binders: data for (a) 2010, (b) 2011, (c) 2012, (d) 2013, (e) 2014, (f) 2015.

in recent years, have used acid modifiers instead of or in addition to common polymers in order to modify neat binder and obtain PG 70-22 and PG 76-22 binders at lower cost. Anecdotally, there are even some PG 70-22 binders that do not contain polymer modifiers and therefore may behave differently. The trends of correlations between creep compliance at 3.2 kPa and the PG rutting parameter with respect to binder suppliers for PG 70-22 and PG 76-22 are shown in Figure 3.5 and Figure 3.6, respectively. Figures 3.5 and 3.6 contain almost the same data records that are shown in Figure 3.3 and Figure 3.4, respectively (suppliers with only a few data records were not used). With some exceptions, it can be seen that the results for binders from a given supplier tend to follow a trend or pattern throughout the year. Those suppliers whose results do not follow a similar trend might be changing their binder formulations throughout the year. Since all of the binders in a given figure meet the same PG grade but perform differently in the MSCR test, this suggests that the MSCR test is more discriminating.

These observations are in line with the findings of previous research, where it has been indicated that the Superpave specification rutting parameter is an inadequate indicator of the permanent strain characteristics of certain binders, particularly modified ones

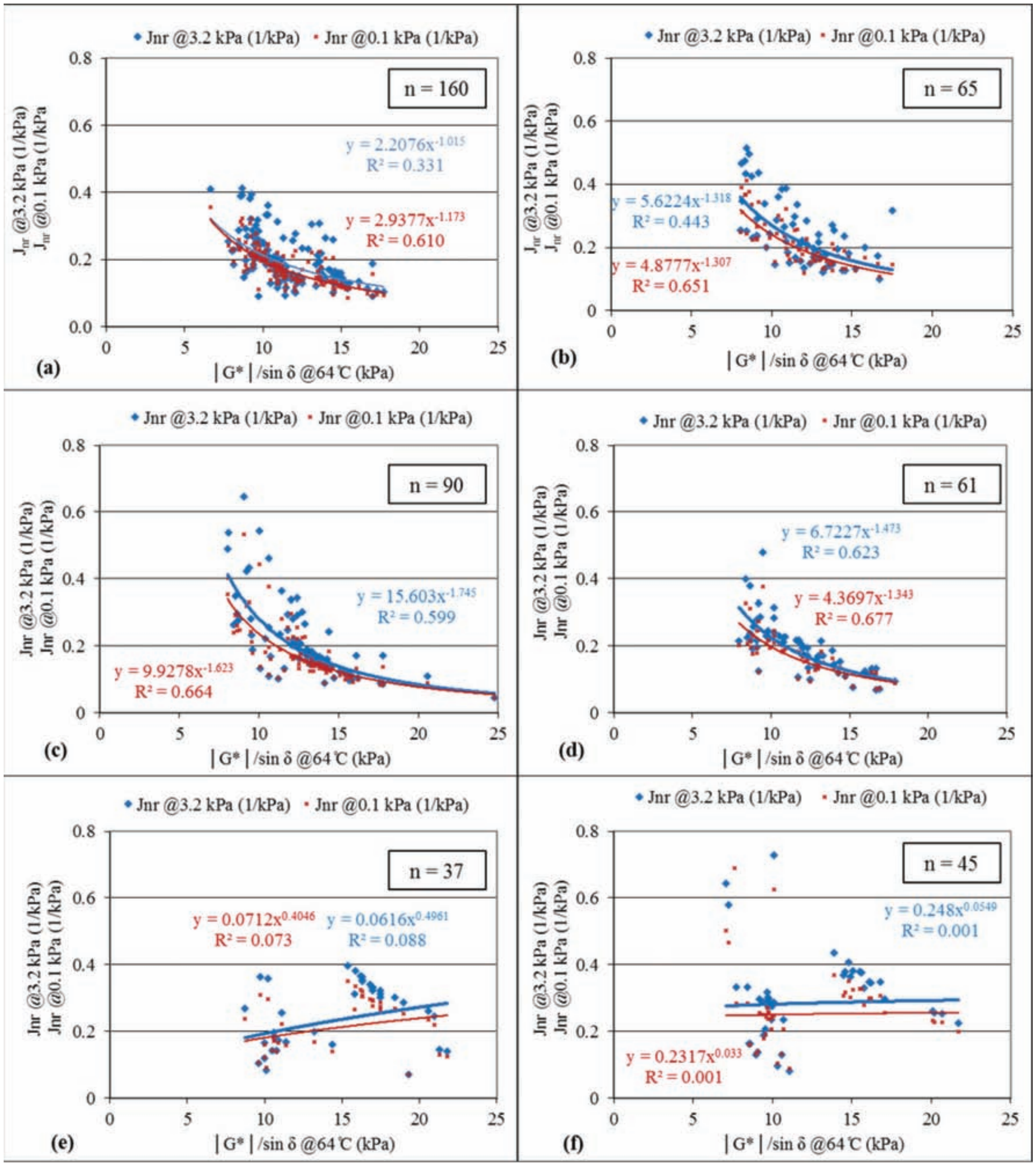

Figure 3.4 Correlation between rutting parameter from PG system and creep compliance from MSCR test for PG 76-22 binders: data for (a) 2010, (b) 2011, (c) 2012, (d) 2013, (e) 2014, (f) 2015.

(Anderson, & Kennedy, 1993; Bahia et al., 2001; Bouldin et al., 2001; Shenoy, 2001; Tabatabaee, & Tabatabaee, 2010). Under NCHRP project 9-10, the relationship between the accumulated permanent strain in mixtures and |G*|/sin δ of the binders was found to provide a poor correlation (R^2=23.77%) (Bahia et al., 2001).

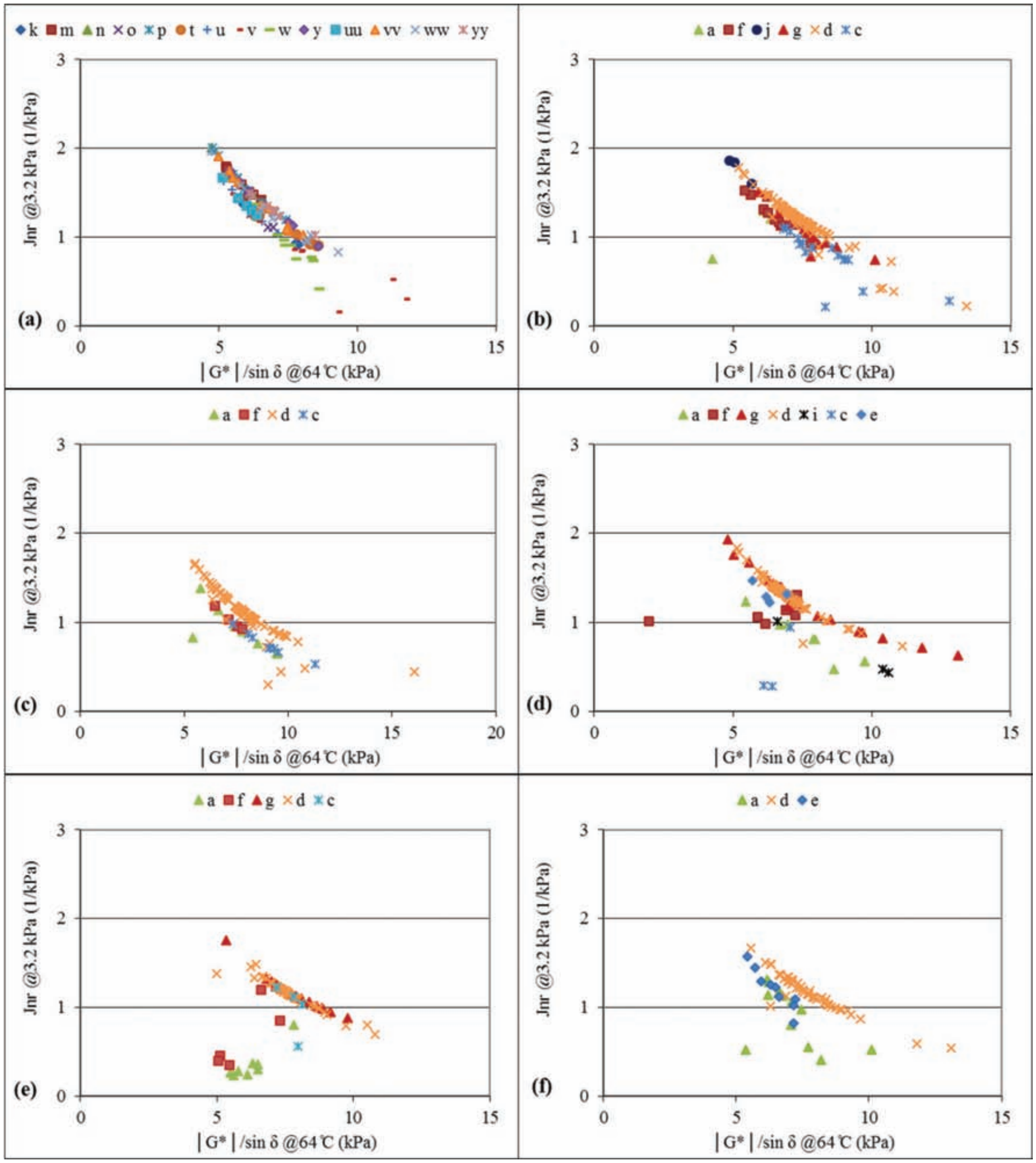

Figure 3.5 Trends with binder suppliers for PG 70-22 binders: data for (a) 2010, (b) 2011, (c) 2012, (d) 2013, (e) 2014, (f) 2015. NOTE: Different letters and symbols indicate different suppliers.

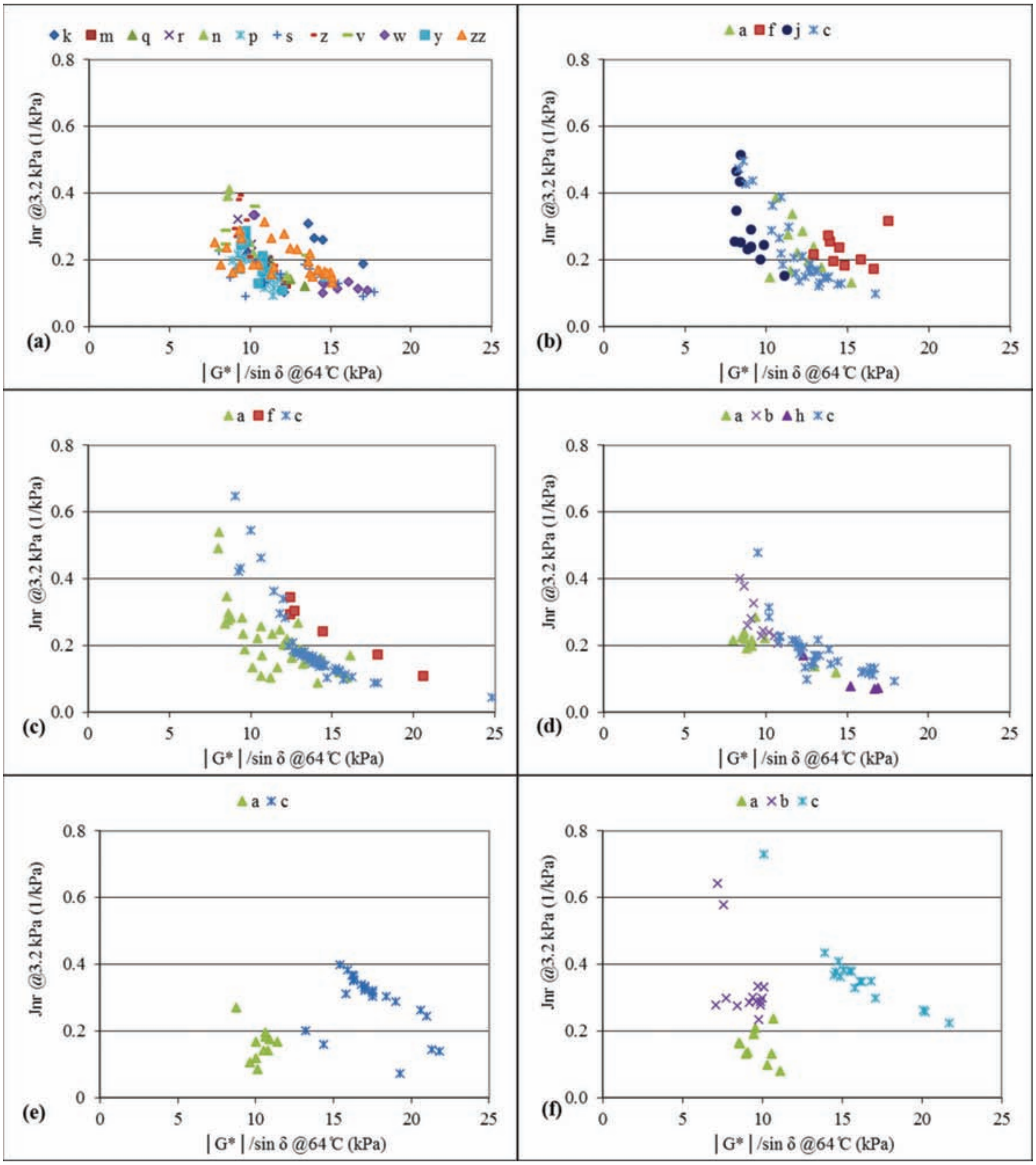

Figure 3.6 Trends with binder suppliers for PG 76-22 binders: data for (a) 2010, (b) 2011, (c) 2012, (d) 2013, (e) 2014, (f) 2015.
NOTE: Different letters and symbols indicate different suppliers.

4. BINDER TESTING PROGRAM

Seventeen different modified and unmodified asphalt binders were collected in order to conduct the binder tests. Table 4.1 shows the binders that were used in this study. It should be noted that these binders were collected from the states of Indiana, Missouri, and Arizona. Some of the Missouri binders, B11 through B16, were specifically formulated to meet the AASHTO M 332 specification. Modified binders included polymers commonly used in the asphalt industry, like styrene-butadiene-styrene (SBS) or ground tire rubber (GTR). The specific sizes of GTR used in each binder are not known. In addition, one binder was known to include polyphosphoric acid (PPA).

TABLE 4.1
Binder IDs and their characteristics.

Binder ID	State	Remarks
B01	IN	PG 64-22, unmodified binder
B02	IN	B01+ SBS
B03	IN	B01+ SBS+PPA
B04	IN	B01+ 12% GTR
B05	IN	B01+ 12% GTR + Vestenamer
B06	IN	PG 70-22
B07	IN	PG 70-22
B08	MO	PG 64-22
B09	MO	PG 70-22
B10	MO	PG 76-22
B11	MO	PG 64H-22
B12	MO	PG 64V-22
B13	MO	10% GTR HYBRID
B14	MO	Highly modified
B15	MO	PG 64H-22
B16	MO	PG 64V-22
B17	AZ	PG 70-28

Figure 4.1 shows the details of binder testing program. The tests conducted on these binders included:

- Superpave performance grading (PG) (AASHTO M 320)
  - Dynamic Shear Rheometer tests (AASHTO T 315)
  - Bending Beam Rheometer tests (AASHTO T 313)
- Multiple stress creep recovery (MSCR) tests (AASHTO T 350)

In addition to investigating the differences between the Superpave performance grading (PG) system and MSCR specification grading system, differences between two dynamic shear rheometer (DSR) devices were also investigated. These devices included a conventional DSR that applies oscillatory loading at different frequencies and a newer DSR that is capable of applying load at multiple stress and creep levels. In other words, the conventional DSR is capable of performing the tests used to grade the binder as per AASHTO M 320 (using T 315 at high temperatures) while the newer DSR can also perform the MSCR (AASHTO T 350) test to grade the binder as per AASHTO M 332. The intent of this comparison was to investigate any potential differences between these two devices when performing the standard T 315 test. The standard T 315 test is used in the MSCR specification to test original (unaged) binders as well as long-term aged binders at intermediate temperatures; it would be advantageous in some cases to be able to use one DSR to run both the MSCR and conventional tests.

4.1 Testing Protocol

The AASHTO M 320 specification and associated laboratory procedures were utilized to grade the asphalt binders. When using these testing protocols, asphalt binders are evaluated at three critical stages of asphalt life using simulated laboratory conditioning procedures. In the first stage, original (virgin or unaged) binder is graded to study its properties during transporting and handling (before mixing) steps. In the second stage, rolling thin film oven (RTFO)-aged asphalt binder is graded to

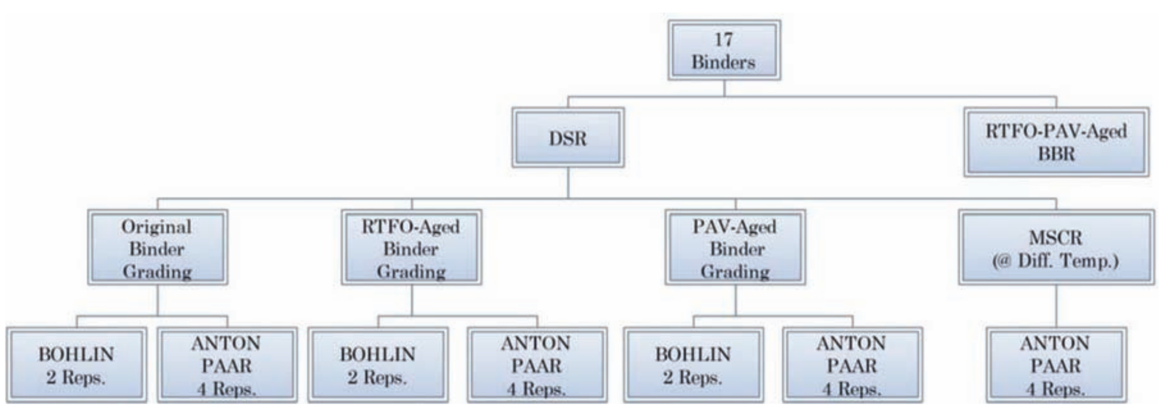

Figure 4.1 Binder testing program details.

investigate the binder properties after a short-term aging process that attempts to simulate asphalt mixture production and construction. In the third stage, pressure aging vessel (PAV)-aged binder is graded to investigate the binder properties after simulated long-term aging to represent the late period in pavement service life. In addition, to evaluate the low temperature properties of asphalt binders, bending beam rheometer (BBR) tests are conducted.

In the current study, the MSCR test was performed on RTFO-aged binders according to AASHTO T 350 at different temperatures by applying two stress levels of 0.1 kPa for twenty cycles followed by 3.2 kPa for ten cycles. Each cycle consisted of 1 s shear creep followed by a recovery period of 9 s. The shear stress of 0.1 kPa characterizes the behavior of a binder in the linear viscoelastic region, and the 3.2 kPa stress level reflects a binder's behavior in the non-linear viscoelastic region for most modified and unmodified binders. The MSCR test generates two key parameters that are, in turn, used to determine the binder grade as per AASHTO M 332. These values are nonrecoverable creep compliance (J_{nr}) and percent recovery. (Percent recovery is currently not utilized as a grading parameter, but is of interest to states that are concerned about whether a polymer modifier is present – a PG+ state.) The percent difference criterion requires the difference in nonrecoverable creep compliance between 0.1 kPa and 3.2 kPa to be less than 75%. Based on the value of J_{nr}, a particular binder can get a grade of **S**tandard, **H**eavy, **V**ery heavy, or **E**xtremely heavy to account for the traffic level. Average nonrecoverable creep compliances at 0.1 kPa ($J_{nr0.1}$) and 3.2 kPa ($J_{nr3.2}$) are expressed as:

$$J_{nr_{0.1}} = \frac{\sum_{N=11}^{20} [J_{nr}(0.1, N)]}{10} \tag{4.1}$$

$$J_{nr_{3.2}} = \frac{\sum_{N=1}^{10} [J_{nr}(3.2, N)]}{10} \tag{4.2}$$

where $J_{nr}(0.1, N)$ and $J_{nr}(3.2, N)$ are the nonrecoverable creep compliances at 0.1 kPa and 3.2 kPa at cycle number N, respectively, and N is the cycle number at each stress level.

Percent difference in nonrecoverable creep compliance between 0.1 kPa and 3.2 kPa is calculated as:

$$J_{nr_{diff}} = \frac{\left[J_{nr_{3.2}} - J_{nr_{0.1}}\right] \times 100}{J_{nr_{0.1}}} \tag{4.3}$$

Average percent recovery at 0.1 kPa ($R_{0.1}$) and 3.2 kPa ($R_{3.2}$) are, respectively, expressed as:

$$R_{0.1} = \frac{\sum_{N=11}^{20} [\in_r(0.1, N)]}{10} \tag{4.4}$$

$$R_{3.2} = \frac{\sum_{N=1}^{10} [\in_r(3.2, N)]}{10} \tag{4.5}$$

where $\in_r(0.1,N)$ and $\in_r(3.2,N)$ are the percent recovery at 0.1 kPa and 3.2 kPa at cycle number N, respectively, and N is the cycle number at each stress level.

TABLE 4.2
P-values of comparison of conventional and new DSRs when $\alpha = 0.05$.

Binder ID	p-Value
B01	0.1210
B02	0.8852
B03	0.6316
B04	0.2630
B05	0.1688
B06	0.1316
B07	0.2614
B08	0.1190
B09	0.1774
B10	0.7994
B11	0.2552
B12	0.1136
B13	0.4984
B14	0.1706
B15	0.2266
B16	0.1148
B17	0.5840

4.2 Binder Test Results

The results of the binder tests are given in this section.

4.2.1 Dynamic Shear Rheometer Tests

To complete the grading of each of the original, RTFO-aged and PAV-aged binders, six replicate samples were prepared for each asphalt binder-aging condition combination and were tested in accordance with AASHTO T 315. Four of the samples were tested using the new DSR. The other two samples were tested using the traditional DSR. The p-values of the comparison tests between conventional and new DSRs are given in Table 4.2. Comparison of the conventional and new DSRs did not show any statistically significant differences (p-values $\geq$ 0.05), indicating that the two DSRs do not perform differently when conducting the conventional DSR tests. Tables 4.3 to 4.5 show the averages and coefficients of variation (C.V.) of the original, RTFO-aged and PAV-aged binder test results, respectively. It should be noted that these values are the average of six replicates (i.e., two replicates using conventional DSR and four replicates using newer DSR) since the two devices gave similar results.

TABLE 4.3
Original binder grading results at high performance grade temperature.

Binder ID	|G*|(kPa)	Phase Angle (δ)	|G*|/sin(δ) (kPa)	C.V. (%)	Pass/Fail Temperature (°C)	High PG Temperature (°C)
B01	1.59	86.55	1.59	2.6	67.8	64
B02	1.05	73.38	1.10	3.7	77.0	76
B03	1.63	75.58	1.67	0.5	75.0	70
B04	1.39	77.95	1.42	4.3	79.7	76
B05	1.59	72.83	1.68	11.6	81.7	76
B06	1.07	80.74	1.08	3.8	70.7	70
B07	1.28	86.58	1.28	3.3	72.1	70
B08	1.23	87.10	1.23	4.1	65.7	64
B09	1.42	80.48	1.44	2.0	73.5	70
B10	1.42	70.68	1.51	3.3	80.3	76
B11	1.15	86.86	1.15	0.7	71.2	70
B12	1.53	76.43	1.59	4.6	74.4	70
B13	1.05	79.83	1.06	3.7	88.7	88
B14	1.60	54.52	1.97	12.4	96.8	88
B15	1.66	82.00	1.68	1.5	68.3	64
B16	1.57	72.55	1.64	1.5	75.1	70
B17	1.21	78.83	1.24	4.7	72.0	70

4.2.2 Bending Beam Rheometer (BBR) Test

The bending beam rheometer (BBR) test provides a measure of low temperature stiffness and relaxation properties of asphalt binders. These parameters give an indication of the ability of asphalt binders to resist low temperature cracking. BBR tests were conducted for each asphalt binder at least two different temperatures (i.e., -12°C, -18°C or -24°C) to allow complete grading of each binder. Three replicate samples were prepared for each temperature-binder combination and the averages of at least two results out of the three were reported. Table 4.6 shows the averages of the slope and stiffness for each temperature-binder combination.

4.2.3 Multiple Stress Creep Recovery (MSCR) Test

For each temperature-binder combination, four replicate samples were prepared for testing in accordance with AASHTO T 350. Figure 4.2 shows the variation of creep compliance at the 3.2 kPa stress level as well as the percent difference between the two stress levels with temperature. It can be seen that different grades can be obtained for each binder considering different temperature-traffic combinations. For example, B02, which was graded as a PG 76-22 binder based on PG system, was also graded as PG 76S-22, PG 70V-22, and PG 64E-22 based on the MSCR protocol. Some binders were successfully graded for extremely heavy traffic or Heavy traffic conditions. (The definition of the traffic levels can be found in Appendix A.) For instance, at 64°C, which is the typical high temperature condition in Indiana, B02, B05, B13 and B17 were successfully graded for extremely heavy traffic conditions; these binders were modified with SBS and/or different types of GTR. At the same climatic condition, B04, B09, B12, and B16 were graded for Very heavy traffic conditions. Based on the percent difference criterion (Figure 3.5b), B04, B05 and B13 failed at higher temperatures (i.e., above 64°C), but were successfully graded at lower temperatures (e.g., 58°C and 64°C); recall that these three binders all contain ground tire rubber.

Figure 4.3 shows the percent recovery values for all 17 binders at 3.2 and 0.1 kPa. As noted in 4.1, this value is not currently used in the specification, but is of interest to states that wish to verify that a polymer modified binder is used. Examination of this figure shows that, in general terms, the addition of a polymer modifier shifts the curve to higher percent recoveries and higher temperatures. For example, compare binder B01, which is an unmodified PG 64-22, to B02 through B05, which have the same base binder with different additives. B02 contains SBS, B03 has SBS +PPA, B04 has 12% GTR, and B05 includes 12% GTR + Vestenamer. All of the modified binders have higher recoveries at

TABLE 4.4
RTFO-aged binder grading results at high performance grade temperature.

Binder ID	|G*|(kPa)	Phase Angle (δ)	|G*|/sin(δ) (kPa)	C.V. (%)	Pass/Fail Temperature (°C)	High PG Temperature (°C)
B01	4.16	82.33	4.20	3.1	69.0	64
B02	2.44	68.58	2.62	4.5	77.9	76
B03	3.96	70.48	4.20	3.9	76.3	70
B04	2.87	71.04	3.03	2.4	79.4	76
B05	3.63	66.55	3.95	2.5	82.5	76
B06	2.56	76.67	2.63	0.8	71.6	70
B07	3.21	82.92	3.24	3.1	72.9	70
B08	3.59	82.44	3.62	3.3	67.7	64
B09	3.84	74.98	3.98	4.7	76.3	70
B10	3.16	64.17	3.51	2.4	81.4	76
B11	3.11	82.65	3.14	2.7	72.6	70
B12	3.70	71.54	3.90	3.6	75.4	70
B13	3.64	66.32	4.60	4.5	89.5	88
B14	4.40	44.98	6.21	2.0	ND*	88
B15	2.29	78.63	2.33	1.3	70.5	64
B16	3.18	65.13	3.51	1.5	75.0	70
B17	3.06	73.68	3.19	0.2	73.4	70

*ND: Not determined (because the binder was very stiff).

TABLE 4.5
PAV-aged binder grading results at intermediate performance grade temperature.

Binder ID	|G*|(kPa)	Phase Angle (δ)	|G*|.sin(δ) (kPa)	C.V. (%)	Pass/Fail Temperature (°C)	Intermediate PG Temperature (°C)
B01	5343	45.2	3795	1.8	22.7	25
B02	5012	46.9	3660	3.7	22.5	25
B03	5852	41.9	3903	3.0	19.7	22
B04	5612	43.3	3846	4.0	19.7	22
B05	7177	38.4	4460	4.4	17.8	19
B06	4892	47.3	3593	7.1	22.4	25
B07	5155	46.4	3733	3.0	25.5	28
B08	6763	44.0	4698	2.1	21.5	22
B09	6882	44.1	4788	3.5	21.6	22
B10	6725	42.1	4505	3.6	24.1	25
B11	5615	45.0	3965	7.3	26.0	28
B12	5668	44.5	3968	3.6	23.0	25
B13	6970	38.0	4283	5.9	17.5	19
B14	ND*	ND	ND	ND	ND	ND
B15	5017	44.5	3520	2.6	22.3	25
B16	4995	48.1	3710	4.0	19.8	22
B17	5277	43.8	3655	4.6	22.3	25

*ND: Not determined (because the binder was very stiff).

TABLE 4.6
Bending beam rheometer (BBR) test results.

Binder ID	Temperature (°C)	Slope (m-Value)	Stiffness (MPa)
B01	-18	0.265	349
	-12	0.326	137
B02	-18	0.279	302
	-12	0.338	149
B03	-18	0.274	275
	-12	0.330	112
B04	-18	0.264	280
	-12	0.330	113
B05	-18	0.274	265
	-12	0.324	110
B06	-18	0.264	350
	-12	0.312	158
B07	-18	0.258	368
	-12	0.302	196
B08	-18	0.281	301
	-12	0.338	135
B09	-18	0.282	350
	-12	0.337	170
B10	-18	0.265	326
	-12	0.306	175
B11	-18	0.239	418
	-12	0.292	222
B12	-18	0.265	319
	-12	0.326	157
B13	-18	0.268	219
	-12	0.318	108
B14	-18	ND*	ND
	-12	ND	ND
B15	-18	0.270	276
	-12	0.315	137
B16	-18	0.277	266
	-12	0.325	129
B17	-24	0.249	532
	-18	0.306	260

*ND: Not determined (because the binder was very stiff).

higher temperatures than the unmodified base asphalt. Binder B08 plots nearly on top of B01 and is also an unmodified PG 64-22.

Table 4.7 shows the summary of MSCR test results. The precision and bias statements for this test method are still being evaluated. Therefore, although coefficients of variation were calculated, they could not be compared to standard values. All of the CVs are less than 12% and most are less than 5%, however, which suggests the test is quite repeatable, in most cases.

In order to investigate the effects of gap size on the MSCR test results, binders B01-B05 were selected to run the test with a 2-mm gap size. This set of tests was performed to see the effects of gap size on the results of testing GTR-modified binders. Some laboratories use a 2-mm gap size to avoid potential problems with particulates in the GTR-modified binders. The results indicated that the difference in the nonrecoverable creep compliance at 3.2 kPa between a standard 1-mm gap and a 2-mm gap was not significant at an α of 0.05 (p-values $\geq$ 0.05 as shown in Table 4.8. The α value indicates the risk of concluding there is a difference between the results when there is not. The summary of the MSCR results with 2-mm gap is given in Table 4.9.

4.3 Binder Tests – Summary and Conclusions

The analysis of the INDOT data indicated that the current high temperature Superpave performance grading (PG), as standardized in AASHTO T 315 and AASHTO M 320, is not sufficient to fully characterize the properties of modified asphalt binders. In the current PG system, the modification/polymer network is never fully activated at the low stress and strain levels used (Anderson et al., 2010). Therefore, modifiers/polymers evaluated under the current PG system appear to act mainly as fillers that stiffen the asphalt.

The new specification (AASHTO M 332) that uses a multiple stress creep recovery (MSCR) test, described in AASHTO T 350, was successfully used to characterize binder behavior (i.e., both unmodified and modified binders). With the new specification, expected traffic levels are specifically addressed through the J_{nr} requirements, thus avoiding the so-called "grade bumping." In addition, the new specification can be expected to allow optimizing binder formulations to avoid over-engineering and higher costs. Grade bumping refers to the use of a higher grade than is demanded for the climatic conditions to account for slow moving or very heavy traffic. For example, according to the mix design standard, M 323, on a typical freeway in a PG 64 climate with a traffic level in excess of 30 million ESALs, one grade bump would be specified suggesting the use of PG 70 (e.g., B09). The same would be recommended for traffic volumes of greater than 0.3 million ESALs in areas with slow moving traffic (speeds between 20 and 70 km/h) For areas with standing traffic, defined as speeds under 20 km/h, and traffic volumes greater than 0.3 million ESALs, the grade would be bumped a second time increasing the required grade to a PG 76 (e.g., B10). However, based on the MSCR test, it would be still possible to use B09, which is presumably less expensive than B10, for standing traffic.

The new specification was successfully used to grade ground tire rubber (GTR) modified binders, which are currently not allowed for use in Indiana. It should be noted that for all of the GTR modified binders (B04, B05, B13), the difference between the creep compliance values at 3.2 kPa and 0.1 kPa was above

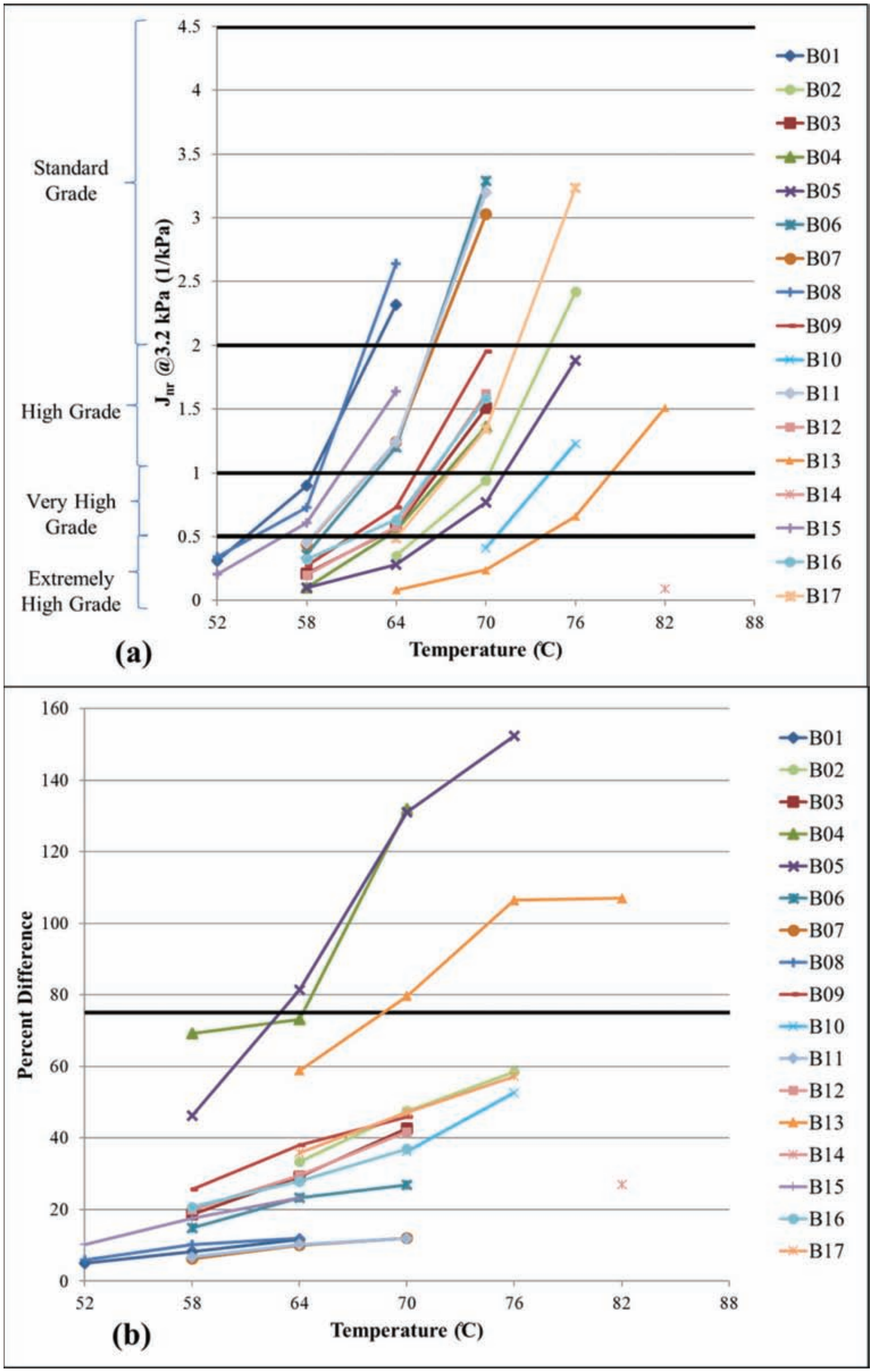

Figure 4.2 Variation of (a) creep compliance at 3.2 kPa with temperature, (b) percent difference with temperature.

the specification criteria (75%) when those asphalt binders were tested at temperatures of 70°C or higher. Therefore, based on the current MSCR specification, the GTR-modified binders tested here would not be appropriate for use at higher temperatures. However, the results showed that at lower temperatures (e.g. 64°C), the GTR-modified binders were successfully graded based on the MSCR system. The advantage of using GTR as a modifier at lower temperatures is that it can help to sustain high traffic loads (i.e., extremely or very

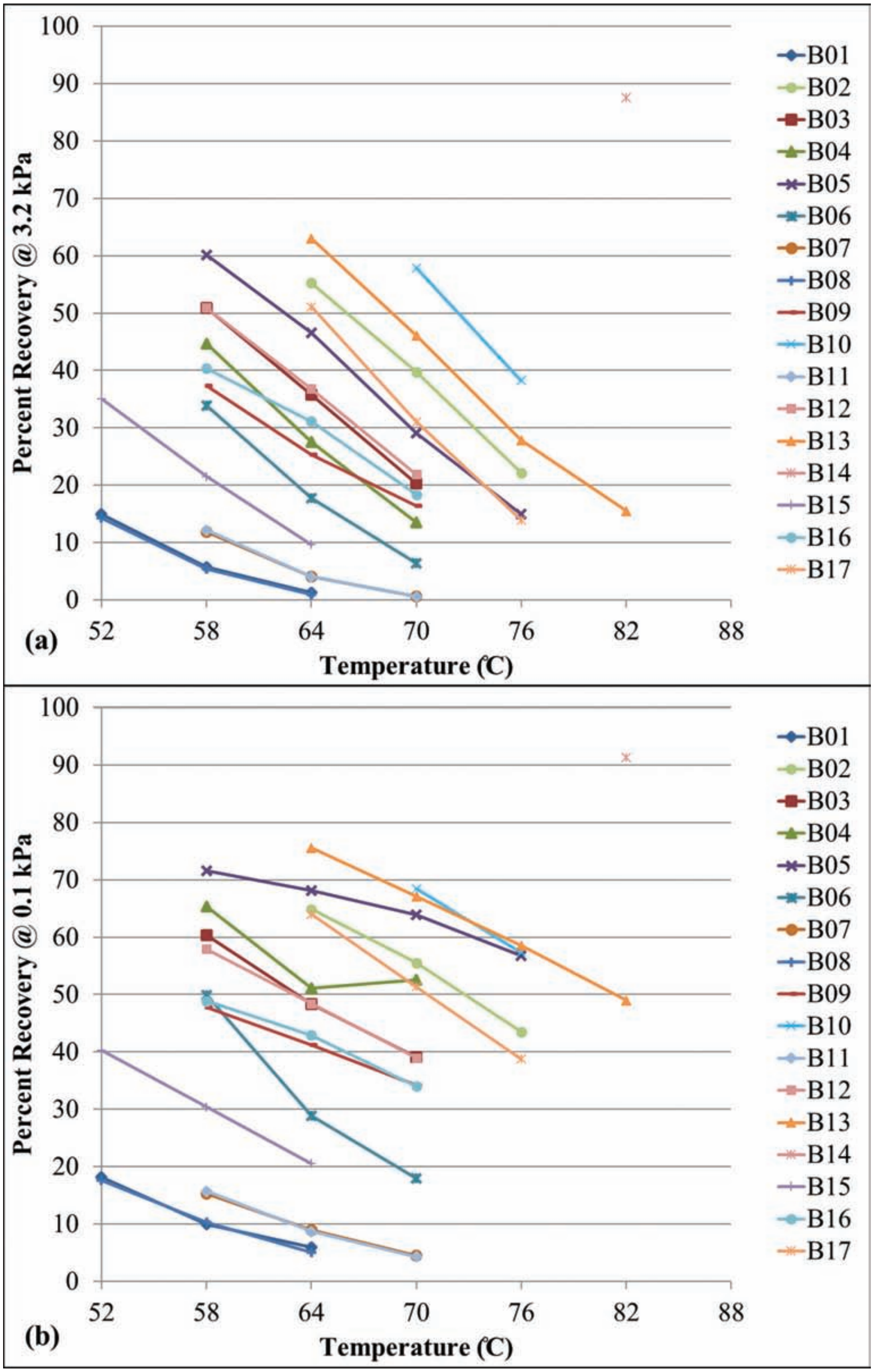

Figure 4.3 Variation in percent recovery at (a) 3.2 kPa and (b) 0.1 kPa.

high grades can be obtained). Since the Indiana climate calls for a PG 64 binder, some of these GTR-modified binders would be appropriate for use in the state and could be suitable for some higher traffic level applications. Reportedly, the Binder Expert Task Group has recommended to AASHTO that the percent difference in J_{nr} be waived for extremely heavy traffic grades; if approved, this change would allow some of these GTR-modified binders to meet the specification at higher temperatures. The percent recovery values do suggest

TABLE 4.7
Summary of the MSCR tests.

Binder ID (Test Temp. (°C))	Average Percent Recovery (%) 0.1 kPa	Average Percent Recovery (%) 3.2 kPa	Average Jnr (1/kPa) 0.1 kPa	Average Jnr (1/kPa) 3.2 kPa	Percent Difference (%)	C.V. of Jnr3.2 (%)	Grade
B01 (52)	17.9860	14.9635	0.2956	0.3106	5.0573	2.6	52E
B01 (58)	9.9428	5.7481	0.8242	0.8930	8.3424	1.9	68H
B01 (64)	5.8953	1.2701	2.0769	2.3174	11.5789	1.3	64S
B02 (64)	64.8910	55.2277	0.2614	0.3487	33.4243	0.0	64E
B02 (70)	55.5462	39.7405	0.6368	0.9397	47.5744	0.0	70V
B02 (76)	43.5333	22.1589	1.5269	2.4198	58.4923	1.8	76S
B03 (58)	57.8819	50.8944	0.1713	0.2032	18.6727	2.8	58E
B03 (64)	48.2813	35.7783	0.4408	0.5699	29.2939	2.5	64V
B03 (70)	39.0579	20.2795	1.0633	1.5158	42.5827	2.8	70H
B04 (58)	65.4013	44.7075	0.1152	0.1948	69.1945	3.0	58E
B04 (64)	51.1590	27.5045	0.3188	0.5518	73.0866	2.3	64V
B04 (70)	52.6025	13.5420	0.6016	1.3605	126.6277	1.5	70H*
B05 (58)	71.6236	60.1383	0.0703	0.1030	46.2510	11.5	58E
B05 (64)	68.0877	46.5915	0.1515	0.2749	81.4319	4.7	64E*
B05 (70)	63.9485	29.0546	0.3322	0.7673	131.0288	2.9	70H*
B05 (76)	56.8277	14.9870	0.7466	1.8836	152.5220	2.2	76H*
B06 (58)	40.8984	33.8199	0.3171	0.3642	14.8276	0.1	58E
B06 (64)	28.8507	17.7815	0.9750	1.2023	23.3027	3.3	64H
B06 (70)	17.9627	6.4076	2.5948	3.2934	26.9206	0.7	70S
B07 (58)	15.2945	11.8667	0.4143	0.4406	6.3396	1.3	58E
B07 (64)	8.9188	4.0249	1.1234	1.2363	10.0517	1.9	64H
B07 (70)	4.5164	0.6269	2.7096	3.0332	11.9582	2.8	70S
B08 (52)	17.6295	14.2552	0.3236	0.3425	5.8490	2.4	52E
B08 (58)	10.3308	5.4239	0.8650	0.9294	10.1491	5.2	58V
B08 (64)	5.0573	0.9510	2.3601	2.6430	11.9891	0.6	64S
B09 (58)	47.7164	37.2800	0.2152	0.2705	25.7141	0.0	58E
B09 (64)	41.1818	25.5639	0.5263	0.7263	38.0040	1.8	64V
B09 (70)	34.1713	16.3989	1.3344	1.9470	45.9170	0.9	70H
B10 (70)	68.4611	57.8893	0.2986	0.4069	36.2773	2.3	70E
B10 (76)	57.3622	38.2301	0.8021	1.2251	52.7310	0.5	76H
B11 (58)	15.6928	12.1608	0.4236	0.4521	6.7458	3.8	58E
B11 (64)	8.6752	4.0642	1.1251	1.2405	10.2556	1.1	64H
B11 (70)	4.2745	0.5625	2.8557	3.1989	12.0178	1.4	70S
B12 (58)	57.9424	51.1592	0.1696	0.2033	19.8747	4.7	58E
B12 (64)	48.4426	36.7856	0.4495	0.5823	29.5402	0.9	64V
B12 (70)	38.9280	21.8595	1.1473	1.6254	41.6730	1.4	70H

TABLE 4.7
(Continued)

Binder ID (Test Temp. (°C))	Average Percent Recovery (%) 0.1 kPa	Average Percent Recovery (%) 3.2 kPa	Average Jnr (1/kPa) 0.1 kPa	Average Jnr (1/kPa) 3.2 kPa	Percent Difference (%)	C.V. of Jnr3.2 (%)	Grade
B13 (64)	75.5344	62.9809	0.0520	0.0826	58.9351	6.1	64E
B13 (70)	67.0900	46.0627	0.1320	0.2372	79.6634	2.1	70E*
B13 (76)	58.5475	27.8168	0.3184	0.6575	106.4667	2.9	76V*
B13 (82)	49.0981	15.2847	0.7237	1.5123	109.0842	0.8	82H*
B14 (82)	91.3212	87.5847	0.0677	0.0857	26.9450	6.8	82E
B15 (52)	40.2849	35.0667	0.1845	0.2034	10.2770	0.47	52E
B15 (58)	30.3883	21.4806	0.5165	0.6067	17.5004	1.84	58V
B15 (64)	20.5313	9.6272	1.3283	1.6386	23.3573	0.70	64H
B16 (58)	48.8534	40.3596	0.2676	0.3232	20.7804	2.22	58E
B16 (64)	42.9171	31.1452	0.4936	0.6313	27.8833	4.23	64V
B16 (70)	33.9889	18.3895	1.1581	1.5858	36.9353	3.28	70H
B17 (64)	63.9975	51.0936	0.3587	0.4876	35.9409	1.91	64E
B17 (70)	51.3336	31.0623	0.9127	1.3436	47.2168	1.30	70H
B17 (76)	38.7826	13.9256	2.0551	3.2318	57.2642	0.93	76S

*Failed percent recovery criterion.
S = Standard grade; H = High grade; V = Very high grade; E = Extremely high grade.

whether a binder contains a polymer modifier or not by comparison to the unmodified base asphalt.

Table 4.10 shows a summary of the designated grades of the binders based on the PG and MSCR systems. The continuous grade (by conventional PG testing) indicates the actual pass/fail points at high and low temperatures. Comparison of the PG and MSCR high temperature grades shows that most of the binders can meet the same high temperature grade at some traffic level; for example, B01 meets a PG 64-22 and a 64S-22. Most of the modified binders would be suitable for Indiana's climate (64) and often meet the requirements for higher traffic levels.

With the GTR modified binders, however, the PG system typically ascribes a higher high temperature grade than the MSCR system; see binders B04, B05 and B13. Nonetheless, at lower temperatures (58 or 64°C) these particular GTR-modified binders would be suitable for high traffic applications. Experiences in several southern US states show that GTR can be used with different base binders for higher temperature climates. For example, B17 was formulated for use in Arizona; it is modified with finely divided rubber (fully digested) plus a polymer. This is the only binder tested where the MSCR grading for standard traffic (PG 76S-28) was higher than the conventional PG grade (PG 70-28). The combination of rubber with a polymer probably accounts for this difference.

TABLE 4.8
The p-values of comparison of 1-mm gap vs. 2-mm gap.

Binder ID	p-Value $\alpha = 0.05$
B01 (52)	0.0524
B01 (58)	0.0531
B01 (64)	0.2442
B02 (64)	0.3286
B02 (70)	0.0652
B02 (76)	0.0996
B03 (64)	0.1220
B03 (70)	0.2344
B04 (58)	0.1206
B04 (64)	0.1148
B04 (70)	0.1858
B05 (58)	0.5506
B05 (64)	0.5840
B05 (70)	0.2266

TABLE 4.9
Summary of the MSCR tests with 2-mm gap.

Binder ID (Test Temp. (°C))	Average Percent Recovery (%)		Jnr (1/kPa)		Percent Difference (%)	C.V. of Jnr3.2 (%)
	0.1 kPa	3.2 kPa	0.1 kPa	3.2 kPa		
B01 (52)	19.5069	16.4662	0.2495	0.2681	7.4394	3.8
B01 (58)	12.7044	7.8128	0.6155	0.6883	11.3109	4.2
B01 (64)	5.3623	0.8477	1.8217	2.0991	15.2674	1.7
B02 (64)	64.8516	55.6297	0.2392	0.3213	34.3411	2.6
B02 (70)	55.5604	39.6168	0.5976	0.9018	50.9195	1.4
B02 (76)	44.6865	22.9605	1.3619	2.3158	62.7297	2.9
B03 (64)	50.6571	38.7640	0.3574	0.5299	31.5033	1.7
B03 (70)	38.2567	21.0611	0.9594	1.3621	41.9148	12.6
B03 (76)	25.9641	6.2915	2.4487	3.7105	51.5515	1.7
B04 (58)	63.5071	46.2020	0.1087	0.1717	58.0512	4.8
B04 (64)	56.8373	28.5860	0.2606	0.4919	88.8374	2.9
B04 (70)	50.2122	14.2923	0.5703	1.3223	131.8604	1.8
B05 (58)	71.1889	60.1001	0.0679	0.0994	46.5330	0.0
B05 (64)	66.6461	45.8598	0.1527	0.2701	76.9474	3.0
B05 (70)	60.5012	28.3239	0.3477	0.7472	114.9300	2.8

TABLE 4.10
Summary of binder grades based on PG and MSCR systems.

Binder ID	Remarks	Continuous Grade	Grade Designation			
			PG System	MSCR System		
B01	PG 64-22, unmodified binder	68-25	PG 64-22	64S-22	58V-22	52E-22
B02	B01+ SBS	76-26	PG 76-22	76S-22	70V-22	64E-22
B03	B01+ SBS+PPA	75-25	PG 70-22	70H-22	64V-22	58E-22
B04	B01+ 12% GTR	80-25	PG 76-22	58E-22	64V-22	
B05	B01+ 12% GTR + Vestenamer	72-25	PG 82-22	58E-22		
B06	PG 70-22	71-24	PG 70-22	70S-22	64H-22	58E-22
B07	PG 70-22	72-22	PG 70-22	70S-22	64H-22	58E-22
B08	PG 64-22	66-26	PG 64-22	64S-22	58V-22	52E-22
B09	PG 70-22	74-26	PG 70-22	70H-22	64V-22	58E-22
B10	PG 76-22	81-23	PG 76-22	76H-22	70E-22	
B11	PG 64H-22	71-21	PG 70-22	70S-22	64H-22	58E-22
B12	PG 64V-22	75-24	PG 70-22	70H-22	64V-22	58E-22
B13	10% GTR HYBRID	88-24	PG 82-22	64E-22		
B14	Highly modified	101-24	PG 82-22	82E-22		
B15	PG 64H-22	68-24	PG 64-22	64H-22	58V-22	52E-22
B16	PG 64V-22	75-25	PG 70-22	70H-22	64V-22	58E-22
B17	PG 70-28	72-29	PG 70-28	76S-28	70H-28	64E-28

NOTE: Blank cells indicate that no more grades were obtained for that particular binder.

5. MIXTURE TESTING PROGRAM

Seven of the seventeen binders that were tested in this study were selected in order to conduct mixture tests. The mixture testing was done in order to explore how well the binder test results reflect the ultimate high temperature mix performance. The procedures conducted on the mixtures containing these binders included:

- Superpave volumetric mix design (AASHTO M 323 and AASHTO R 35)
- Dynamic modulus of hot mix asphalt (AASHTO T 342) at 4°C, 21°C, 37°C, 54°C
- Flow number of hot mix asphalt (AASHTO TP 79) at 51°C

The dynamic modulus test is used to evaluate the stiffness of the mixture at various temperature and frequency (rate of loading) combinations. The flow number test is used to characterize the resistance of a mixture to permanent deformation (rutting).

Binders that were used to conduct the mixture tests included: B01, B02, B03, B05, B07, B15, and B16. As shown in Table 4.1, these binders include unmodified and modified binders; B15 and B16 were formulated to meet the MSCR specification, and B05 contained GTR. Aggregate sources used in this project included:

- #11 Stone, U. S. Aggregate, Delphi, IN
- #12 Stone, U. S. Aggregate, Delphi, IN
- #24 Stone Sand, U. S. Aggregate, Delphi, IN
- #24 Natural Sand, U. S. Aggregate, Swisher, IN
- Baghouse fines

5.1 Testing Protocol

All of the mixtures were designed using the Superpave volumetric mix design, which is the standard in Indiana. The binder content was held constant and the aggregate gradation was adjusted slightly to obtain $4 \pm 0.5\%$ air voids at N_{design} (100 gyration levels). The gradation differences are within normal construction variations.

To complete the dynamic modulus and flow number tests, four to six replicate asphalt mixture samples were prepared for each selected binder. A Superpave Gyratory Compactor (SGC) with 600 kPa pressure and 1.16° internal angle was used to prepare the laboratory specimens in accordance with AASHTO T 312. The asphalt mixture specimens were prepared in such a way (i.e., by adjusting the number of gyrations) that the cored and cut specimens contained $7 \pm 0.5\%$ air content. A water-cooled coring machine with a diamond bit and a masonry saw were used for cutting test specimens and obtaining the required test dimensions of 100 mm in diameter and 150 mm high for both dynamic modulus and flow number tests.

A servo-control testing machine, the Asphalt Mix Performance Tester (AMPT), that produces a controlled sinusoidal (haversine) compressive loading was used to conduct the dynamic modulus tests over a range of frequencies from 0.1 to 25 Hertz at four different temperatures (i.e., 4°C, 21°C, 37°C, and 54°C). The same machine was also used to conduct flow number tests.

The following tests were conducted to determine the properties of the aggregates, which are given in Table 5.1:

- Materials finer than 75 μm by washing (AASHTO T11)
- Specific gravity and absorption of fine aggregate (AASHTO T84)
- Specific gravity and absorption of coarse aggregate (AASHTO T85)

5.2 Mixture Test Results

This section describes the results of asphalt mixtures tests and compares/correlates these results with those of the binder tests.

5.2.1 Superpave Volumetric Mix Design

Table 5.2 shows the job mix formulas (JMF) that were used for different binders/mixtures. It can be seen from this table that the aggregate structures are virtually the same for all of the binders, with minor exceptions.

5.2.2 Dynamic Modulus

Following the dynamic modulus procedure, the absolute value of the complex modulus and the phase angle were measured at the aforementioned temperatures and frequencies. Detailed results are provided in Appendix B, where Tables B1-B7 present the dynamic modulus results for the seven asphalt mixtures. Figure 5.1 shows the master curves fit for the seven asphalt mixtures

TABLE 5.1
Properties of the aggregates that were used to prepare the mixtures.

Property	#24 Nat. Sand	#24 Stone Sand	#11 Stone	#12 Stone
Percentage of material finer than 75 μm, %	2.2	1.3	0.8	0.5
Bulk Specific Gravity	2.613	2.729	2.710	2.691
Bulk Specific Gravity (SSD)	2.646	2.766	2.741	2.727
Apparent Specific Gravity	2.701	2.835	2.796	2.792
Absorption (%)	1.2	1.4	1.1	1.3

TABLE 5.2
Job mix formulas for different binders/mixtures.

	Binder ID						
Particle Size and Volumetrics	**B01**	**B02**	**B03**	**B05**	**B07**	**B15**	**B16**
% passing 12.5 mm	100.0	100.0	100	100.0	100.0	100.0	100.0
% passing 9.5 mm	96.4	96.4	93.4	96.4	96.4	96.4	96.4
% passing 4.75 mm	66.1	66.1	64.7	66.1	66.1	66.1	66.1
% passing 2.36 mm	41.8	41.8	41.8	41.8	41.8	41.8	41.8
% passing 1.18 mm	25.9	25.9	25.9	25.9	25.9	25.9	25.9
% passing 600 µm	16.8	16.8	16.8	16.8	16.8	16.8	16.8
% passing 300 µm	10.1	10.1	10.1	9.6	9.6	10.1	10.1
% passing 150 µm	6.1	6.1	6.1	4.5	4.5	6.1	6.1
% passing 75 µm	3.8	3.8	3.8	3.1	3.1	3.8	3.8
Mix temp. °F	295	315	315	315	295	295	295
Compaction temp. °F	285	295	300	300	285	280	280
% AC	5.8	5.8	5.8	5.8	5.8	5.8	5.8
Gsb	2.692	2.692	2.692	2.692	2.692	2.692	2.692
Gmb @ Ndes	2.422	2.438	2.443	2.417	2.426	2.431	2.437
Gmm @ Ndes	2.537	2.539	2.531	2.524	2.538	2.529	2.536
Gse @ Ndes	2.793	2.795	2.785	2.776	2.794	2.783	2.792
Air voids @ Ndes	4.5	4.0	3.5	4.3	4.4	3.9	3.9
VMA @ Ndes	15.3	14.7	14.5	15.5	15.1	15.0	14.7
VFA @ Ndes	70.2	73.0	76.1	72.5	70.8	74.0	73.5
Pba	1.37	1.39	1.26	1.14	1.38	1.23	1.35
Pbe	4.51	4.49	4.61	4.73	4.50	4.64	4.53
Dust/effective asphalt	0.84	0.85	0.82	0.66	0.69	0.82	0.84

on the usual log-log scale. (The master curves and data tables reflect the average of at least four replicates after removing the outliers.) Figure 5.2 shows the same information by changing the vertical axis to an arithmetic scale to better reflect the differences in the mixtures. These graphs show that at lower temperatures (high stiffnesses) there is some differentiation between the different mixes. It is widely recognized that the binder controls low temperature mixture stiffness. In this case, however, all of these binders meet the same low temperature grade, so large differences in the stiffnesses at lower temperatures would not be expected, all other things being equal. At high temperatures, the mix behavior is controlled by the aggregate structure, which is essentially the same for all the mixtures. One interesting observation is that the asphalt mixture containing GTR-modified binder (B05) had the lowest stiffness at low and intermediate temperatures and highest stiffness at high temperatures.

Analysis of variance was used to explore whether there were significant differences between mixes, and there were. Bonferroni's comparison of means test was then used to determine which mixes were similar and which were different. This test places mixes with similar means into the same group, as shown by the example in Table 5.3 (all of the comparisons are shown in Tables B8-B15 in Appendix B). There are different groupings for all the tested combinations of temperature and frequency, but because of variability in the dynamic modulus data there is substantial overlap between most of the groupings.

The data was further analyzed using two-sample t-tests in some cases. For example, the effect of acid was explored by comparing B02 with SBS to B03 with SBS+PPA. At low and intermediate temperatures the stiffness values of B02 and B03 are statistically different (p-values < 0.05) as shown in Table B16. However, at high temperatures, their stiffnesses are not significantly different (p-values ≥ 0.05), which is as expected since the gradations are similar. Comparing B15, the PG 64H-22, with B16, the PG 64V-22 (Table B17) did not

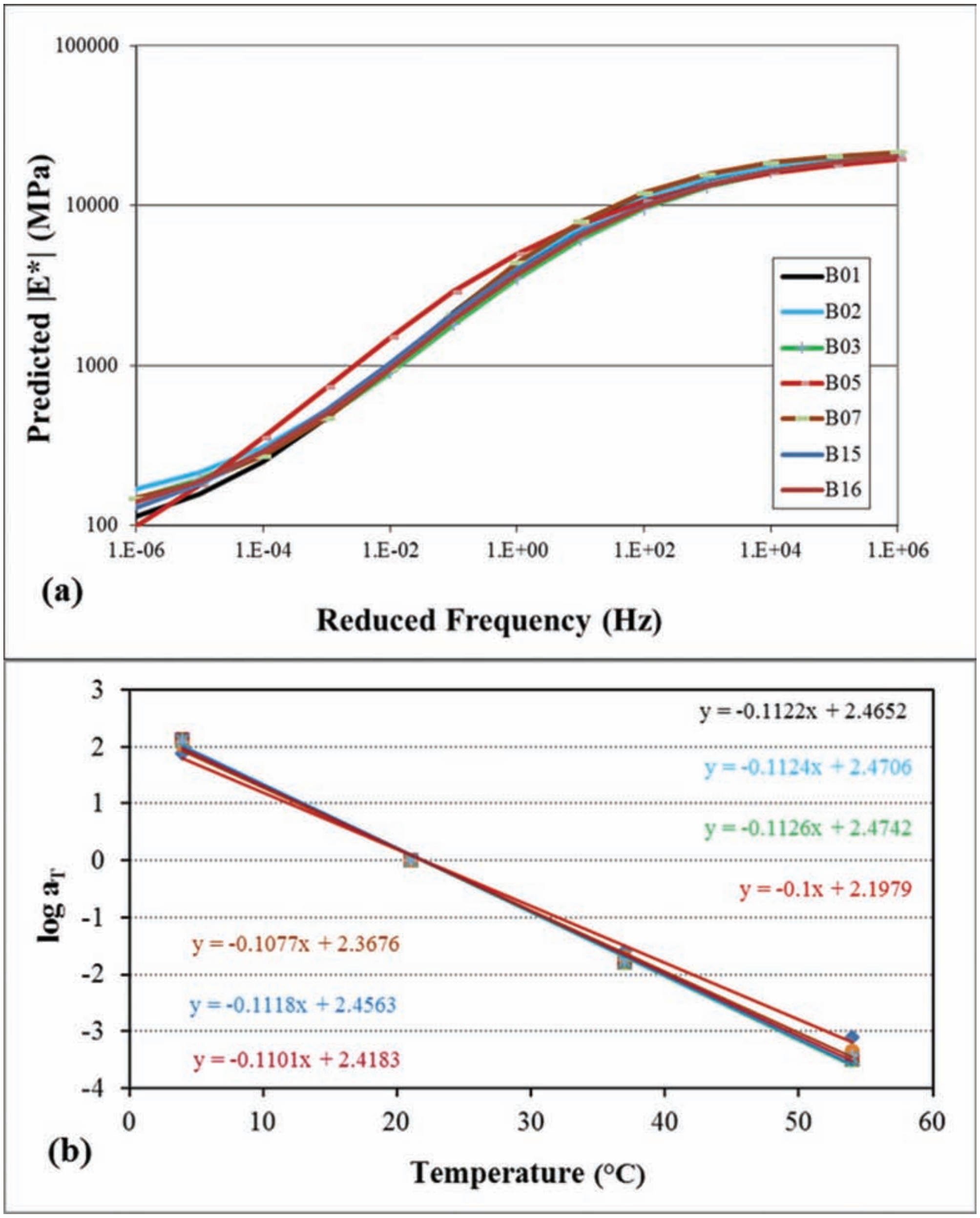

Figure 5.1 (a) Master curve fits for asphalt mixtures made with the selected binders; (b) shift factors used to develop the master curves (T_{ref} = 21°C).

show statistically different results, except at 37°C; the explanation of this behavior is unknown.

5.2.3 Flow Number

Flow number test results (the average of at least four samples) for the selected binders along with the corresponding binder rutting parameters and creep compliances are given in Table 5.4. The variation of flow number test results with respect to binder type (after removing outliers) is shown in Figure 5.3. It can be seen that even after removing the outliers, the variation in flow number tests results of B05, which is modified with GTR and Vestenamer, is still considerable. Figure 5.4 shows the correlation between the binder test results and flow number results. With regard to the binder tests, four values were investigated: PG rutting parameter obtained from original binder, PG rutting parameter obtained from RTFO-aged binder, inverse of creep compliance at 3.2 kPa obtained from RTFO-aged binder, and inverse of creep compliance at 0.1 kPa obtained from RTFO-aged binder. For this comparison, the binder test results at the high climatic temperature of 64°C and the flow number results at an effective temperature for rutting in West Lafayette, Indiana (51°C), which was determined by LTPP Bind software, were used. Correlation between mixture flow number cycles and binder test results reveals that the

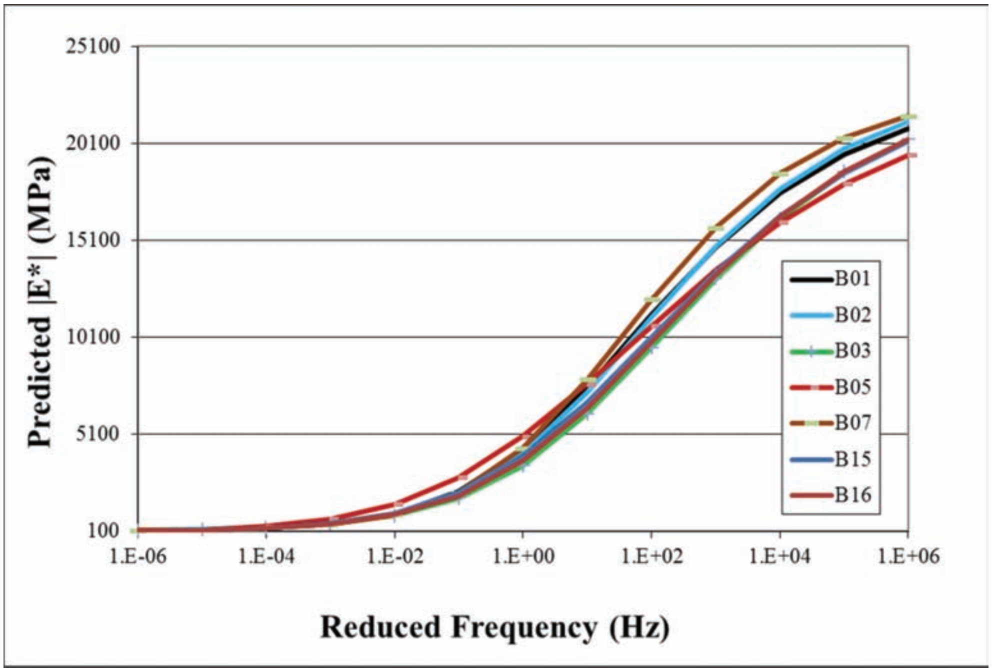

Figure 5.2 Master curve fits for asphalt mixtures made with the selected binders (changing vertical axis to arithmetic scale; same shift factors as Figure 5.1).

TABLE 5.3
Comparison of stiffness values at 4°C and 10 Hz by Bonferroni's comparison of means test.

Binder ID	Reported Grade/ Composition	Mean Stiffness	Bonferroni Grouping		
B07	PG 70-22	15545.5	A		
B01	PG 64-22	14899.4	A	B	
B02	B01 + SBS	14841.0	A	B	
B15	PG 64H-22	13955.8		B	C
B03	B01+SBS+PPA	13580.0			C
B16	PG 64V-22	13547.8			C
B05	B01+GTR+Vest	13020.8			C

flow number test results are better correlated with the MSCR test results than the PG rutting parameter. The best correlation coefficient (i.e., $R^2 = 0.707$) can be observed between flow number cycles and inverse of creep compliance at 3.2 kPa. The low stress level, 0.1 kPa, also provides a better correlation coefficient (i.e., $R^2 = 0.569$) with flow number cycles compared to the correlation of the PG rutting parameter and flow number cycles (i.e., $R^2 = 0.479$). Correlation of the PG of RTFO-aged binders with flow number cycles showed an even lower R^2 value (0.372).

A comparison of dynamic modulus at 51°C, which is the critical temperature for flow number, was also conducted and did not show any difference in the relative ranking of the mixes.

To allow for a better comparison, additional binder testing was conducted on RTFO-aged binder at the non-standard temperature of 51°C; Figure 5.5 shows the correlation between these binder test results and flow number results conducted at the same temperature. Again, it can be seen that the best R^2 values are associated with the correlations between the flow number cycles with the MSCR test results rather than between flow number and the conventional PG rutting parameter.

5.3 Mixture Tests – Summary and Conclusions

Master curves show that the stiffnesses of these particular asphalt mixtures are somewhat similar, especially at high temperatures (low stiffnesses) where the mixture behavior is dependent on the aggregate structure, which is essentially the same for these mixes. At low temperatures (high stiffnesses) where the binder is known to play a greater role in determining the mix behavior, there is some differentiation between the mixes. The differences are moderated somewhat by the fact that all

TABLE 5.4
Average flow number at 51°C with PG rutting parameter and creep compliances at 64°C.

Binder ID	Reported Grade/ Composition	Flow Number (cycles)	1/Jnr @ 3.2kPa (kPa)	1/Jnr @ 0.1kPa (kPa)	|G*|/sin(δ) (kPa)
B01	PG 64-22	238	0.43	0.48	1.59
B02	B01 + SBS	1265	2.86	3.85	3.85
B03	B01+SBS+PPA	816	1.75	2.27	3.14
B05	B01+GTR+Vest	938	3.70	6.67	5.80
B07	PG 70-22	175	0.81	0.89	2.58
B15	PG 64H-22	476	0.61	0.75	1.67
B16	PG 64V-22	449	1.59	2.04	3.00

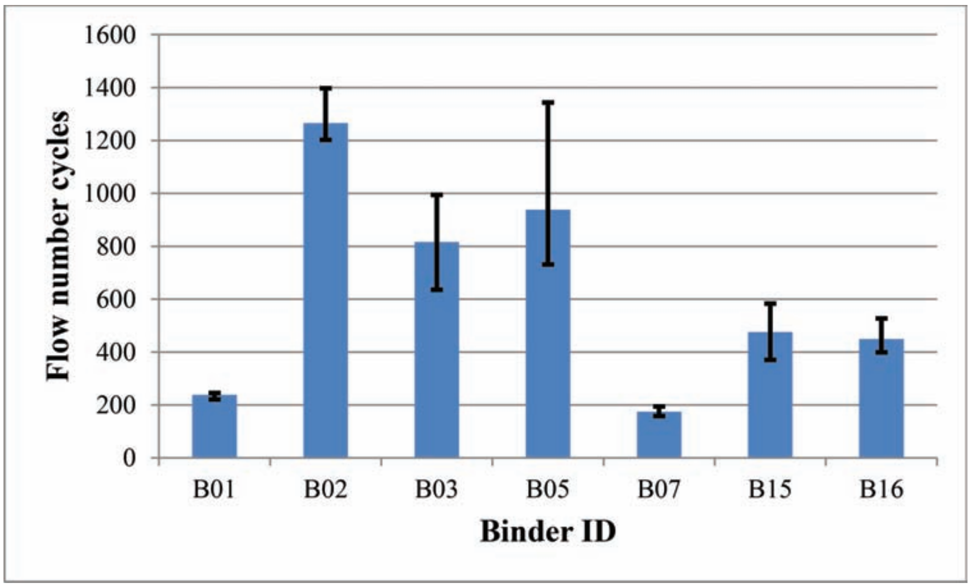

Figure 5.3 Variation of flow number test results with respect to binder type.

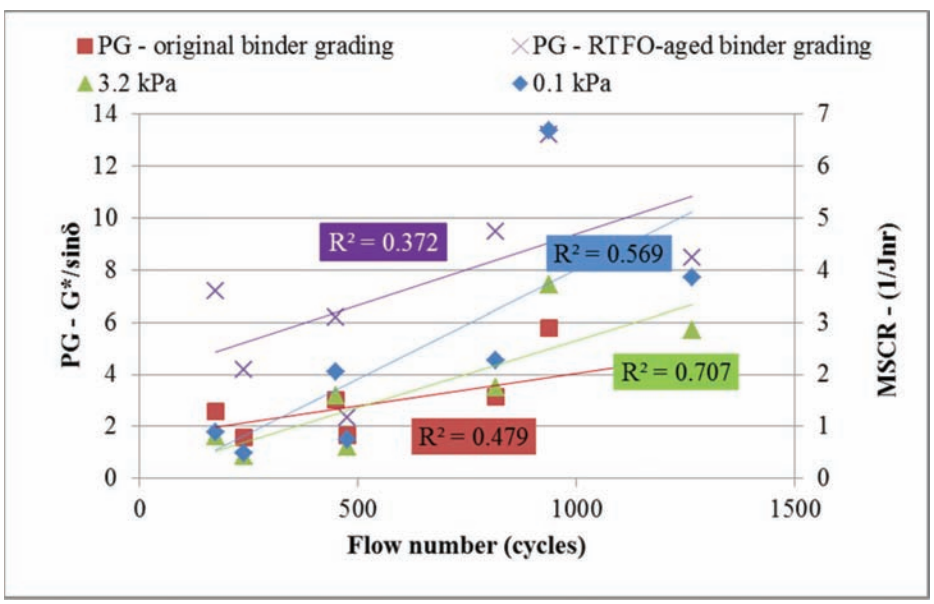

Figure 5.4 Correlation between average flow number at 51°C with PG rutting parameter/creep compliance at 64°C.

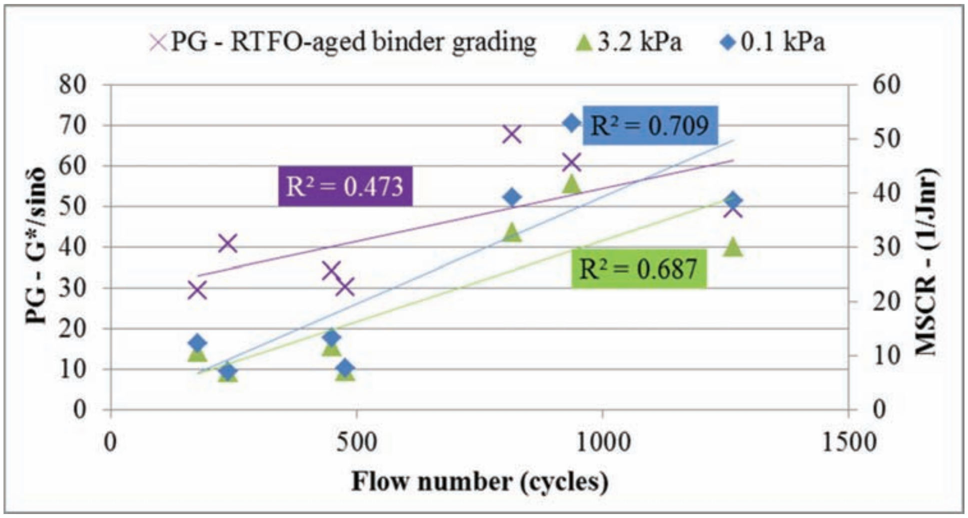

Figure 5.5 Correlation between average flow number at 51°C with PG rutting parameter/creep compliance at 51°C.

of these binders meet the same low temperature grade (as well as similar intermediate temperatures).

In addition to mixture stiffness, it is important to consider the resistance of a mixture to permanent deformation, which can be evaluated with the flow number test. Correlation between mixture flow number cycles and binder test results revealed that the flow number test results were better correlated with the MSCR test results than with the PG rutting parameter. The best correlation coefficient (i.e., R^2 = 0.707) was observed between flow number cycles and inverse of creep compliance at 3.2 kPa. The low stress level, 0.1 kPa, also provided a better correlation coefficient (i.e., R^2 = 0.569) with flow number cycles, compared to the correlation of the PG rutting parameter and flow number cycles (i.e., R^2 = 0.479). Correlation of the PG of RTFO-aged binders with flow number cycles showed even lower R^2 value. Similar findings were observed when the binder tests were conducted at 51°C. However, a limited number of binders were studied to correlate the flow number cycles with binder results. Further studies might be required in terms of the use of different types of unmodified binders and modified binders to strengthen this conclusion.

6. OVERALL SUMMARY AND CONCLUSIONS

This research was conducted to determine if implementing the MSCR test could lead to selecting binders with optimized properties for use in Indiana. To determine if nonrecoverable creep compliance can be utilized as a standard measure of the high-temperature performance of asphalt binders, a statistical analysis of OMM data and experimental research were conducted. The conclusions based on the results of this study are as follows:

1. The MSCR creep compliance and Superpave rutting parameter do not correlate well to each other, especially with regard to modified binders, as shown by a comparison of paired test results on over 2400 binder samples over a six-year period. At higher concentrations of modifiers in the asphalt binders, the coefficient of determination between the creep compliance and rutting parameter decreased drastically. This is due to the fact that these two grading systems capture the viscoelastic behavior of modified asphalt binders differently.
2. The MSCR can be used to test and successfully rank neat, GTR and polymer-modified binders. This means that the MSCR specification (M 332) could be implemented and applied to all binders regardless of modification.
3. The MSCR test grades the binders considering both environmental and traffic conditions. That is, the expected traffic levels do not have to be addressed by so-called "grade bumping" anymore. In addition, the MSCR test is expected to optimize the binder formulation to avoid the use of over-engineered binders.
4. The MSCR test uses two stress levels, which allow studying a wider range of the viscoelastic domain of asphalt binders. In the current PG system, the low stress/strain levels are not sufficient to fully characterize the properties of modified asphalt binders. At these stress/strain levels, the modifier/polymer network is never fully activated. Therefore, modifiers/polymers tested and graded using the current PG system appear to act mainly as fillers that stiffen the asphalt.
5. Correlation between asphalt binder performance with asphalt mixture performance shows that the MSCR provides a better coefficient of correlation at both stress levels with flow number test results than the PG rutting parameter. That is, the MSCR grading would be expected to better reflect ultimate high temperature mixture performance, specifically resistance to rutting. Since the MSCR specification uses the same low temperature test and criteria, no changes in the low temperature mixture behavior would be expected.
6. These results suggest that the Indiana Department of Transportation could implement the MSCR test and have reasonable expectations that binders meeting the needed climatic and traffic conditions would perform well and could possibly be less expensive.

6.1 Recommendations for Implementation

Results of the statistical and experimental approaches that were applied in the current study suggest that the MSCR test provides a better tool than the currently used PG grading system for characterizing high temperature performance properties of commonly used asphalt binders in the state of Indiana. This change can be accommodated by revising Section 902 of the Standard Specifications, along with applicable design guidance. The pay items will also have to be changed to include the new binder grade designations. If AASHTO adopts a waiver of the percent difference requirement for binders meeting E grades for extremely heavy traffic, INDOT could chose to accept this change as well; this may allow additional binders to meet the specifications.

Due to the stress dependent behavior of asphalt binders, however, further research is recommended for some uncommon binders such as rubber-modified binders and how to handle softer grades to be used with high recycled asphalt binder contents. Decisions would also have to be made regarding how to handle solubility with GTR-modified binders, which contain particulate matter that will not meet the solubility requirements.

As one example of how the specification could be implemented, the Florida Department of Transportation (FDOT) specifications were reviewed. FDOT specifies creep compliance and percent recovery on modified binders (higher than PG 67) and only creep compliance on unmodified binders (PG 67 and lower). All binders are tested at 67°C except softer grades used with high recycled contents; PG 58 grades are tested at 58°C and PG 52 grades at 52°C.

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APPENDICES

APPENDIX A: LITERATURE REVIEW

A.1 Background

For many years, asphalt binders used in the paving industry were characterized and graded using empirical methods such as penetration, ductility, and softening point. Empirical tests rely solely on practical experience and observation related to performance of the pavement. Therefore, the test results are only valid for a given set of conditions. Once the conditions change, the results may no longer be the same.

One major problem with these empirical tests is the temperature at which the tests are performed. All of these tests are performed at one or two temperatures that do not cover the range of temperatures that a pavement endures. In addition, there is no widely accepted requirement for asphalt binder stiffness at low temperature to control thermal cracking. Figure A.1 shows three different asphalt binders that all meet the same grade when graded using empirical tests. However, due to the viscoelastic behavior of asphalt binders, differences in their behavior can be seen at temperatures outside the ranges of the empirical tests.

Grading without considering the aging conditions of asphalt binders is another drawback of previous systems. These systems do not account for the long-term asphalt aging which happens due the reaction of asphalt with oxygen in the atmosphere during its service life. Testing under these systems is only performed on unaged and artificially short-term aged binder to simulate construction aging, which adds to the unreliability of these systems.

A.2 Empirical Testing

A brief literature review about the history of empirical testing to grade the asphalt binders is given in this section.

A.2.1 The Penetration Test

A test method called penetration test has been used since the late 1880s when it was introduced by the Barber Asphalt Paving Company (Halstead & Welborn, 1974). In this test, the depth to which a standard needle travels into a tin of binder at a temperature of 25°C in 5 seconds under a load of 100 g is measured in tenths of a millimeter (decimillimeter, dmm), which is called a penetration unit. The test is an indirect measurement of the viscosity of the asphalt binder at 25°C. Typical values for the penetration grade of paving asphalt binders are between 15 to 200 dmm. A lower penetration grade is associated with a harder binder and is more appropriate to be used in warmer regions. Further information regarding penetration grading apparatus and test procedure can be found in AASHTO T 49 and ASTM D5, standard test methods for "Penetration of Bituminous Materials."

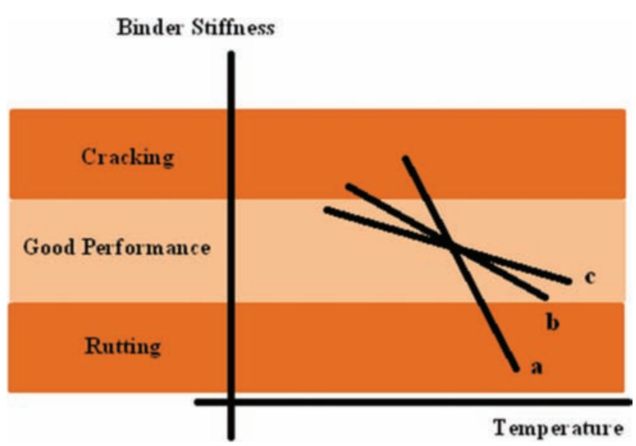

Figure A.1 In-service behavior of asphalt binders graded based on empirical test.

A.2.2 The Softening Point Test

The ring-and-ball softening point is usually conducted to determine the consistency of an asphalt binder by measuring the temperature at which the binder softens enough to flow a set amount. In this test, a standardized steel ball is placed on an asphalt sample contained in a brass ring. A frame holds two samples side-by-side in a water or glycerin bath, and the bath temperature is raised at the rate of 5°C per minute. A water bath is used for an asphalt binder with a softening point of 80°C or lower, whereas glycerin is used for softening points greater than 80°C (Read & Whiteoak, 2003). As the temperature increases, the two disks of asphalt soften until they deform enough to touch a base plate 25 mm below the ring. The mean of the temperatures at which the two disks touch the base plate is reported as the softening point. Typical values for the softening point of paving asphalt range from 35°C and 65°C. Generally, a higher softening temperature corresponds to a harder binder while a lower softening temperature indicates a softer binder (Lesueur, 2009). Standard test methods for softening point test are AASHTO T 53 and ASTM D36: Standard Test Methods for "Softening Point of Bitumen (Ring-and-Ball Apparatus)."

A.2.3 Viscosity Tests

An asphalt grading system based on viscosity was introduced in the early 1960s as a replacement for the penetration test. Viscosity is the resistance of a material to flow and is the ratio of applied shear stress and the resulting strain rate. The viscosity test, then, measures the resistance of asphalt binder to flow, which is related to how the material will behave at given temperatures. Viscosity can be measured either as absolute or kinematic viscosity.

Absolute or dynamic viscosity is measured at 60°C, which is the approximate maximum surface temperature of asphalt pavement. In this test, a specified volume of binder flows through a thin tube under a vacuum and the time it takes to flow is measured. The viscosity is reported in units of Pascal seconds (Pa?s). Further information regarding absolute or dynamic viscosity test procedure can be found in AASHTO T 202 and ASTM D2171: Standard Test Methods for "Viscosity of Asphalts by Vacuum Capillary Viscometer."

Kinematic viscosity of an asphalt binder is the absolute viscosity divided by its density and is reported in units of centistoke (cSt) where 1 centistoke is equal to 1 mm^2/s. The test is conducted at 135°C, which simulates the mixing and laydown temperatures that are typically encountered in Hot Mix Asphalt (HMA) pavement construction. At this high temperature, the binder flows under capillary action without a vacuum. Standard test methods to conduct kinematic viscosity of asphalt binders are AASHTO T 201 and ASTM D2170: Standard Test Methods for "Kinematic Viscosity of Asphalts (Bitumens)."

Compared to the penetration test, viscosity tests have some advantages as follows (Roberts, Kandhal, Brown, Lee, & Kennedy, 1996):

- Viscosity test is a fundamental engineering parameter.
- The tests are conducted at different temperatures including 60°C and 135°C that correlate with typical high pavement temperature and HMA mixing temperature, respectively.
- Viscosity can be a measurement of temperature susceptibility since it is measured at different temperatures.

Although the viscosity test was introduced as an improved grading system to replace the penetration test, it still has some disadvantages. For example, viscosity tests are not able to simulate the behavior of asphalt binder at low temperatures.

TABLE A.1
Superpave binder tests and their purposes.

Superpave Binder Test	Purpose
Dynamic Shear Rheometer (DSR)	Measure properties at high and intermediate temperatures on Original, RTFO- and PAV-aged binders
Rotational Viscometer (RV)	Measure properties at high temperatures for mix production on Original binder
Bending Beam Rheometer (BBR)	Measure properties at low temperatures on RTFO/PAV-aged binder
Direct Tension Tester (DTT)	Measure properties at low temperatures on RTFO/PAV-aged binder (rarely used)
Rolling Thin Film Oven (RTFO)	Simulate aging (hardening) characteristics (short term)
Pressure Aging Vessel (PAV)	Simulate aging (hardening) characteristics after RTFO aging (long term)

A.3 Superpave Binder Property Measurements

In 1993, Superpave, which stands for **Su**perior **Per**forming Asphalt **Pave**ments, was introduced as the main product of the SHRP asphalt research program. Superpave was intended to provide a useful and improved method to specify materials, mix design method and analysis, and in the prediction of pavement performance.

Superpave is a performance-related specification. Under the Superpave binder specifications, the binder properties are measured at typical in-service pavements conditions such as temperature and aging. Based on this grading system, requirements for the physical properties of the binders remain the same; however, the testing temperature changes.

Performance graded (PG) binders are designated PG XX-YY, where XX and YY indicate two numbers. The first number, XX, is the seven-day maximum pavement temperature (°C) measured 20 mm below the surface, often called the "high temperature grade." The high temperature grade indicates the maximum temperature up to which the pavement must perform, with some level of reliability. The second number, YY, is the minimum pavement surface temperature likely to be experienced (°C) and is often called the "low temperature grade." The low temperature grade reflects the minimum temperature at which the pavement is expected to perform, again with some level of reliability. As an example, a PG 64-22 binder is expected to possess adequate physical properties in a region where the average seven-day maximum pavement temperature is 64°C and the minimum pavement temperature that is likely to happen is -22°C.

Physical properties that are measured by Superpave binder tests can be related to in-service performance of the pavements by engineering principles (Roberts et al., 1996). As mentioned previously, the Superpave tests characterize asphalt binder at a wide range of temperatures and ages. Table A.1 shows a summary of these tests.

A.4 Binder Characterization and Tests for Rutting

This section provides detailed information about different methods and protocols that have been proposed to characterize the high temperature properties of asphalt binders.

A.4.1 Superpave Specification Rutting Parameter

Medium to high temperature viscoelastic properties of asphalt binders can be studied using the dynamic shear rheometer (DSR). An asphalt binder's resistance to rutting and fatigue cracking is measured based on its viscous and elastic properties. It needs to be stiff and elastic to resist rutting; and it needs to be flexible and elastic to resist fatigue cracking.

An asphalt binder sample is placed between two circular plates in the DSR. Generally, the upper plate oscillates at 10 rad/sec (1.59 Hz), and the lower plate is fixed, which applies a shear force. The DSR tests are conducted on unaged, rolling thin film oven (RTFO) aged and pressure aging vessel (PAV) aged asphalt binder samples. Further details of the DSR test can be found in AASHTO T 315 "Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer."

As the force (or oscillatory shear stress, τ) is applied to the asphalt held between the upper plate and the lower plate, the DSR measures the response (or shear strain, γ) of the asphalt to the force; this is called a stress-controlled test. In addition to performing stress-controlled tests, some DSRs are capable of doing strain-controlled tests in which shear strain is applied to the asphalt sample and shear stress is measured. Either way, the DSR reports two important parameters to characterize the viscoelastic behavior of asphalt binder. The first one is the complex shear modulus ($|G^*|$) that is simply the ratio of maximum shear stress to the maximum shear strain. The second one is the phase angle (δ), which is the time lag between the applied stress and resulting strain. $|G^*|$ is the ability of the asphalt binder to resist deformation under shear stress, while δ is a measure of the proportions of the overall resistance caused by the viscous response and by the elastic response. Figure A.2 shows how the DSR is used to study the viscoelastic behavior of asphalt by measuring G^* and δ. In the Superpave specification, $|G^*|/\sin\delta$ was introduced as rutting parameter to indicate the high temperature performance of asphalt binders.

The Superpave mix design standard, AASHTO M 323, uses grade bumping to account for high traffic levels or slow speeds. Grade bumping requires a binder with higher temperature for these conditions. For example, on a pavement in a PG 64 climate if there is a high traffic level, the binder grade can be bumped up one grade, which increases the required grade to a PG 70. If there is slow moving traffic, at places such as toll facilities or in urban areas, a second grade bump can be specified suggesting the use of PG 76. The idea behind grade bumping is that a 6°C increase in the temperature will double the stiffness of the binder to resist higher traffic. There are two main assumptions associated with this idea. The first assumption is that rutting is a linear phenomenon. The second assumption is that all binders have similar temperature susceptibility (i.e., all binders behave similarly while the temperature changes). These assumptions are not completely true since asphalt binder is a viscoelastic material that shows nonlinear behavior. In addition, the viscoelastic behavior of asphalt binder is different from binder to binder.

Subsequent research (Anderson & Kennedy, 1993; Bahia et al., 2001; Bouldin, Dongré, & D'Angelo, 2001; Shenoy, 2001; Tabatabaee & Tabatabaee, 2010) has indicated that the Superpave specification rutting parameter is inadequate in reflecting the permanent strain characteristics of certain binders, particularly modified ones. Under NCHRP project 9-10, the relationship between a mixture's accumulated permanent strain and its binder's rutting parameter $|G^*|/\sin\delta$ was found to provide a poor correlation (R^2=23.77%) (Bahia et al., 2001). In that study, the Repeated Shear Constant Height (RSCH) test was performed to obtain the accumulated permanent strain of the mixtures.

A.4.2 Repeated Creep and Recovery Test

The repeated creep and recovery test (RCR) was proposed as a method to separate permanent deformation and delayed elasticity. The RCR test, which was developed under the NCHRP 9-10 project, applies a shear stress in the range of 30 Pa to 300 Pa for 100 cycles at a rate of 1 s loading time followed by a 9 s unloading time (Bahia et al., 2001).

Viscous modulus (G_v) was introduced as a new parameter to characterize the rutting susceptibility of asphalt binders (Bahia et al., 2001). The total shear strain is expressed as:

$$\gamma(t) = \gamma_E + \gamma_{DE} + \gamma_V \quad (A.1)$$

where, for a constant shear stress τ_0:

$$\gamma_E = \frac{\tau_0}{G_0} \quad (A.2)$$

$$\gamma_{DE} = \frac{\tau_0}{G_1}\left(1 - exp\frac{-tG_1}{\eta_1}\right) \quad (A.3)$$

$$\gamma_V = \frac{\tau_0}{\eta_0} t(\text{A.4}) \quad (A.4)$$

Under constant shear stress, the above equations lead to Eq. A5:

$$\gamma(t) = \frac{\tau_0}{G_0} + \frac{\tau_0}{\eta_0} t + \frac{\tau_0}{G_1}\left(1 - exp\frac{-tG_1}{\eta_1}\right) \quad (A.5)$$

where, η_0 and G_0 are viscosity coefficient and instantaneous elastic modulus of the Maxwell's model respectively. η_1 and G_1 are the indicators for viscoelastic properties which are related to the deformations under creep loading. These deformations are not recoverable after removing the load.

The formula of creep compliance can be obtained by dividing both sides of above Eq. A5 by shear stress as follows:

$$J(t) = \frac{1}{G_0} + \frac{t}{\eta_0} + \frac{1}{G_1}\left(1 - exp\frac{-tG_1}{\eta_1}\right) = J_E + J_{DE}(t) + J_V(t) \quad (A.6)$$

in which three terms are superimposed: elastic creep compliance, delayed elastic creep compliance, and viscous creep compliance. The inverse of viscous creep compliance ($J_v(t)$) in Eq. A6 was defined as the viscous component of stiffness (G_v).

The main advantage of the RCR test is that it represents the actual loading on the pavement better than a cyclic reversible loading (Delgadillo, Cho, & Bahia, 2006). Passing traffic applies a repeated loading with a sinusoidal loading pulse in which a part of the pavement deformation is not recoverable. However, some of the deformation is recovered due to elastic energy stored in the material layer. The Superpave rutting parameter $|G^*|/\sin\delta$ does not allow direct evaluation of delayed elasticity. Unlike cyclic oscillation, RCR allows differentiating between recovered and unrecovered deformations (Bahia et al., 2001; Delgadillo, Nam, & Bahia, 2006). In addition, due to the low strain level, $|G^*|/\sin\delta$ is insufficient to represent the resistance of polymer modified binders to rutting. Under this low level of stress and strain, the polymer network is not fully mobilized or activated (Anderson et al., 2010). Therefore, the effect of the polymer in the original PG system is only measured as a filler that stiffens the asphalt.

Although the RCR test provides valuable information about the susceptibility of asphalt binders to rutting, it has been proposed that multiple stress levels need to be used to completely study the stress-dependent behavior of polymer modified binders, which might require an extensive amount of time using the RCR test (D'Angelo, Dongre, & Reinke, 2007). Compared to the strain of the asphalt mixtures, the strain in the asphalt binders in the mixes is much higher (Kose, 2001). This high strain makes binder to exceed its linear viscoelastic domains. Higher localized stress and strain in the asphalt binder compared to the field stress and strain was reported by other researchers as well (Drakos, Roque, & Birgisson, 2001; Lakes, Kose, & Bahia, 2002; Masad et al., 2001). Therefore, the stress levels should be selected such that they capture the properties of asphalt binders in both the linear and non-linear domains.

Bouldin, Dongré, and D'Angelo (2000, 2001) utilized the repeated creep and recovery test for binders (RCRB) that was proposed by (Bahia et al., 2001) to study the resistance of asphalt binders to rutting. In their study, the use of one of the following approaches was suggested:

- The first approach requires measuring the accumulated strain obtained after performing a RCRB test at high specification temperature and appropriate loading rate. The specification criterion is the measured value after N cycles.
- In the second approach a numerical approach is used to develop a phenomenological model using the individual repeated creep. Then, binders are ranked using the curve-fitting parameters obtained from the model based on suggestion of Bahia et al. (2001).
- In the third approach, using the data generated from the conventional frequency sweep tests, a semi-empirical model is developed which fits the RCRB results.

The third approach was later used by Bouldin et al. as it allows to account for the increased influence of the phase angle (δ) on the accumulated strain (Bouldin et al., 2001).

The disadvantage of Bouldin's approach is that at phase angles between 40° and 75°, the parameter may not fully capture the viscoelastic properties of many modified binders (Bouldin et al., 2001).

A.4.3 Other Refinements to the Superpave High Temperature Specification Parameter

Shenoy (2001) suggested another approach to modify the Superpave high temperature specification parameter. Unlike curve-fitting approach, he considered more basic principles and fundamental concepts. He proposed measuring the nonrecoverable compliance through a dynamic oscillatory test using a frequency, time, strain, or sweep test. The Shenoy parameter $|G^*|/1-(1/\tan\delta \sin\delta)$ was suggested as a refinement to the Superpave rutting parameter (Shenoy, 2001). The use of this parameter to values below $\delta = 52°$ was questioned because of predicting unrealistic negative values of $(1-(1/\tan\delta \sin\delta))$. The values of $\delta < 52°$ may be obtained at low or moderate temperatures. For the values between $\delta = 52$ and $90°$, the validity of this parameter would be statistically reasonable for most binders in their high temperature regime. In another study conducted by Shenoy (2004) this performance-based parameter was found to provide a better correlation with rutting and was shown to be more sensitive to the changes in δ than the parameter $|G^*|/\sin\delta$.

In a recent study, Motamed and Bahia studied the influence of test conditions including temperature, stress level, geometry, and loading duration on binder properties measured using the DSR (Motamed & Bahia, 2011). They concluded that the test geometry (parallel plates vs. cone and plate) used in the DSR has significant effects on measured properties, particularly at longer durations of loading or high stress levels. It was found that parallel plates with a 1 mm standard gap may allow the binder to flow, especially when a higher number of cycles is applied. Although decreasing the gap between plates helps to increase the confining stress and mitigate the problem, the use of a cone and plate geometry instead of a conventional parallel plate set is may facilitate studying the true viscoelastic properties of asphalt binder. A homogeneous strain is not maintained throughout the cylindrical asphalt specimen when parallel plates are used (Allen, 1999; Macosko, 1994).

A.4.4 Multiple Stress Creep Recovery (MSCR)

To overcome the limitations of M 320, especially regarding modified binders, the multiple stress creep recovery (MSCR) test method and standard specification have been adopted by AASHTO. The new specification (M 332) uses a multiple stress creep recovery (MSCR) test, described in AASHTO T 350, to characterize binder behavior at high temperatures. The test is

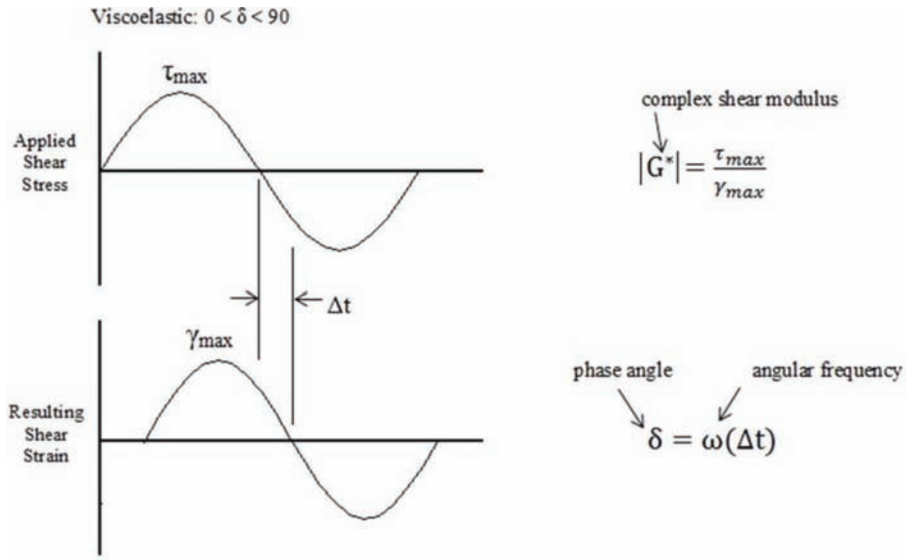

Figure A.2 Computation of |G*| and δ.

expected to more accurately reflect the binder contribution to rutting resistance, especially with modified binders, than the current M 320 standard.

M 332 establishes binder grades and specification limits based on environmental factors (such as PG 64-22 or PG 70-22) as well as design traffic volumes (Standard, Heavy, Very heavy or Extreme), leading to grades such as PG 64S-22, PG 64H-22, etc. The design Equivalent Single Axle Loads (ESALs) and speeds for various grades are shown in Table A.2 as specified in AASHTO M 332. The intent is to replace the current, poorly supported grade bumping for traffic with a more rigorous and technically sound approach to accounting for traffic. Grade bumping is eliminated by reducing the required compliance to provide a more rut-resistance binder.

The MSCR test was proposed as a refinement of the RCR test. The MSCR test procedure uses 1 s creep loading followed by 9 s recovery at zero load for various stress levels; originally stresses of 25, 50, 100, 200, 400, 800, 1600, 3200, 6400, 12800 and 25600 Pa were used, applying ten cycles at each stress level (D'Angelo, 2007). The test wass started at the low stress level and increased to the next stress level at the end of every 10 cycles, with no time lags between cycles. The average non-recoverable strain for the 10 creep and recovery cycles is then divided by the applied stress for those cycles. The obtained value is the nonrecoverable creep compliance J_{nr}, which is intended to replace the current, |G*|/sin δ parameter in M 320, and percent recovery is intended to replace PG+ tests, such as elastic recovery.

Upon correlation between binder permanent deformation and mixture rutting, D'Angelo (2009a,b) selected two stress levels of 100 Pa and 3200 Pa at ten cycles for each stress level instead of the original 11 stress levels. A shear stress of 100 Pa was proposed to study the behavior of asphalt binder in the linear region whereas 3200 Pa is in the nonlinear viscoelastic region for most modified and unmodified binders.

Since the test covers a wide range of stress levels, MSCR has the ability to reflect both the linear and nonlinear viscoelastic properties of asphalt binders. The main advantage of MSCR test is that it is blind to asphalt binder's modification. D'Angelo and Dongre (2009) studied creep and recovery behavior of polymer modified asphalts (PMA) using the MSCR test. Their findings showed that MSCR test results (J_{nr} and percentage recovery) are able to detect the dispersion of styrene-butadiene-styrene (SBS) in PMAs. That is, MSCR is able to discriminate between the dump-and-stir types of PMAs and those that have been optimally dispersed.

Wasage Stastna, and Zanzotto (2011) studied the rheological properties of unmodified and modified asphalt binders using the MSCR test. They reported that for unmodified asphalt binders, the accumulated compliance is a function of time for stress levels up to 10 kPa. With regard to polymer (or rubber) modified asphalt binders, the accumulated compliance is a function of applied stress and time, except for very low stress levels (Wasage et al., 2011). In addition, they studied the correlation between J_{nr} with laboratory wheel tracking test results (Wasage et al., 2011). The best result was obtained when J_{nr} and rut depth were correlated at the high stress levels of the MSCR test.

Although results of the MSCR test are promising, a detailed literature review showed some important concerns about current testing methodology and analysis procedures. Some of these concerns include variability in the test results, stress sensitivity, steady state, percent recovery (R%), and conversion of PG grade shift for traffic (Golalipour, 2011).

A.4.4.1 Variability Although not many DOTs have implemented the MSCR test to date, there is significant interest in the test by most states and a few industry groups. To evaluate the variability of the MSCR test, Golalipour (2011) did a statistical analysis of data collected by the Western Cooperative Testing Group (WCTG). The data used to evaluate the vaiability included the experimental results of six different binders. He reported that the values of J_{nr} vary significantly among binders. Moreover, it was reported that the varibility depends on the stress level (0.1 kPa and 3.2 kPa) and testing temperaure.

Using the same data set, reproducibility analysis of identical binders tested by different laboratories showed a wide range of covariance from 4.1% to 188.2%. Similar statistical analysis done on the tests in the PG system showed a range from 2.2% to 11.5%. Taking these observations into account, (Golalipour, 2011) concluded that operator error cannot be considered as the main cause of high variability of MSCR test results. Therefore, compared to PG system, a wider range of behavior can be expected for asphalt binders based on experimental conditions such as stress level and temperature. This is in line with the findings of Bahia et al. (2011), where it was observed that the variability in the MSCR test results is significantly higher than that observed in PG related results. However, it should be noted that when PG system was initially introduced, the variablity of its related parameters was very high and it reduced over time.

Variability has been found to be more critical for binders that have high delayed elastic recovery and a relatively low J_{nr}, which is typical binder used in cold climates (Golalipour, 2011). Golalipour reported that at higher stress, the response of the asphalt binder shows a dramatic change (Golalipour, 2011). Therefore, in the MSCR standard procedure, taking the average of 10 cycles could be misleading as the response significantly varies by changing the number of cycles. In another study, Motamed et al. (2008) reported that considering only a few cycles could lead to significant errors in ranking binders and mixtures. This phenomenon is known as Mullins effect, which is a softening that occurs in rubber-like materials during the first deformation cycles (Diani, Fayolle, & Gilormini, 2009). Due to the activated polymer network at higher stress levels, it might be expected that PMAs show more significant change in their behavior compared to unmodified asphalts.

To mitigate the problems associated with the varying response, Golalipour suggested calculating the J_{nr} and percent recovery based on the second half of the creep and recovery cycles at each stress level (Golalipour, 2011).

A.4.4.2 Effect of Number of Cycles A sufficient number of cycles is required to reach a desirable steady state (Marasteanu et al., 2005). Bahia et al. (2001) reported that in order to get to a steady state, at least 50 cycles are required. At the high grade tempertures, the rate of strain accumulation becomes constant after 40 to 50 cycles and independent from the level of accumulated starin.

To investigate the effect of number of cycles on asphalt binder behavior, Golalipour (2011) conducted RCR testing for 1000 cycles at three different stress levels: 100 Pa, 3200 Pa and 10000 Pa. It was found that most change occurs before 100 cycles and after that a constant rate of increasing strain can be expected.

With regard to the MSCR tests, Golalipour (2011) examined the following methods to investigate the effect of the number of cycles:

- "Method A - Conducting the tests for 10 cycles of creep and recovery cycles at each of two stress levels of 0.1 kPa and 3.2 kPa, as described in AASHTO TP 70 or ASTM D7075.
- Method B - Conducting the tests for 30 cycles of creep and recovery cycles at each of three stress levels of 0.1 kPa, 3.2 kPa, and 10 kPa.
- Method C - Conducting the tests for 60 cycles of creep and recovery at each of three stress levels of 0.1 kPa, 3.2 kPa, and 10 kPa."

The results of ANOVA analysis indicated the importance of having more cycles, especially at high temperatures (Golalipour, 2011). Moreover, the results of analyzing a four-element Burger model indicated a considerable difference (higher than 10%) between binder behavior in Method A and Method B. However, by comparing Method C with Method B, it was found that due to the consistent response observed for 30 cycles, there is no need to examine further cycles. Therefore, 30 cycles for each stress level was suggested as a good alternative for the current MSCR test. In addition, J_{nr} of mixture results showed better correlation with Method B in comparison with the other two methods. It should be noted that in the case of Method B, the last 10 cycles were used to calculate the average J_{nr}.

A.4.4.3 Effect of Stress Level Selecting the stress level(s) which is (are) representative of field conditions is an integral task to characterize asphalt binder behavior. Stress dependency of the asphalt binders varies for different asphalt binders and appears to be small for unmodified binders. The nonlinear behavior of many unmodified binders makes it necessary to use higher stress levels that are more representative of the stress state between the aggregate particles in the mixture. Some researchers have shown that stress levels higher than 3.2 kPa are required to study the behavior of asphalt binders in the nonlinear region (D'Angelo, 2007; Gardel, Planche, & Dreessen, 2009). Regardless of the stress level, RCR test results show a good correlation with mixture permanent deformation up to 10,000 Pa. Wasage et al. (2011) reported that the applied stress level and the applied temperature considerably affect the boundary of linear viscoelastic behavior. Moreover, the accumulated compliance in PMAs is a function of applied stress. Therefore, it was concluded that performing the MSCR test at the high Superpave temperature and one or two pre-defined stress levels may not be warranted.

Some asphalt binders show nonlinear behavior at relatively higher stress levels (Wasage et al., 2011). In addition, it is hard to determine the distinction between some modified binders at lower stress levels since binders behave similarly. The stress dependencies of PMAs are more complex than neat binders since they have a two phase systems. However, by increasing the the testing stress levels, it gets easier to differentiate and identify the performance of binders. To investigate the effect of stress level, Golalipour (2011) added 10 kPa to the MSCR test as last stress level proceeding 3.2 kPa to the previously mentioned Method B and Method C. It was reported that more pronounced stress sensitivity was observed at higher stress levels. In addition to the stiffening effects of the polymer, delayed elastic effects can also be captured when higher stress levels are applied (Golalipour, 2011). Moreover, higher stress levels show less variability and more repeateble results (Bahia et al., 2011; Golalipour, 2011).

TABLE A.2
Binder selection on the basis of traffic speed and traffic level for the MSCR test (after AASHTO M 332).

Design ESALs[a] (Million)	Traffic Load Rate		
	Standing[b]	Slow[c]	Standard[d]
< 0.3	V	H	S
0.3 to <3	V	H	S
3 to <10	V	H	S
10 to <30	V	H	H
≥ 30	E	V	V

[a]The anticipated project traffic level expected on the design lane over a 20-year period. Regardless of the actual design life of the roadway, determine the design ESALs for 20 years.

[b]where the average traffic speed is less than 20 km/h.

[c]where the average traffic speed ranges from 20 to 70 km/h.

[d]where the average traffic speed is greater than 70 km/h.

NOTE: S, H, V, and E designate **S**tandard, **H**igh, **V**ery High, and **E**xtremely high grade under AASHTO M 332 standard.

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APPENDIX B: DYNAMIC MODULUS TEST RESULTS

TABLE B.1
Dynamic modulus test results for B01 (unmodified PG 64-22).

Condition		Average Measured Modulus (MPa)	Standard Deviation	C.V. (%)	Average Measured Phase Angle (degrees)
Temperature (°C)	Frequency (Hz)				
4	25	16202	483	2.98	11.9
4	10	14899	441	2.96	12.1
4	5	13836	419	3.03	12.8
4	1	10986	470	4.28	15.3
4	0.5	9935	457	4.60	16.8
4	0.1	7760	430	5.54	21.7
21	25	9151	360	3.93	30.4
21	10	8311	508	6.11	33.8
21	5	6701	269	4.01	30.4
21	1	4081	140	3.43	31.3
21	0.5	3357	115	3.41	32.5
21	0.1	2057	156	7.58	34.1
37	25	3473	132	6.36	45.2
37	10	2691	102	6.86	43.1
37	5	2060	74	6.41	37.8
37	1	1157	42	5.67	32.9
37	0.5	928	30	5.20	30.9
37	0.1	628	19	4.02	26.7
54	25	900	71	7.84	41.2
54	10	632	46	7.27	35.3
54	5	500	35	7.00	32.9
54	1	322	18	5.61	25.5
54	0.5	275	14	4.95	22.9
54	0.1	211	10	4.69	18.3

TABLE B.2
Dynamic modulus test results for B02 (B01 + SBS).

Condition		Average Measured Modulus (MPa)	Standard Deviation	C.V. (%)	Average Measured Phase Angle (degrees)
Temperature (°C)	Frequency (Hz)				
4	25	15736	654	4.15	10.8
4	10	14841	529	3.56	12.1
4	5	13682	294	2.15	12.7
4	1	10918	352	3.22	15.1
4	0.5	9895	385	3.89	16.5
4	0.1	7730	260	3.36	21.1
21	25	8745	322	3.68	27.9
21	10	7608	314	4.13	29.0
21	5	6390	246	3.86	28.2
21	1	3984	140	3.51	29.6
21	0.5	3289	118	3.59	30.6
21	0.1	1968	317	16.12	35.0
37	25	3132	118	3.76	39.9
37	10	2405	103	4.29	36.6
37	5	1899	83	4.35	34.1
37	1	1106	31	2.84	31.6
37	0.5	900	24	2.68	30.0
37	0.1	615	13	2.11	26.5
54	25	924	61	6.57	36.7
54	10	696	41	5.89	34.4
54	5	566	25	4.43	30.2
54	1	387	13	3.28	24.2
54	0.5	338	10	2.93	22.0
54	0.1	268	7	2.58	18.7

TABLE B.3
Dynamic modulus test results for B03 (B01 + SBS + PPA).

Condition		Average Measured Modulus (MPa)	Standard Deviation	C.V. (%)	Average Measured Phase Angle (degrees)
Temperature (°C)	Frequency (Hz)				
4	25	14331	395	2.76	12.3
4	10	13580	600	4.42	14.1
4	5	12357	414	3.35	14.2
4	1	9545	395	4.13	16.8
4	0.5	8564	379	4.43	18.4
4	0.1	6630	381	5.74	23.1
21	25	7533	330	4.38	30.4
21	10	6592	313	4.75	31.9
21	5	5385	300	5.57	29.5
21	1	3310	200	6.05	30.2
21	0.5	2729	193	7.08	30.7
21	0.1	1865	84	4.52	29.4
37	25	2919	230	7.89	43.3
37	10	2261	205	9.05	39.5
37	5	1765	168	9.49	35.5
37	1	1032	88	8.57	31.9
37	0.5	841	69	8.15	30.3
37	0.1	583	39	6.67	26.9
54	25	813	162	19.88	47.6
54	10	614	114	18.56	33.7
54	5	509	89	17.41	30.3
54	1	354	44	12.53	24.3
54	0.5	310	34	10.87	22.3
54	0.1	249	20	8.11	18.4

TABLE B.4
Dynamic modulus test results for B05 (B01 + GTR + Vestenamer).

Condition		Average Measured Modulus (MPa)	Standard Deviation	C.V. (%)	Average Measured Phase Angle (degrees)
Temperature (°C)	Frequency (Hz)				
4	25	14110	103	0.73	12.1
4	10	13021	259	1.99	12.7
4	5	11788	235	1.99	12.7
4	1	9482	235	2.48	14.9
4	0.5	8578	244	2.84	16.2
4	0.1	6726	256	3.80	20.2
21	25	7282	279	3.83	26.1
21	10	6463	264	4.09	27.1
21	5	5447	230	4.23	25.8
21	1	3599	188	5.21	27.5
21	0.5	3052	169	5.52	28.4
21	0.1	2200	147	6.69	31.8
37	25	3949	167	4.22	43.7
37	10	3371	135	4.01	42.6
37	5	2667	106	3.98	35.5
37	1	1545	66	4.26	33.3
37	0.5	1254	52	4.13	32.8
37	0.1	839	36	4.25	26.3
54	25	1656	167	10.07	54.1
54	10	1344	149	11.12	41.7
54	5	1055	121	11.47	34.7
54	1	649	56	8.60	30.3
54	0.5	530	43	8.12	28.9
54	0.1	371	29	7.78	26.4

TABLE B.5
Dynamic modulus test results for B07 (PG 70-22).

Condition		Average Measured Modulus (MPa)	Standard Deviation	C.V. (%)	Average Measured Phase Angle (degrees)
Temperature (°C)	Frequency (Hz)				
4	25	16826	200	1.19	10.27
4	10	15545	318	2.04	11.07
4	5	14582	425	2.91	11.76
4	1	11824	414	3.50	14.11
4	0.5	10774	464	4.31	15.49
4	0.1	8542	467	5.59	20.10
21	25	9486	258	2.72	26.52
21	10	8527	214	2.51	28.08
21	5	6993	367	5.25	26.04
21	1	4311	384	8.92	27.31
21	0.5	3451	458	13.29	28.82
21	0.1	2150	408	18.96	31.06
37	25	3179	287	9.02	33.95
37	10	2512	290	11.56	41.08
37	5	1974	271	13.75	35.73
37	1	1114	143	12.85	31.96
37	0.5	903	110	12.22	30.69
37	0.1	567	95	16.73	27.63
54	25	1002	220	21.95	43.77
54	10	713	147	20.59	33.47
54	5	556	108	19.36	29.84
54	1	354	63	17.65	25.39
54	0.5	301	51	16.90	23.49
54	0.1	228	32	13.83	19.48

TABLE B.6
Dynamic modulus test results for B15 (PG 64H-22).

Condition		Average Measured Modulus (MPa)	Standard Deviation	C.V. (%)	Average Measured Phase Angle (degrees)
Temperature (°C)	Frequency (Hz)				
4	25	14937	484	3.24	12.0
4	10	13956	460	3.30	12.7
4	5	12801	472	3.69	13.2
4	1	10124	514	5.08	15.5
4	0.5	9133	492	5.38	16.8
4	0.1	7092	434	6.12	21.1
21	25	8083	121	1.50	26.5
21	10	7086	279	3.93	28.0
21	5	5882	235	4.00	26.5
21	1	3807	202	5.31	28.2
21	0.5	3176	189	5.96	29.2
21	0.1	2143	168	7.86	31.9
37	25	3278	73	2.24	37.2
37	10	2575	133	5.16	36.1
37	5	2018	95	4.70	32.7
37	1	1222	56	4.57	30.4
37	0.5	998	45	4.55	29.1
37	0.1	642	113	17.65	28.8
54	25	990	94	9.50	36.0
54	10	728	75	10.34	34.6
54	5	573	55	9.68	30.7
54	1	377	26	6.98	25.5
54	0.5	321	19	5.88	23.2
54	0.1	244	11	4.38	18.9

TABLE B.7
Dynamic modulus test results for B16 (PG 64V-22).

Condition		Average Measured Modulus (MPa)	Standard Deviation	C.V. (%)	Average Measured Phase Angle (degrees)
Temperature (°C)	Frequency (Hz)				
4	25	14579	322	2.2	12.07
4	10	13548	238	1.8	13.06
4	5	12269	142	1.2	13.54
4	1	9677	308	3.2	16.19
4	0.5	8682	268	3.1	17.65
4	0.1	6691	226	3.4	22.19
21	25	7987	292	3.6	27.48
21	10	6885	375	5.5	28.86
21	5	5713	258	4.5	27.24
21	1	3618	206	5.7	28.87
21	0.5	3006	190	6.3	29.69
21	0.1	2034	152	7.5	32.03
37	25	3016	131	4.4	37.75
37	10	2328	115	4.9	36.33
37	5	1827	109	5.9	32.93
37	1	1104	56	5.0	29.82
37	0.5	910	44	4.8	28.22
37	0.1	594	66	11.1	26.88
54	25	980	137	14.0	26.37
54	10	713	92	12.9	32.79
54	5	570	65	11.4	29.90
54	1	381	35	9.2	24.67
54	0.5	327	24	7.4	22.53
54	0.1	254	11	4.3	18.30

TABLE B.8
Comparison of stiffness values at 4°C and 10 Hz by Bonferroni's test.

Binder ID	Reported Grade/ Composition	Mean Stiffness	Bonferroni Grouping		
B07	PG 70-22	15545.5	A		
B01	PG 64-22	14899.4	A	B	
B02	B01 + SBS	14841.0	A	B	
B15	PG 64H-22	13955.8		B	C
B03	B01+SBS+PPA	13580.0			C
B16	PG 64V-22	13547.8			C
B05	B01+GTR+Vest	13020.8			C

TABLE B.9
Comparison of stiffness values at 4°C and 25 Hz by Bonferroni's test.

Binder ID	Reported Grade/ Composition	Mean Stiffness	Bonferroni Grouping			
B07	PG 70-22	16825.8	A			
B01	PG 64-22	16202.4	A	B		
B02	B01 + SBS	15736.2		B	C	
B15	PG 64H-22	14937.0			C	D
B16	PG 64V-22	14579.4				D
B03	B01+SBS+PPA	14331.2				D
B05	B01+GTR+Vest	14109.8				D

TABLE B.10
Comparison of stiffness values at 21°C and 10 Hz by Bonferroni's test.

Binder ID	Reported Grade/ Composition	Mean Stiffness	Bonferroni Grouping			
B07	PG 70-22	8545.0	A			
B01	PG 64-22	8310.6	A	B		
B02	B01 + SBS	7607.5		B	C	
B15	PG 64H-22	7086.2			C	D
B16	PG 64V-22	6885.4				D
B03	B01+SBS+PPA	6591.8				D
B05	B01+GTR+Vest	6462.5				D

TABLE B.11
Comparison of stiffness values at 21°C and 25 Hz by Bonferroni's test.

Binder ID	Reported Grade/ Composition	Mean Stiffness	Bonferroni Grouping			
B07	PG 70-22	9485.8	A			
B01	PG 64-22	9151.0	A	B		
B02	B01 + SBS	8745.3		B		
B15	PG 64H-22	8083.4			C	
B16	PG 64V-22	7986.8			C	
B03	B01+SBS+PPA	7533.0			C	D
B05	B01+GTR+Vest	7281.8				D

TABLE B.12
Comparison of stiffness values at 37°C and 10 Hz by Bonferroni's test.

Binder ID	Reported Grade/ Composition	Mean Stiffness	Bonferroni Grouping		
B05	B01+GTR+Vest	3275.5	A		
B01	PG 64-22	2691.0		B	
B15	PG 64H-22	2574.8		B	C
B07	PG 70-22	2491.8		B	C
B02	B01 + SBS	2405.2		B	C
B16	PG 64V-22	2328.0		B	C
B03	B01+SBS+PPA	2261.0			C

TABLE B.13
Comparison of stiffness values at 37°C and 25 Hz by Bonferroni's test.

Binder ID	Reported Grade/ Composition	Mean Stiffness	Bonferroni Grouping		
B05	B01+GTR+Vest	3953.5	A		
B01	PG 64-22	3472.5		B	
B15	PG 64H-22	3277.8		B	C
B07	PG 70-22	3179.2		B	C
B02	B01 + SBS	3132.0		B	C
B16	PG 64V-22	3016.4			C
B03	B01+SBS+PPA	2919.2			C

TABLE B.14
Comparison of stiffness values at 54°C and 10 Hz by Bonferroni's test.

Binder ID	Reported Grade/ Composition	Mean Stiffness	Bonferroni Grouping	
B05	B01+GTR+Vest	1343.5	A	
B15	PG 64H-22	727.5		B
B07	PG 70-22	712.8		B
B16	PG 64V-22	712.6		B
B02	B01 + SBS	696.0		B
B01	PG 64-22	632.2		B
B03	B01+SBS+PPA	614.2		B

TABLE B.15
Comparison of stiffness values at 54°C and 25 Hz by Bonferroni's test.

Binder ID	Reported Grade/ Composition	Mean Stiffness	Bonferroni Grouping	
B05	B01+GTR+Vest	1656.0	A	
B07	PG 70-22	1002.2		B
B15	PG 64H-22	989.5		B
B16	PG 64V-22	980.4		B
B02	B01 + SBS	923.7		B
B01	PG 64-22	900.4		B
B03	B01+SBS+PPA	812.8		B

TABLE B.16
Pairwise comparison of stiffness values between B02 and B03.

Temperature (°C)	Frequency (Hz)	p-Value
4	10	0.0066
4	25	0.0026
21	10	0.0008
21	25	0.0004
37	10	0.2066
37	25	0.1142
54	10	0.3996
54	25	0.4306

TABLE B.17
Pairwise comparison of stiffness values between B15 and B16.

Temperature (°C)	Frequency (Hz)	p-Value
4	10	0.1944
4	25	0.8696
21	10	0.3464
21	25	0.4984
37	10	0.0264
37	25	0.0104
54	10	0.7952
54	25	0.6184

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On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,500 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

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