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**CORRELATION BETWEEN MULTIPLE STRESS CREEP RECOVERY (MSCR)
RESULTS AND POLYMER MODIFICATION OF BINDER**

By

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A Thesis

Submitted to the

Department of Civil Engineering

College of Engineering

In partial fulfillment of the requirement

For the degree of

Master of Science in Civil Engineering

at

Rowan University

Feb. 26, 2014

Thesis Chair: Yusuf Mehta, Ph.D., P.E.

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Dedication

I would like to dedicate this manuscript to my family, friends and professors, who have encouraged me and challenged me to be the very best.

Acknowledgements

I would like to express my deepest gratitude to my Thesis Chair, Dr. Yusuf Mehta and Aaron Nolan, for their mentorship and guidance throughout my collegiate academic career. Additionally I must acknowledge the support and assistance from the entire Civil Engineering department, faculty, staff, graduate and undergraduate students.

Abstract

Eric DuBois

CORRELATION BETWEEN MULTIPLE STRESS CREEP RECOVERY (MSCR) RESULTS AND POLYMER MODIFICATION OF BINDER

2012/2013

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Master of Science in Civil Engineering

Nationwide traffic loads are increasing, pushing conventional asphalt to its limit, while in New Jersey matters are made worse by the heavy use of the Northeast Corridor. Polymer modification of asphalt, which can improve both low and high temperature performance, is already available; however, but in many cases traditional Superpave testing is not sensitive enough to quantify the impact of modification, dimensioning its use. Superpave Performance Grade Plus tests, are sensitive to polymer modification but are time intensive and costly, leading the New Jersey Department of Transportation to require styrene-butadiene or styrene-butadiene-styrene to be incorporated in all modified binder to ensure performance, causing supply shortages and rising cost in the state. A relatively new test developed by the Federal Highway Administration, Multiple Stress Creep Compliance (MSCR), offers a simpler procedure using the Dynamic Shear Rheometer (DSR), thus it does not require the expense of purchase additional testing equipment.

The objective of this study is to determine the feasibility of using MSCR as a specification for binder testing. Upon testing a variety of binders it has been determined that MSCR binder testing is sensitive to flow time results. Binders with non-recoverable compliance value (J_{nr}) of less than 0.5 kPa^{-1} appear to show better high temperature performance. The guidelines set forth by AASHTO MP 19-10, in which the binders are graded according to traffic (ESALs) by using J_{nr} is recommended.

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Chapter 1

Introduction

1.1 Background

The use of polymer modified binder has increased as conventional bitumen is pushed to its limits by ever increasing traffic demands. While there are a variety of modifiers, the New Jersey Department of Transportation (NJDOT) currently requires styrene-butadiene or styrene-butadiene-styrene to be incorporated in all modified binder, causing supply shortages and rising cost. The requirement is imposed by the NJDOT to ensure a level of quality because styrene-butadiene and styrene-butadiene-styrene have a proven record of performance and unlike conventional or “neat” binders, which have a standard measure of performance in the Superpave performance grading (PG); modified binders have several tests none of which are widely agreed upon. Superpave has attempted to incorporate elastic recovery (ER) and forced ductility (FD), which, are the most widely used tests for modified binders, in a newer grading scheme, called PG Plus grading, to recognize the benefits of the polymer modification. Unfortunately ER and FD are not very reliable indicators of performance and costly as they both require specialty equipment and are time intensive. The Multiple Stress Creep Compliance (MSCR) test, a new test developed by the Federal Highway Administration (FHWA), offers a simpler procedure that may hold the key to quantitatively rating modified binder for expected performance.

The MSCR test is performed on the Dynamic Shear Rheometer, a device already used for Superpave performance grading, and requires a fraction of the time it would take to run other tests. The MSCR parameter J_{nr} , measures the non-recoverable creep compliance and is determined by dividing the non-recoverable (or permanent) shear strain by the applied shear

stress. To determine if non-recoverable compliance can be utilized as a standard measure of performance of modified binder, testing and analysis will need to be conducted to quantify its sensitivity to mixture performance. If non-recoverable compliance of the binder correlates well with mixture performance this could open the door to the use of a wider variety of modified binders reducing the cost of modified binders, ultimately improve pavement performance by taking advantage of a broad range of polymers.

1.2 Objectives

To verify and qualify the MSCR parameter, non-recoverable compliance J_{nr} , as a standard measure of modified binder performance the following objectives will need to be achieved:

1. Determine from the existing literature the state of practice and the challenges and successes of using polymer and crumb rubber modified binders. This includes types of polymers, test methods to evaluate polymer modified binders; as well as, field and lab performance of mixtures.
2. Conduct traditional Superpave binder tests (AASHTO M 320 Table 1), Superpave PG Plus testing Elastic Recovery and Forced Ductility, to be compared to the non-recoverable creep compliance parameter J_{nr} .
3. Perform performance testing to link the non-recoverable creep compliance parameter J_{nr} to performance.
 - a. Dynamic Complex Modulus (DCM) testing will be conducted to determine the viscoelastic properties of asphalt mixes and will be used as an input for Mechanistic-Empirical Pavement Design Guide (MEPDG) analysis.
 - b. Flow Time testing will be used to determine the Flow Time at which under a constant static load the asphalt sample begins to “flow” or deteriorate quickly.

4. Provide a final recommendation to the state of New Jersey if the non-recoverable creep compliance J_{nr} parameter can be used, with appropriate specification limits.

1.3 Hypothesis

The MSCR parameter J_{nr} is a suitable parameter to predict the performance of polymer modified binders and is thus a suitable parameter to be used by the NJDOT as a standard provision. Upon the NJDOT's acceptance of the J_{nr} parameter, contractors will be able to select from a variety of polymer modified asphalt binders, reducing cost, and SBS shortages, as well as potentially improving pavement quality.

1.4 Research Approach

Task 1. Conduct Literature Review

First a thorough literature review was conducted to access the current state of practice. Polymer modification was defined, as well; the most commonly used modifiers were identified. Current testing methods, including MSCR testing, were reviewed for their prevalence and application. Available lab and field performance was evaluated for pertinent information.

Task 2. Conduct Traditional Superpave Testing

Tradition Superpave lab testing commenced on a host of provided and in house modified binders to determine traditional parameters to later be correlated with chemical properties and Superpave PG Plus parameters.

Task 3. Conduct Superpave PG Plus Testing

Superpave PG Plus testing method, such as Elastic Recovery, and Forced Ductility were conducted. These tests are already used in some states to measure parameters that are more sensitive to polymer modification. These results will be correlated with traditional Superpave test and MSCR tests.

Task 4. Conduct MSCR Testing

The bulk binder testing concluded with MSCR testing for the non-recoverable creep compliance, J_{nr} , and percentage recovery.

Task 5. Correlate Parameters Measured from Binder Testing

The results of all binder testing were analyzed to clearly assess the impact of polymer modification and the correlation between each parameter measured in binder test and non-recoverable compliance (J_{nr}). In addition, non-linear viscoelastic parameters were determined using the creep and recovery curve measured in MSCR.

Task 6. Conduct Mix Performance Testing

Once binder testing was complete, performance testing was conducted on select binders based on their J_{nr} to determine whether low non-recoverable creep compliance of binders will lead to poor high temperature performance of mixtures. Dynamic complex modulus testing was initially considered to evaluate mix performance but ultimately Flow Time testing was conducted as the main parameter to evaluate performance of mix. The higher strains of Flow Time testing, which leads to failure of the test samples, was selected in favor of the low, nondestructive, stresses in which DCM testing is conducted under.

Task 8. Correlate Mix and Binder Test Results

The results of all testing were analyzed to assess the impact of polymer modification and the connection to J_{nr} on high temperature mix performance.

Task 10. Recommendations

Finally, a recommendation for the use of J_{nr} as a design specification was developed. The specification will include recommended ranges of use and a comparison to the current standard.

1.5 Scope of work

The scope of the work is presented below in Table 1, with the test performed, its specification, the property it determines and the number of binders tested. The number of binders tested for each procedure was dependent on the availability of the binder.

Table 1. Scope of Work

Test	Specification	Property
Superpave	AASHTO M320	High temperature true grade
Superpave	AASHTO M320	Low temperature true grade
Elastic Recovery	AASHTO T301	Percent Recovery (%)
Forced Ductility	AASHTO T300	Peak Ratio
MSCR	AASHTO TP 70	J_{nr} (kPa ⁻¹) and Percent Recovery (%)
DCM	T 342	Dynamic Complex Modulus
Flow Time	TP79-11	Flow Time (sec)

1.6 Significance

The direct impact of this study is the creation of a new specification for the use of polymer modified binders that would alleviate the need to perform Elastic Recovery or Force Ductility. The new testing method is less costly and is performed quicker than the previous methods, thus, allowing industry to implement them more readily. The NJDOT can then use the specification to allow contractors the use of a wider variety of polymer modifiers. More variety should alleviate

the supply shortages of SBS and drive down the price of polymer modification. Pavement performance should generally be improved as polymer modification becomes a more affordable option, and is thus made more available.

The cost implications of utilizing MSCR testing over Elastic Recovery can be divided into two categories: expense per test and apparatus expense. The contributing factor to the difference in expense per test is time per test. MSCR testing requires approximately 15 minutes while a single elastic recovery test requires 4 hours from start to finish. It should be noted that although the Elastic Recovery sample must be monitored during the entire testing process there are stages that a lab technician could be performing another task but from experience it can be expected to require approximately half of the 4 hours. MSCR testing is conducted using the Dynamic Shear Rheometer, which is already a commonly used piece of equipment for Superpave testing, while the Elastic Recovery test would require the purchase of a ductilometer, which is priced at about \$15,000. Therefore the savings of eliminating elastic recovery binder testing would be approximately \$500 per binder characterization in addition to the capital cost mentioned earlier.

Chapter 2

LITERATURE REVIEW

2.1 Polymer Modifiers

Bitumen obtained from distillation of crude oil is a flexible material with a density of 1g/cm^3 at room temperature. But at low temperatures it becomes brittle and high temperatures flows like a viscous liquid. The physical, mechanical and rheological properties of the bitumen primarily depend on its colloidal structure, linked to the chemical composition especially to the proportion of asphaltenes and maltenes. Asphaltenes are polar materials of high molecular weight (10,000 to 100,000) that are insoluble in n-heptane, a non-polar solvent, and is the straight chain alkane with chemical formula $\text{H}_3\text{C}(\text{CH}_2)_5\text{CH}_3$ or C_7H_{16} [1] and constitutes 5% to 25% of the bitumen. Maltenes are constituted by resins, aromatic and saturated oils that are soluble in n-heptane and possess low molecular weight. Several polymers (thermoplastics and elastomers) are mixed with bitumen in proportions below 10% to improve the properties of the binder [2] [3]. The polymers used for bitumen modification are divided into two groups, namely elastomers and plastomers. Approximately 75% of modified binders are classified as elastomers, 15% as plastomers and 10% either rubber or miscellaneous modifiers.

Elastomers used in bitumen modification are styrene-butadiene-styrene (SBS), natural rubber, reclaimed tire rubber/crumb rubber, Polybutadiene, Polyisoprene, Isobutene isoprene copolymer, Polychloropren and styrene butadiene rubber (SBR) [4] [5]. In the elastomeric group styrenic block copolymers like SBS have shown the greatest potential when blended with bitumen. The polymers that are classified as plastomers or thermoplastics are Ethyl-vinyl-acetate (EVA), Polyvinyl chloride (PVC), Ethylene propylene (EPDM), Ethylene Acrylate Copolymer and ethylene butyl acrylate (EBA) [5] [6].

2.2 Different Types of Polymers

2.2.1 Styrene Butadiene- Rubber (SBR)

Styrene Butadiene Rubber (SBR) has been widely used as an asphalt modifier as it has been documented: to improve the low-temperature ductility, increase viscosity and elastic recovery; as well as, improves adhesive and cohesive properties of the mixes. The rubber particles are very small and uniform, leading to rapid dispersion and a homogenous mixture. A study by Florida Department of Transportation (DOT) showed that adding SBR increases elasticity, improves adhesion and cohesion, and reduces the rate of oxidation, reducing the effects of aging. Texas DOT found that cement-SBR coated aggregates increased stability when used in HMA. However, it has shown relatively poor tensile strength and poor resistance to cracking [7] [8] [9] [10] [11].

2.2.2 Styrene-Butadiene-Styrene (SBS)

Styrene Butadiene Styrene (SBS) is a tri-block copolymer or a thermoplastic rubber which significantly increases strength at higher temperatures as well as flexibility at lower temperatures [12]. The molecular structure of SBS can be linear or radial. In linear SBS, two polystyrene (PS) blocks are placed at the ends with polybutadiene (PB), an elastomeric block, in the middle. In radial SBS, the molecule of SBS has a star structure with more than three polystyrene blocks. The polar and rigid polystyrene (PS) blocks in SBS make the polymer binder system more resistant to deformation. More polar groups in the polymer provide stronger interactions between the polymer, the asphaltene and the polar aromatic components of asphalt. [13]. Therefore, SBS can improve the mechanical properties and rheological behavior of conventional asphalt compositions as it is provided with a two-phase morphology. The glassy polystyrene (PS) domains are connected together by the rubbery polybutadiene (PB) segments. [14] [15].

The researchers found that the polystyrene end blocks impart the strength to the polymer while the rubbery matrix blocks of polybutadiene gave the material its exceptional viscosity. That means the glassy ST domains of SBS increase the stiffness of asphalt for high temperature use, whereas the rubbery BT midblocks resist thermal cracking at low service temperatures. They also found that maltene, the soluble fraction extracted from the asphalt by n-heptane, interacts preferentially with the polybutadiene unit of SBS whereas asphaltene, the insoluble fraction, interacts predominantly with the polystyrene unit [16] [17]. Viscosity increases with interactions of asphaltene with polystyrene (PS) units of SBS [18] [17] [4].

2.2.3 Elvaloy

Elvaloy is a terpolymer comprising of ethylene, normal butylacrylate and glycidyl methacrylate (GMA). The molecular weight and comonomer levels may vary during manufacturing of polymers. It has an active ingredient, ethylene glycidyl acrylate (EGA) that chemically reacts with asphalt and becomes stable. The modified binder is elastically improved and more resilient. The GMA portion of the molecule is responsible for this reaction. Elvaloy copolymers react with asphalt and form a polymer linked asphalt system with improved performance properties. The epoxide ring in the glycidal structure undergoes an additional reaction with various functional groups in a typical asphaltene molecule. The asphaltenes which can have carboxylic acid functionality open the epoxy ring and form an aromatic ester. Polymers with higher levels of GMA were evaluated in asphalt. These polymers allow the use of fewer polymers to give the same response in high temperatures [5]. The reaction mechanism of Elvaloy with asphaltene is shown in Figure 1 below.

Figure 1. Reaction Mechanism of Elvaloy [5]

2.2.4 Ethylene Vinyl Acetate (EVA)

EVA is a semi crystalline copolymer and is one of the principal plastomers used to improve both the workability of asphalt during construction and its deformation resistance in service [19]. The EVA polymers are classified as plastomers as they modify bitumen by formation of a tough and rigid network to resist deformation. The characteristics of EVA fall between those of low density polyethylene, semi rigid translucent product and those of a transparent rubbery material, like plasticized PVC and certain types of rubbers.

2.2.5 Polyphosphoric Acid (PPA) and Gilsonite

Polyphosphoric acid is a liquid mineral polymer having generic composition $H_{n+2} P_n O_{3n+1}$. PPA has a minimum of two phosphorus atoms and a minimum average molecular weight of 258 [20]. Gilsonite is a resinous hydrocarbon that occurs naturally and could be used as a modifier [20].

2.2.6 Crumb Rubber Modifiers (CRM)

Crumb Rubber Modifiers (CRM), are the product of ground tire rubbers that are then added to asphalt to introduce an environmentally friendly method of recycling tires while improving asphalt performance. CRM has been documented to improve rutting resisting properties as well

as fatigue life. CRM increases the stiffness and elasticity at high service temperatures while at very low service temperatures stiffness is reduced. However, there is no established procedure for proper use of CRM and consequently obtaining an optimum modification of properties is difficult [21]. This difficulty is due in part to the lack of a test sensitive to polymer modifications impact on performance.

2.3 Testing Methods

Polymer modification is a documented method to improve mix performance; however, the current Superpave binder specification (AASHTO M-320, *Specification for Performance Graded Asphalt Binders*) does not adequately ensure that modified binders will perform well in intended applications. As a result, many state DOTs have added additional tests, to complement the Superpave binder specification, in an attempt to ensure that an acceptable modifier is included in the binder. These “Superpave Plus” tests do not relate directly to performance, but only relate to the presence of a particular modifier in the binder [22]. Several state agencies (Figure 2), including New Jersey, have developed a PG “plus” specification that complements the current Superpave specifications to ensure that a preferred binder is selected.

The PG “plus” specifications includes one or more of the following tests 2,3,18:

2. Toughness and Tenacity (ASTM D5801-95R01 Test Method for Toughness and Tenacity of Bituminous Materials) (Used by 10% of state agencies)

4. Force Ductility (ASTM STP 203-19 Force Ductility of Polymer Modified Binder)

6. Multiple Stress Creep Recovery Testing of Asphalt Binders (recently developed by FHWA)

the force ductility test. In a study conducted by the University of Wisconsin, “no correlations could be found to indicate the relevance of the ductility in terms of fatigue or rutting resistance of asphalt” [24]. The MSCR test, a new test, recently developed, could potentially replace many PG-Plus tests as a reliable indicator of performance.

2.3.1 Superpave AASHTO M320

Asphalt binders are required to meet present Superpave binder specifications (AASHTO M-320, 2001). The Superpave Performance Grade (PG) System focuses on climate effects, construction, aging (during construction and in-service), traffic speed, and traffic volume. Justifications for these focuses are that the behavior of asphalt binders depends on temperature, time of loading, and aging. Properties related to pavement performance are based on rheology; the study of flow and deformation. Tests used in PG specifications are Rotational Viscosity (RV) for construction (workability), Dynamic Shear Rheometer (DSR) for rutting and fatigue, and Bending Beam Rheometer (BBR) for thermal cracking. [25]

Three aging levels are used for the PG tests. Original or virgin binders are tested for RV and DSR (for rutting at high temperatures). Rolling Thin Film Oven (RTFO) aged binders are tested for DSR (for fatigue at high temperatures) and BBR. Binders aged in the Pressurized Aging Vessel (PAV) are tested for DSR (for fatigue at intermediate temperatures) and BBR. RTFO is a short term aging method designed to imitate aging undergone by hot mixing and construction. PAV is designed for long term aging resulting from in-service use.

Superpave Performance Grade (PG), AASHTO M-320, specifications used today to categorize asphalt binders are based on unmodified asphalt binders. AASHTO M-320 includes original

DSR, RTFO DSR, PAV DSR, BBR, and RV. Since the introduction of polymer modifiers, AASHTO M-320 has not been able to adequately characterize the performance of modified binders in the field. In response, states have added Superpave Plus tests to ensure the presence of polymer modification. Superpave Plus tests may include Elastic Recovery (ER) ASTM D113-86, Force Ductility AASHTO T-300, and Multiple Stress Creep Recovery (MSCR) which was developed by the FHWA. New Jersey currently uses Elastic Recovery [4].

2.3.2. Multiple Stress Creep Recovery Testing of Asphalt Binders

The Multiple Stress Creep Recovery (MSCR) test, a new test developed by the FHWA, has been shown to be sensitive to polymer modification in many studies, including a University of Massachusetts Dartmouth study that tested a base binder that was then modified, separately, with two different polymers and different proportions. Both MSCR parameters: non-recoverable creep compliance, or J_{nr} , and percentage of elastic recovery improved with the addition of polymer and with the increase of polymer [26]. In the case of many of the other tests, specialized equipment is required, which is often very expensive; however, MSCR testing can be conducted using the same sample and dynamic shear rheometer (DSR) equipment as the AASHTO M320 specification test [27] [28] [29] [30]. This would allow for the new testing method to be integrated into practice fairly seamlessly in comparison to a test that would require the purchasing of more equipment.

The MSCR test is performed using the DSR by applying a controlled shear stress of 0.1 kPa using a haversine load for 1 second followed by a 9-second rest period. During each cycle, the asphalt binder reaches a peak strain, and then recovers before the shear stress is applied again. Figure 3 is a typical plot of the first 10 cycles. The difference between the peak strain and the

final strain is divided by the peak strain to get the percentage of elastic recovery for each cycle, calculated in Equations 1 and 2. Ten creep-recovery cycles are used, at 0.1 kPa shear stress, and the average elastic recovery is determined. Immediately after ten cycles are completed at shear stress value of 0.1 kPa, the testing continues with an additional ten creep-recovery cycles, using a shear stress value of 3.2 kPa. The average creep recovery is calculated from Equations 3 and 4 and non-recoverable creep compliance is calculated using Equations 5-8.

Figure 3. Typical plot of the First 10 Cycles of MSCR Testing [31]

Equation 1 $\epsilon_r (0.1, N) = \frac{(\epsilon_1 - \epsilon_{10}) * 100}{\epsilon_1}$ for N= 1 to 10

Equation 2 $\epsilon_r (3.2, N) = \frac{(\epsilon_1 - \epsilon_{10}) * 100}{\epsilon_1}$ for N= 11 to 20

Equation 3 $R_{0.1} = \frac{SUM(\epsilon_r(0.1, N))}{10}$ for N=1 to 10

Equation 4 $R_{3.2} = \frac{SUM(\epsilon_r(3.2, N))}{10}$ for N=11 to 20

Equation 5 $J_{nr}(0.1, N) = \frac{\epsilon_{10}}{0.1}$

Equation 6 $J_{nr}(3.2, N) = \frac{\epsilon_{10}}{3.2}$

Equation 7 $J_{nr0.1} = \frac{SUM(J_{nr}(0.1, N))}{10}$ for N = 1 to 10

Equation 8 $J_{nr3.2} = \frac{SUM(J_{nr}(3.2, N))}{10}$ for N = 11 to 20

The high temperature specification parameter in Table 1 of AASHTO M320— $G^*/\sin \delta$ —has been shown to relate poorly to rutting for many “premium grade” modified asphalt binders. This has led to the development of the multiple stress creep-recovery (MSCR) test as a potential replacement for the conventional $G^*/\sin(\delta)$ test in the specification. From the MSCR test, the new high temperature specification parameter is determined by dividing the non-recoverable (or permanent) shear strain by the applied shear stress, calculated from Equation 5 and 6 for each stress level and an average of the stress level for Equations 7 and 8. The result is called the non-recoverable creep compliance, or J_{nr} . The binder can then be graded with J_{nr} , falling into traffic levels that are broken into ranges of equivalent single axle loads (ESALs), Table 2. For example a binder tested at 64°C and 3.2 kPa with a resulting J_{nr} of 0.75 kPa^{-1} would be graded as a PG64H capable of 10 million or greater ESALs. This grading process elevates the need to temperature bump binders when heavy traffic is expected, which is the case under the current standards, instead J_{nr} make the distinction based on expected performance.

Table 2. Traffic Grading according to J_{nr}

J_{nr} (3.2kPa)	Temperature	Traffic	ESALs
≤ 4.0	64	Standard	<10 million
≤ 2.0	64	Heavy	10-30 million
≤ 1.0	64	Very Heavy	>30 million
≤ 0.5	64	Extremely Heavy	>30 million Standing traffic

While the MSCR test (AASHTO TP70) can be used to generate the J_{nr} value, it can also be used to determine the elasticity of the asphalt binder by measuring the recovery percentage from peak loading. In this, the test operates similarly to other PG-Plus tests, such as the Elastic Recovery test (AASHTO T301), in ensuring the degree of elasticity response due to polymer modification in an asphalt binder. Research conducted by the Federal Highway Administration has correlated J_{nr} and recovery values from the MSCR test for many modified asphalt binders. Based on this data, minimum recovery values can be specified for certain values of J_{nr} . Asphalt binders that fall below the curve in Figure 4 are considered to have low elasticity; those that are above the curve are considered to have high elasticity.

Figure 4. Percentage recovery versus J_{nr} [31]

The high temperature binder specification parameter from the MSCR test is J_{nr} . If the asphalt binder meets the appropriate J_{nr} specification, then it should be expected that it will minimize its contribution to rutting. In addition, if the user agency wants to verify the presence of a polymer and/or evaluate the elasticity of the binder adding the appropriate MSCR recovery value as a minimum requirement is an option [18]. However, the appropriate specification limits and test reproducibility needs to be evaluated.

2.3.2 Elastic Recovery

This test is performed by pulling a binder briquette specimen a rate of 5 cm/min with a ductilometer. Upon reaching 20 cm the sample is no longer elongated and after five minutes the sample is severed. The sample then remains in the ductilometer for one hour, to allow the sample to retract. The elongated sample is finally measured by releasing the ductilometer and matching the severed ends so that they just touch. In addition to a lengthy testing procedure the preparation of the binder specimen requires at least two and a half hours, to pour, trim and equilibrate the sample to the ductilometer bath.

Elastic recovery (ER) is the degree to which a substance recovers to its original shape after release of stress. A certain degree of ER is desirable in pavement to avoid permanent deformation. The ER is measured with an instrument called a ductilometer. ER is used to test the polymer modified binders by different departments of transportation. Most recently, the test is typically being performed at 25°C on RTFO aged material at 5 cm/min to 20 cm. A state agency will allow a modified binder if it produces an elastic recovery greater than an agency specified percentage.

2.3.3 Forced Ductility

The Force Ductility test, AASHTO T-300, measures the tensile properties of polymer modified asphalt binders. During testing, a specimen is elongated at a constant rate of 2 in/min to produce a load versus time relationship which is converted to a load versus displacement relationship [34]. Using this data, the peak ratio and area under the force displacement curve can be calculated. Peak ratio is the ratio of the force of the second peak and the initial peak. The initial peak is the first high peak and the second peak is the first succeeding lower peak as shown in Figure 5.

Figure 5. Typical Forced Ductility Data Plot

2.3.4 Dynamic Complex Modulus (DCM)

The new AASHTO Mechanistic-Empirical (M-E) Design Guide uses the dynamic complex modulus as the primary test protocol to characterize the modulus response of hot mix asphalt.

Dynamic complex modulus or E^* is the ratio of stress to strain under dynamic conditions, refer to Equation 13.

Equation 9 $|E^*| = \frac{\sigma}{\varepsilon}$

Where σ = the amplitude of stress

ε = the amplitude of strain

The test was conducted at three temperatures 4, 20, and 40 °C, as well as multiple frequencies ranging from 0.1 to 10 Hz. Subsequently, a master curve was developed using the procedure in AASHTO PP-62, [39] developed to extrapolate more data points.

2.3.5 Mechanistic Empirical Pavement Design Guide (MEPDG)

MEPDG software evaluates the major flexible pavement distresses, permanent deformation (rutting), and fatigue cracking (alligator and longitudinal cracking). The software uses traffic data, climatic data, the structure of the pavement, and asphalt layer properties to predict performance [40]. For the asphalt layer properties data, MEPDG has three levels of inputs with level 3 using default values for Performance Grades, level 2 using some binder properties and level 1 using dynamic complex modulus test results and binder information [40] .

2.3.6 Flow Time

The mixtures described previously were tested in accordance with AASHTO TP79-11 Standard Method of Test for Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT). Flow time is a quick and simple measurement of the resistance of AC mixtures to permanent deformation for rutting evaluation. MSCR testing was conducted in accordance with AASHTO TP70-12 to determine the J_{nr} parameter.

During this uniaxial static creep test, the specimen is subjected to a constant compressive load of 600 KPa (30 psi) at a test temperature of 52.5°C (130°F). For this study, the test was performed without confining pressure. While MSCR testing uses standard values during testing, the temperature of 52.5°C (130°F) for flow time testing was selected to match conditions in New Jersey. Flow time was conducted for 10,000 seconds or until the sample failed due to cracking initiation. The resulting axial strain is measured as a function of time and numerically differentiated to calculate the flow time which is defined as the time corresponding to the minimum rate of change of axial strain. The flow time is found by fitting the axial strain model (Equation 14) to the axial strain data using nonlinear least squares, then determining the inflection point (flow time) from the second derivative of the model (Equation 15).

Equation 10 $\varepsilon = At^B - C(e^{Dt} - 1)$

Equation 11 $\frac{d^2\varepsilon}{dt^2} = AB(B-1)t^{B-2}CD^2e^{Dt}$

Where:

ε = axial strain, microstrains

t = time, seconds

A, B, C, and D = fitting coefficients

The total compliance at any given time, D(t), is calculated as the ratio of the measured strain (ε_t) to the applied stress σ_0 (Equation 16).

Equation 12 $D(t) = \frac{\varepsilon_t}{\sigma_0}$

Tests in the AMPT were conducted on 100 mm (4 in) diameter by 150 mm (6 in) high test specimens that are cored and cut from larger 150 mm (6 in) diameter by 170±mm (6.75 in) high gyratory specimens prepared in a Superpave gyratory compactor to target 7% air voids. Specimens are prepared according to AASHTO PP 60 *Provisional Standard Practice for*

Preparation of Cylindrical Performance Test Specimens Using the Superpave Gyratory Compactor (SGC) (FHWA 2013). Figure 6 shows a typical result of the flow time test. The plot is divided into three basic regions or stages of deformation: primary, secondary, and tertiary. The primary region is where the strain rate decreases sharply and is associated with a densification type of permanent deformation. This behavior continues until the mixture reaches an optimum density level that is followed by the secondary region of the curve where the strain rate remains almost constant under the applied static load. As loading continues within the secondary region, densification will continue until a point is reached where the mixture becomes unstable and significant deformation occurs reaching the tertiary region. The time corresponding to the start of the tertiary zone is referred to as the flow time. Flow time can therefore be considered as the time when the rate of change of compliance is the lowest. The slope represents the rate of change in permanent deformation as a function of the change in loading time. High flow times and low slopes are desired properties for rutting resistant mixtures.

Figure 6. Typical Flow Time Test Results

2.4 Laboratory Performance of Modified Binders

Laboratory evaluation of the modified bitumen containing styrene-ethylene-butylene-styrene (SEBS), ethylene vinyl acetate (EVA) and ethylene butyl acrylate (EBA) copolymers [7] [8] [4] indicated that the morphology and storage stability of the modified binders were largely dependent on the polymer content and were influenced by the characteristics of the base bitumen and the polymers. At a low polymer content (3% by weight), the modified binders showed dispersed polymer particles in a continuous bitumen matrix [7] [8] [4] [41]. At a sufficiently high polymer content (6% by weight), a continuous polymer phase was observed. Regardless of the nature of the two phases, the storage stability of the modified binders decreased as polymer content increased.

Polymer modification improved bitumen rheological properties such as increased elastic responses at high temperatures and reduced creep stiffness at low temperatures. The degree of improvement generally increased with polymer content, but varied with bitumen source/grade and polymer type [41] [42] [43]. Polymer modification also influenced bitumen aging properties. Evaluation of aging effects was dependent on testing conditions (e.g. temperature and frequency).

The source of asphalt and polymer significantly impacts the dispersion properties of SBS particles [42]. If there are two, interlocked continuous polymer phases, rather than one continuous polymer phase, this will lead to a more homogenous mixture; leading to higher stiffness and hence lower rutting resistance.

The NJDOT currently requires the use of SB or SBS formulations for all polymer modified binders to ensure mix performance due to the lack of a standardized test to determine the expected performance of other polymers. By Requiring SB or SBS for all polymer modified binders the NJDOT is effectively limiting the use of other polymers and creating supply shortages of SB and SBS, thus increasing the cost of polymer modified binders. This has created the need to develop/identify a test method to evaluate the performance of polymer modified binders.

2.5 Field Performance of Modified Binders

In a study by Sirin et al, 2008, the researchers evaluated the rutting performance of a typical Superpave mixture, PG67-22 used in Florida and the same mixture modified with SBS polymer. FDOT's heavy vehicle simulator (HVS) was used to evaluate the long term performance of these Superpave mixtures and SBS modified Superpave mixtures with emphasis on rutting resistance. This HVS simulates 20 years of interstate traffic on a test pavement within a short period of time. There were a total of 15 test sections as shown in Figure 7. The testing program is divided into two phases. Phase I testing was conducted on five test sections, 1C-5C, at ambient conditions. Phase II was conducted on the other ten test sections with temperature control. In Phase II, lanes 1 & 2 have two 5 cm lifts of SBS modified Superpave mixture and were tested at controlled pavement temperatures of 50 and 65°C. All the other sections in Phase II were tested at only one temperature i.e., 50°C. The results from the Heavy Vehicle Simulator showed that the pavement sections with two 5-cm lifts of SBS modified mixture outperformed the two 5 cm lifts of unmodified mixture which had two to two and half times the rut rate. From the changes in thickness and density of the cores from the test sections they concluded that the rutting of the unmodified mixtures was due to combination of densification and shoving while the rutting of SBS modified mixtures is primarily due to densification. [54]

Figure 7. HVS Testing Sequence (Plan View) [54]

2.6 Summary of Literature Review

- Styrene Butadiene Rubber (SBR) improves the low-temperature ductility, increase viscosity and elastic recovery; as well as, improves adhesive and cohesive properties of the mixes.

- Styrene Butadiene Styrene (SBS) significantly increases strength at higher temperatures as well as flexibility at lower temperatures
- There are varieties of other modifiers that show improvements: Elvaloy, Ethylene Vinyl Acetate (EVA), Polyphosphoric Acid (PPA) and Crumb Rubber Modifiers (CRM).
- Superpave binder specifications are not sensitive enough to polymer modification
 - not adequately ensure that modified binders will perform well in intended applications
- New tests have been developed to be sensitive to polymer modification, including: Elastic Recovery (ER), Forced Ductility (FD) and Multiple Stress Creep Recovery (MSCR)
- MSCR testing is simpler and quicker to perform than its counterparts ER and FD.
 - Performed using the Dynamic Shear Rheometer (DSR) with 1 second of controlled shear stress and then 9 seconds of recovery.
 - The first 10 cycles (cycles 1-10) are run again at 0.1 kPa and represent the results for 0.1 kPa
 - The next 10 cycles (cycles 11-20) are run at 3.2 kPa
 - The test results are J_{nr} , the non-recoverable creep compliance and average creep recovery for each stress condition
- Elastic Recovery measures the percentage recovery of a stretched asphalt sample
- Forced Ductility measures the load the resulting of the stretching of an asphalt at a constant rate, with the resulting parameters:
 - Peak Ratio- is the ratio from the first load peak to the second load peak
 - Area under the force displacement curve
- Dynamic Complex Modulus (DCM) testing is a performance test performed at a range of temperatures and frequencies that can be used to develop a master curve of the visco-elastic properties
 - The master curve can be extrapolated to determine properties outside the original testing
- The Mechanistic Empirical Pavement Design Guide(MEPDG) is a software that uses the results of DCM testing in conjunction with site and environmental conditions to predict pavement performance
- Flow Time testing is a lab performance test for rutting
 - The asphalt mix is compacted and tested under a constant load
 - “Flow Time” is achieved, after the primary and secondary phases, when the mix becomes unstable with significantly deformation occurring rapidly
- The results from the Heavy Vehicle Simulator showed that the pavement sections with two 5-cm lifts of SBS modified mixture outperformed the two 5 cm lifts of unmodified mixture which had two to two and half times the rut rate.

Chapter 3

EXPERIMENTAL DESIGN

The experimental design is categorized into three components: Mechanical Binder Testing, Chemical Binder Testing and Mix Performance Testing. Table 3 is the test matrix for the entire project, encompassing each component, it includes: specification followed, property measured, and the number of binders tested.

Table 3. Test Matrix

Test	Specification	Property	Number of binders and mixes tested
Superpave	AASHTO M320	High temperature true grade	39
Superpave	AASHTO M320	Low temperature true grade	16
Elastic Recovery	AASHTO T301	Percent Recovery (%)	31
Forced Ductility	AASHTO T300	Peak Ratio	20
MSCR	AASHTO TP 70	J_{nr} (kPa ⁻¹) and Percent Recovery (%)	34
DCM	T342	Dynamic Complex Modulus	3
Flow Time	TP79-11	Flow Time (sec)	10

3.1 Mechanical Binder Testing

A binder study was initiated to better understand the relationship between polymer, type and concentration amongst the Superpave, MSCR, Elastic Recovery (ER), and Forced Ductility (FD) testing. In-House modified binder was used to examine the impact of concentration of modification on testing; while plant produced modified binders were also examined for the impact of different modifiers on testing. The binders tested along with identifiers to be used throughout the paper are listed in Table 4. The table also includes the source, either a plant or in-house mix, and the PG grade of the binder.

Table 4. Binder Identifier

Binder Identifier	Binder	Source	PG High Temperature Grade
1	NS 82-22	NuStar	82
2	NS 82-22 Tank 73	NuStar	82
3	NS 76-22	NuStar	76
4	NS 76-22 Tank 1007	NuStar	76
5	Road Science 76-28	Road Science	76
6	76-28 Rat 295	NJDOT	76
7	CRM V=2900	NJDOT	94
8	CRM V=3200	NJDOT	94
9	Valero 937	Valero	64
10	NS 64-22	NuStar	64
11	Valero 937, 1.5% K	In-House	64
12	NS 64-22, 1.5% E, 0.8% PPA	In-House	64
13	NS 64-22, 1.5% E	In-House	70
14	NS 64-22, 2.5% E	In-House	70
15	NS 64-22, 1% K	In-House	70
16	NS 64-22, 1.5% K	In-House	70
17	NS 64-22, 2% K	In-House	70
18	NS 64-22, 3% K	In-House	76
19	NS 64-22, 4.5% K	In-House	82
20	NS 64-22, 5% K	In-House	82
21	NS 64-22, 7% K	In-House	82

*NS- Nu Star; *CRM – Crumb Rubber Modifier; *E – Elvaloy modified; *K – Kraton modified

The first step in evaluating modifier concentration was to determine an appropriate blending procedure. In order to minimize complexity, cross-linking agents were not evaluated. It was determined that along with the benefit of reduced complexity, the polymer could be evaluated without the contribution of the agent. It was thought that cross linking agents would also cloud the chemical analysis and possibly mask the molecular weight distribution of the polymer in question. The team adapted and adopted a procedure provided by NuStar Energy for blending SBS.

The asphalt was heated to a temperature of 190°C and then polymer is added slowly while mixing. Mixing continued for two hours at temperature. These were both incorporated into our mixing process. Initially the asphalt was heated to a high temperature above 140°C, and then moved from the oven to the heating mantle covered by fiberglass insulation. A thermocouple was used to monitor the temperature of the asphalt. A Ross high shear mixer was then used to mix the asphalt. This helps to ensure a uniform temperature throughout the asphalt and is necessary when mixing SBS. Once the asphalt is heated and being maintained at a temperature of 190°C, the polymer is slowly added over a 30 minute period. Once the polymer is added, the mixture is mixed for 2 hours while frequently scraping the side of the can to move polymer towards the impellor of the mixer and ensure a uniformly mixed binder. After 2 hours, if the binder exhibits the proper consistency, it is removed from heat and allowed to cool. The lab acknowledges the importance of the cross-linking the modifier and base binder, and although the in-house produced binders may not have fully developed the cross linking, the same procedure was followed for each mix, therefore comparison within in-houses mixes is reasonable.

3.2 Mix Performance Testing

Performance testing is the crucial step necessary to link binder testing to performance. Dynamic Complex Modulus (DCM) testing and subsequent analysis using the Mechanistic Empirical Pavement Design Guide (MEPDG) was initially selected as the performance test; however, after initial testing Flow Time testing was selected. The higher strains of Flow Time testing, which leads to failure of the test samples, was selected in favor of the low, nondestructive, stresses in which DCM testing is conducted under.

3.2.1. Dynamic Complex Modulus /Mechanistic Empirical Pavement Design Guide

The Mechanistic Empirical Pavement Design Guide was used for analysis of three mixes using the results of dynamic complex modulus (DCM), to determine a correlation between predicted pavement performance and J_{nr} values. The traffic used was a 4 lane highway (2 each direction) with AADTT of 4740, 50% of trucks in design direction and 95% of trucks in the design lane. Table 5 shows the pavement structure. Table 5 shows the level 1 analysis inputs for binder data. Table 6 shows all of the mix data including the second level 1 analysis input, the stiffness data, E^* along with the binder content for each mix and the gradation of the mixes. To compare the effects of the binder the gradation of each mix were kept consistent. MEPDG uses Fahrenheit instead of Celsius for temperature inputs.

Table 3 Pavement Structure

Layer Material	Thickness (inches)	Modulus (psi)
HMA DCM Layer	6.2	Level 1 Analysis
A-1-a Gravel	7.5	40000
A-1-b Subgrade	Semi-infinite	26500

Table 4 MEPDG Binder Data for the Surface Layer

NS 70-22		
Temperature, °F	G*	Phase Angle
147	5.285	76.89
158	3.553	79.37
169	1.823	81.85
NS 76-22		
Temperature, °F	G*	Phase Angle
158	5.431	66.69
169	3.747	69.14
180	2.065	71.59
NS 82-22 Tank 73		
Temperature, °F	G*	Phase Angle
158	4.087	66.34
169	2.283	67.8
180	1.307	69.71

Three binders were preliminarily selected: NuStar 70-22, 76-22 and 82-22. The binders were selected as each binder had a different high grade while all shared the same low grade and the varied J_{nr} . By selecting different binders with similar PG grades and different J_{nr} the interaction between J_{nr} and PG grade can be compared, in addition to J_{nr} 's interaction to DCM and MEPDG.

3.3.2 Flow Time

Flow time testing was conducted to determine the high temperature laboratory performance in regards to permanent rutting deformation and determine its relationship to the multiple stress creep recovery (MSCR) parameter J_{nr} . Ultimately the objective is to make a case for or against the use of J_{nr} as a valid test parameter for polymer modified binder.

During this uniaxial static creep test, the specimen is subjected to a constant compressive load of 600 KPa (30 psi) at a test temperature of 52.5°C (130°F). The test may be conducted with or without confining pressure (NCHRP 2008). For this study, the test was performed without confining pressure. While MSCR testing uses standard values during testing the temperature of 52.5°C (130°F) for flow time testing was selected to match conditions in New Jersey.

A total of ten different mixtures including conventional and unconventional mixtures were obtained for this study. The conventional mixtures consist of hot mix asphalt (HMA) with different performance-graded (PG) binders as follows: PG 64-22, PG70-22, PG76-22, and PG82-22. The mixes with PG 70-22, PG 76-22 and PG82-22 binder were mixed in house and shared the same gradation. The plant-produced unconventional mixtures analyzed in this study were Warm Mix Asphalt (WMA) and Reclaimed Asphalt Pavement (RAP), Stone Matrix Asphalt (SMA), Binder Rich Intermediate Course (BRIC), and Bridge deck asphalt. WMA is the generic name of technologies that allow lower production temperatures, leading to several benefits, including: cutting fuel consumption and decreasing the production of greenhouse gases. According to the National Asphalt Pavement Association (NAPA), engineering and construction benefits include better compaction of pavements; the ability to pave at lower temperatures, extending the paving season; and the potential to be able to recycle at higher rates, as well. WMA is also comprised of 25% reclaimed asphalt pavement (RAP). RAP is the end product of old roads that have milled for replacement. SMA is a gap-graded HMA that is designed to maximize rutting resistance and durability by using a structural basis of stone-on-stone contact. Because the aggregates are all in contact, rutting resistance relies on aggregate properties rather than asphalt binder properties. Since aggregates do not deform as much as asphalt binder under

load, this stone-on-stone contact greatly reduces rutting [55]. BRIC is specifically designed to help mitigate reflective cracking. Bridge deck asphalt employs a highly modified binder to allow for thin overlays on bridge decks. An additional dense graded aggregate sample was provided by the Rhode Island Department of Transportation. Table 7 summarizes the materials used in this project including mixtures characteristics, while Figure 8 is plot of the aggregate gradation for each mix.

Table 7. Mix properties

	Mixtures									
Mixture Properties	HMA PG82-22	HMA PG76-22	HMA PG70-22	HMA PG64-22A	HMA PG64-22B	WMA-RAP	SMA	BRIC	Dense Graded Aggregate	Bridge Deck
PG grade	82-22	76-22	70-22	64-22	64-22	64-22	76-22	70-22	70-28	76-28
RAP (%)	0	0	0	0	0	35	0	0	0	0
AC Content (%)	5.41	5.02	4.83	5.69	6.42	5.25	4.87	8.4	6.42	7.5

Figure 8. Asphalt Mix Aggregate Gradation

Chapter 4 RESULTS

The results of testing are presented within this chapter, raw tabular binder data is available in the Access database that is explained in chapter 6.

4.1 Mechanical Binder Testing Results

The results of tradition Superpave testing conducted using the Dynamic Shear Rheometer (DSR) are presented in Figures 9, 10 and 11 for the following parameters: phase angle (δ), G^* and $G^*/\sin(\delta)$, respectively. Table 4 list the binders with their identifiers, source and PG grade, mixes 11 through 21 were modified in-house.

The largest phase angle was recorded in binder 9, Valero 93, while the smallest phase angle was recorded by binder 5, Road Science 76-22. Of the in-house modified binders binder 12, Ns 64-22 with 1.5% Elvaloy and 0.8% PPA, recorded the smallest phase angle, while binder 15, NS 64-22, 1% K had the largest phase angle. Within the modified binders their phase angle does decrease as the binder becomes more modified, as is the case with binders 15 to 21, however it does not appear to be significant. Nebraska, Wisconsin, Michigan, Arizona, South Carolina, Utah, Ohio, Georgia, and Florida require the phase angle of the original DSR to be 75° or less.

Figure 9. Phase Angle (δ) from ODSR at PG Grade

For Figure 10, the largest complex modulus, G^* , is binder 11, Valero 937 modified with 1.5% Kraton, however this appears to be a false result as it is outside the expected values. Binder 2, NS76-22, has the largest complex modulus amongst plant modified binders while binder 21, NS 64-22 with 7% Kraton, has the largest amongst in-house modified binders. The in-house modified binders have shown an increasing trend as modification increases, from binders 18 to 21.

Figure 10. Complex Shear Modulus from ODSR at PG Grade

The $G^*/\sin(\delta)$ results of Figure 11 closely follows the results of Figure 10's G^* , which is reasonable because the phase angles from Figure 9 were fairly close to each other for most of the binders, therefore, the number dividing G^* ($\sin(\delta)$) was fairly close from sample to sample. Again Binder 11 appears to be a false result.

Figure 11. $G^*/\sin(\delta)$ of ODSR at High temperature PG Grade

The results of elastic recovery testing are presented in Figure 12 and are categorized according to their high performance. It is evident that as the performance grade increased, the elastic recovery also increased. However, at the higher performance grades, the binders did not vary greatly regardless of the base binder or polymer percentage. The addition of a polymer, at different percentages, had an effect on the elastic recovery of the binder. As seen with NS 64-22, with the addition of Kraton polymer from zero to 3%, there was a steady increase in elastic recovery.

Figure 12. Elastic Recovery (%) at 25°C with identifiers

The peak ratio and area under the load displacement curve as measured by the forced ductility test are presented in Figures 13 and 14. Once again, Figure 13 displayed the incremental effects of polymer modification were observed in the area under the load displacement curve. The area increased with the addition of higher polymer percentages. Similar to peak ratios, area under the load displacement curve did not show sensitivity to performance grade. The area does show sensitivity to changes in base binder with respect to a particular polymer. It appeared that Force Ductility may verify the presence of polymer. However, conclusive evidence has not been found to suggest that Force Ductility can: (1) be used to identify or quantify the specific polymers within mixes without the aid of test statistics data, or (2) exhibit sensitivity to performance grades.

Figure 13. Peak Ratio at 4°C

Figure 14. Forced Ductility Area Under the Load Displacement Curve 4°C

The results of MSCR testing of J_{nr} and Recovery are presented in Figures 15 and 16 both test were conducted at 64°C and at both stress 0.1 and 3.2 kPa. Table 4 should again be used to

discern the identifiers used, please note that data is not available for some binders, however, they remain to hold their place.

Figure 15. MSCR J_{nr} results at 64°C

Figure 16. MSCR Recovery results at 64°C

4.1.1. Impact of Modification on Binder Grade based on AASHTO MP-19

The results have shown that PG 76-22, PG 76-28, PG 82-22, and PG 64-28, all could be graded as PG 64E. Extreme traffic indicates more than 30 million ESALs or standing traffic. The last binder PG 64-28 would be graded as PG 64E due to the modification to provide better low temperature performance. Therefore, there could be a case, where a binder graded as PG 64E may not actually be able to withstand Extreme traffic and may perform poorly at high temperatures. One way to resolve this issue is by closely looking at the ODSR result of binders. For example, at 64°C, if the $G^*/\sin(\delta)$ is below 2.0 kPa, it is unlikely to pass a higher grade and withstand heavy traffic.

4.3 Mechanical Properties of Mix

4.3.1 DCM

The results of the three binders preliminarily selected for performance testing by means of Dynamic Complex Modulus testing: NuStar 70-22, 76-22 and 82-22, are presented in table 8.

Table 8 Dynamic Complex Modulus Testing Results

Binder	Binder Content, %	Dynamic Complex Modulus, E*, ksi					Gradation	
		Temp, °F	Frequencies				Sieve Size	CPP, %
			10 Hz	5 Hz	1 Hz	0.5 Hz		
NS 70-22	4.65	10	5000	4048	4071	4101	3/4"	100
		39.5	2444	2263	1831	1653	1/2"	92.33
		68	1022	860	557	451	3/8"	88.53
		104	232	182	93	68	No. 4	58.72
		130	97	75	30	23	No. 8	40.01
NS 76-22	5.00	10	4996	4226	4208	3214	No. 16	30.2
		39.5	2418	2255	1885	1719	No. 30	20.71
		68	1141	992	681	557	No. 50	13.62
		104	268	211	115	869	No. 100	8.97
		130	66	58	34	22	No. 200	6.86
NS 82-22 Tank 73	5.20	10	3010	2902	2613	2472	Pan	4.74
		39.5	2221	2035	1615	1444		
		68	1098	928	615	506		
		104	218	169	89	68		
		130	51	39	21	17		

4.3.2 Flow Time

Figure 17 illustrates the results of the flow time testing conducted, with each sample reaching the primary, secondary and tertiary phases with the exception of the SMA, Bridge Deck and the PG 64-22A. The SMA and PG 64-22A samples reached each phase in testing but is not entirely shown in Figure 17 because it did not fit the scale of the graph, while the Bridge Deck sample did not reach the tertiary phase after 10,000 seconds. In addition to a high flow time, a shallow slope during the secondary region is desired; the Bridge Deck mix had the lowest rate of increase during the secondary phase.

Figure 5. Flow Time Results

Table 9 shows the binder testing results of each binder as well as the flow time results for each binder. Each binder has three sets of data for flow time testing: the time in seconds and micro strains between: the primary to secondary, secondary to tertiary (flow time) and the differences between the two. The time and microstrains accumulated from the primary to secondary region was considered as this phase is typically a result of a densification of the aggregate matrix. While the flow time is the time at which the mixture transitions from the secondary to tertiary, micro cracks become macro cracks and ultimately leads to the failure of the sample. When the flow time is subtracted the flow time by the transition point from primary to secondary, the secondary phase is captured. By capturing the secondary phase, the response of the binder

during testing is captured. The highlighted results in Table 9 are test results from extracted and recovered binder and are, therefore, aged samples compared to the remaining samples.

The Bridge Deck mix did not reach the tertiary phase and thus a flow time was not reached, this was after 10,000 seconds of testing so it is safe to say that the mix would have the highest flow time and is rut resistant. As shown in both Figure 17 and Table 9, the SMA mix registered the highest flow time value for reaching the tertiary flow stage as compared to the remaining mixtures. The lowest flow time value was reached by the HMA PG70-22 mixture. Results from flow time testing indicate that among all the mixtures tested SMA, Bridge Deck and 64-22A are the most rut resistant. SMA is designed to rely on aggregate to aggregate interlock making it more resist rutting. Bridge Deck mixes are highly modified and should be expected to perform well in rutting conditions.

Table 9 Flow Time and Corresponding Binder Results

	MSCR results	Flow time results							Binder results	
Mix	J _{nr}	Primary to secondary (I)		Secondary to Tertiary (II)		(II)- (I)		Slope (IV)/(I II)	G*/sin(δ) (KPa) @64C	G*/sin(δ) (KPa) @70C
		Time (sec.)	Micro Strain	Flow time (sec.)	Micro Strain	Time (sec.) (III)	Micro Strain (IV)			
WMA RAP	1.68	83.5	25379	175.5	33119	92	7740	84.13	14.46	8.026
PG 76-22 SMA PG	1.26	892	15136	4001 1	39661	39119	24525	0.626	1.258	0.5829
PG 70-22	1.09	23	16671	53	25424	30	8753	291.76	1.793	0.9702
70-28 BRIC	0.58	121	29068	206	36808	85	7740	91.05	1.281	0.6703
PG 76-22	0.18	170.5	17913	384.5	31721	214	13808	64.52	1.812	0.9746
Dense Graded Aggregate	0.16	50	25540	105.5	35243	55.5	9703	174.82	5.362	2.533
PG 82-22	0.13	110.5	19055	262	30302	151.5	11247	74.24	1.385	0.7616
Bridge Deck	0.35	68.5	9382	-	-	-	-	-		
Rat 71 PG 64-22A	3.425	23	8558	2064	13686	2041	5128	2.51	1.658 5	0.759
PG 64-22B	3.11	15.5	12612	61	16818	45.5	4206	92.43	3.514	1.696
Note: Extraction and recovered binder										

Chapter 5 ANALYSIS

5.1 Binder Correlations

New Jersey, along with several other states, specifies Elastic Recovery (ER) to be greater than 60%. Figure 18 is a plot of ER and J_{nr} with the 60% recovery criteria, the ER decreases as J_{nr} increases.

Figure 18. Elastic Recovery at 25°C vs. J_{nr} (3.2 kPa) at 64°C

According to New Jersey's ER specification, only two binders failed: Valero 937 with 1.5% Kraton and NS 64 with 1.5% Elvaloy. Although the NS 64-22 with 1.5% Elvaloy does not meet specification, the addition of 0.8% PPA improved the recovery enough to be greater than 60%. Valero 937 with 1.5% Kraton is an extreme outlier, proving that polymers can react differently with different base binders. For percentage recovery (%Re) versus J_{nr} , there is no longer a 60%

standard. However, binders must fall above the line with equation, $\%Re = 29.371 * J_{nr}^{-0.2633}$, to be considered up to specification as shown in Figure 19.

Figure 6 Percentage Recovery (3.2 kPa) at 64°C vs. J_{nr} (3.2 kPa) at 64°C

The same binders that did not meet the ER specification, (NS 64-22 with 1.5% Kraton and Valero 937 with 1.5% Kraton), are not meeting the standard set for percent recovery. Once again, the Valero 937 with 1.5% Kraton acted as an extreme outlier in comparison to the rest of the binders. The %Re specification accepted much fewer binders. Of the 9 binders that it did not accept, 7 of them were mixed in house with various percentages of Elvaloy and Kraton using a NuStar base binder. Since the binders were mixed in house, additional equipment would be necessary to determine when the binder is completely networked, hence completing the mixing process. For the binders that are above the curve, it shows that the elastic response is due to the

elastomers. Of the binders that showed elastic response due to elastomers, all of them fell above the dotted line in Figure 19 at 40% recovery from MSCR.

5.1.1 Temperature Dependency

In order to test the temperature dependency of percent recovery (%Re), four binders were tested at the high temperatures of 64, 70, and 76°C. The four binders tested were Kraton NS BD, NS 76-22, NS 76-22 Tank 1007, and NS 64-22 with 1.5% Elvaloy. As shown in Figure 20, NS 64-22 with 1.5% Elvaloy starts with a very low recovery when tested at 64°C.

Figure 20 Percentage Recovery (3.2 kPa) at 64°C vs. J_{nr} (3.2 kPa) conducted at 64°C, 70°C and 76°C

When the temperature was raised to 70 and 76°C, the %Re decreased as the J_{nr} dramatically increased. The same trend is seen with the NS 76-22 Tank 1007. There was a high percentage recovery at the low temperature, and J_{nr} increase as the percent recovery increased decreased. The NS 76-22 and Kraton NS BD started with a much higher %Re for the 64°C testing temperature. The NS 76-22 once again followed the aforementioned trend when tested at 64 and 70°C; however at 76°C, J_{nr} decreased, and %Re increased. This is seen more profoundly with the Kraton NS BD. When the testing temperature increased from 70 to 76°C, the J_{nr} remained relatively constant, and the %Re increased dramatically. Therefore, there does seem to be a temperature dependency for binders that exhibit high %Re values. Binders, however, that have low %Re at the 64°C temperature, will have decreasing recoveries in relation to an increasing J_{nr}.

5.1.2 Correlation Between Properties Measured on Original DSR

Many states including Georgia, Florida, and Arizona require phase angles to be 75° or less to ensure elasticity in binders. Most of the binders in Figure 21 did not meet this requirement. The binders that had phase angles less than 75° included 2 received binders NS 76-22, NS 82-22 Tank 73, and 2 In-House mixes NS 64-22 with 1.5% Elvaloy and 0.8% PPA, and NS 64-22 with 7% Kraton. It is interesting to observe that NS 64-22 with 2.5% Elvaloy had greater phase angle and J_{nr} values than NS 64-22 with 1.5% Elvaloy and 0.8% PPA. Although there is 1% more Elvaloy and 0.2% more net polymer in the NS 64-22 with 2.5% Elvaloy mix, this was not shown through performance testing. This seems to support indications that certain polymers behave differently with base binders.

Figure 7. Phase Angle (δ) from ODSR at PG grade vs. J_{nr} (3.2 kPa) at 64°C

New Jersey requires binders to exhibit at least 60% recovery from ER testing at 25°C. To compare this specification to the phase angle specification used in other states, boundary lines for both are shown in Figure 22. It appears that most binders, both received and In-House mixes, had recoveries greater than 60%. However, of the 13 binders with recoveries greater than 60%, 6 binders had phase angles greater than 75°, seven binders had phase angles less than 75°. Therefore, Figure 22 suggests that the phase angle specification is stricter than the ER specification.

Figure 8. Phase Angle from ODSR at PG grade vs. Elastic Recovery at 25°C

Phase angles from DSR run on original binders at PG temperature were compared to %Re from MSCR. MSCR testing characterizes binders in the nonlinear visco-elastic region. Therefore, in Figure 23, the phase angle specification was correlated to the effects of polymers within the binder. As mentioned previously, results showed that when binders have 40% or greater recovery from MSCR the elastic response is most likely due to the presence of elastomers. From Figure 22, with the exception of CRM v=3200, %Re of 40% appears consistent with the phase angle specification. CRM v=3200 may have behaved as an outlier in this comparison as it is often more difficult to test these types of binder. More binder testing is needed to converge on a specific level of recovery from MSCR to agree with the phase angle specification. If consistency

from MSCR with ER and phase angle is achieved, it may be possible to retrieve the necessary data from MSCR alone.

Figure 9. Phase Angle (δ) from ODSR at PG grade vs. Percentage Recovery (3.2 kPa) at 64°C

The binders circled in Figure 24 were In-House mixes of NS 64-22 with Kraton. The PG high temperature of those binders has been noted on the graph. As the PG high temperatures of the binders increased from 70°C, to 76°C, to 82°C, significant changes in Jnr were observed. It was also observed that the PG high temperatures did not increase in grade level from 4.5% K to 7%K. This showed that the effects of polymer additions on Jnr were converging to a plateau.

Although the 4.5%, 5%, and 7% mixes did not decrease significantly with J_{nr} , the $G^*/\sin(\delta)$ values increased considerably. Binders appeared to be stiffer, having high $G^*/\sin(\delta)$, at low strains. A similar effect was not observed in J_{nr} . From these results, it is evident that at high strains performance properties of binders become strain dependent.

Figure 10. $G^*/\sin(\delta)$ from ODSR at PG grade vs. J_{nr} (3.2 kPa) at 64°C

5.1.3 Force Ductility

Peak ratios displayed a linear trend against phase angles at 64°C, Figure 25. The linear trend would make sense if keeping in mind that with greater modification, peak ratios increased and phase angles decreased. It appeared that phase angles would steadily reduce with greater response from the second Force Ductility peak. In turn, that would indicate greater networking at high peak ratios. However, 64°C is not the specified temperature to check phase angles. As the phase angle temperature was raised to PG temperature in Figure 26, the phase angle values

increased, but the linearity was not preserved. Due to polymer activations at different temperatures, peak ratios do not seem to make any strong indications towards polymer networking. From Figures 25 and 26, Force Ductility did not provide any correlation to performance at high temperatures.

Figure 11. Peak Ratio at 4°C vs. Phase Angle (δ) from ODSR at 64°C

Figure 26. Peak Ratio at 4°C vs. Phase Angle (δ) from ODSR at PG grade

5.3 Correlating MSCR Parameters to Predicted Performance in MEPDG

The results of MEPDG analysis are presented in Table 10, with the following predicated parameters: terminal IRI, longitudinal cracking, alligator cracking, transverse cracking, and permanent deformation. The final row of the table is the J_{nr} of each binder used for the mix. The MEPDG analysis follows the same pattern of the dynamic complex modulus results. All of the predicted parameters increased as the mixes binder J_{nr} decreased, or in other words, cracking increased as the binder became stiffer. However, the difference between mixes could be considered negligible and does not correlate well with the large difference in J_{nr} between the mixes with NS 70-22 and NS 76-22 and the small difference between NS 76-22 and NS 82-22 Tank 73. The small strains of DCM testing may not capture the full effects of polymer modification. Flow Time testing was chosen for further testing to expose the mixes to higher strains.

Table 10. MEPDG Evaluation Analysis

Performance Criteria	Distress Target	Reliability Target	NS 70-22		NS 76-22		NS 82-22 Tank 73	
			Distress Predicted	Reliability Predicted	Distress Predicted	Reliability Predicted	Distress Predicted	Reliability Predicted
Terminal IRI (in/mi)	172	90	107.5	98.34	109.2	97.93	113.3	96.8
AC Surface Down Cracking (Long. Cracking) (ft./mile):	2000	90	2880	35.39	4050	19.52	6330	3.76
AC Bottom Up Cracking (Alligator Cracking) (%):	25	90	2.6	97.29	3.3	94.64	5.5	91.71
AC Thermal Fracture (Transverse Cracking) (ft./mi):	1000	90	0.2	99.999	1	99.999	1	99.999
Permanent Deformation (AC Only) (in):	0.25	90	0.15	97.51	0.17	90.18	0.23	59.99
Permanent Deformation (Total Pavement) (in):	0.75	90	0.38	99.999	0.41	99.999	0.49	99.69
Jnr(3.2kPa) at 64°C	--		1.09		0.18		0.13	

5.4 Correlating MSCR with Flow Time

The results of the Flow time testing and respective J_{nr} of each binder are plotted in Figures 27, 28, and 29. The SMA, Bridge Deck and Rt71 PG 64-22A results were excluded because their flow time was magnitudes greater than the other results. In Figure 27 Flow time increasing as J_{nr} decreases from 1 kPa^{-1} and is generally low beyond 1 kPa^{-1} . The same trend is present in figure 28, which isolates the time during the secondary phase; by subtracted the flow time by the transition point from the primary to secondary phases. The secondary phase was isolated to study the response of the binder of each mix. The trend is more consistent throughout Figure 29, when the compressive strains accumulated during the secondary phase are graphed, microstrains increase as J_{nr} decreases. All three figures show better performance as the J_{nr} values decrease from 1 kPa^{-1} while the best performance are clustered as J_{nr} approach 0.5 kPa^{-1} or lower. Of the three mixes not included in the figures, the Bridge Deck supports the trend with a high flow time and low J_{nr} , while the SMA and PG 64-22A have larger J_{nr} and higher flow times. The high flow time results of SMA may not be consistent with high J_{nr} values because the gradation and aggregate structure is significantly different than the rest. It is unclear why the flow time results of the mix with PG 64-22A was not consistent with the large non-recoverable compliance values.

Figure 12. J_{nr} vs. Flow Time Results

Figure 13. J_{nr} vs. the Time of Secondary Region

Figure 14. J_{nr} vs. Micro Strains Accumulated During the Secondary Phase

There is no correlation between $G^*/\sin(\delta)$ and Flow time (Figure 30). This may be primarily due to the difference in the strain regimes of the two tests. There is also no correlation observed between recovery from MSCR and flow-time results as shown in Figure 31. The three mixes not included in the graph, due to their large flow that didn't fit the scale of the plotted results, would have added to the scatter.

Figure 15 $G^*/\sin(\delta)$ (kPa) at 70°C vs. Flow Time Results

Figure 16. MSCR Percent Recovery vs. Flow Time Results

The non-recoverable compliance J_{nr} has been demonstrated to correlate with rutting performance, as measured by flow time testing, with rutting resistance improving as J_{nr} decreased. Generally as J_{nr} increases from 0.5 1/kPa rutting resistance drops off. The Superpave parameter $G^*/\sin(\delta)$ and the MSCR recovery didn't correlate well with the flow time results.

In terms of rutting resistance, J_{nr} correlates well and should be consider as a simpler and more affordable alternative to elastic recovery and forced ductility testing for polymer modified binders. Mixes with a J_{nr} approaching 0.5 1/kPa, or lower can be expected perform well from a binder perspective, making it a reasonable criteria when selecting polymer modified binders.

5.5 Cost –Benefit Analysis of Eliminating Elastic Recovery and Using MSCR

MSCR testing poses savings in the test process as compared to the current PG Plus specification elastic recovery. The cost per test is slightly less with MSCR testing typically costing \$150 while elastic recovery is \$250 for three tests and with an additional cost of \$250 to RTFO the greater material needed to operate the test, for a grand total of \$167 per test. The greatest savings are in equipment and time. MSCR testing uses the DSR and would not typically incur additional equipment cost while elastic recovery requires the purchase of approximately \$15,000 in large equipment to be bought. The number of test that can be conducted per day per apparatus is limited for elastic recovery, typically its take approximately 4 hours per sample. MSCR testing requires approximately fifteen minutes; allow many test to be run in a single day. In all the MSCR procedure requires less upfront cost, is less per sample and can be performed much faster.

Chapter 6

SUMMARY CONCLUSIONS AND RECOMENDATIONS

6.1 Summary of Findings

- The percent recoveries of polymer modified binders at 3.2kPa measured in MSCR vary significantly (as much as six to seven times) within the same performance grade.
- The percent Elastic recoveries at 25C of polymer modified binders vary significantly (as much as three to four times) within the same performance grade.
- The addition of PPA in the 1.5% Elvaloy in NuStar 64-22 quadrupled the recovery measured in the MSCR test. However, such a dramatic improvement was not observed when Elastic Recovery was tested at 25°C.
- All received binders and the binder modified with PPA had recovery values greater than 60% while binders that graded at 64 and 70°C fell below the 60% recovery.
- All binders with a J_{nr} at 3.2kPa at 64 °C less than 0.6 kPa^{-1} exhibited elastic recovery more than 60%.
- All binders that had the MSCR recovery at 3.2 kPa greater than 40% was above the MSCR elastic recovery curve.
- All binders that were above the MSCR elastic recovery curve passed the elastic recovery requirement of 60%.
- There was no correlation observed between continuous grade of the binder and the non-recoverable creep compliance.
- Under AASHTO MP19 some PG 64-28 binders could grade similar to PG 82-22 at PG 64E. However, they may not actually be able to withstand Extreme traffic and may perform poorly at high temperatures. One way to address this issue is by analyzing the ODSR result of binders at 64C. AASHTO MP19 calls for a DSR on original material at

the environmental grade. If $G^*/\sin(\delta)$ is below 2.0 kPa at the environmental grade it is unlikely it would pass the DSR requirement at next PG temperature.

- Based on the polymer modified binders tested in this study, more pass the elastic recovery requirement of 60% at 25C and the phase angle requirement of 75 degrees at high PG grade established by various states. On the other hand, very few (Sem Strata, Road Science and NuStar 82-22) are above the proposed MSCR elastic curve.
- Phase angle slightly increases with J_{nr} , and decrease with percentage of recovery.
- The peak ratio decreased with increase in non-recoverable compliance.
- Peak ratios and areas under the load displacement curve did not show sensitivity to performance grades
- The areas under the load-displacement curve have not provided clear trends when compared to J_{nr} or percent recovery. However, the areas under the load-displacement curve are sensitive to the percent by volume of modifier added in the asphalt binders.
- Elvaloy and PPA significantly impact the non-linear viscoelastic component of the strains.
- Dynamic complex modulus and MEPDG did not appear to be sensitive to polymer modification
- Mixes with a non-recoverable creep compliance (J_{nr}) lower than 0.5 kPa^{-1} performed well, while mixes with higher J_{nr} performed poorly in the flow-time test.

6.2 Conclusion

The conclusions of the study are as follows:

- 1) Upon testing a variety of binders it has been determined that MSCR binder testing is sensitive to asphalt mix performance. Binders with non-recoverable compliance value (J_{nr}) of less than 0.5 kPa^{-1} appear to show better high temperature performance. The results are in

line with the AASHTO MP 19-10 specification. It should be noted that the scope of this study was limited to binder selection and many other parameters impact the performance of roadways.

- 2) The MSCR elastic curve requirement appears to be the most stringent of the requirements to evaluate elastic response as compared to elastic recovery at 25°C and phase angle of 75.
- 3) An MSCR recovery at 3.2kPa greater than 40% will ensure that it is above the MSCR elastic recovery curve. This could serve as an alternative specification to the MSCR elastic recovery curve.
- 4) Some modified binders with a lower PG-grade (-28 versus -22) may grade high on the AASHTO MP-19, which could be misleading that they can withstand heavy traffic.
- 5) New Jersey DOT is limited in its selection of modified binders as the NJDOT currently requires styrene-butadiene or styrene-butadiene-styrene to be incorporated in all modified binder, causing supply shortages and rising cost. This limitation is imposed by the NJDOT to ensure performance, while the underlining issue is; there currently is no simple and effective test to predict modified asphalt performance. However, using the MSCR parameter in the binder specification will have the potential to allow the state to open the market to a broad range of modified binders.
- 6) The MSCR test for non-recoverable creep compliance (J_{nr}) is a simple and quick test to perform and does not require the purchase of an additional testing apparatus since it uses the Dynamic Shear Rheometer (DSR), which is already a common piece of lab equipment in the asphalt industry. Current test method such as Elastic Recovery (ER) and Force Ductility (FD) are time intensive and require the purchasing of additional testing apparatus and are not necessary to evaluate polymer modified binders.

6.3 Recommendations

After conducting a thorough literature review, executing the proposed research plan and subsequent analysis of the results it is the recommendation of this paper for MSCR testing using the parameter J_{nr} , to become a standard means to evaluate polymer modified binders in New Jersey. The guidelines set forth by AASHTO MP 19-10, in which the binders are graded according to traffic (ESALs) by using J_{nr} is recommended. Additionally:

- New Jersey DOT could eliminate the use of elastic recovery, thus saving almost \$15,000 dollars on capital cost of equipment and up to \$500 per binder characterization considering labor and depreciation cost. These could lead to considerable savings of thousands of dollars over several years.
- Additional testing, including field performance should be conducted on binders with low J_{nr} (less than 0.5 kPa^{-1}) and with a lower PG-grade, such as PG 64-28 versus PG64-22.
 - This can be addressed by closely looking at the ODSR result of binders. For example, at 64°C , if the $G^*/\sin(\delta)$ is below 2.0 kPa , it is unlikely to pass a higher grade and withstand heavy traffic.
- Low non-recoverable creep compliance ($J_{nr} < 0.5 \text{ kPa}^{-1}$) coupled with high MSCR recovery at 3.2 kPa (recovery greater than 40%) and $G^*/\sin(\delta)$ high enough to pass the next high grade will ensure that the binder selected will withstand heavy and extreme traffic levels.
- Most of the binders provided by the refinery do not have specific compositions. Some binders may have several polymers meeting the target specifications. Therefore, it is not known how other polymers influence the non-recoverable compliance. A detailed evaluation of the impact of a broad range of polymer modification on the non-recoverable compliance is

needed. However, appropriate interlocking should be evaluated using direct measurement tools, such as the fluorescent microscope.

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