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NYSDOT
SPR Project Number: C-08-20

Grade Determination of Crumb Rubber-Modified Performance Graded Asphalt Binder

Final Report

August 29th, 2013

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1. Report No. C-08-20	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Grade Determination of Crumb Rubber-Modified Performance Graded Asphalt Binder		5. Report Date August 29th, 2013
		6. Performing Organization Code
7. Author(s) Thomas Bennert, Ph.D.		8. Performing Organization Report No.
9. Performing Organization Name and Address Center for Advanced Infrastructure and Transportation (CAIT), Rutgers University		10. Work Unit No.
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address NYS Department of Transportation 50 Wolf Road Albany, New York 12232		13. Type of Report and Period Covered Final Report
		14. Sponsoring Agency Code

15. Supplementary Notes

Project funded in part with funds from the Federal Highway Administration

16. Abstract

Due to particulates common in crumb rubber-modified asphalt binders, conventional PG grading using the Dynamic Shear Rheometer (DSR) with a gap height of 1.0 mm may not be valid and in accordance with current specifications. Asphalt binder testing and mixture testing was conducted on binders with and without crumb rubber modification to determine an asphalt binder test method which best matches the mixture performance. It was determined that the Multiple Stress Creep Recovery (MSCR) test, conducted with a gap height of 2.0 mm and at in-service temperatures, best correlated with Flow Number testing in the Asphalt Mixture Performance Tester (AMPT). This relationship was found to be better than that of the current DSR test procedure for high temperature PG grading.

17. Key Words Crumb Rubber Modified, PG Grading, Multiple Stress Creep Recovery (MSCR)	18. Distribution Statement No Restrictions		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 75	22. Price

EXECUTIVE SUMMARY

The use of crumb rubber to modified asphalt mixtures has been used for over 50 years. To date, a majority of these projects have shown to perform well, and if not better, than conventional modified binders. Unfortunately, the quantification of the amount of modification occurring in crumb rubber modified binders is often done utilizing viscosity techniques that do not adhere to current Superpave PG grading specifications. For local, state, and federal agencies to properly specify the use of crumb rubber modified (CRM) asphalt binders, a better means of measuring and quantifying the performance of CRM binders is necessary.

Current Superpave PG grading specifications utilizes the Dynamic Shear Rheometer (DSR) at a gap height of 1.0 mm to determine the high temperature performance grade of asphalt binders. Unfortunately, the current gap height may create issues with CRM asphalt binders that contain rubber particulates, sometimes as large as the current 1.0 mm gap height itself. The fear is that particulates greater than 25% of the gap height may interfere with the measurements, and thereby resulting in a DSR measurement that may not represent the actual liquid being tested.

The research effort looked at evaluating a variety of different CRM asphalt binders and determining their high temperature performance using current AASHTO PG grading, as well as utilizing the Multiple Stress Creep Recovery (MSCR) test procedure at a gap height of 2.0 mm. Testing during the study on conventional asphalt binders showed that increased gap heights caused testing variability at test temperatures greater than the PG grade of the asphalt binder (i.e. – failing temperature during PG grading). However, as long as the test temperature remains at PG grade temperature (i.e. – passing temperature during PG grading) or lower, testing variability was within the allowable Precision and Bias statement of AASHTO T315, *Standard Method of Test for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR)).* The evaluation of a proposed “Cup and Bob” test procedure, using alternate geometry in the DSR apparatus, was also evaluated during the study.

The asphalt binder test results indicated that a strong correlation was found between the current high temperature PG grading protocol and the MSCR protocol at 2.0 mm gap height. Testing using the MSCR test showed that although the CRM asphalt binder resulted in low non-recoverable creep compliance (J_{nr}) values, the respective Percent Recovery values did not pass the proposed “proper modification” line. A good relationship was found between the Percent Recovery property from the MSCR test and the Elastic Recovery using ASTM D6084. However, the test results indicated that a greater sensitivity to elastomeric response was found using the MSCR test as opposed to ASTM D6084. $G^*/\sin \delta$ from the Cup and Bob method was found to correlate to $G^*/\sin \delta$ in the DSR. However, the average difference between the measurements was approximately 18% with the Cup and Bob test procedure resulting in greater $G^*/\sin \delta$ values. It is hypothesized that this may be due to inaccurately measuring the phase angle in the Cup and Bob test as fluctuations in this measurement were found in the test data.

When comparing the asphalt binder test results to asphalt mixture permanent deformation testing, it was determined that the MSCR protocol with a 2.0 mm gap height best correlated to the Flow Number measured in the Asphalt Mixture Performance Tester (AMPT). The MSCR test at a gap height of 2.0 mm tested at the in-service temperature for New York State (64^{o}C) was proposed for measuring the high temperature performance of the CRM asphalt binder. However, additional testing comparing compacted air voids of conventional and CRM asphalt binders showed that simply switching CRM asphalt binder with particulates for conventional asphalt binders in established mix designs is not prudent. Failing compacted air void levels were found in the CRM asphalt binders containing particulates. Therefore, asphalt mixture designs should be conducted for the respective CRM asphalt binder being used to ensure that proper void space in the aggregate structure exists to allow the remaining crumb rubber particulates to reside in asphalt mixture without causing density issues.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

1.1 INTRODUCTION

A surplus of discarded tires poses an environmental hazard in New York State. For some time now, New York State has shown interest in mitigating the environmental impact of these tires by incorporating them as a crumb rubber (Figure 1) into performance graded asphalt binder (PGAB). The crumb rubber acts as a modifier in the asphalt binder, similar to an SBS polymer, and provides enhanced high and low temperature mechanical properties in the final hot mix asphalt.

Figure 1 – Typical Crumb Rubber Used in Asphalt Binders and Mixtures

There are three general methods of utilizing crumb rubber in asphalt; 1) "Dry" Process, 2) "Wet" Process, and 3) Terminally Blended Process. In the "Dry" Process, the crumb rubber is added during the mixing phase (mixing of aggregates and asphalt binder). Depending on the size of the crumb rubber, some modifications may need to be done to the aggregate blend to allow for the crumb rubber to reside in the aggregate skeleton. This often results in the "Dry" Process being primarily used for more gap-graded type mixtures (i.e. – open-graded friction course and/or stone matrix asphalt). In the "Wet" Process, the crumb rubber is blended into the asphalt binder under temperatures of approximately 350^{o}F. During this time, the materials are continually mixed/blended for a minimum time period (previously determined in the laboratory) and then mixed at elevated temperatures with the aggregates. In the "Wet" Process, the potential exists for the crumb rubber not to break down completely into the asphalt binder, and often, larger amounts of crumb rubber particles still reside in the asphalt binder, potentially causing an issue with the aggregate skeleton. The other issue commonly associated with both the "Dry" and "Wet" Process is the potential for particulates and "blue smoke" to enter the atmosphere during the production process.

In the "Terminal Blend" Process, the crumb rubber is introduced into the asphalt binder in a wetting vessel, where, depending on the base binder and required PG grade, SBS polymer is also added. The asphalt binder and crumb rubber is then "cooked" for approximately 16 hours under high pressure and a high shear mixer with temperatures in excess of 425°F. Under this process, almost a complete breakdown of the crumb rubber occurs in the asphalt binder. The Terminally Blended asphalt binder is then loaded into tanker transports and shipped directly to the contractor's storage tanks where the binder is commonly treated as any normal polymer-modified asphalt binder. In general, the advantages of using the Terminal Blend process over the "Dry" and "Wet" process are:

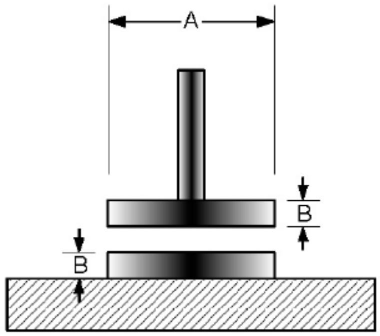
- No need for specialized blending equipment at the hot mix asphalt plant;
- No additional holding areas for storing crumb rubber on site;
- Completely eliminates potential problems with heating and blending of crumb rubber in hot mix asphalt; and
- Eliminates smoke and particulates, commonly associated with the "Dry" and "Wet" process, from entering the atmosphere.

It is for these reasons that the NYSDOT is interested in potentially using the Terminal Blend process, provided that the Terminal Blend asphalt binder can be accurately tested to the Performance Graded specifications outlined in AASHTO M320, *Standard Specification for Performance-Graded Asphalt Binder*.

Potential Issues with Performance Grading Binders with Crumb Rubber

The adoption of NYSDOT accepting the crumb rubber modified asphalt binder as an accepted method of asphalt modification is contingent on the crumb rubber modified performance graded binder (CRM PGB) being able to be accurately tested and capable of conforming to the standard practices and criteria established in AASHTO M320. In particular, potential issues may arise during the asphalt binder testing due to residual crumb rubber particles interfering with the testing configurations of the different test apparatus. For example, Figure 2 shows the required dimensions of the Dynamic Shear Rheometer test plates. The gap spacing between the plates during testing is 1 mm for the 25 mm plates and 2 mm for the 8 mm plates, as specified in AASHTO T315, Section 9, *Standard Method of Test for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR).* With the required gap distances ranging between 1 to 2 mm thick, residual crumb rubber particles may interfere in the accuracy and repeatability of the test measurements.

Some researchers have questioned the validity of testing asphalt rubber modified binders using conventional Superpave testing protocols. Bahia and Anderson (1995) reviewed work conducted by the National Center of Asphalt Technologies (Hanson and Duncan, 1995) and concluded that variability associated with the test results were much higher than acceptable limits used with conventional asphalt binders. Additional work conducted by McGeneiss (1995) indicated that the rolling thin film oven (RTFO) aging of asphalt rubber binders may not be suitable due to the formation of a veil of material across the bottle. Currently, TxDOT only requires PG grading of the base binder to be used with crumb rubber due to the understanding that the test results will be influenced by the residual crumb rubber found in the final blended product.



Dimension	8-mm Nominal	25-mm Nominal
A	8 ± 0.02 mm	25 ± 0.05 mm
B	≥ 1.50 mm	≥ 1.50 mm

Figure 2 – Configuration of Dynamic Shear Rheometer (DSR) Parallel Plates (Adapted from AASHTO T315, *Standard Method of Test for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR))*

1.2 RESEARCH NEED STATEMENT

As previously described, the NYSDOT is interested in specifying the use of crumb rubber modified asphalt binder as an alternative means of asphalt binder modification, similar to SB or SBS polymer modified asphalt binders. However, due to the differences in asphalt rubber modified binder production processes (i.e. – dry process, wet process, and terminal blend) and the possibility of residual crumb rubber influencing the dynamic shear Rheometer (DSR) and possibly the RTFO aging, requires the NYSDOT further evaluate whether or not crumb rubber modified asphalt binders can be performance graded in accordance with Superpave specifications (AASHTO M320, *Performance-Graded Asphalt Binder).*

Another issue the NYSDOT needs to consider is the possible implication of utilizing an asphalt binder modified with crumb rubber that contains residual crumb on the hot mix asphalt mixture design. It is common to utilize crumb rubber modified asphalt binders in gap-graded mixtures (i.e. – stone matrix asphalt, SMA or open graded friction course, OGFC) since the aggregate skeletons of these mixtures allow for the residual crumb rubber to reside in-between in the aggregates. However, dense-graded mixtures do not use the same aggregate skeleton (i.e. – gap graded) and therefore, the residual crumb may actually push the aggregate particles away from each other.

To help evaluate these issues, the Research Team had begun an extensive research study to evaluate the performance grading protocols when utilizing crumb rubber modified asphalt binders. In doing so, the Research Team has developed a Literature Review to help understand these issues and aid in developing a test plan.

CHAPTER 2

STATE OF PRACTICE

2.1 Introduction

In the project statement for NYSDOT RFP C-08-20, "Grade Determination of Crumb Rubber-Modified Performance Graded Asphalt Binder", a Literature Review is required to assess the current state of the practice with respect to the performance grading of crumb rubber-modified asphalt binders. Along with crumb rubber-modified asphalt binder, a review of processes of producing crumb rubber-modified asphalt binders was also conducted.

To help the reader, subsequent sections of this chapter are organized by topic. The first section discusses the processes used to produce crumb rubber-modified asphalt binders. The second section discusses the state of the practice with respect to evaluate asphalt rubber-modified asphalt binders. The third and final section is a summary of the literature search. Individual summaries are provided for each reference.

2.2 Modification of Asphalt Binder by the Addition of Crumb Rubber

One method to beneficially utilize scrap tires is to use processed crumb rubber to modify hot mix asphalt (HMA). The crumb rubber is produced by processing whole tires using some form of grinding method, at either ambient or cryogenic temperatures, to reduce the size of the rubber to a fine powder having particle sizes generally smaller than 2.0 mm.

The concept of using scrap tires to modify hot mix asphalt was first introduced in the mid1960's for use as thin lift asphalt surface treatments. Later in the 1970's, the use of crumb rubber modified (CRM) asphalt included its use in dense graded asphalt mixtures and has continued to evolve.

Crumb rubber modifies the asphalt binder through a process of diffusion, where the crumb rubber particle absorbs a portion of the aromatic fraction of the asphalt binder resulting in the swelling of the crumb rubber particle (Putman and Amirkhanian, 2006). The swelling of the particle, compounded with the reduction in the oily fraction of the binder results in an increase in the CRM asphalt binder viscosity. This increase in viscosity results in the thick asphalt films commonly associated with asphalt mixtures containing CRM asphalt binders. Increased film thickness is associated with more durable asphalt mixtures.

However, the degree of interaction between the crumb particle and the asphalt binder is highly dependent on a number of factors. First is the compatibility between the crude source of the asphalt binder and the rubber composition of the crumb rubber particle. Since the interaction that occurs with CRM asphalt binders is dependent on the presence of aromatic oils in the asphalt binder, the crude source of the asphalt binder has a significant effect.

Another important factor in the degree of interaction is the crumb particle size. A large number of studies have shown that the specific surface area of the crumb rubber particle has a direct impact of the degree of interaction with the asphalt binder (Heitzman, 1992; West et al, 1998). The majority of the CRM asphalt binders produced in the United States uses ambient ground crumb rubber as this particle type has the greatest surface area compared to cryogenic grinding. Grinding at ambient temperatures produces crumb rubber with irregular and rough surfaces, resulting in more interaction with and possible digestion into the asphalt binder. Meanwhile, the cryogenic grinding produces a smooth, blocky crumb rubber particle due to being frozen with the liquid nitrogen. This decreases the overall surface area of the cryogenic crumb rubber particle (Blumenthal, 1994). And since surface area has been shown to influence the interaction of the asphalt binder and crumb rubber particle, it would make sense that particle size does as well. This is why many states and specifications require the use of finer crumb rubber particles. Although, it should be noted that the coarser crumb rubber mixtures produced in Arizona and California have performed well for years.

The degree of interaction and modification of the CRM asphalt binders have been traditionally measured using viscosity. While viscosity is an important property in the assessment of pumpability at the asphalt plant, it does not directly relate to the in-service performance (i.e. – rutting, fatigue, thermal cracking) of the asphalt binder in the hot mix asphalt. Earlier forms of viscosity grading of asphalt binders were quickly abandoned upon the development of the Superpave Performance Grade testing. However, to date, few researchers or practioners have utilized the DSR to measure the interaction and modification of CRM asphalt binders.

2.3 Crumb Rubber-Modified Asphalt Binder Production Processes

There are primarily three different approaches to produce an asphalt mixture that is modified with crumb rubber. Two approaches, "Wet" Process and Terminal Blend, modifies the asphalt binder directly prior to mixing with the aggregates. The third approach, "Dry" Process, blend the crumb rubber with the asphalt binder and aggregates during the mixing process.

2.3.1 "Wet" Process

The "Wet" Process of producing crumb rubber modified asphalt binders generally follows the specifications and properties outlined in ASTM D6114, *Standard Specification for Asphalt Rubber Binder*. The ASTM specification defines that asphalt rubber binders are;

> "…a blend of paving grade asphalt cements, ground recycled tire (that is, vulcanized) rubber and other additives, as needed for use as binder in pavement construction. The rubber shall be blended and interacted in the hot asphalt cement sufficiently to cause swelling of the rubber particles prior to use."

The blending of the crumb rubber and asphalt binder generally occurs at the asphalt plant in a portable blending tank. “Super sacks” of crumb rubber, meeting the gradation specification as determined by the agency, are delivered to the asphalt plant and then loaded into a metering chamber using a forklift (Figure 3). The meeting chamber adds the correct percentage of crumb rubber by total weight of the final asphalt blend and then transfers the material into the blending chamber (Figure 3, right side of photo). The blending continues until the viscosity of the CRM asphalt binder meets a minimum, usually in accordance with ASTM D6114, generally greater than 15 centi-Poise and less than 40 centi-Poise (Figure 4). This “compatibility” and viscosity check is usually conducted prior to field blending in the laboratory to provide general guidance as to the amount of time required for optimal blending to occur, as well as the amount of time the CRM asphalt binder can remain under heated conditions before an issue may occur. The viscosity measurements are commonly conducted using a portable Haake hand-held viscometer with a sample of the CRM asphalt binder in a 1-gallon container heated over a hot plate (Figure 5).

Figure 3 – Crumb Rubber “Super Sack” Being Emptied into Metering Chamber with Reaction Tank Immediately to the Right

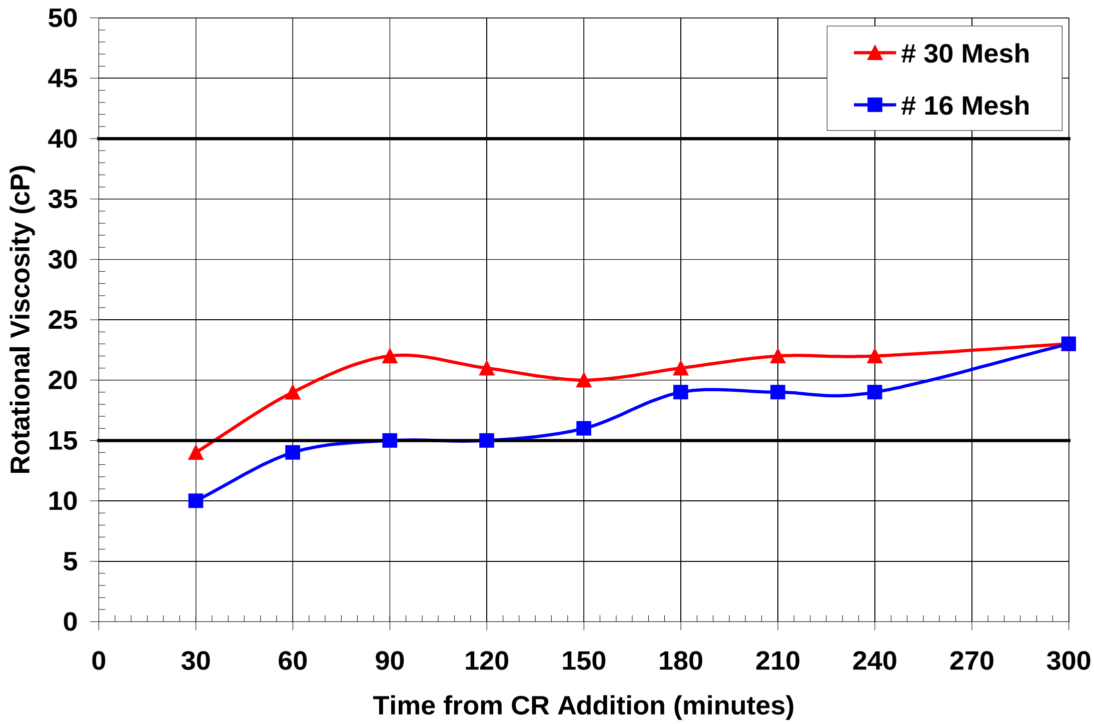


Figure 4 – Example of Viscosity Measurements Conducted with Haake Viscometer to Ensure Reaction and Compatibility (Bennert, 2004)

(a)

(b)

Figure 5 – Photos of Haake Viscometer: a) Laboratory Set-up to Check Viscosity; b) Measured Output Screen from Viscometer (Bennert, 2004)

2.3.2 "Dry" Process

The "Dry" Process of CRM asphalt is conducted by adding the crumb rubber particles to the asphalt mixture during the mixing process. During this method, it is normally required that a slight modification is done to the aggregate gradation to allow the crumb particles to reside in the aggregate skeleton. This essentially results in assuming the crumb rubber particles takes the place of some of the aggregate blend. This is different to the "Wet" Process where the crumb rubber is allowed to react and breakdown in the heated asphalt binder prior to mixing. With a greatly reduced amount of time to allow crumb rubber and asphalt binder to react, the "Dry" Process does not provide the same degree of asphalt modification as the "Wet" Process.

2.3.4 "Terminal Blend" Process

The "Terminal Blend" Process is produced in a closed-system plant that prevents any of the crumb rubber particulates to enter the atmosphere. The raw crumb rubber is delivered into the processing plant and introduced to polymer (typically SBS) in the wetting vessel (Figure 6). In the wetting vessel, both products are precisely blended by weight and then "cooked" for approximately 16 hours under high pressure and temperatures as high as 425^{o}F. This process allows for a complete breakdown of the crumb rubber while still modifying the asphalt binder with the crumb and polymer. After the reaction is complete, the CRM asphalt binder is loaded into tanker transports and supplied to asphalt plants in a similar manner to conventional asphalt binder.

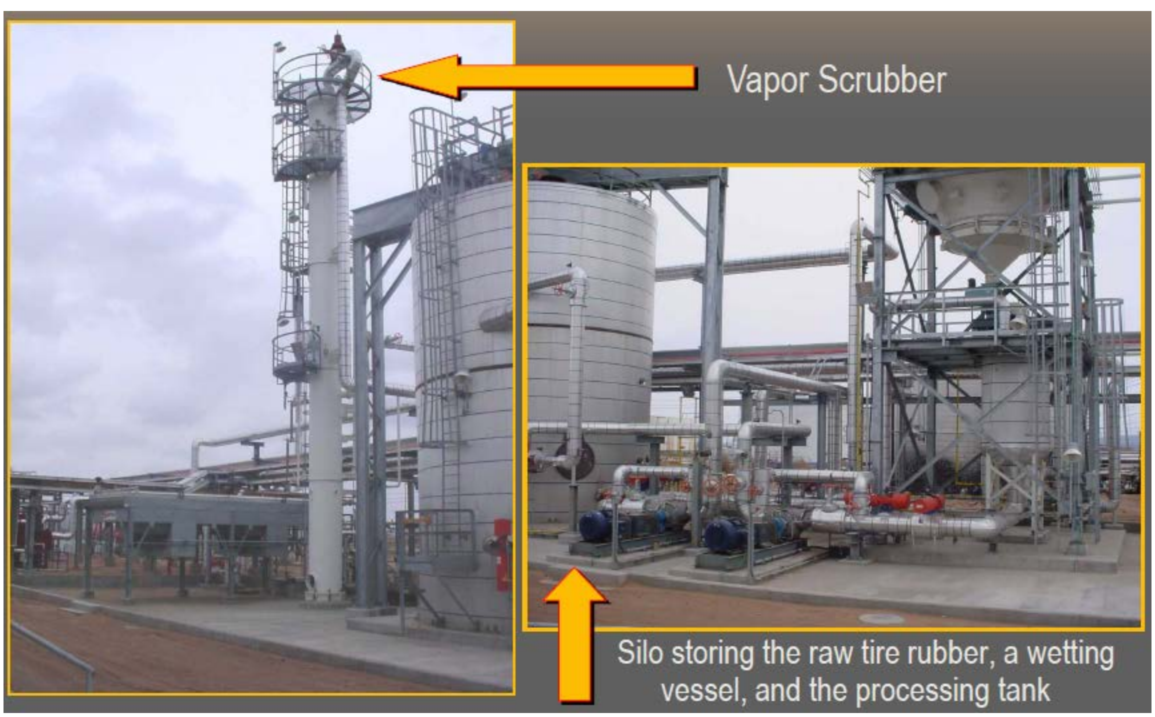


Figure 6 – General Processing Equipment Used to Produce "Terminal Blend" Asphalt Rubber

2.4 Use of PG Grading Procedures to Test Crumb Rubber Modified Asphalt Binders

As mentioned earlier, due to the way Terminal Blend crumb rubber modified asphalt binders are produced, they are easily tested using current Superpave PG test specifications. However, due to residual crumb rubber particles in the asphalt binder, the "Wet Process" crumb rubber modified asphalt binders may be difficult to characterize using current Superpave test procedures (i.e. – 1.0 mm gap height in the Dynamic Shear Rheometer).

This section of the Literature Review summarizes information found that describes the testing of crumb rubber modified asphalt using current, and modified, Superpave performance grading test procedures.

1. Bahia, H. and R. Davies, 1995, "Factors Controlling the Effects of Crumb Rubber on Critical Properties of Asphalt Binders", ***Journal of the Association of Asphalt Paving Technologists*****, Volume 64, p. 131 – 143.**

The paper is probably the earliest research reference regarding the use of Superpave PG testing protocols and asphalt binder modified with crumb rubber. The researchers measured rotational viscosity, dynamic shear modulus and phase angle, and low temperature stiffness and cracking properties with the bending beam rheometer and direct tension test. To use the DSR, the authors increased the gap height of the DSR to 2.0 mm to minimize any effect the crumb rubber may induce.

Through the use of the Superpave PG specifications, the authors indicated that the high temperature properties of the CRM asphalt binders were highly dependent on crumb rubber content, temperature, and the asphalt source. The effect of rubber source was found to be less important.

The researchers used a 2.0 mm gap height to limit any possible affect due to larger crumb rubber particles interfering with the DSR parallel plates. Prior to testing, the researchers conducted a strain sweep to determine the linear elastic region of the asphalt binders using the 2.0 mm gap height. The results indicated that the 2.0 mm gap height provided linear elastic limits similar to the 1.0 mm gap height.

2. Tayebali, A.A., B. Vyas, and G. Malpass, 1997, "Effect of Crumb Rubber Particle Size and Concentration on Performance Grading of Rubber Modified Asphalt Binders", Progress of Superpave (Superior Performing Asphalt Pavement): Evaluation and Implementation, ASTM STP 1322, R.N. Jester, Ed., American Society for Testing and Materials, p. 30 – 47.

The authors investigated two aspects of the performance related Superpave asphalt binder specification methodology; 1) Applicability of the dynamic shear rheometer (DSR) to crumb rubber modified binders, and 2) The effect of crumb rubber particle size and concentration on the higher temperature performance grading of asphalt cements commonly used in North Carolina.

To conduct the testing, the authors increased the gap height of the DSR from 1.0 to 2.0 mm for high temperature PG grade testing, while increasing the gap height from 2.0 to 4.0 for the intermediate temperature PG grade testing. The percent difference in the measured values due to difference in specimen thickness varies between 0.5 to 21 percent. For the unaged (Original) binders, there seemed to be a general trend of increased percent difference with increase in crumb rubber modifier concentration. The difference varied from 6.4% for the unmodified asphalt binder to 10% for the 14% CRM asphalt binder.

With respect to the influence on the aged condition of the asphalt binders, the overall averages for the unaged, RTFO, and PAV aged binders are 7.7, 8.5, and 11%, respectively.

With regards to the crumb rubber particle size, the percent difference for the coarse rubber modified binder is lower than that for the fine rubber modified binder.

Overall, the author's found an average coefficient of variation of 6.2% due to the increase in gap height of the DSR. Replicate testing enabled evaluation of sample to sample variance. The average coefficient of variation obtained due to replication was 6.5%, almost the same value as that obtained from the increase in DSR gap height. The author's noted:

> "It may be inferred that the differences are primarily associated to the sample variance itself and the specimen setup process (operator related), and not because of interference due to crumb rubber particles. This argument is substantiated by the fact that the results showed thicker specimens give higher G*/sinδ values compared to thinner specimens in some cases, but in other cases the trend is reversed. It can therefore be concluded that the AASHTO test protocol is applicable for the crumb rubber modified binders used in this study."

3. Putman, B., J. Thompson, and S. Amirkhanian, 2005, "High Temperature Properties of Crumb Rubber Modified Binders", *MAIREPAV 4 – International Symposium: Maintenance and Rehabilitation of Pavements and Technological Control*, iSMARTi, Belfast, Northern Ireland.

The researchers evaluated the high temperature performance of asphalt binders that were modified using the "Wet" Process. Two different crumb rubber manufacturing process (ambient ground and cryogenic ground) were used to produce three different sized crumb rubber samples each, as shown in the table below taken from the paper.

Table 1 – Crumb Rubber Source and Size Used in Study by Putman et al., (2005)

	Percent Passing *(% by weight)*					
	Ambient			Cryogenic		
Seive Size	**-14 mesh**	**-30 mesh**	**-40 mesh**	**-14 mesh**	**-30 mesh**	**-40 mesh**
No.16 (1.18mm)	97.1	100.0	100.0	100.0	100.0	100.0
No. 20 (850µm)	70.3	100.0	100.0	63.8	100.0	100.0
No. 30 (600µm)	44.1	100.0	100.0	26.9	99.5	99.3
No. 40 (425µm)	27.0	60.8	91.0	4.0	34.2	91.7
No. 50 (300µm)	16.7	19.3	59.1	3.3	3.6	45.9
No. 80 (180µm)	9.0	13.1	26.2	3.3	3.6	11.5
No. 100 (150µm)	7.6	11.1	18.6	3.3	3.6	7.4

The researchers blended the different crumb rubber sources and sizes with three different asphalt binders; 2 PG64-22 asphalt binders from different sources, called Source C and P in the study, and a PG58-22 from Source C. The researchers blended the asphalt rubber binders with a high-shear radial flow impeller at a rotational speed of 700 rpm and at a temperature of 177°C. The asphalt rubber binder was blended at 2 different percentages, 10 and 15%, and for three different blending times; 15, 30, and 45 minutes.

The researchers used the DSR, in accordance with AASHTO T315, with exception of the gap size. In order to accommodate the larger rubber particles present in the minus 14 mesh, the gap in the parallel plate set up was increased from 1.0 mm to 2.0 mm. To justify the increase in gap height, the researchers conducted a strain sweep test in the DSR to ensure that the asphalt binders were still being tested in the linear viscoelastic region. The authors noted that this practice had been employed by others in the past (Bahai and Davies, 1995).

The authors concluded that the addition of the crumb rubber had a significant impact on the failure temperature (continuous high temperature PG grade) of the CRM asphalt binders. Depending on the base binder, the addition of 10% CRM increased the PG grade for a 64-22 to a 70-22. The addition of 15% CRM increased the PG grade from a 64-22 to 76-22. The authors also noted that the crumb rubber size had a greater impact on the viscosity than the DSR measurements.

The authors also noted that the CRM type, ambient or cryogenic, had a significant effect on the viscosity of the CRM binders as the ambient CRM always produced higher viscosities. However, neither source was found to have a more significant impact on the high PG grade failure temperature.

Asphalt binder source did have a major impact on both the viscosity and the failure temperature of the CRM asphalt binders. For source P, the PG grade increased one and two grades at the 10% and 15% crumb rubber contents. Meanwhile, for source C, the PG grade increased two and three grades at the 10% and 15% crumb rubber contents.

4. Putman, B. and S. Amirkhanian, 2006, "Crumb Rubber Modification of Binders: Interaction and Particle Effects", Submitted for publication to the *International Journal of Road Materials and Pavement Design*.

The authors attempted to quantify the interaction and particle effects of CRM, which contributes to the increased rheological properties of CRM asphalt binders. The effects were measured and quantified using a rotational viscometer and dynamic shear rheometer (DSR).

For the DSR testing, the authors increased the gap height on the DSR from 1.0 to 2.0 mm. The excerpt below from the publication summarizes the authors' justification for using a 2.0 mm gap height:

> "Previous research conducted by several researchers used a 2.0 mm gap to test CRM binders using a DSR (Bahia and Davies, 1994 and 1995; and Tayebali et al., 1997). In each of these studies, the CRM binders tested with the 2.0mm gap were tested in the linear visco-elastic region and the data had less variability than with the 1.0 mm gap. This decreased variability was attributed to less contact of the CRM particles with both the parallel plates. If a 1.0 mm gap was used to test a CRM binder containing CRM that measured 1 mm or greater, the CRM particles would contact the plates and the resulting measurement would be a ready of the rheology of the CRM particles instead of the binder, therefore providing inaccurate results."

The authors concluded that:

- The effects of CRM on asphalt binders can be separated into interaction effect (IE) and particle effect (PE). The IE is the effect of the lighter fractions of the binder diffusing into the CRM particles. The PE is the effect of the CRM particles acting as filler in the binder.
- The IE is greatly influenced by the crude source of the binder and could potentially be used as an indicator of a binder's compatibility with CRM. The IE is also significantly influenced by the amount of CRM present in the binder. Higher rubber contents yield greater IE values.
- The PE is most significantly affected by the CRM content of the binder. Higher CRM contents results in greater PE values. The effect of CRM size on the PE follows the same trends as either the viscosity or G* of the CRM binders.

5. Thodesen, C., S. Biro, and J. Kay, 2009, "Evaluation of Current Modified Asphalt Binder Using the Multiple Stress Creep Recovery Test", *Asphalt Rubber 2009*.

The authors evaluated the creep and recovery properties at elevated temperatures of various asphalt binders, including crumb rubber modified asphalt binders, using the Multiple Stress Creep Recovery (MSCR) test procedure, as outlined in ASTM D7405-08. Other asphalt binder modifiers included; Elvaloy, EVA (EVATENE 3325), SBS-PPA, SBS-Crumb Rubber, and SBS only. The authors modified the crumb rubber modified binder (CRM) with 20% crumb rubber by total weight of the asphalt binder. The crumb rubber size conformed with Arizona DOT requirements and was ambient ground. Although it is not mentioned directly, it is assumed that the authors tested all of the asphalt binders using the identical test procedure, as outlined in ASTM D7405-08, which would utilize a dynamic shear rheometer gap height of 1.0 mm.

Figure 7 shows a figure of % Recovery, tested at 64, 70, and 76^{o}C, for each of the asphalt binders tested in accordance with ASTM D7405. The results indicate that the CRM asphalt (20% by weight) resulted in the largest percent recovery for all asphalt binders tested at the 70^{o}C test temperatures. The SBS only provided the second largest % Recovery (at a polymer dosage rate of 3% by total weight of asphalt binder) and the SBS-Crumb Rubber binder achieved the third highest % Recovery (at a polymer dosage of 1% and 10% crumb rubber by total weight of asphalt binder).

Figure 8 shows the resultant non-recoverable creep compliance, J_{nr}, results of the asphalt binders tested at 3,200 Pa. At the highest test temperature (76^{o}C), the CRM binder and the SBS modified binders achieved the lowest J_{nr} values, indicating that both asphalt binders would be highly rut resistant. It should also be noted that the SBS-CRM asphalt binder achieved the second lowest J_{nr} value.

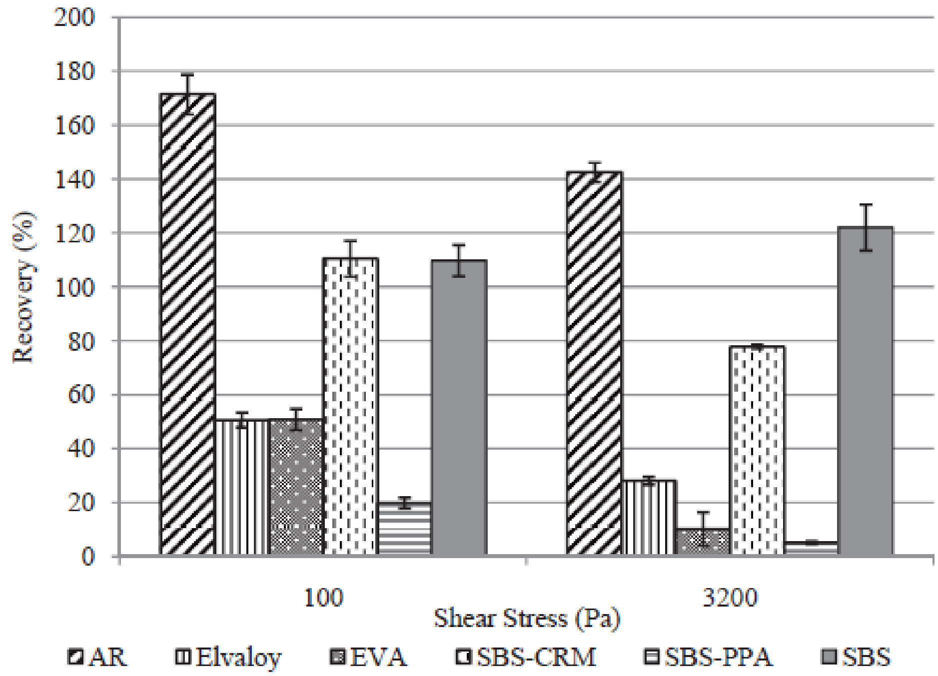


Figure 7 - % Recovery Measurements from the Multiple Stress Creep Recovery, MSCR Test (ASTM D7405-08), from Thodesen et al., 2009

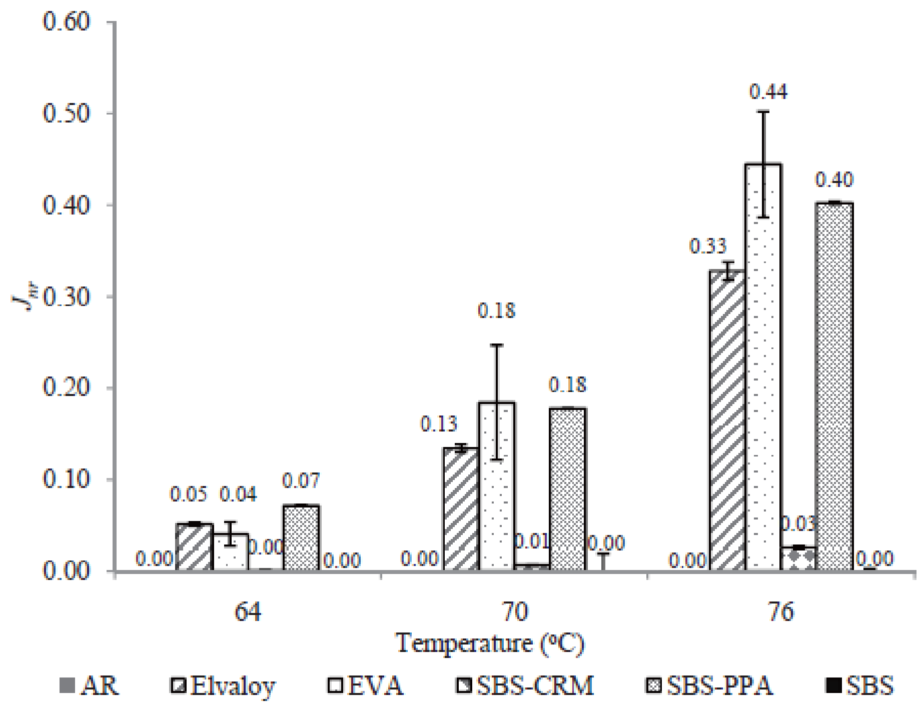


Figure 8 – Non-recoverable Creep Compliance, J_{nr}, of Asphalt Binders Tested at 3,200 Pa, from Thodesen et al., 2009

6. Tabatabaee, N. and H. Tabatabaee, 2010, "Multiple Stress Creep and Recovery and Time Sweep Fatigue Tests: Crumb Rubber Modified Binder and Mixture Performance", *Presented and Published at the 89th Annual Meeting of the Transportation Research Board*, Washington, D.C, 15 pp.

The authors utilized the dynamic shear rheometer (DSR) to assess the permanent deformation and fatigue cracking properties of a PG58-22 asphalt binder that had been modified using 5 different crumb rubber percentages (by total weight of asphalt binder); 3, 5, 8, 12, and 15%. The rubber particle gradation was relatively coarse, with 88% passing the #30 sieve and 20% passing the #50 sieve.

The authors used two asphalt binder tests, both conducted in the DSR, to assess the permanent deformation and fatigue cracking properties of the CRM asphalt binders; MSCR and Time Sweep Binder Fatigue Test (TSBF). The MSCR test was conducted in accordance with ASTM D7405-08. It is assumed that the test samples were tested using a 1.0 mm gap height. The TSBF tests were conducted using the 8 mm diameter plates for the DSR at a gap height of 2.0 mm. The test samples were subject to a controlled cyclic loading at a strain level of 10% until the complex shear modulus (G*) reached 20% of its initial value. The tests were performed at a 15 Hz loading frequency during testing. Prior to testing, the asphalt samples were RTFO and PAV aged in accordance to Superpave specifications (AASHTO T240 and AASHTO R28, respectively).

Additionally, the same asphalt binders were mixed with a coarse-graded 12.5mm Superpave mixture to compare mixture permanent deformation and fatigue cracking properties using the unconfined dynamic creep test and indirect tensile strength test, respectively.

The test results from the DSR showed that both G* and phase angle, resulting in improved high and intermediate temperature performance grades. G*/sin δ increased with crumb rubber content due to higher stiffness and elasticity at high temperatures. Meanwhile, G* sin δ decreased as crumb rubber content increased, indicating an increase in asphalt binder elasticity at intermediate temperatures, and therefore, an improvement in fatigue resistance.

Additionally, the MSCR test results compared very well to the mixture permanent deformation tests, while dissipated energy at failure from the IDT test compared favorably to the fatigue binder testing. The results presented indicated that the asphalt binder testing in the DSR with CRM asphalt binders compared well to mixture results, further validating the use of a 1.0 mm gap height in the DSR.

2.5 Gap Height Sensitivity Study at Rutgers University

As mentioned earlier and shown, only a small amount of literature was able to be located regarding the use of Superpave performance grading of CRM asphalt binders due to lack of published reports/research documents. All of the information found provided general test results of CRM asphalt binders tested in the DSR but there was a lack of information pertaining to the general sensitivity of the gap height on the influence of the shear modulus properties and resultant PG grading; more specifically for gap heights greater than 2.0 mm. Therefore, to help strengthen the State of the Practice, Rutgers University took it upon themselves to evaluate the DSR gap height and its sensitivity in regards to the measured properties and high temperature PG grading.

As noted in AASHTO T315-10, *Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR),* Section 1.3 of the specification notes that, "Particulate material in the asphalt binder is limited to particles with the longest dimensions less than 250 μm." The 250 μm particle size would pertain to any material retained on the No. 60 sieve. The main purpose for the inclusion of this statement is to ensure that no particle interference would take place when using the DSR at a gap height of 1 mm or 1,000 μm. This would represent four (4) times the maximum particle size of any particulate allowed in the asphalt binder. Under this rationale, it would be possible to see gap heights as large as 4 mm or 4,000 μm considering many CRM asphalt binders are produced with crumb rubber particles as large as a No. 30 sieve, or 600 μm. Table 2 shows the typical gradation band of crumb rubber used to produce crumb rubber modified asphalt binders, as specified in ASTM D6114.

Table 2 – Typical Ground Crumb Rubber Gradation Used in the Production of Asphalt Rubber (ASTM D6114)

Typical Ground Crumb Rubber Gradation	
Sieve Size	**Gradation**
No. 8	100
No. 16	65 – 100
No. 30	20 – 100
No. 50	0 – 45
No. 200	0 – 5

The intent of the Superpave PG grading system was to provide a means of grading asphalt binders that were blind to modification. Therefore, if it was to be specified that a larger gap height should be used with CRM modified binders, under the "theory" of the Superpave PG grading system, the larger gap height would also be applicable for asphalt binders without crumb rubber.

To evaluate this concept, Rutgers University procured three different asphalt binders to evaluate the influence of gap height on the DSR measurements and resulting PG grade. The three asphalt binders were procured from NuStar Asphalt and were; 1) PG58-28, PG70-22, and PG82-22. The asphalt binders were chosen to represent a wide range of asphalt binder stiffness and modification (i.e. – polymer content). The results of the continuous high temperature PG grading are shown in Figures 9 and 10. The results show a decreasing trend of high temperature grading for all asphalt binders as the gap height increases. In general, a change of at least 1.0^{o}C in high temperature PG grade can

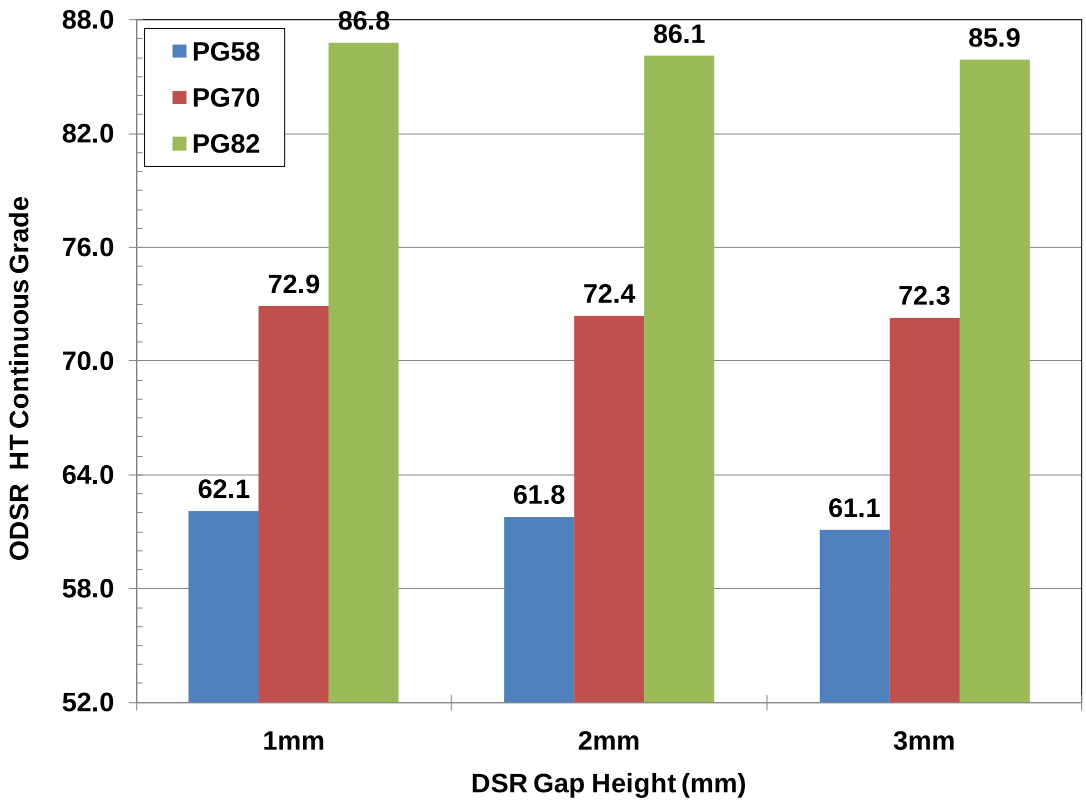


Figure 9 – Influence of Gap Height on Original DSR High Temperature PG Grade

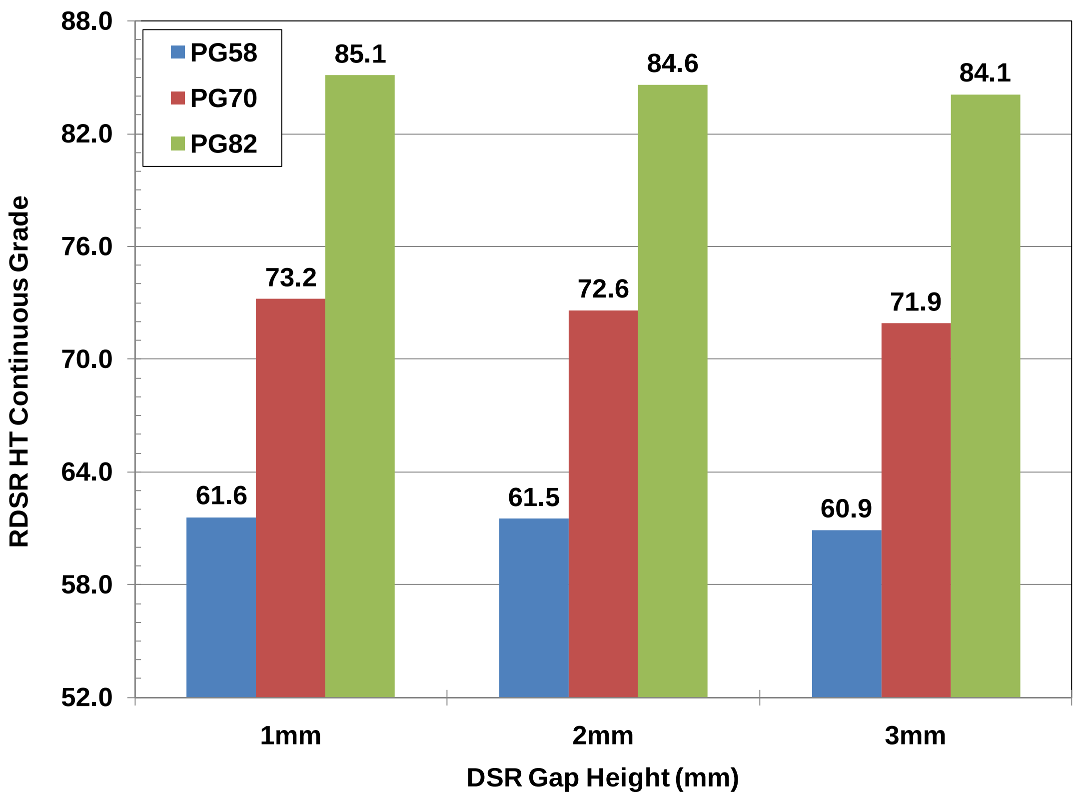


Figure 10 – Influence of Gap Height on RTFO DSR High Temperature PG Grade

be expected when increasing the gap height from 1 mm to 3 mm. Meanwhile, an approximate 0.5°C change in high temperature PG grade would be expected when increasing the gap height from 1 mm to 2 mm.

The main reason for the reduction in high temperature PG grade is due to the decrease in shear modulus (G*) values measured during the testing, especially at the failure temperature (i.e. – higher temperature used in the PG grading procedure). The change in the failure temperature of the DSR PG grading was further reviewed using the precision statement provided in AASHTO T315. According to Table 4 of AASHTO T315, the Acceptable Range of Two Test Results (Single Operator) is the following:

- Original Binder: G*/sin δ = 6.4%
- RTFO Residue: G*/sin δ = 9.0%

Using the range as an acceptable difference between the asphalt binder tested at 1.0 mm gap height, a comparison between the difference in results and the allowable range of results when increasing the gap height was conducted. The results are shown in Figures 11 and 12 for the Original aged condition and Figures 13 and 14 for the RTFO aged condition.

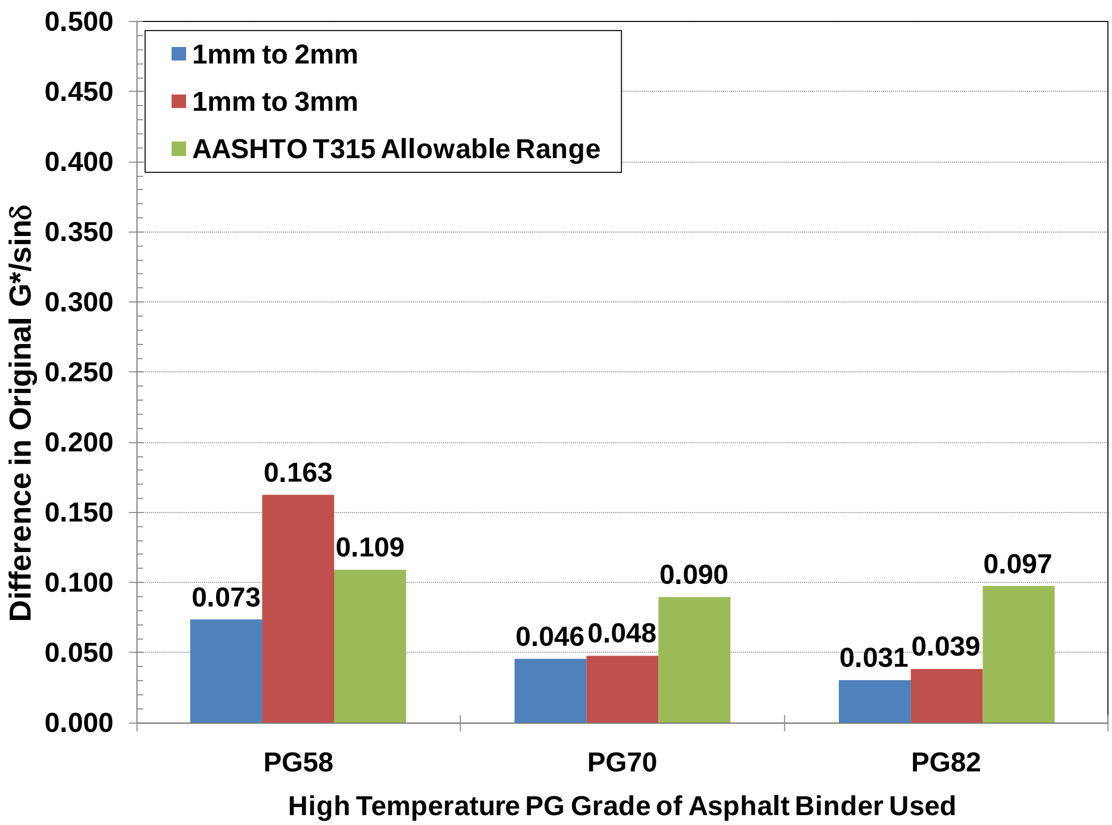


Figure 11 – PG Grade Temperature Results for Original Aged Binder Condition

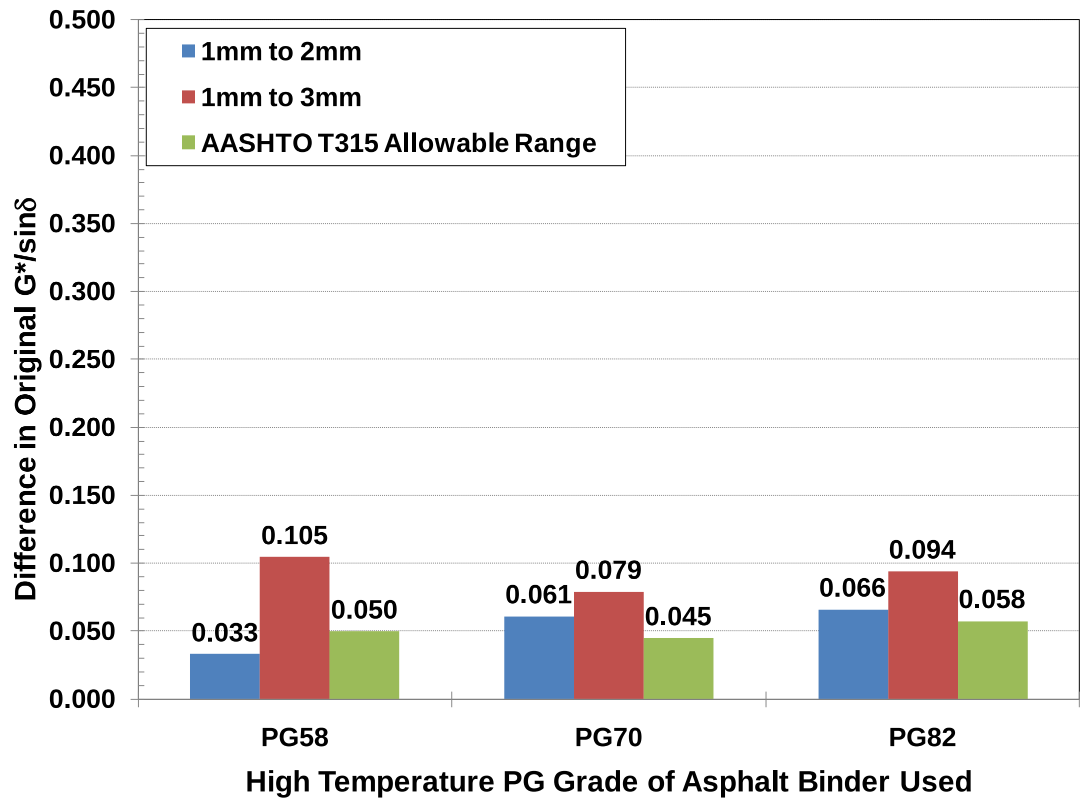


Figure 12 – Failure Temperature Results for Original Aged Binder Condition

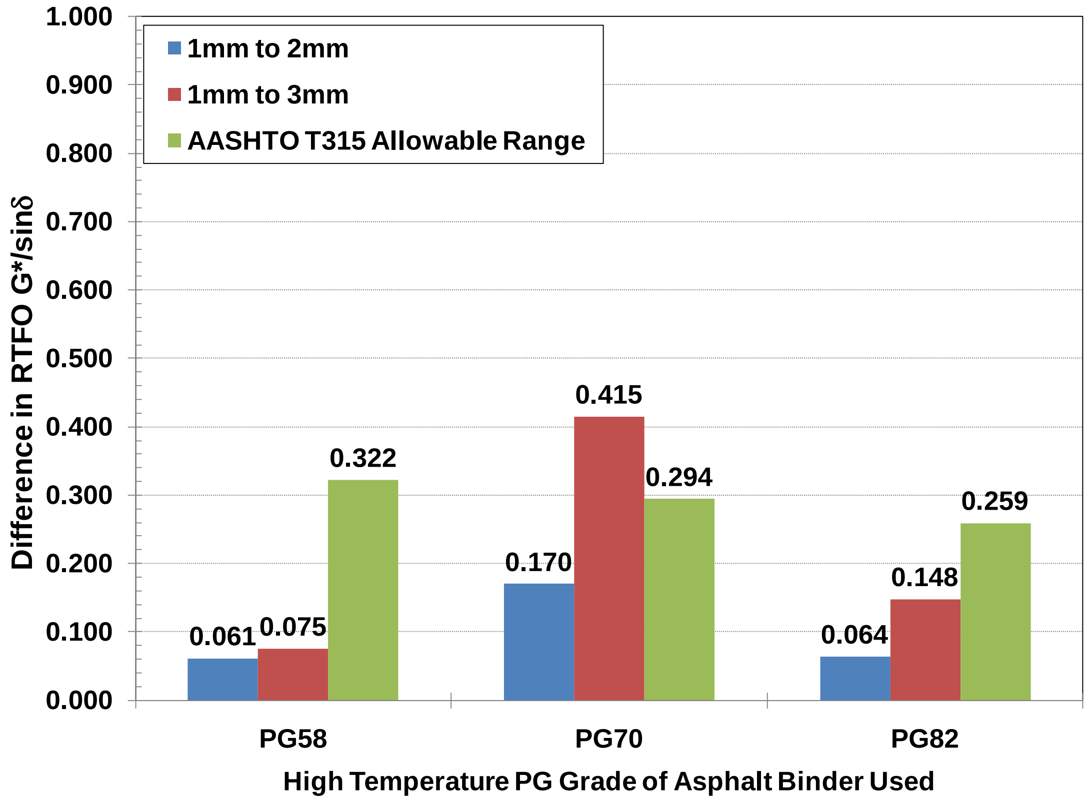


Figure 13 – PG Grade Temperature Results for RTFO Aged Binder Condition

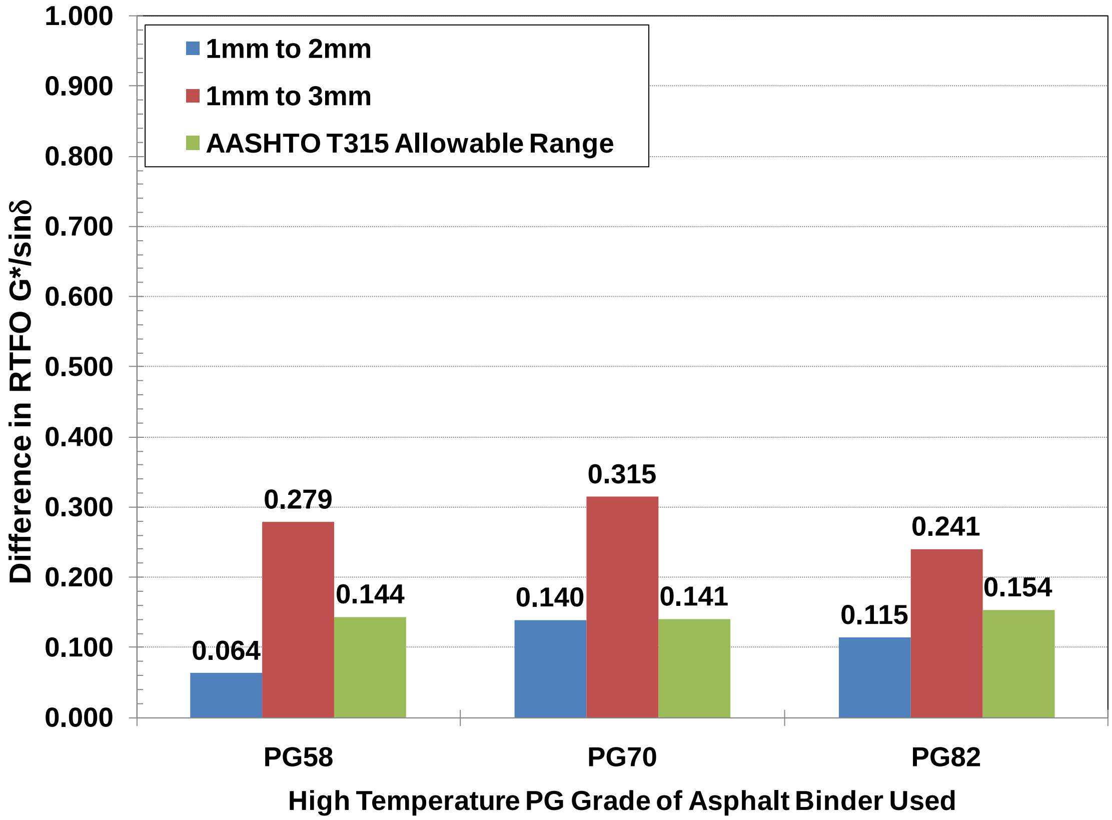


Figure 14 – Failure Temperature Results for RTFO Binder Condition

For the Original aged binder condition, the test results indicate that at the PG grade temperature, the difference between results when increasing the gap height meets the allowable range of results as defined in AASHTO T315. However, at the failure temperature, the difference between test results when increasing to either 2.0 or 3.0 mm gap height failed the allowable range of results.

For the RTFO aged binder conditions, as with the Original aged condition, the PG grade temperature results indicates that testing the asphalt binder at either 2.0 or 3.0 mm gap heights provides results that still fall within the allowable range of results when compared to the specified 1.0 mm gap height. However, for the failure temperature of the RTFO aged condition, the 2.0 mm gap height would fall within the allowable range, but certainly not the 3.0 mm gap height.

The gap height sensitivity study showed that testing at the PG grade temperature can be precisely achieved even at gap heights as high as 3.0 mm. However, a reduction in $G^*/\sin \delta$ occurs at increased gap heights (greater than 1.0 mm) when testing is conducted at the failure temperature. This reduction in $G^*/\sin \delta$ was also found to fall out of the allowable range, as specified by AASHTO T315, when the results of the increased gap heights were compared to the 1.0 mm.

Further investigation using a high resolution digital camera indicated that as the gap height increased, especially from 1 mm to 3 mm, asphalt binder begins to leak out from between the DSR plates, especially at the failure temperature of the PG grading (i.e. – for the 58-28 asphalt binder, this would be the 64°C test temperature; for the 82-22 asphalt binder, this would be the 88°C test temperature). Figures 15 to 20 visually show the progression of asphalt binder leaking out between the DSR plates.

Based on the results of the change in gap height testing, it can be concluded that if using the four (4) times smaller criteria proposed in AASHTO T315, CRM asphalt binders should not contain crumb rubber larger than 0.50 mm, or no material retained on the No. 35 sieve. This may be difficult to achieve unless specifically specified as typical crumb rubber gradations can be much coarser, as shown in table from ASTM D6114, *Standard Specification for Asphalt Rubber Binder*, also shown here as Table 1.

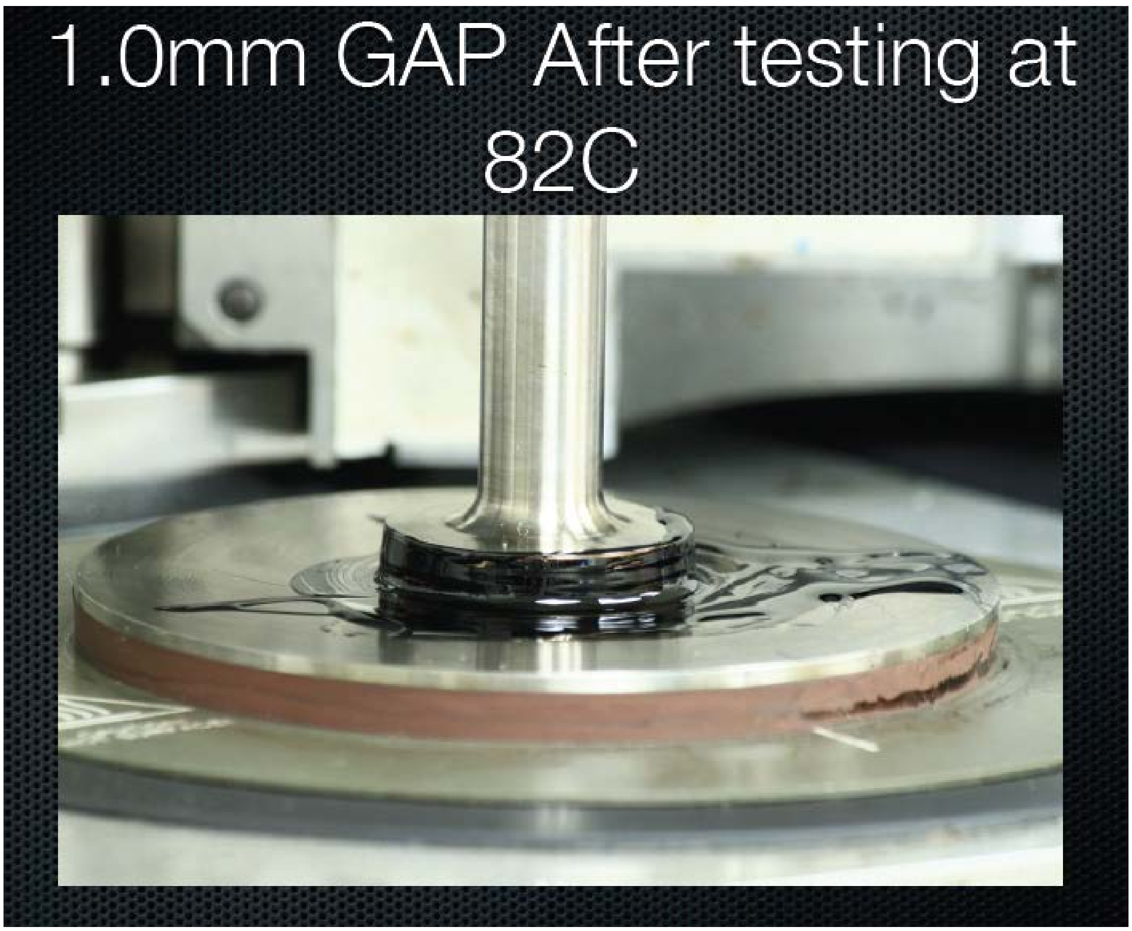


Figure 15 – 1.0mm Gap Height Immediately After Testing at 82°C

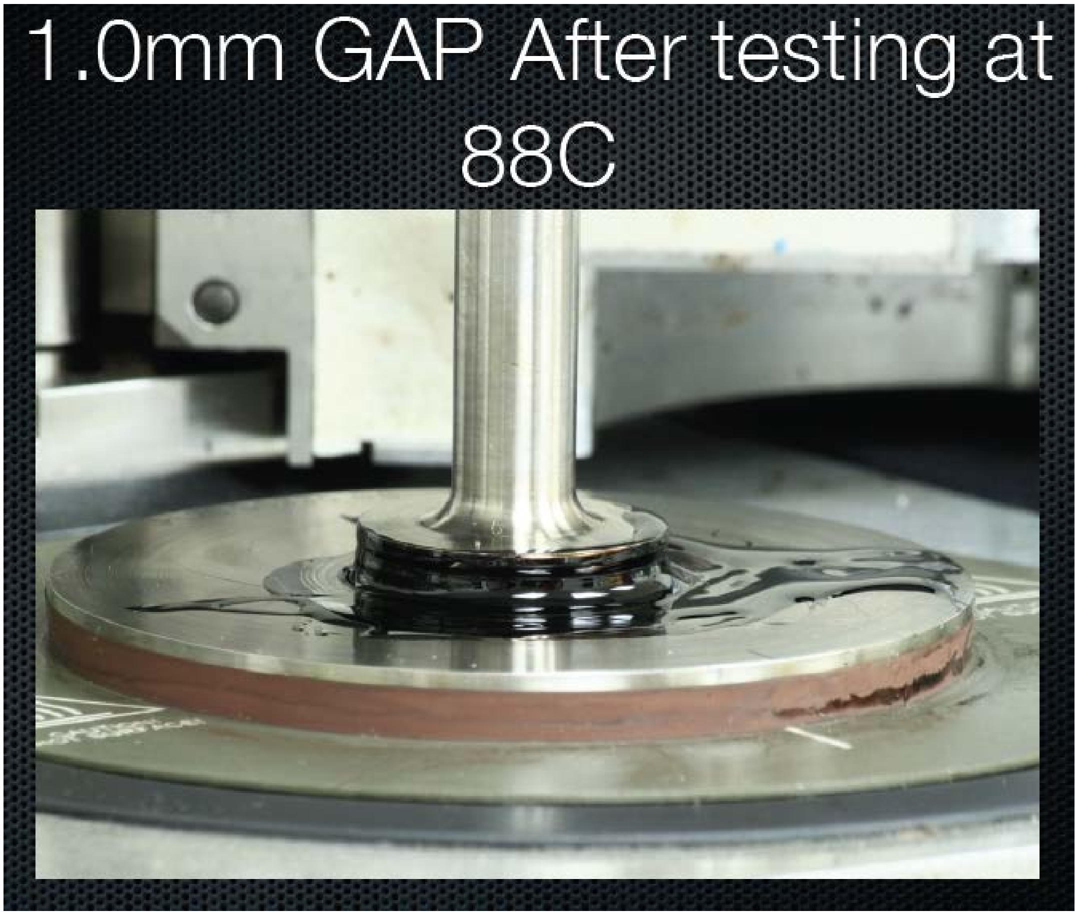


Figure 16 – 1.0mm Gap Height Immediately After Testing at 88^{o}C

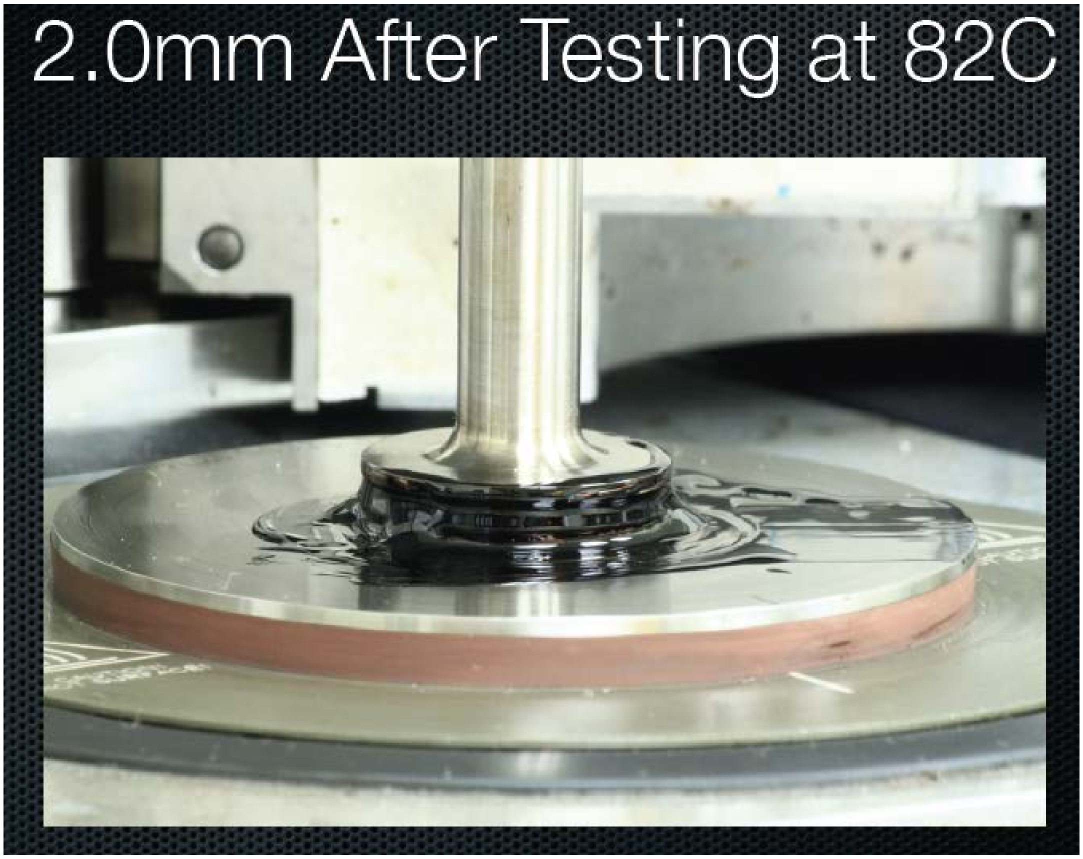


Figure 17 – 2.0mm Gap Height Immediately After Testing at 82^{o}C

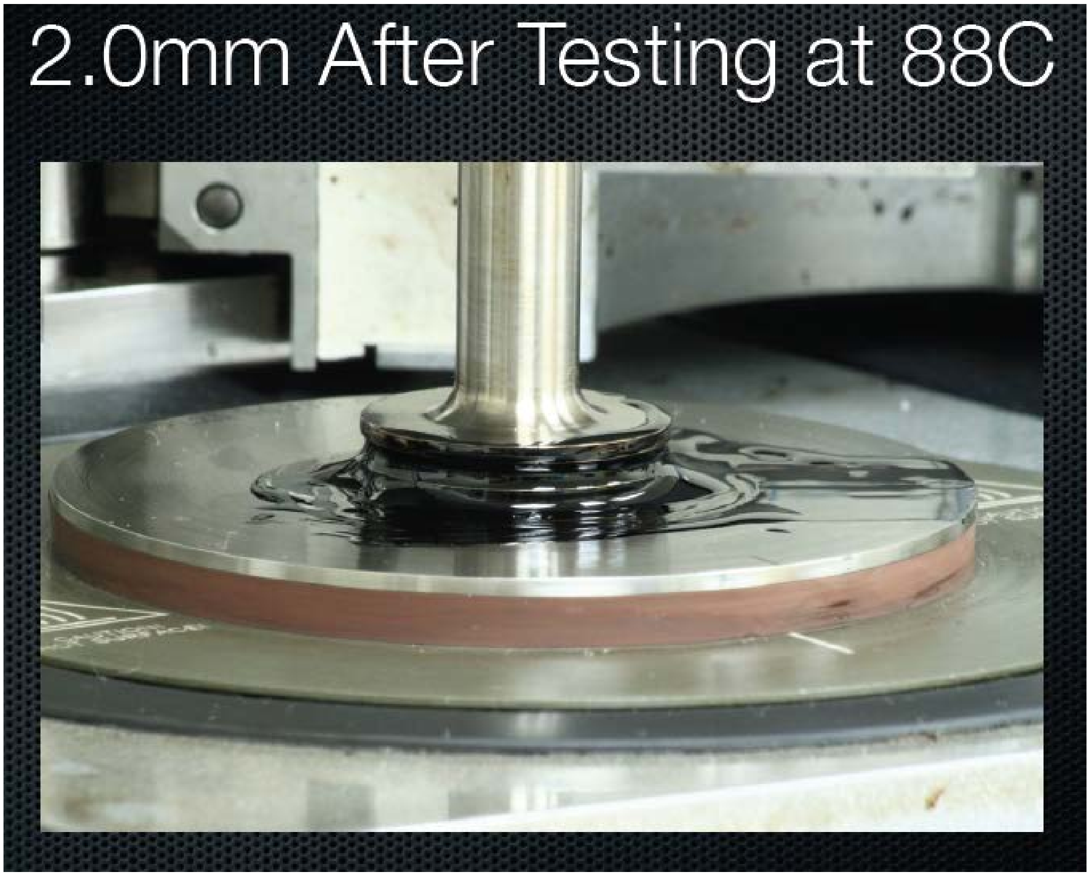


Figure 18 – 2.0mm Gap Height Immediately After Testing at 88^{o}C

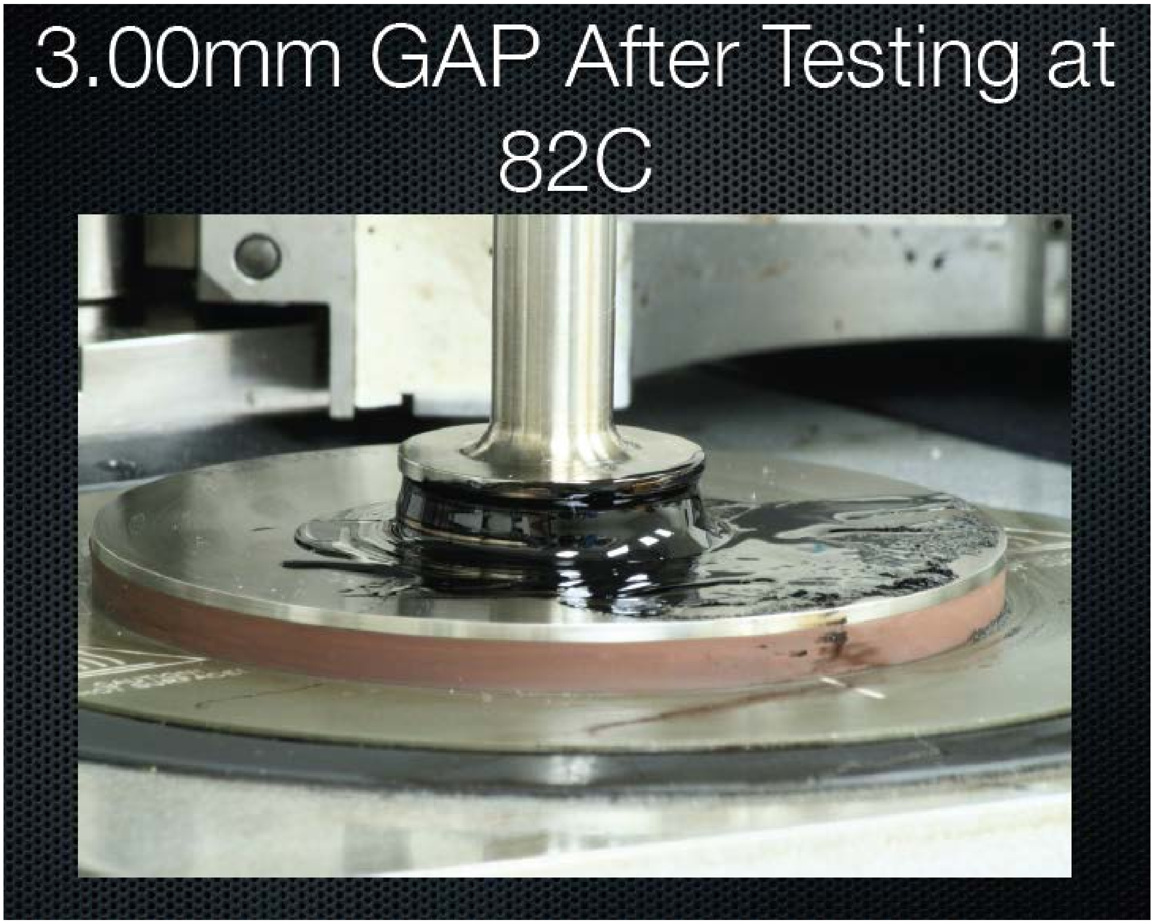


Figure 19 – 3.0mm Gap Height Immediately After Testing at 82^{o}C

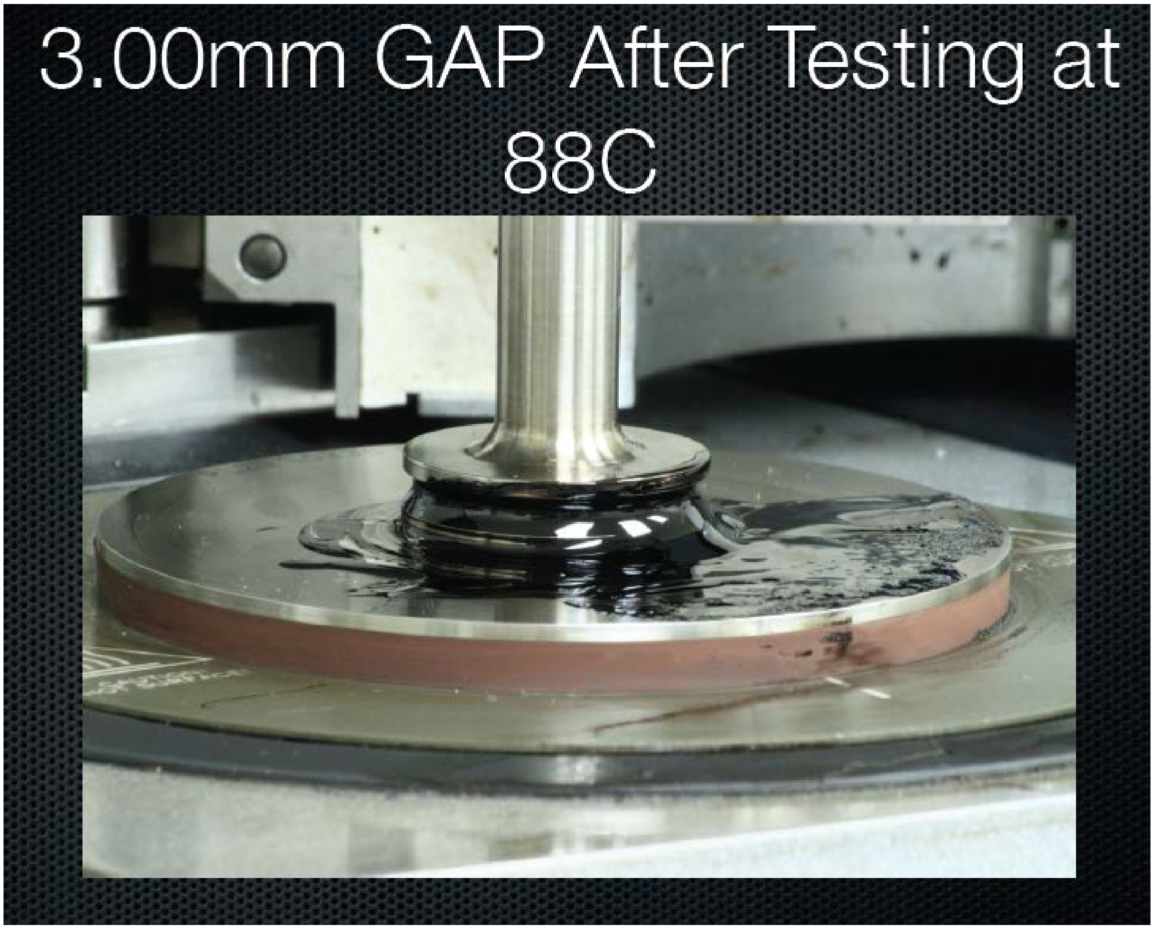


Figure 20 - 3.0mm Gap Height Immediately After Testing at 88°C

2.6 Update on FHWA Research Regarding CRM Asphalt Binders

During the gathering of information for the State of the Practice document, Rutgers University contacted Dr. John D'Angelo, former Asphalt Team Leader for the FHWA and now a consultant, to collect any information FHWA has been recently working on regarding the performance grading of CRM asphalt binders.

A general summary of current activities is summarized in a presentation by D'Angelo and Baumgardner (2010) at the 2010 Petersen Conference at the Western Research Institute (WRI). FHWA had conducted similar gap height studies as the one previously reported by Rutgers University and found very similar results. The FHWA funded study being conducted by D'Angelo and Baumgardner even attempted to look at gap heights as high as 4.0 mm, but this was nearly impossible to maintain the asphalt binder within the parallel plates (Figure 21).

Figure 21 – Leaking of Asphalt Binder from 4.0 mm Gap Height in the Dynamic Shear Rheometer (After D'Angelo and Baumgardner, 2010)

However, one of the possibilities currently being explored is to conduct the high temperature performance grading only using the Multiple Stress Creep Recovery (MSCR) testing program and eliminate the current PG grading procedure. This was based on the fact that the MSCR is run at PG grade of the asphalt binder, a temperature where the asphalt binder did not appear to leak out at gap heights as high as 3.0 mm. Table 3 shows test results conducted by D'Angelo and Baumgardner (2010) showing MSCR test results of a PG76-22 asphalt binder at 3 different gap heights and at two different test temperatures. The test results indicate that both the Non-recoverable Creep Compliance (Jnr) and the % Recovery were consistent at the respective test temperatures when gap heights increased. The fact that the test temperatures used in the MSCR test are recommended to be conducted at the in-service temperature at the respective location and not above the PG grade temperature of the asphalt binder itself would most likely allow the asphalt binder to be retained with the DSR plates and not leak out during testing.

Table 3 – MSCR Test Results for a PG76-22 Asphalt Binder Tested at Varying Gap Heights and Test Temperatures (D’Angelo and Baumgardner, 2010)

GAP(mm)	TEMP (°C)	COMPLEX MODULUS (kPa)	3.2 kPa STRESS J_{nr} (1/kPa)	3.2 kPa STRESS % Recovery
1	64	8.81	0.212	62.8
2	64	9.22	0.205	62.8
3	64	9.51	0.208	62.5
GAP(mm)	**TEMP (°C)**	**COMPLEX MODULUS (kPa)**	**3.2 kPa STRESS J_{nr} (1/kPa)**	**3.2 kPa STRESS % Recovery**
1	76	2.93	1.579	27.2
2	76	2.97	1.558	27.1
3	76	3.03	1.640	25.8

The second possibility noted by D’Angelo and Baumgardner (2010) is to test the CRM asphalt binder using geometries different than the parallel plate to allow a greater amount of asphalt binder to be tested, hoping to limit any possible interaction between the testing geometry and the asphalt binder. Two potential geometries noted by the researchers were the Bob & Cup and Vane & Cup. These geometries have been used in other studies to measure the loading response of polymers and oil compounds and it is thought that this work may be able to be transferred to the asphalt industry.

After the gap height mini-experiment showed there potentially could be an issue when using a gap height greater than 2.0 mm, Rutgers University began investigating the potential use of alternate geometries that could possibly be used in substitute for the DSR parallel plates. Figure 22a and b show pictures of the geometries manufactured by Malvern Instruments, which is the manufacturer of the DSR at Rutgers University.

(a) (b)

Figure 22 – Possible Alternate DSR Geometries for Measuring High Temperature Properties of CRM Asphalt Binders; (a) Couette & Bob and (b) Vane & Couette

Rutgers University was able to procure the alternate geometries to evaluate whether their use should be recommended for inclusion in the final workplan of this study. Initial testing and visual observation of the testing showed that the top portion of the asphalt binder in the cup appeared to be cooling during testing. Rutgers University further evaluated this by placing a number of thermo-couples on the vane and lowering the vane into the cup filled with asphalt binder as shown in figure 23.

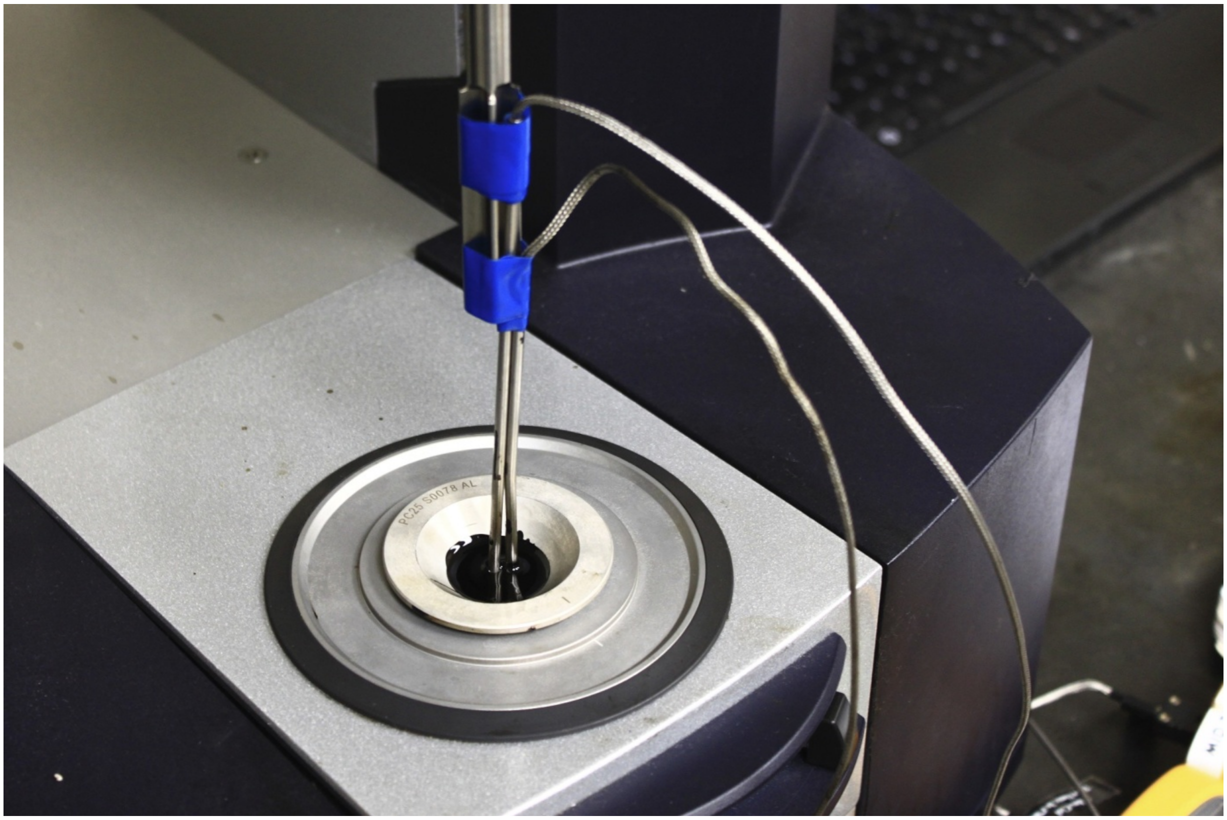


Figure 23 – Thermo-couples Attached to Shear Vane to Test Thermal Gradients

Figure 24 shows the resultant temperature gradients of the asphalt binder in the Cup of the Malvern DSR. It is obvious from the figure that there is an extremely large temperature gradient within the cup, not allowing for accurate testing. Rutgers University reached out to Malvern Instruments to try and rectify these issues. Malvern Instruments is currently working on this issue. Rutgers University had also contacted Dr. John D'Angelo, who is working on similar protocols for the FHWA. Dr. D'Angelo verified that their research grade unit from Anton Paar, which is being used for their research, did not have the same temperature gradient issue as the Malvern DSR.

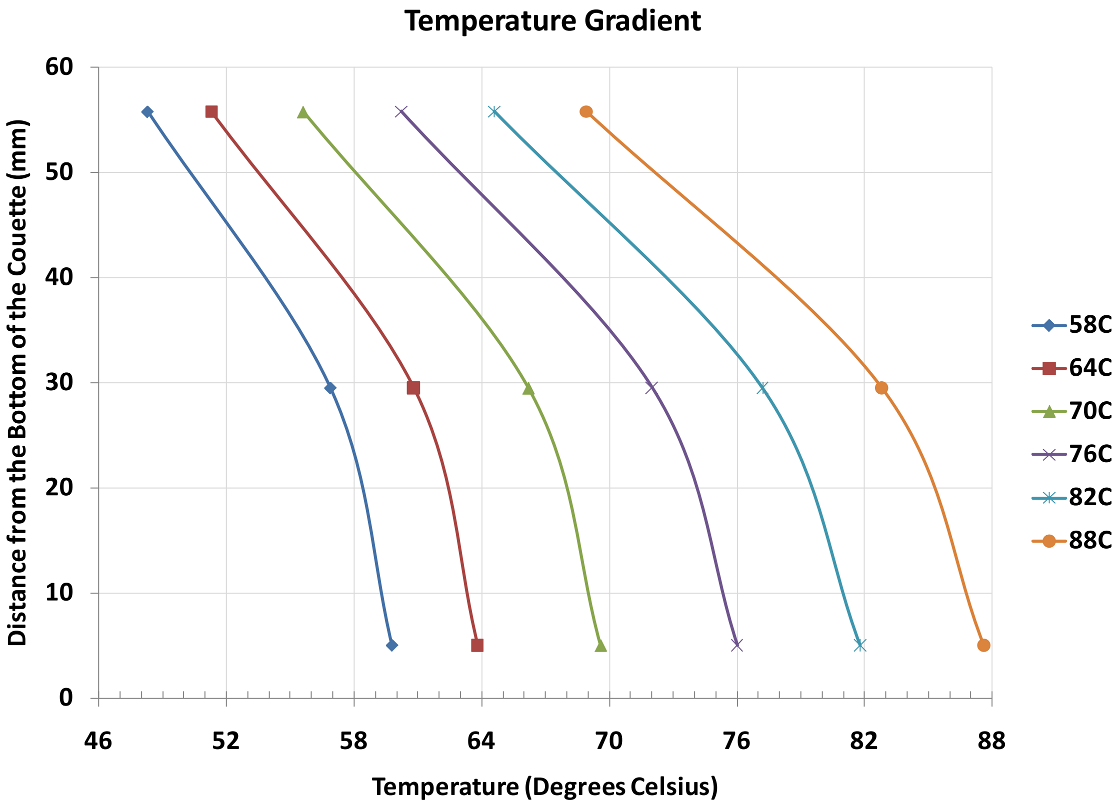


Figure 24 – Measure Temperature Gradient in the Cup Configuration in the Malvern Instruments DSR

2.7 Final Conclusions from Literature Review

An extensive effort was conducted to generate a State of the Practice document for the NYSDOT regarding the use of the Superpave performance grading system on crumb rubber modified (CRM) asphalt binders. Along with a literature review, phone and email interviews were conducted with leading experts in the asphalt binder industry. Based on the information gathered, the following conclusions can be drawn:

1. Early use of the Superpave PG testing protocols with CRM asphalt binders were found to be satisfactory when testing CRM asphalt binders of finer crumb sizes (minus #30 sieve). The use of strain sweeps to ensure the asphalt binder was being tested in its linear elastic range was conducted prior to PG testing to assess if there were any detrimental influences of the crumb rubber on the parallel plate geometry. However, at the time of these studies, precision and bias statements had yet to be developed for the dynamic shear rheometer.
2. Recent references that would found indicated that researchers were either ignoring the effect of the crumb rubber by testing at a 1.0 mm gap height, or again used the strain sweep premise as verifying the CRM asphalt binder was able to be evaluated at a 2.0 mm gap height. These tests included both Superpave PG grading and more recently the Multiple Stress Creep Recovery (MSCR).
3. On-going work funded by the FHWA is looking to enforce the 4:1 ratio of DSR gap height to maximum crumb rubber particle size. By doing this, current testing

protocols (i.e. – 1.0 mm gap height) would limit CRM asphalt binders to using crumb rubber finer than a #60 mesh (0.250 mm). The FHWA funded work looked at implementing the MSCR test to "grade" the high temperature performance of the CRM asphalt binders instead of the current linear elastic, oscillatory testing. The main reason is that increased gap heights can be implemented since the MSCR test is conducted at test temperatures generally at or lower than the actual PG grade of the asphalt binder. Therefore, there is a lesser risk of the asphalt binder leaking out of the DSR plates at the failure temperatures, as witness by both the FHWA and Rutgers University.

4. The Sensitivity Study conducted by Rutgers University validated the work by the FHWA by showing that indeed at the failure temperature of the PG grade testing the asphalt binders have a tendency to begin to leak out of the DSR plates, even at gap heights of 2.0 mm. Comparing the differences between the 1.0 to 2.0 mm and 1.0 to 3.0 mm gap height DSR results to the precision and bias statement of AASHTO T315, it was evident that for both the Original and RTFO aged binder conditions the differences were significant and therefore failed the allowable range of two tests. This further confirms the preliminary recommendation by the FHWA that high temperature performance testing at increased gap heights needs to be conducted at or below the PG grade of the asphalt binder. This would lend credence to the proposition of using the Multiple Stress Creep Recovery (MSCR) test the at in-service pavement temperature to evaluate the high temperature performance of CRM asphalt binders.
5. Another possibility to help in evaluating the high temperature performance of CRM asphalt binders is the use of alternate geometries that would allow for the testing of a greater amount of CRM asphalt binder, accentuating the "bulk" properties of the CRM asphalt binder. The alternate geometries would also negate some of the issues currently encountered with the parallel plates as both the Bob and Vane geometry system utilize a "Cup" for the CRM asphalt binder to be tested in (similar to the rotational viscosity test).

CHAPTER 3

PROPOSED WORKPLAN

3.1 Introduction

The proposed workplan utilized two phases of laboratory testing to evaluate the high temperature performance of crumb rubber modified (CRM) asphalt binders; 1) Asphalt binder performance testing and 2) Asphalt mixture performance testing. The Research Team looked at three different asphalt binder high temperature performance tests and then compared those results to high temperature asphalt mixture performance tests. Since the goal of the asphalt binder tests was to rank the high temperature performance of the asphalt pavement, the mixture performance tests were utilized to compare and rank the high temperature asphalt binder results.

Along with the asphalt binder and mixture performance testing, a mini-experiment was also conducted to evaluate whether or not the CRM asphalt binders can be simply substituted for typical asphalt binders currently approved and used in NYSDOT asphalt mixtures. The fear is that residual crumb rubber particles may interfere with the compaction of the asphalt mixture.

3.2 High Temperature Asphalt Binder Testing

For the high temperature asphalt binder testing, the Research Team evaluated three test methods that were discussed and summarized in the Literature Review/State of the Practice; 1) Conventional high temperature performance grading (AASHTO M320); 2) Multiple Stress Creep Recovery, MSCR (AASHTO TP70) with a gap height of 2.0mm, and 3) Use of Cup & Bob alternate geometries.

Along with the three high temperature performance tests, to be described in further detail below, the elastic recovery, as per NYSDOT specifications, was also determined.

3.2.1 – AASHTO M320, Performance Graded Testing

All asphalt binders included in the study were high temperature performance graded in accordance with AASHTO M320. The current concern with AASHTO M320 is the 1.0 mm gap height and the possibility that residual crumb rubber in the asphalt binder may interfere with the accuracy and repeatability of the DSR measurements.

3.2.2 – Multiple Stress Creep Recovery at 2.0 mm Gap Height

The second high temperature performance test conducted on the asphalt binders was the Multiple Stress Creep Recovery (MSCR) at an increased gap height of 2.0 mm. As noted by the Research Team in the Literature Review, testing conducted at increased gap heights in the DSR showed that when the test temperature was increased to the PG Grade

+ 6^{o}C, the asphalt binder began to "leak" out from in between the DSR plates. However, this did not occur at the PG grade temperature. Since the MSCR test is intended to be run at the state's regional high temperature grade, not corrected for traffic volume or speed, it stands to reason that at a 2.0 mm gap height, the asphalt binder should be able to be tested under the MSCR test protocol and provide accurate and repeatable results. Preliminary data from the FHWA at the laboratory in Turner-Fairbanks has verified this hypothesis, although testing was limited.

3.2.3 – Alternate Geometry – Cup & Bob

Current work with respect to CRM asphalt binders is moving towards the possible use of alternate geometries besides the current parallel plate system employed in the dynamic shear rheometer (DSR). The proposed Cup & Bob geometry allows for a larger bulk volume of asphalt binder to be tested, thereby better capturing the enhancement properties of the crumb rubber modification while not being influenced by residual crumb rubber particle and geometry contact.

Although test procedures are not currently available for this test setup, the methodology currently being explored by the FHWA and its consultants were used.

3.3 High Temperature Asphalt Mixture Testing

One of the major difficulties associated with the project is determining whether or not the asphalt binder testing equipment is measuring accurate test results of the CRM asphalt binders. Although the test information may indicate a particular PG grade or test parameter, uncertainties still exist regarding whether the asphalt binder properties are those measured or if they were influenced by crumb rubber particles still residing in the asphalt binder. According the AASHTO M320, Section 5;

> "This specification (i.e. – AASHTO M320) is not applicable for asphalt binders in which fibers or other discrete particles are larger than 250 μm in size."

To verify the CRM asphalt binder performance, mixture performance testing was conducted. The purpose behind the mixture performance was to:

1. Compare the ranking of the asphalt binder test results to the mixture performance results. Occasions where the rankings conflict one another, issues with the asphalt binder testing may have occurred.
2. Compare mixture performance of the CRM asphalt binders to the mixture performance of "typical" neat and polymer-modified asphalt binder of equivalent PG grade. If mixture performance was found to be statistically equal, it can be concluded that the asphalt binder testing was accurate.

For the mixture evaluation, the Research Team believes it is important to not only look at small strain stiffness properties, similar to the AASHTO M320 procedure in determining

G*, but also the mobilized/flow properties of the asphalt mixture, similar to the MSCR test. Therefore, the following high temperature mixture performance tests were conducted;

1. General Mixture Stiffness – Dynamic Modulus (AASHTO TP79);
2. Rutting Resistance – Flow Number as measured during Repeated Load Testing (AASHTO TP79);
3. Rutting Resistance - Asphalt Pavement Analyzer (AASHTO T340)

All mixture performance testing were conducted using the same aggregate source and aggregate blend. The proposed asphalt mixture shall be designed using the NYSDOT 5.16 Mixture Design protocols.

3.4 Gyratory Compaction Mini-Experiment

One of the concerns of the Research Team is the possible use of a CRM asphalt binder in a "tight" asphalt mixture. Depending on the CRM procedure, residual crumb rubber particles may still exist in the asphalt binder. Unfortunately, if the aggregate blend of the asphalt mixture is designed along the maximum density line, minimal space between the aggregates will exist. If this is the case, residual crumb rubber in the asphalt binder may actually cause the aggregates to push apart, causing the compacted mixture to swell.

To evaluate this, the Research Team conducted a mini-experiment consisting of compacting approximately 5 asphalt mixtures using typical asphalt binders, and asphalt binders modified with crumb rubber. It was hopeful that the mini-experiment would shed some light on whether or not the CRM asphalt binders could be used in an "either or" bid announcement by the NYSDOT.

CHAPTER 4

ASPHALT BINDER TESTING

In the original workplan, it was agreed upon that the following asphalt binders would be evaluated in the study:

- NuStar Asphalt Refining Baseline Binders (No CRM)
  - PG64-22
  - PG70-22
  - PG76-22
- All States CRM Binders
  - PG58-28 + 17.5% crumb rubber
  - PG64-22 + 17.5% crumb rubber
- Wright Asphalt Terminal Blend
  - PG58-34 + 10% Tire Rubber (TR)
  - PG64-22 + 10% TR
  - PG70-22 + 10% TR
  - PG76-22 + 10% TR
- Suit Kote
  - 64-22 30 Mesh Ground Tire Rubber (GTR)
  - 64-22 50 Mesh GTR

The above asphalt binders were selected from the different manufacturers as they were what each respective manufacturer would be able to supply to NYSDOT on a routine basis. More extravagant binders would be able to be manufactured by each of the asphalt suppliers, however, this would clearly increase the cost of the material and not be cost competitive to the conventional binders. The Baseline binder grades were chosen to provide a wide range of typical high temperature PG grades that the CRM binders would fall under.

During the process of binder sample procurement, more than the eleven (11) binders shown above were obtained. To help with establishing a stronger correlation between the asphalt binder test procedures, 22 different asphalt binders were tested. These ranged from different mesh size, different starting PG grades, and other suppliers not shown above. However, due to time constraints, it should be noted that only the asphalt binders shown above were included in the asphalt mixture testing.

4.1 Continuous High Temperature PG Grade

The high temperature continuous performance grade (PG) was determined in accordance to AASHTO R29, *Grading or Verifying the Performance Grade (PG) of an Asphalt Binder*. The dynamic shear rheometer (DSR) used a gap height of 1.0 mm for all testing as this is the current test procedure adopted typical asphalt binder PG grading. The test results for all of the asphalt binders measured during the testing is shown in Figure 25. It should be noted that the coarsest crumb rubber particle sample utilized in the binders evaluated and shown in Figure 25 was a 20 mesh (850 microns).

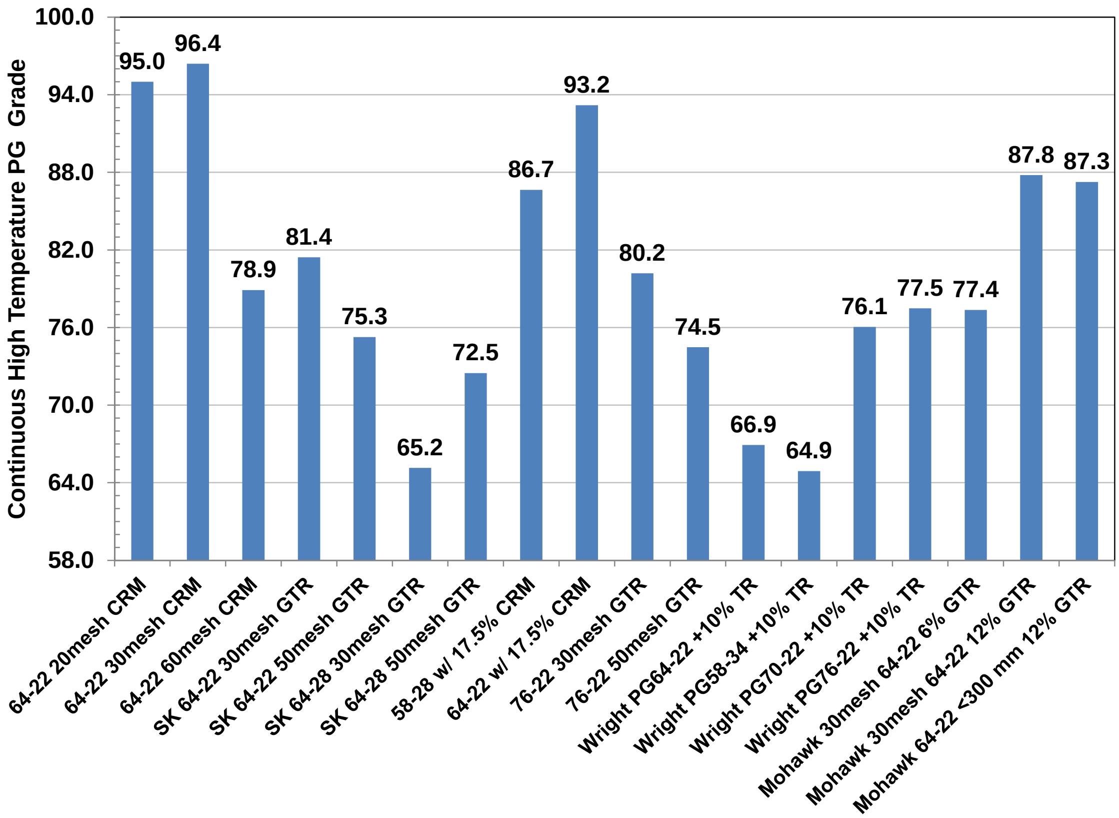


Figure 25 – Continuous High Temperature PG Grade Results

At first look of the continuous high temperature (CTH) PG grades in Figure 25, there is no clear indication as to the trend with CTH and mesh size. Since the performance of the CRM asphalt binder is highly dependent on the chemical composition of the tire rubber and the base asphalt binder itself, it would not be prudent to compare the effects of mesh size or tire rubber content using the entire data set. Therefore, individual suppliers binders, assuming the base binder source and crumb tire source was consistent, was compared.

In general, the continuous high temperature PG grades, determined when using a 1.0 mm gap height in the DSR show;

- A general increase in PG grade with an increase in crumb rubber particle size. This was found in Source #1, #2, and #4.
- As expected, the base grade of asphalt binder influence the continuous high temperature PG grade. Within each Source, when softer base binders were used to blend the tire rubber, using the identical size and dosage rate, the resultant high temperature PG grade was lower. This was found in Source #2 and #3. In fact, a closer look at Source #2 shows that even though the high temperature PG grade was the same (i.e. – PG64-22 and PG64-28), when the asphalt supplier used a "softer" PG64-28 to blend the tire rubber, it resulted in reduced high temperature PG grades when compared to the PG64-22. It is assumed that both the PG64-22 and PG64-28 were from the same crude source.

Table 4 – Continuous High Temperature PG Grade Determined using the Dynamic Shear Rheometer (DSR) with 1.0 mm Gap Height

Source ID	Binder Type and Supplier	Continuous High Temp PG Grade
#1	64-22 20mesh CRM	95.0
	64-22 30mesh CRM	96.4
	64-22 60mesh CRM	78.9
#2	SK 64-22 30mesh GTR	81.4
	SK 64-22 50mesh GTR	75.3
	SK 64-28 30mesh GTR	65.2
	SK 64-28 50mesh GTR	72.5
#3	58-28 w/ 17.5% CRM	86.7
	64-22 w/ 17.5% CRM	93.2
#4	76-22 30mesh GTR	80.2
	76-22 50mesh GTR	74.5
#5	Wright PG64-22 +10% TR	66.9
	Wright PG58-34 +10% TR	64.9
	Wright PG70-22 +10% TR	76.1
	Wright PG76-22 +10% TR	77.5
#6	Mohawk 30mesh 64-22 6% GTR	77.4
	Mohawk 30mesh 64-22 12% GTR	87.8
	Mohawk 64-22 <300 μm 12% GTR	87.3

- As the percent of tire rubber used to modify the asphalt binder increased, the continuous high temperature PG grade increased. This is shown with the data generated from Source #6.

4.2 Elastic Recovery @ 25°C (ASTM D6084-04, Procedure A)

To ensure modified asphalt binders have been properly modified with elastomeric-based polymers, the NYSDOT includes the Elastic Recovery test. The Elastic Recovery test is conducted in accordance with ASTM D6084-04, Procedure A at a test temperature of 25°C. A minimum of 60% recovery is required by the NYSDOT for all polymer-modified asphalt binders.

The Elastic Recovery test was included in this study to evaluate whether or not crumb rubber modification of asphalt binders results in similar elastic response as SBS modified asphalt binders. The Elastic Recovery test results are shown in Figure 26. The test results suggest that all of the asphalt binders tested met the 60% minimum requirement except for the SK 64-28 30 Mesh sample, which obtained an elastic recovery of 50%. Based on these test results, it suggests that the addition of crumb rubber modifies the asphalt binder in a similar manner to an elastomeric polymer.

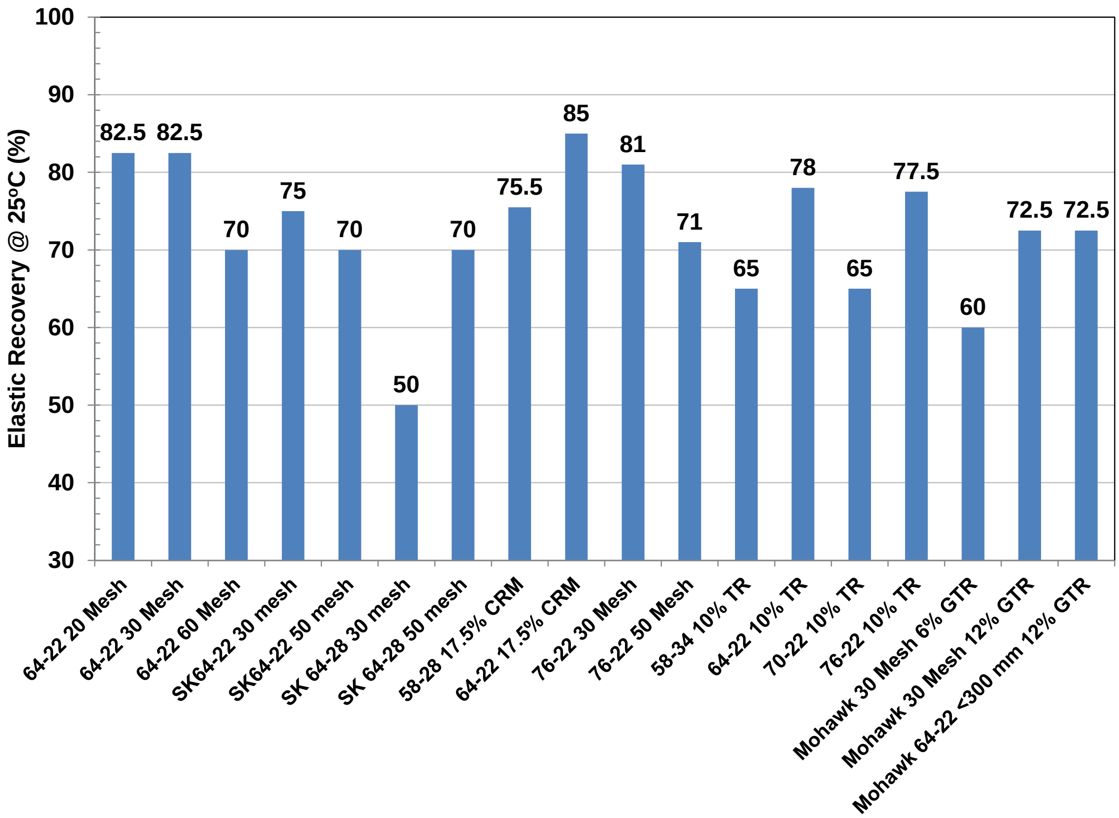


Figure 26 – Elastic Recovery (ASTM D6084) Test Results

4.3 Multiple Stress Creep Recovery (MSCR) Test using 2.0 mm Gap Height

The Multiple Stress Creep Recovery (MSCR) test was conducted in accordance with AASHTO TP70-12, *Multiple Stress Creep Recovery (MSCR) Test of Asphalt Binder Using a Dynamic Shear Rheometer*. The non-recoverable creep compliance (J_{nr}) and the % Recovery were measured at 64°C, as determined by the NYSDOT Technical Working Group as the high temperature in-situ pavement temperature. The test results are shown in Figure 27 and Table 6.

In general, the non-recoverable creep compliance (J_{nr}), determined when using a 2.0 mm gap height in the DSR show;

- A general decrease in J_{nr} with an increase in crumb rubber particle size. This was found in Source #1, #2, and #4 (Table 5).
- When using a stiffer asphalt binder with the identical crumb rubber dosage rate and particle size, the J_{nr} value decreased. This is most likely due to general increased stiffness of the base binder used. This was found in Sources #2 and #3 (Table 5).

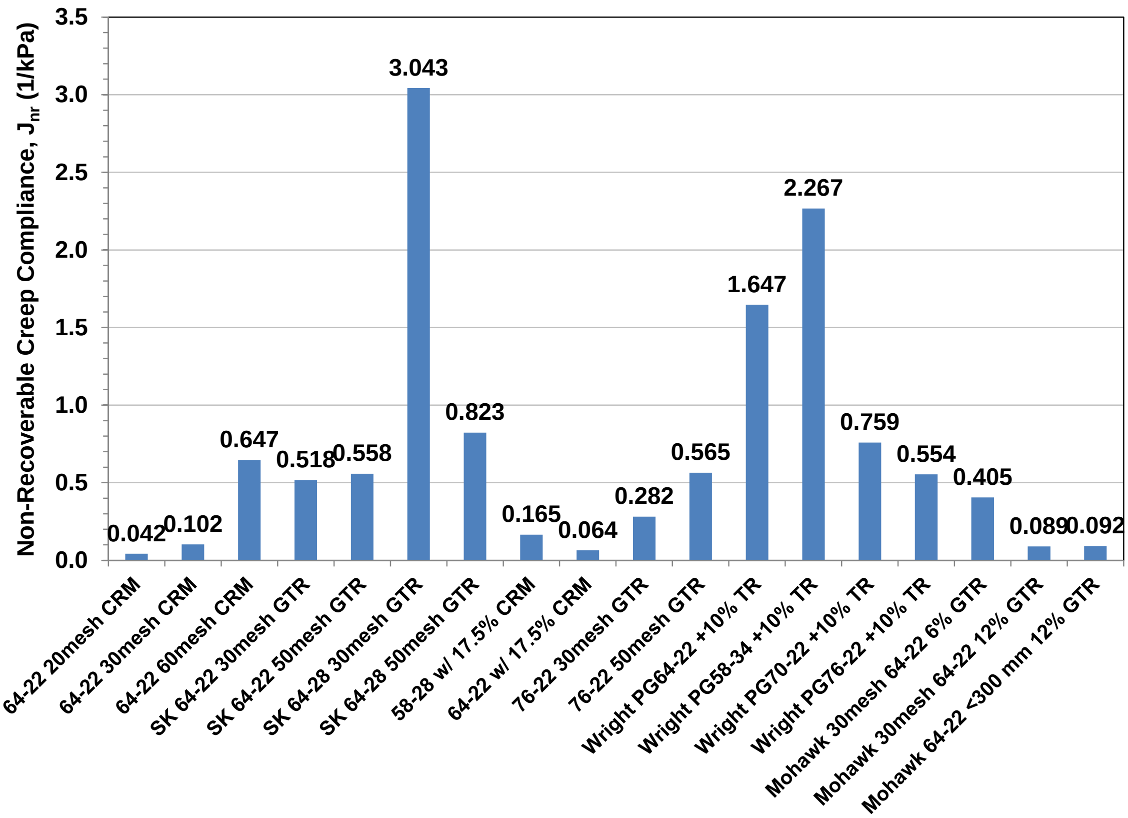


Figure 27 – Multiple Stress Creep Recovery (MSCR) Non-recoverable Creep Compliance (J_{nr}) Results at 64°C

The resultant MSCR test data for each of the asphalt binders was also plotted on the Jnr - % Recovery chart and is shown in Figure 28. Along with the crumb rubber modified binders, conventional asphalt binders (PG64-22, PG64-28, PG70-22, and PG76-22) were also plotted on the chart. The results indicate that only the asphalt binders that had a J_{nr} value less than 0.5 kPa^{-1} recorded % Recovery values that plotted above the MSCR Elastic Recovery line (shown as Black in Figure 28). The data shown in Figure 28 may indicate that even though the asphalt binder shows a “stiffening” due to the addition of the crumb rubber, the modification may not be as elastomeric as previously thought and indicated during the Elastic Recovery test (Figure 26). It should be noted that the trendline generated from the crumb rubber modified binders (Red dashed line) fits the conventional binders (SBS modified PG76-22 and unmodified PG70-22, PG64-28, and PG64-22) as well. The conflicting results in Figures 26 and 28 have been noted before, in particular by Dongre and D’Angelo (2008). In a study looking at the effect of polymer amount, cross-linking agent amount, and blending time, the % Recovery parameter from the MSCR was found to be sensitive to these parameters and how the asphalt binder reacted under these conditions. Meanwhile, the Elastic Recovery test showed limited sensitivity to any of the same parameters. The authors concluded the although the Elastic Recovery test can identified the presence of an elastomeric material in the asphalt binder, the test is not sensitive enough to determine whether proper dispersion and cross-linking has occurred – something the MSCR % Recovery parameter was clearly able to capture.

Table 6 - Multiple Stress Creep Recovery (MSCR) Non-recoverable Creep Compliance (J_{nr}) Results at 64°C

Source ID	Binder Type and Supplier	Jnr
#1	64-22 20mesh CRM	0.042
	64-22 30mesh CRM	0.102
	64-22 60mesh CRM	0.647
#2	SK 64-22 30mesh GTR	0.518
	SK 64-22 50mesh GTR	0.558
	SK 64-28 30mesh GTR	3.043
	SK 64-28 50mesh GTR	0.823
#3	58-28 w/ 17.5% CRM	0.165
	64-22 w/ 17.5% CRM	0.064
#4	76-22 30mesh GTR	0.282
	76-22 50mesh GTR	0.565
#5	Wright PG64-22 +10% TR	1.647
	Wright PG58-34 +10% TR	2.267
	Wright PG70-22 +10% TR	0.759
	Wright PG76-22 +10% TR	0.554
#6	Mohawk 30mesh 64-22 6% GTR	0.405
	Mohawk 30mesh 64-22 12% GTR	0.089
	Mohawk 64-22 <300 μm 12% GTR	0.092

A comparison of the Elastic Recovery and the MSCR % Recovery results is shown in Figure 29. The figure shows a relatively good correlation exists between the two test methods, although the general range of results is somewhat limited for the Elastic Recovery test. A majority of the Elastic Recovery values fell between 60% and 85%. Meanwhile, the majority of the MSCR % Recovery values fell between 10% and 75%. The larger scattering of data for the MSCR % Recovery values may verify the statements noted earlier by Dongre and D'Angelo (2008), where the authors indicated that the MSCR % Recovery results provides a better indication of the overall networking within the asphalt binder and not simply an indicator that an elastomer is present, as perhaps the Elastic Recovery test shows.

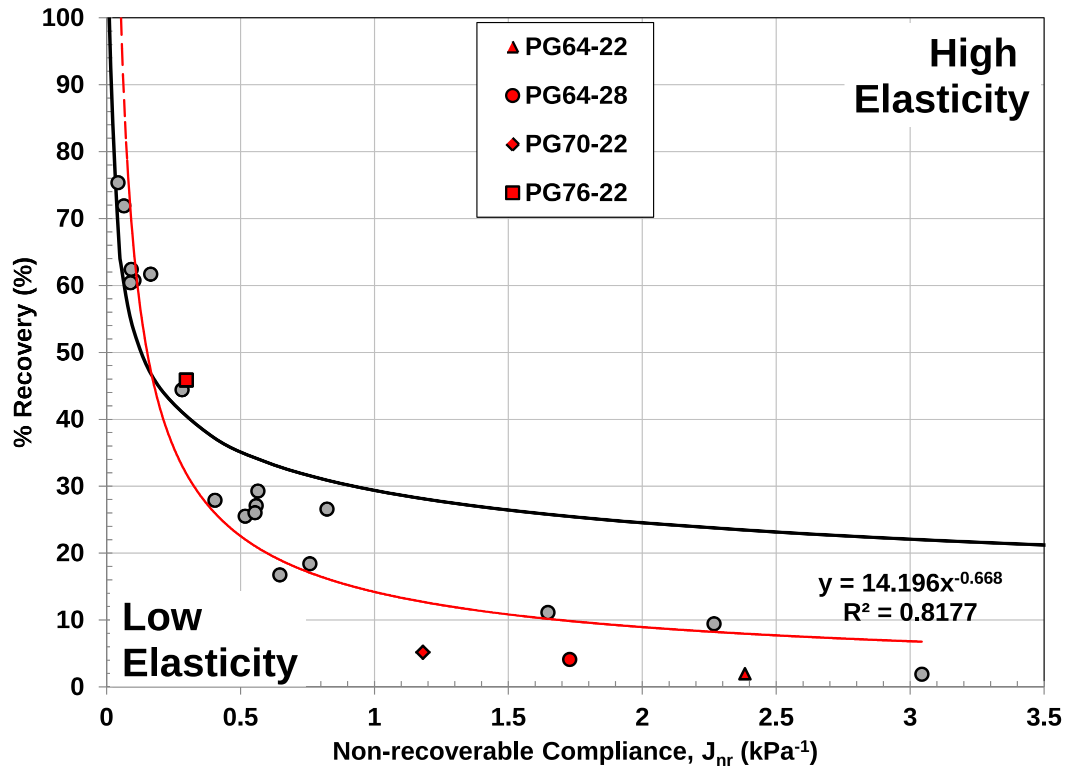


Figure 28 – J_{nr} - % Recovery Curve and Data for Binders Tested at 64^oC

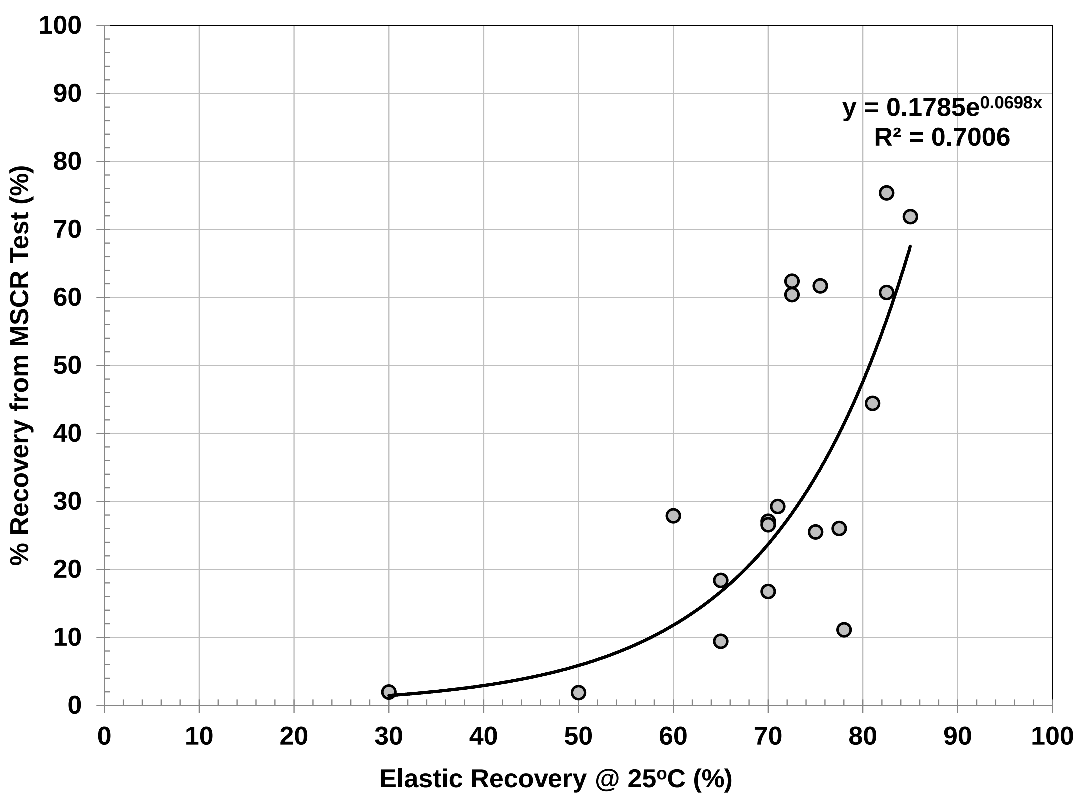


Figure 29 – Elastic Recovery (ASTM D6084) vs MSCR % Recovery Test Results

4.4 Alternate Geometry Testing Using the Cup & Bob

As discussed earlier in Chapter 2, the use of alternate test geometries to determine the high temperature properties of crumb rubber modified is currently being explored to help alleviate particulate interference with the DSR parallel plates. The Cup & Bob procedure has an advantage over the parallel plates as a larger bulk sample can be tested and possibly eliminate any particle interaction that may influence the final measured properties. Unfortunately, no standardized test procedure exists and the current procedure used is based on mirroring the same general format used with the DSR (i.e. – test temperatures, loading rates, etc.) except the obvious change in geometry.

Since the testing method is in its preliminary stages, the testing was conducted at the high temperature PG grade previously determined and noted earlier. The Cup & Bob determined G*/sin δ for each asphalt binder, at Original and RTFO conditions, were compared to the DSR values and plotted in Figure 30. The results show that on average, the Cup & Bob measured G*/sin δ values are 15% higher than that determined with the DSR parallel plates and gap height of 1.0 mm.

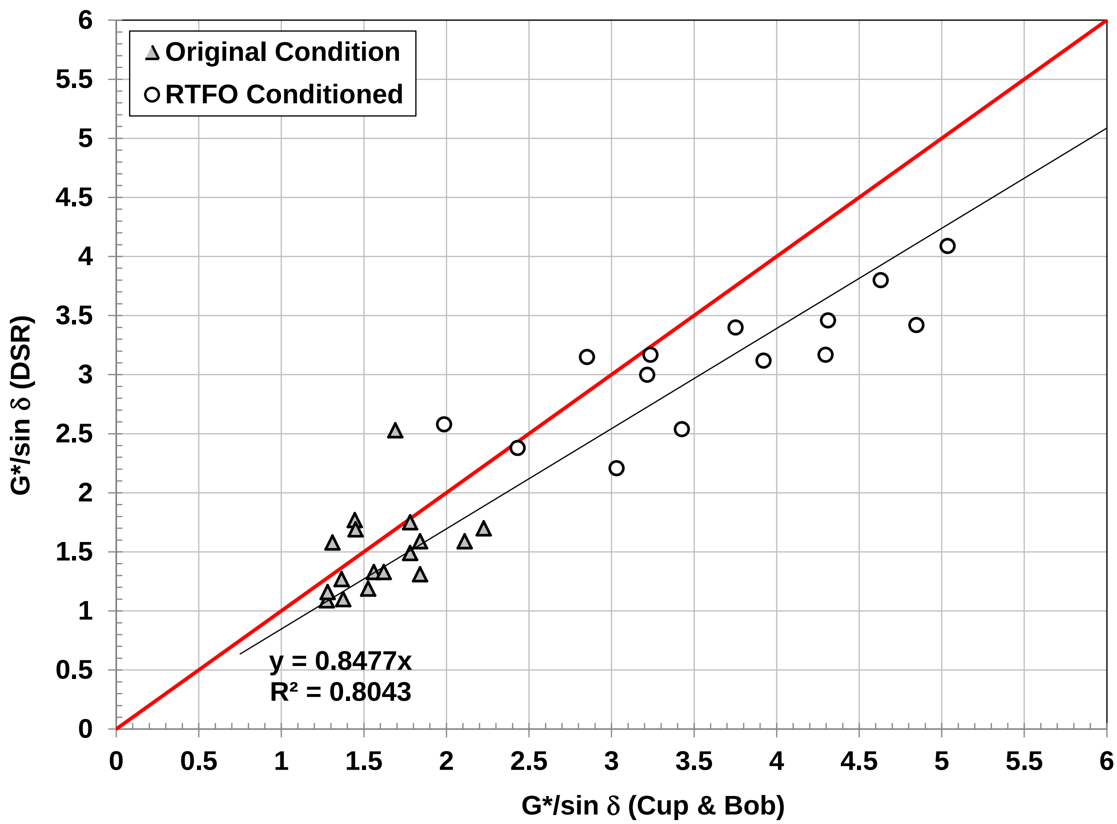


Figure 30 – G*/sin δ for Cup & Bob and DSR Testing Configurations

Both the shear modulus (G*) and phase angle (δ) were separated out from Figure 30 and plotted separately as Figures 31 and 32, respectively. In Figure 31, it indicates that the shear modulus measured by the Cup & Bob geometry is approximately 17% greater than the DSR parallel plates set at a gap height of 1.0 mm. Figure 32 shows the phase angle

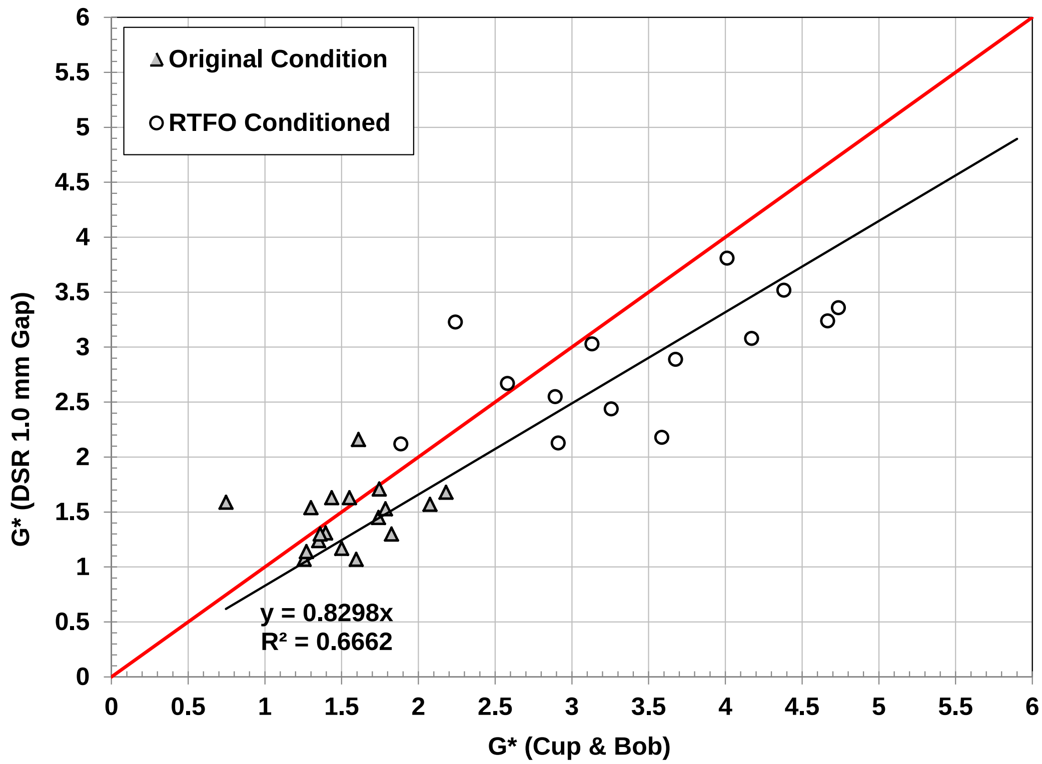


Figure 31 – G* for Cup & Bob and DSR 1.0 mm Gap Testing Configurations

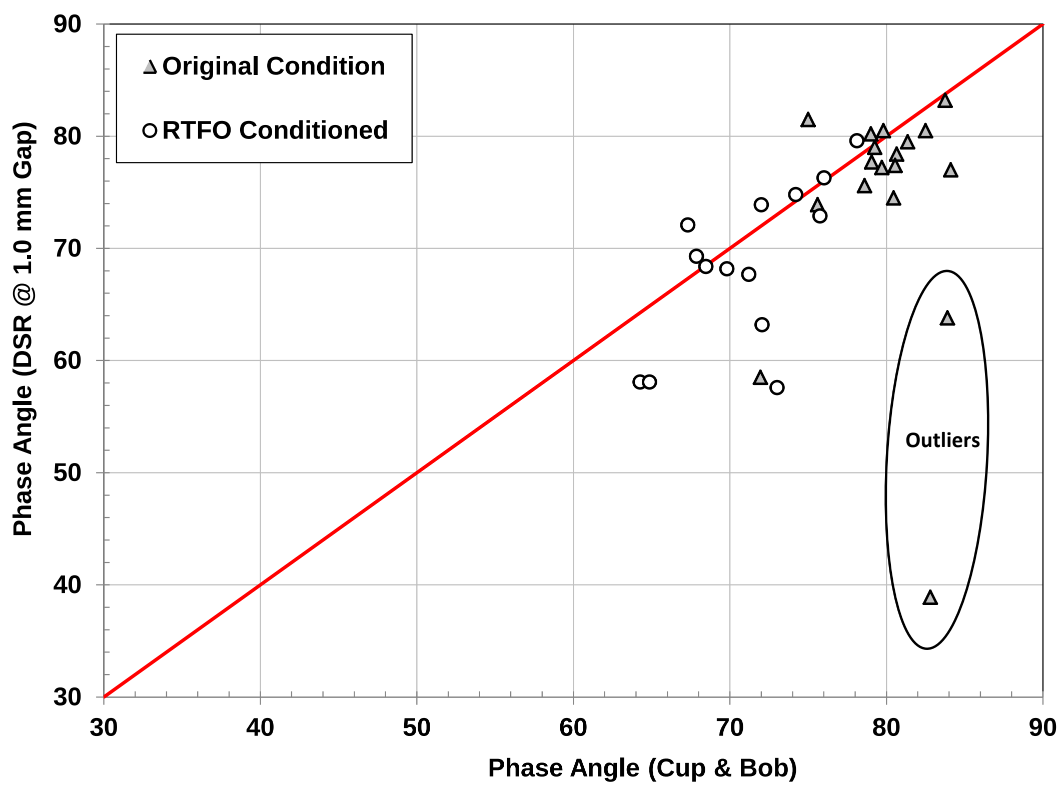


Figure 32 – Phase Angle (δ) for Cup & Bob and DSR 1.0 mm Gap Testing Configurations

comparisons between the Cup & Bob and DSR parallel plates set at a gap height of 1.0 mm. The phase angle results show two binders that are clear outliers and are circled in the chart. Both binders were provided by the same asphalt supplier. Comparisons between the test results show that:

- Original Aged Condition
    - Using all data, the phase angle from the Cup & Bob is on average 5.6 degrees higher than the parallel plates configuration
    - Eliminating the 2 outliers in Figure 32, the phase angle from the Cup & Bob is on average 2.3 degrees higher than the parallel plate configuration
- RTFO Aged Condition
    - Using all data, the phase angle from the Cup & Bob is on average 2.5 degrees higher than the parallel plates configuration
    - Eliminating the 2 outliers in Figure 32, the phase angle from the Cup & Bob is on average 0.9 degrees higher than the parallel plate configuration

The results shown in Figures 30 to 32 indicate that the Cup & Bob geometry provides results that are consistent with the DSR parallel plate configuration with a gap height setting of 1.0 mm. At this time, there is no indication as to which test method may be more accurate. However, it does appear that when utilizing crumb rubber modified binders with crumb rubber particle size of 20 Mesh or finer, the results are consistent with one another.

4.5 Comparison of Parallel Plate Configurations – 1.0 mm G*/sin δ and 2.0 mm MSCR

As shown earlier, the test results between the Cup & Bob and the DSR parallel plates at 1.0 mm gap height were similar when evaluating crumb rubber modified binders, thereby indicating that perhaps the test results of the DSR at the 1.0 mm gap height may be applicable when using crumb rubber modified binders with crumb rubber particles of 20 Mesh or finer. The G*/sin δ determined using the 1.0 mm gap height in the DSR was also compared to the MSCR properties, J_{nr} and % Recovery, using a 2.0 mm gap height in the DSR. As shown earlier, it was determined that asphalt binders appropriate for NY State conditions (i.e. – high temperature PG grade of 64^{o}C or higher) can maintain proper shape and volume within the parallel plates at a 2.0 mm gap height and therefore would be able to be tested using currently recommended MSCR test procedures.

Figure 33 shows the determine continuous high temperature PG Grade versus the MSCR Jnr value determined at 64^{o}C, which is the in-situ high temperature as determined by the NYSDOT. The results show an extremely good agreement between the two tests when testing the crumb rubber modified binders. Asphalt binders of different PG grades, not modified with crumb rubber, were also tested and superimposed on the figure (shown in Red). The non-crumb rubber modified binders are in very good agreement with the crumb rubber modified data, indicating that this relationship between 1.0 mm gap height DSR high temperature PG grade and 2.0 mm gap height MSCR J_{nr} holds for neat and modified asphalt binders, with and without crumb rubber.

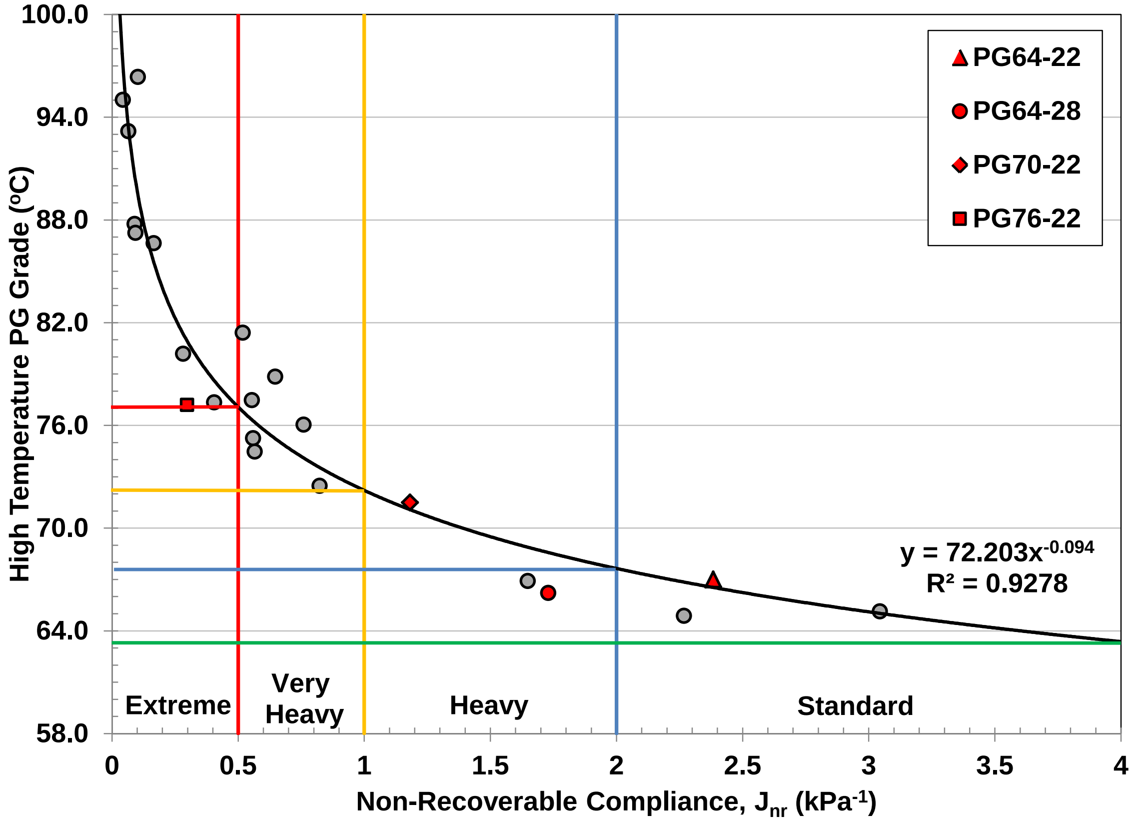


Figure 33 – High Temperature PG Grade with 1.0 mm Gap Height vs MSCR J_{nr} with 2.0 mm Gap Height at 64°C Test Temperature

The high temperature PG grade, determined at a 1.0 mm gap height in the DSR, was also compared to the MSCR % Recovery using a 2.0 mm gap height and a test temperature of 64°C. The resultant comparison is shown in Figure 34. The test results between the different tests again compare well, indicating the elastic response measured in the % Recovery test is obviously picked up in the G*/sin δ parameter of the high temperature PG grade.

The strong correlation between the asphalt binder properties of the high temperature PG grade at 1.0 mm gap height and the MSCR test conducted at 2.0 mm gap height suggests that it would appear a 1.0 mm gap height can be used by NYSDOT to appropriately PG grade crumb rubber modified binders, as long as the crumb rubber particle size is 20 Mesh or finer.

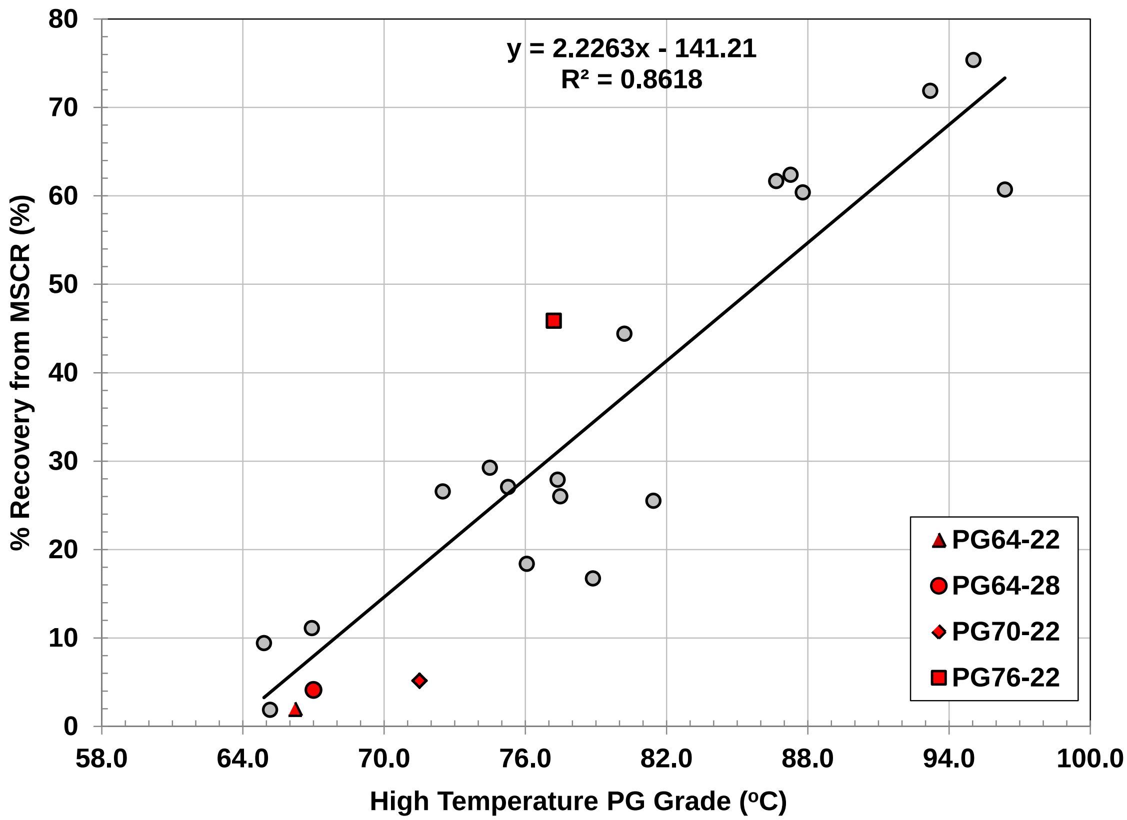


Figure 34 – High Temperature PG Grade with 1.0 mm Gap Height vs MSCR % Recovery with 2.0 mm Gap Height at 64°C Test Temperature

4.6 Separation Testing

Separation testing was conducted on the asphalt binders to evaluate whether or not the crumb rubber modified asphalt binders are prone to separating when stored at elevated temperatures with no agitation. The fear is that the crumb rubber particulates may possibly settle out of suspension, resulting in a heavier concentration of crumb rubber at the bottom of the storage tank than at the top. Although the Separation test is most commonly used to determine the tendency of a polymer to separate from the asphalt binder, the test procedure was used to evaluate the potential of the crumb rubber particles to fall out of suspension.

The Separation testing was conducted in accordance with ASTM D7173, *Standard Practice for Determining the Separation Tendency of Polymer from Polymer Modified Asphalt*. A summary of the test procedure is as follows:

- Fill aluminum tube that is 25mm dia. by 125-140mm in length with asphalt binder;
- Crimp top of aluminum tube, place tube vertically in a container and place in an oven at 163±5 °C for 48 hours;
- Remove container from the oven and place specimen in freezer while still vertical until specimen is cooled between -10 ± 10 °C;

- Remove the specimen from the freezer and cut sample tube in 3 equal pieces.
- Throw out the middle piece and keep the top and bottom tube sections; and
- Test the top and bottom sections for softening point (ASTM D 36) or rheological properties using the DSR (AASHTO T 315 or ASTM 7175).

For this study, the top and bottom of the sections were tested for the G*/sin δ using the Dynamic Shear Rheometer (DSR) at a 1.0 mm gap height. A common threshold of 10% maximum difference between rheological properties of the top and bottom of the tube is commonly used and was implemented in this study as the failure criteria.

The % Difference is calculated as follows:

$$\% \, Difference = \frac{(G^*/sin\ \delta)_{Top} - (G^*/\sin\delta)_{Bot}}{(G^*/sin\ \delta)_{Top}} x\ 100$$

The test results for the Separation testing are shown in Table 7. The test results show that only 2 binders tested met the 10% limit on the percent difference between the top and the bottom of the aluminum tube. This would indicate that the crumb rubber modified binders evaluated in this study should be stored in containers that provide continuous agitation/mixing so as separation of the crumb rubber particles does not occur.

Table 7 – Separation Testing Results for Asphalt Binders Tested

Binder Type	% Difference	Separation Type
64-28	-2.9	Passed
64-22 20 Mesh	-371.6	Separated to Bottom
64-22 30 Mesh	-416.9	Separated to Bottom
64-22 60 Mesh	8.8	Passed
SK64-22 30 mesh	-330.6	Separated to Bottom
SK64-22 50 mesh	-361.7	Separated to Bottom
SK 64-28 30 mesh	-130.4	Separated to Bottom
SK 64-28 50 mesh	-384.9	Separated to Bottom
58-28 17.5% CRM	-27.8	Separated to Bottom
64-22 17.5% CRM	-25.8	Separated to Bottom
76-22 30 Mesh	-306.6	Separated to Bottom
76-22 50 Mesh	-409.8	Separated to Bottom
58-34 10% TR	61.1	Separated to Top
64-22 10% TR	43.4	Separated to Top
70-22 10% TR	18.3	Separated to Top
76-22 10% TR	-21.5	Separated to Bottom
Mohawk 30 Mesh 6% GTR	-175.1	Separated to Bottom
Mohawk 30 Mesh 12% GTR	-294.8	Separated to Bottom
Mohawk 30 Mesh 12% GTR 300 μm	-153.4	Separated to Bottom

CHAPTER 5

ASPHALT MIXTURE TESTING

As shown earlier with the asphalt binder testing, good relationships were found among all three asphalt binder test procedures evaluated in this study. This indicates that for asphalt binders modified with crumb rubber of particle size finer than 20 Mesh, any of the three test procedures should provide the same relative ranking of high temperature performance. However, these rankings are purely based on solely testing the asphalt binder, and not how the asphalt mixture performs at high temperature. Therefore, to evaluate whether or not the high temperature asphalt binder tests relate to mixture performance, asphalt mixture test specimens were compacted using the asphalt binders noted earlier and a NYSDOT approved mixture design.

The approved NYSDOT mixture was a 9.5 mm Nominal Maximum Aggregate Size (NMAS) produced by Hanson out of Region 3 in New York. The aggregate gradation for the mixture used is shown in Figure 35. The optimum asphalt content of the mix design was 6.7% by total weight of the mix. Final specimen density was targeted for 6 to 7% air voids. Test specimens were prepared for three different high temperature mixture tests:

- Asphalt Pavement Analyzer (APA) - AASHTO T340
- Asphalt Mixture Performance Tester (AMPT) Flow Number – AASHTO TP79
- Asphalt Mixture Performance Tester (AMPT) Dynamic Modulus (E*) – AASHTO TP79

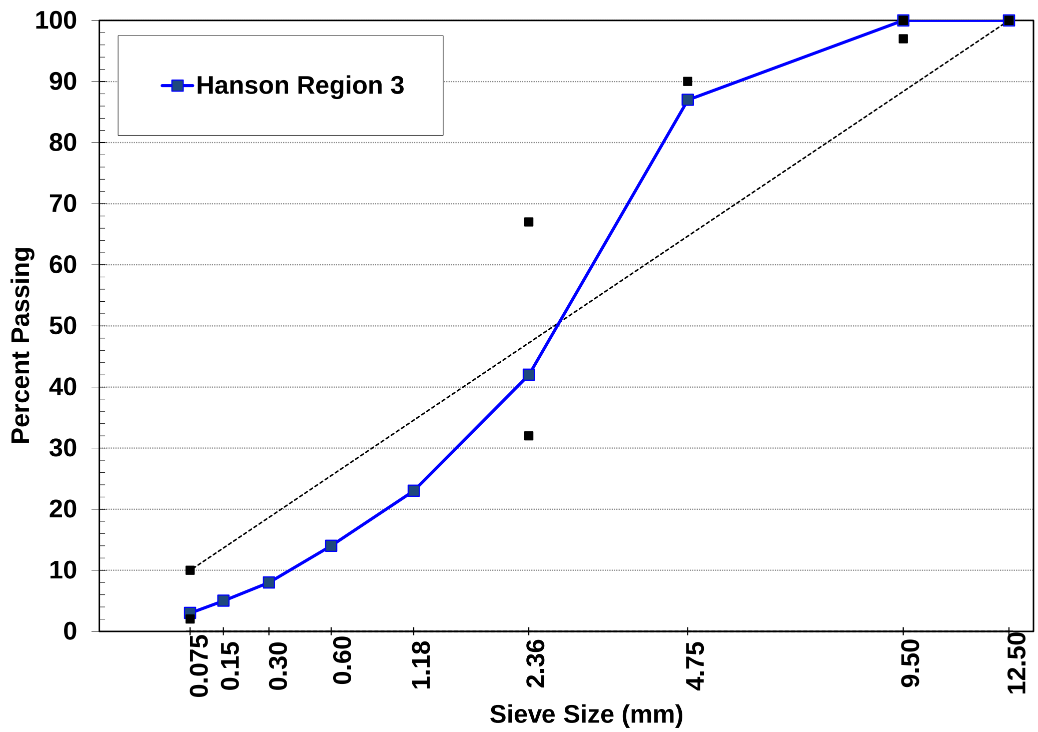
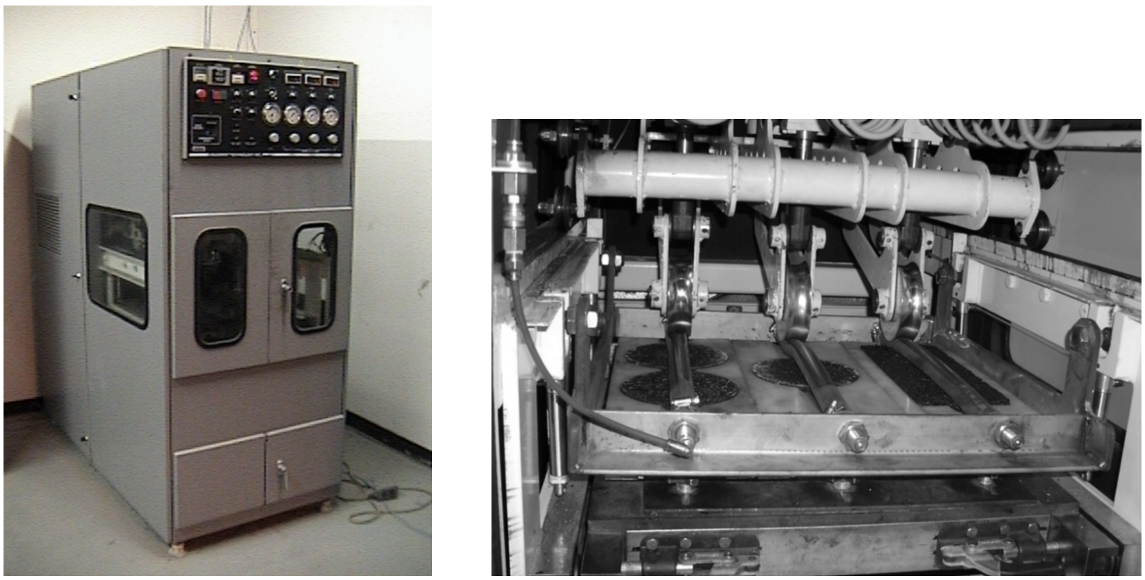


Figure 35 – Aggregate Blend Gradation for 9.5 mm NMAS NYSDOT Asphalt Mixture

5.1 Asphalt Pavement Analyzer (APA), AASHTO T340

The Asphalt Pavement Analyzer (APA) was conducted in accordance with AASHTO TP 63-09 (see Table 2 AASHTO test Method for APA), *Determining Rutting Susceptibility of Asphalt Paving Mixtures Using the Asphalt Pavement Analyzer (APA).* A hose pressure of 100 psi and a wheel load of 100 lb were used in the testing. Testing was continued until 8,000 loading cycles and APA rutting deformation was recorded at each cycle. The APA device used for testing at Rutgers University is shown in Figures 36a and 36b.



(a) (b)

Figure 36 – a) Asphalt Pavement Analyzer (APA) at Rutgers University; b) Inside the Asphalt Pavement Analyzer Device

Prior to testing, each sample was heated for 6 hours (+/- 15 minutes) at the testing temperature to ensure temperature equilibrium within the test specimen was achieved. Testing started with 25 cycles used as a seating load to eliminate any sample movement during testing. After the 25 seating cycles completed, the data acquisition began recording test information until a final 8,000 loading cycles was reached. Samples were tested at a test temperature of 58^{o}C, as per the request of the NYSDOT.

The test results for the APA testing are shown in Figure 37. The results show that a range of APA rutting was found between 3.48 mm to 9.15 mm, depending on the binder source and target PG grade.

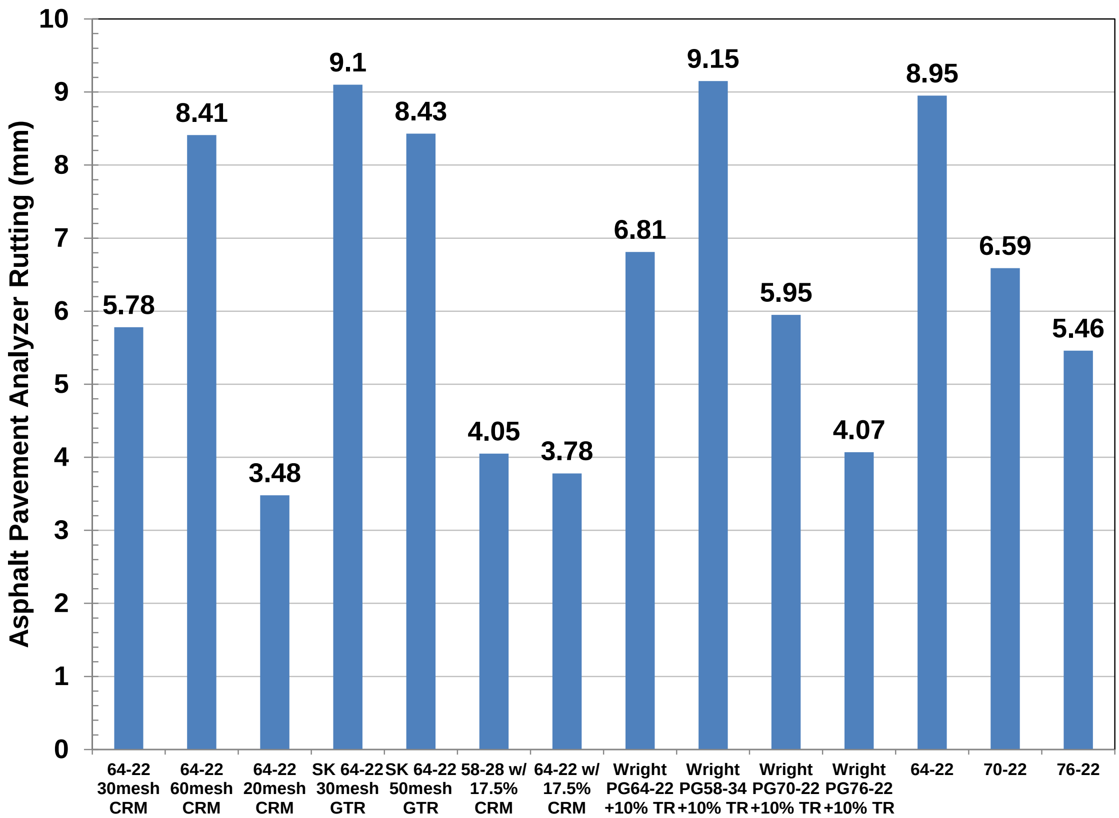


Figure 37 – Asphalt Pavement Analyzer (APA) Test Results

To determine which asphalt binder test best represents the asphalt mixture performance, comparisons between the APA rutting and the different asphalt binder tests were conducted. Since the ($G^*/\sin \delta$) of the Cup & Bob method correlated well with both the MSCR at 2.0 mm gap height and the DSR parallel plates at 1.0 mm gap height, it was not further compared with the mixture tests. This decision was made since the testing configuration and procedures are not standardized yet and may be difficult to implement on different Dynamic Shear Rheometers not manufactured by the same equipment manufacturer used in this study.

The comparison between the Asphalt Pavement Analyzer rutting and the continuous high temperature PG grade is shown in Figure 38. The results show a modest correlation between the data with an $R^2 = 0.45$. Although the trend in the data is what was expected (i.e. – APA rutting increases at continuous high temperature PG grade decreases), there is some scatter in the test results.

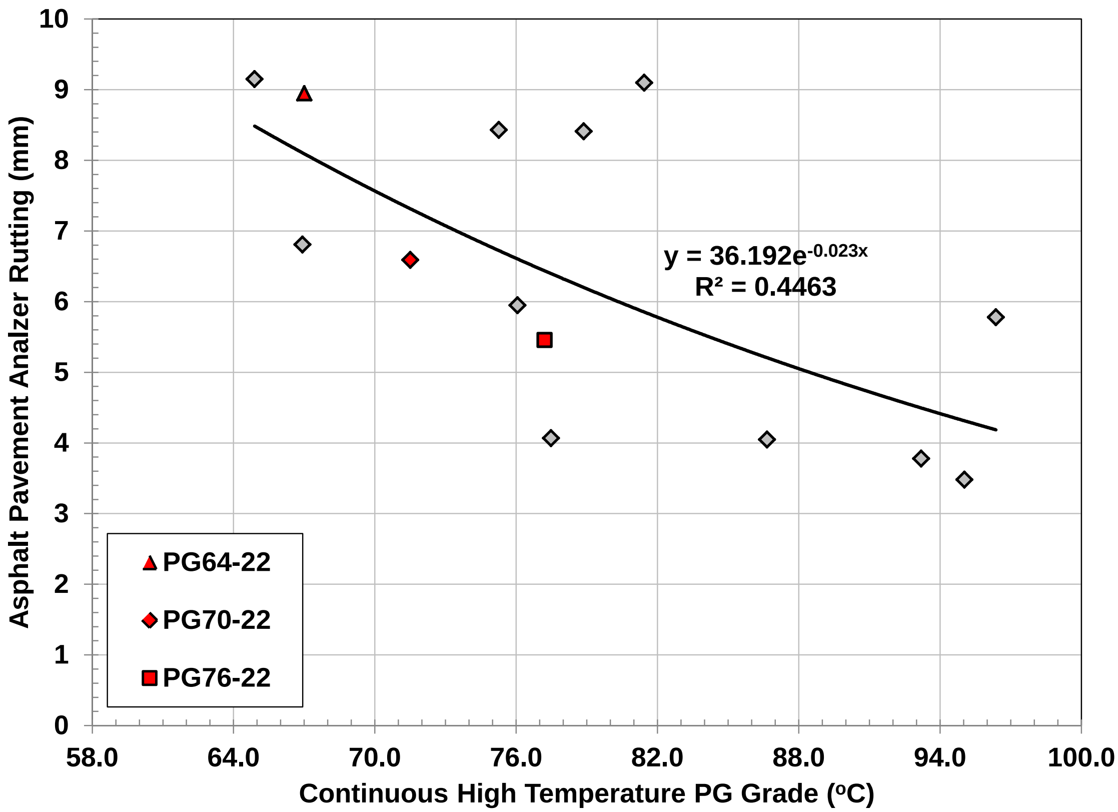


Figure 38 – Asphalt Pavement Analyzer Rutting vs Continuous High Temperature PG Grade

The MSCR J_{nr} parameter measured at 64°C was also compared to the APA rutting and is shown in Figure 39. The comparison between the APA rutting and MSCR J_{nr} parameter was found to have a better correlation than the continuous high temperature PG grade (R^2 = 0.59).

Based on the APA Rutting tests, it would appear that the MSCR J_{nr} parameter, measured at 64°C and a DSR gap height of 2.0 mm, provided the better correlation to the mixture rutting performance.

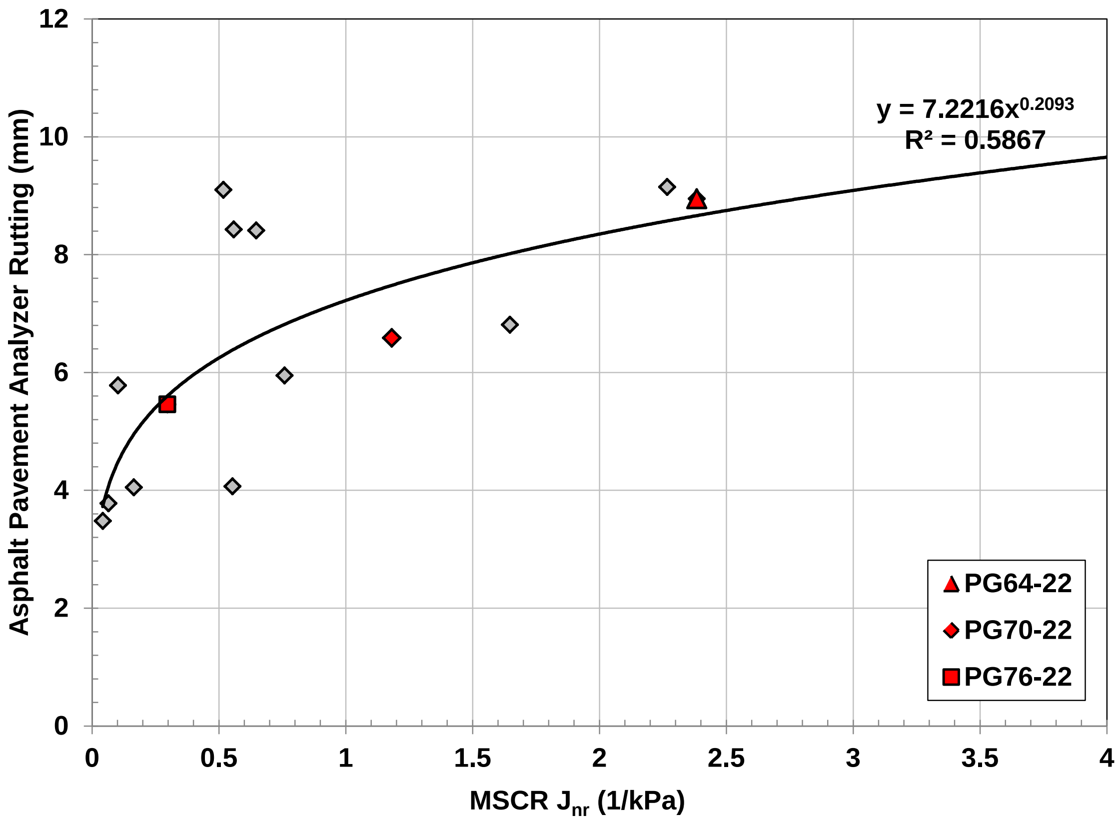


Figure 39 – Asphalt Pavement Analyzer Rutting vs MSCR J_{nr} Parameter at 64°C

5.2 Asphalt Mixture Performance Tester Flow Number, AASHTO TP79

Repeated Load permanent deformation testing was measured and collected in uniaxial compression using the Asphalt Mixture Performance Tester (AMPT) following the method outlined in AASHTO TP79, *Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT)*. The unconfined repeated load tests were conducted with a deviatoric stress of 600 kPa and a test temperature of 50°C, as per the recommendations of the NYSDOT. The Asphalt Mixture Performance Tester (AMPT) used in the study is shown in Figure 40. All test specimens were compacted in a gyratory compactor in accordance with AASHTO PP60-09, *Preparation of Cylindrical Performance Test Specimens Using the Superpave Gyratory Compactor (SGC)*. An air void level of 6 to 7% air voids was targeted for the test samples.

It was found that some test specimens were difficult to achieve an air void level within the targeted range noted earlier. The asphalt binders, CRM 64-22 30 Mesh and PG58-28 w/ 17.5% CRM, created issues during compaction and resulted in air void levels above the targeted range. Both mixtures were attempted multiple times but air void levels below 9.5% could not be attained. Therefore, the data points were noted and carefully monitored during the analysis. The same issues were not found during compaction of the APA rutting samples.

The comparison between the AMPT Flow Number, determined in the AMPT at a test temperature of 50°C, and the continuous high temperature performance grade, is shown in Figure 40. When including all of the test data, a resultant correlation coefficient of 0.38 was determined. However, when the two asphalt binders that resulted in test specimen density issues were eliminated (noted as Outliers), the R^2 value increased to 0.76 (shown as the Dotted Line).

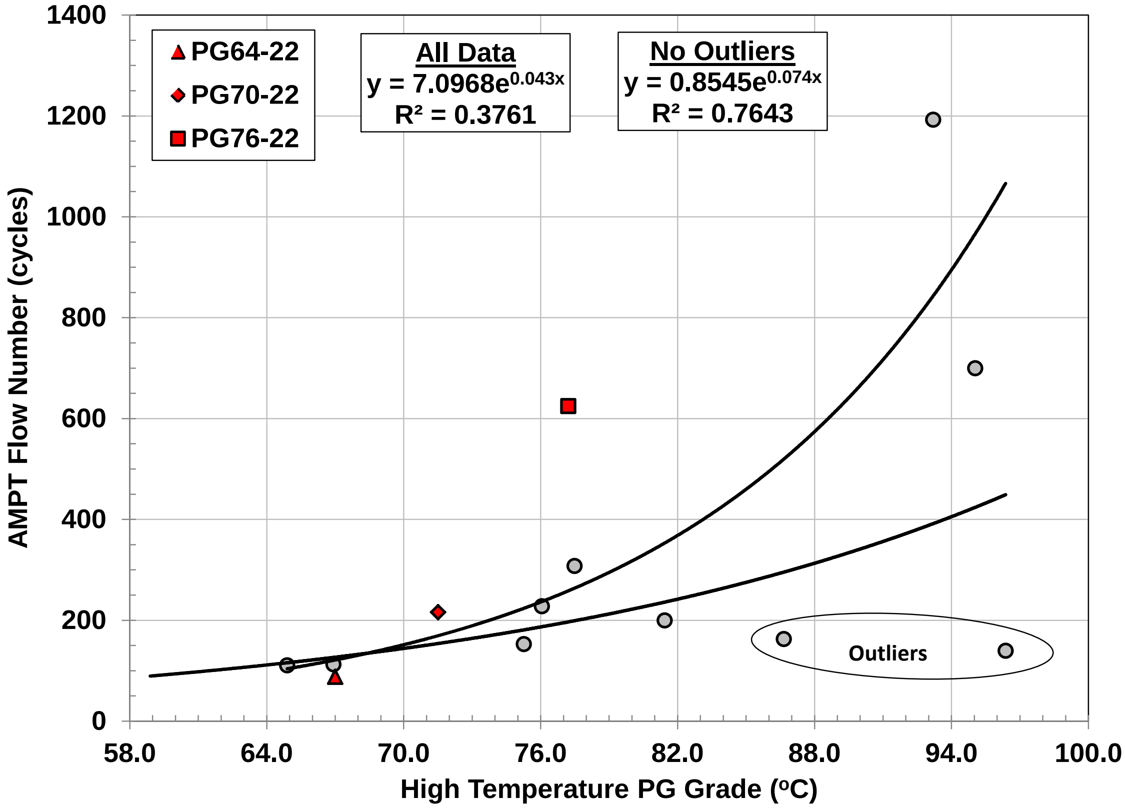


Figure 40 – AMPT Flow Number at 50°C vs Continuous High Temperature Performance Grade

The AMPT Flow Number values were also compared to the MSCR J_{nr} parameter, determined at 64°C and a parallel plate gap height of 2.0 mm. The results of the comparison are shown in Figure 41. The results show that when considering all test data, a correlation coefficient (R^2) of 0.51 was determined. However, if the two test mixtures with density issues are taken out of the comparison (noted as Outliers in Figure 41), the correlation ratio increases to 0.84, shown as the Dotted Line in Figure 41. This clearly indicates a good relationship exists between the AMPT Flow Number measured at 50°C and the MSCR J_{nr} parameter measured at 64°C and a parallel plate gap setting of 2.0 mm.

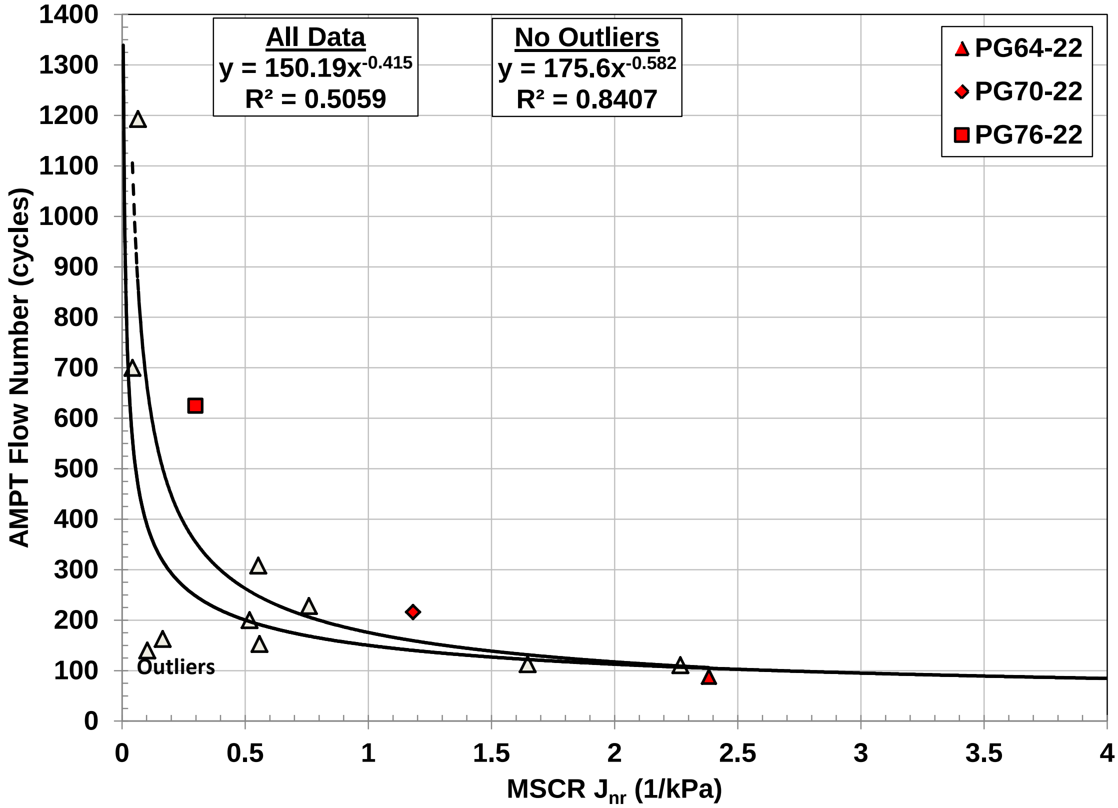


Figure 41 – AMPT Flow Number at 50°C vs MSCR J_{nr} Parameter at 64°C and Parallel Plate Gap Setting of 2.0 mm

A minimum MSCR J_{nr} value is recommended for different ESAL levels based on research conducted at the Federal Highway Administration (FHWA) and is proposed in AASHTO MP 19-10, *Performance-Graded Asphalt Binder Using Multiple Stress Creep Recovery (MSCR) Test*. According to MP 19-10, the MSCR Jnr parameter is measured at the environmental high pavement temperature, which according to the NYSDOT Technical Working Group, has been selected to be 64°C – the test temperature used in this study. Meanwhile, work conducted in NCHRP Project 9-33, *A Manual for Design of Hot Mix Asphalt,* developed recommended Flow Number values for basically the same traffic levels. The two performance criteria, based on traffic level, are shown in Table 8.

The regression equation, shown in Figure 41 for “No Outliers” data, was used to determine what the equivalent Flow Number value based on the measured laboratory data. In turn, the laboratory data based Flow Number for this study was compared to the NCHRP 9-33 recommended Flow Number values and is shown as Table 8. Also included in Table 8 is the recommended AMPT Flow Number value for Warm Mix Asphalt (WMA), as recommended from NCHRP Project 9-43, *Mix Design Practices for Warm Mix Asphalt (WMA).*

Table 8 – Recommended MSCR J_{nr} and AMPT Flow Number Values Based on Traffic Levels

HMA Flow Number (cycles)	WMA Flow Number (cycles)	Traffic Level (MESAL's)	MSCR Jnr (kPa^{-1})
---	---	< 3	---
> 53	> 30	3 to <10	< 4.0
> 190	> 105	10 to < 30	< 2.0
> 740	> 415	> 30	< 1.0
> 740	> 415	> 30 (Standing Traffic)	< 0.5

Although the AMPT Flow Number recommendations does not include a "Standing Traffic" level, the MSCR J_{nr} recommendations does and so it was included in Table 8.

The same testing information was attempted to be replicated using the data generated in this study and the regression curve developed in Figure 41. The resultant testing information is shown as Table 9. The NYSDOT lab study determined AMPT Flow Number, based on the correlation with the laboratory measured J_{nr} (regression equation from Figure 41), shows comparable values to the WMA Flow Number but lower than the HMA Flow Number. This is expected as the Flow Number values recommended in NCHRP 9-33 were based on national test results and not regionally calibrated for specific materials, environmental and traffic conditions. This is further shown in Table 10, where regionally calibrated AMPT Flow Number values were developed for the state of Wisconsin. This indicates that the measured test results from this study are valid for the materials tested. However, what needs to be conducted for the state of NY is to regionally calibrate the measured field rutting performance to measured AMPT Flow Number and MSCR Jnr values on the corresponding asphalt mixtures and binders utilized on those pavements. This will provide further confidence in recommended performance limits for these laboratory tests.

Table 9 – Correlated AMPT Flow Number Results to MSCR J_{nr} Requirements

HMA Flow Number (cycles)	WMA Flow Number (cycles)	NYSDOT Flow Number (cycles)	Traffic Level (MESAL's)	MSCR Jnr (kPa^{-1})
---	---	---	< 3	---
> 53	> 30	79	3 to <10	4.0
> 190	> 105	118	10 to < 30	2.0
> 740	> 415	177	> 30	1.0
> 740	> 415	264	> 30 (Standing Traffic)	0.5

Table 10 – Wisconsin Developed Minimum Flow Number Values with NYSDOT Study Results

Flow Number, WisDOT (cycles)	NYSDOT Flow Number (cycles)	Traffic Level (MESAL's)	Flow Number, NCHRP 9-33 (cycles)
15	---	< 3	---
50	79	3 to <10	53
135	118	10 to < 30	190
415	177	< 100 (or > 30)	740

5.3 Dynamic Modulus (AASHTO TP79)

Dynamic modulus and phase angle data were measured and collected in uniaxial compression using the Simple Performance Tester (SPT) following the method outlined in AASHTO TP79, *Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT)* (Figure 1). The data was collected at three temperatures; 4, 20, and 35^{o}C using loading frequencies of 25, 10, 5, 1, 0.5, 0.1, and 0.01 Hz.

Figure 42 – Photo of the Asphalt Mixture Performance Tester (AMPT)

For this study, since the high test temperatures are of concern, only the test data at 35^{o}C and 1 Hz was used for comparative purposes. The Dynamic Modulus, E*, measured at 35^{o}C and 1 Hz compared to the continuous high temperature PG grade and MSCR J_{nr} parameter are shown in Figures 43 and 44, respectively. Again, some compaction issues occurred with the taller specimens and are shown as Outliers in the figures.

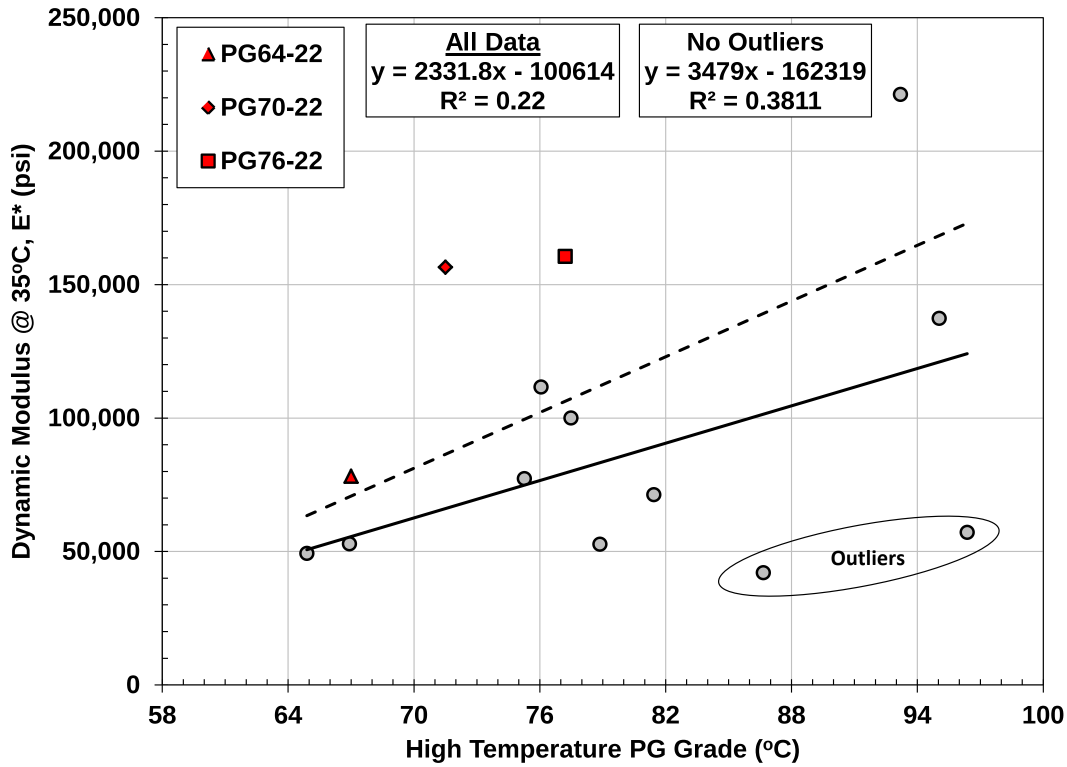


Figure 43 – Continuous High Temperature PG Grade vs Dynamic Modulus Measured at 35°C and 1 Hz

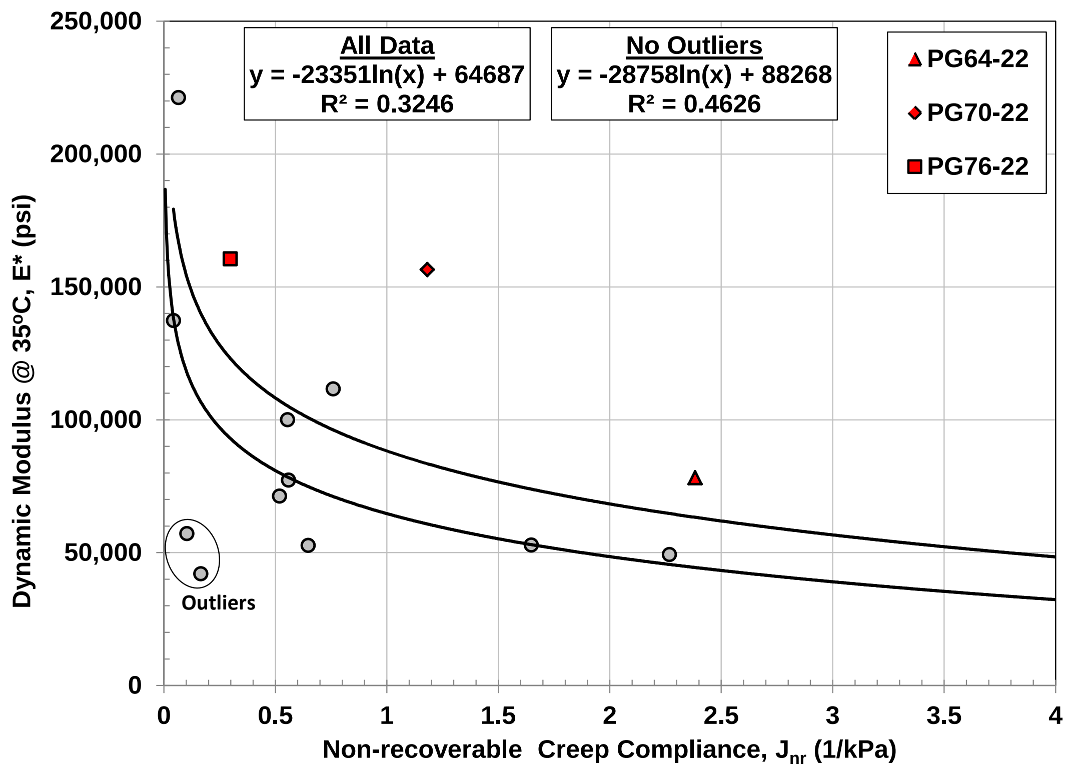


Figure 44 – MSCR Jnr Measured at 64°C vs Dynamic Modulus Measured at 35°C and 1 Hz

Figure 43 indicates that there is not a strong relationship between the continuous high temperature PG grade of the asphalt binders and the measured dynamic modulus of the asphalt mixture. Figure 44 indicates that a slight correlation exists between the MSCR Jnr value, measured at 64^{o}C, and the dynamic modulus of the mixture measured at 35^{o}C and 1 Hz. Unfortunately, due to the nature of the mixture and asphalt binders utilized, a maximum high temperature of 35^{o}C was selected for the dynamic modulus testing to ensure testing error was minimized.

Based on the laboratory testing conducted in the study, it would appear that the MSCR J_{nr} parameter, measured at 64^{o}C and a DSR gap height of 2.0 mm, provided the strongest correlation to the mixture performance when using the AMPT Flow Number, Asphalt Pavement Analyzer, and AMPT Dynamic Modulus.

CHAPTER 6

GYRATORY COMPACTION STUDY

As mentioned previously during the mixture evaluation, some issues were found compacting the crumb rubber modified (CRM) asphalt mixtures. In particular, high air voids (> 10%) were discovered in two of the mixtures when compacting to a target air void range of 6 to 7%. It should be highlighted that the asphalt mixture utilized during the mixture performance evaluation was an existing, pre-approved NYSDOT HMA design and not an asphalt mixture specifically designed for CRM binders. It is hypothesized that the reason for the high air voids was that the asphalt mixture utilized could not allow for the residual crumb rubber particles to reside in between the aggregate skeleton, and therefore, pushed the aggregates particles apart increasing the compacted air void level of the mixture. This has been noted by the Research Team is previous research when using coarser crumb rubber particles in combination with dense-graded asphalt mixtures.

The compaction study utilized two NYSDOT approved mixture designs – a coarse and a fine-graded mixture. The gradations for each mix are shown in Figure 45. The asphalt binders chosen for the compaction study was targeted at evaluating different crumb rubber size and solubility (i.e. – how much residual crumb rubber particles are remaining in the asphalt binder), as well as two baseline asphalt binders – a neat PG64-22 and a polymer modified PG76-22. Two different mesh sizes (#30 and #60 mesh) and terminal blended crumb rubber modified asphalt binders were compared to conventional PG64-22 and PG76-22 asphalt binders. The compacted air voids for both mix designs are shown in Figures 46 and 47, respectively. The results show that both the conventional binders (PG64-22 and PG76-22) resulted in compacted air voids that would be within acceptable limits (3.0 to 5.0%) with regards to typical variability when replicating asphalt mixtures. Similar results are shown for the terminal blended asphalt binders provided by Wright Asphalt. However, the asphalt binders containing the #30 and #60 mesh resulted in compacted air voids much higher than allowable. This is most likely due to the residual crumb rubber within the asphalt binder of the #30 and #60 mesh CRM asphalt binders pushing away the aggregate skeleton. It should be noted that the terminal blended binders are produced with minimal to no residual crumb rubber.

The test results in Figures 46 and 47 suggest that the full adoption of all crumb rubber modified binders will be difficult due to the residual crumb rubber in some of the asphalt binders. The terminal blended binders appear to be more forgiving and would be recommended for full adoption (i.e. – where the Terminal Blend can be used in current mix designs). Other crumb rubber modified binders containing residual rubber would require a mix design specifically conducted to allow asphalt binders that contain residual rubber. These mix designs would require a more “gapped” aggregate gradation, similar to those currently used for Stone Matrix Asphalt (SMA) and Open Graded Friction Course (OGFC).

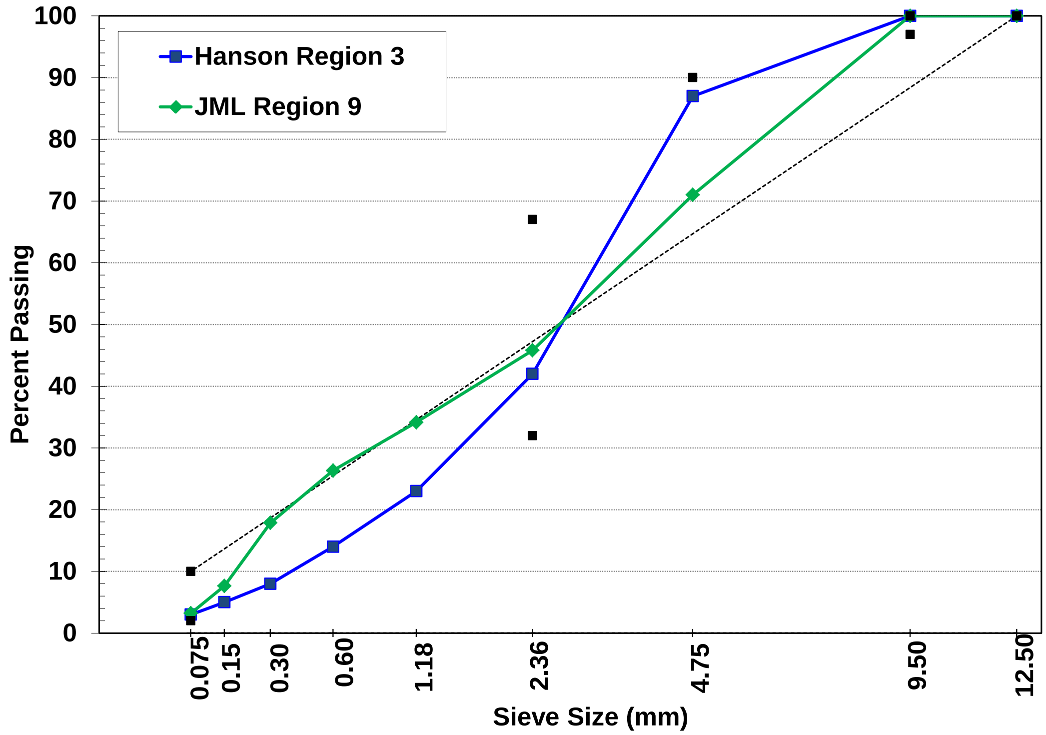


Figure 45 – Gradations Used in Compaction Study

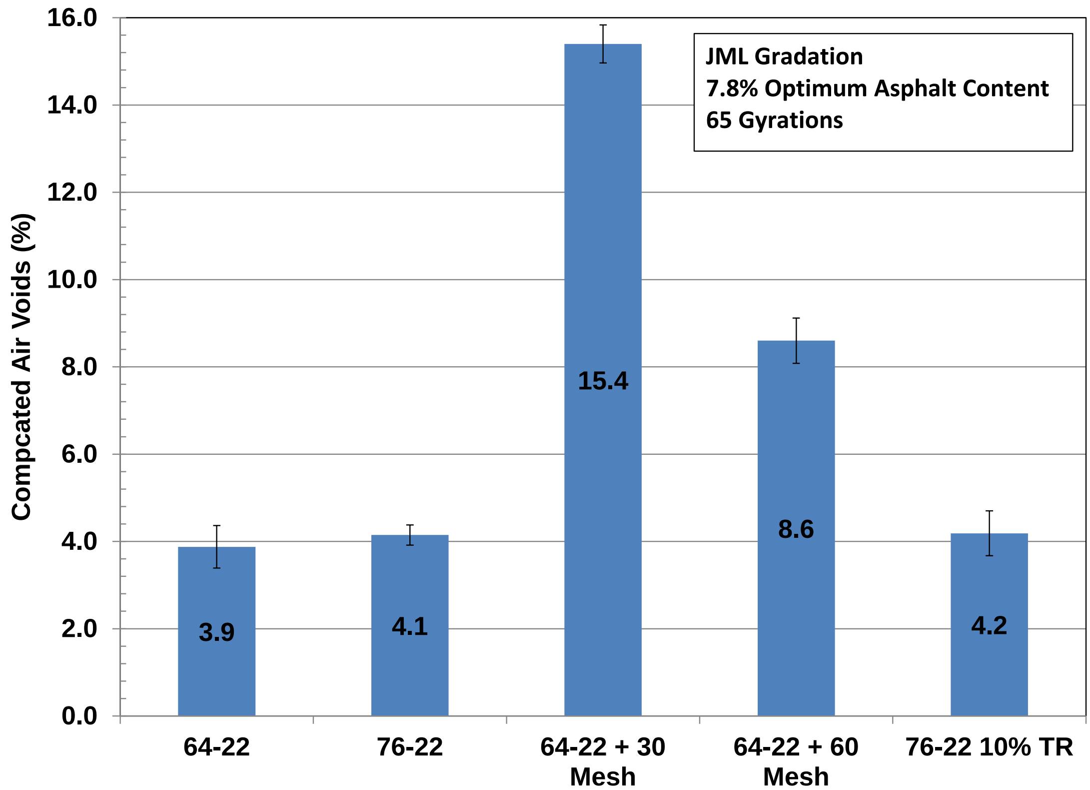


Figure 46 - Compaction Study using JML Aggregates and Mix Design

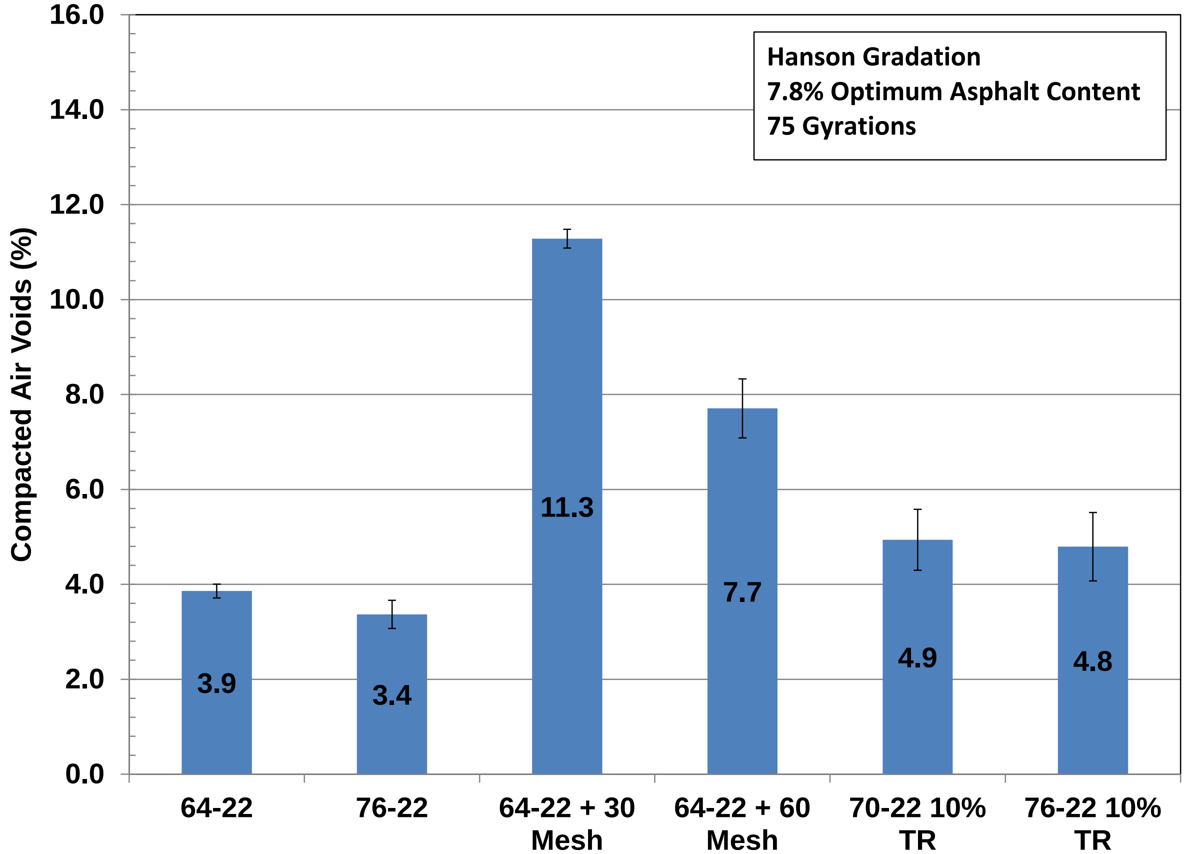


Figure 47 – Compaction Study Using Hanson Aggregates and Mix Design

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

The adoption of NYSDOT accepting the crumb rubber modified asphalt binder as an accepted method of asphalt modification is contingent on the crumb rubber modified performance graded binder (CRM PGB) being able to be accurately tested and capable of conforming to the standard practices and criteria established in AASHTO M320. In particular, potential issues may arise during the asphalt binder testing due to residual crumb rubber particles interfering with the testing configurations of the different test apparatus. For example, the Dynamic Shear Rheometer (DSR) gap spacing between the plates during testing is 1 mm for the 25 mm plates and 2 mm for the 8 mm plates, as specified in AASHTO T315, Section 9, *Standard Method of Test for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR).* With the required gap distance of 1 mm thick for high temperature performance grading, residual crumb rubber particles may interfere in the accuracy and repeatability of the test measurements. Currently, AASHTO T315, *Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR),* limits the testing of asphalt binders containing particulate matter with the longest dimension less than 250 microns. This is to ensure a minimum of 4:1 gap height to particle size is maintained so little to no particulate interference occurs during testing.

A research effort was undertaken to determine how to properly high temperature performance grade asphalt binders modified with crumb rubber. Crumb rubber modified (CRM) binders from varying sources using different technologies were procured and evaluated using current and experimental testing procedures/configurations. The asphalt binder test results were then compared to asphalt mixture tests to determine which asphalt binder test parameter best compared to laboratory permanent deformation performance. Along with the high temperature performance testing, a mini-experiment was performed to determine if potential issues may arise when directly substituting CRM asphalt binders with currently approved polymer modified binders.

Based on the work conducted in this study, the following conclusions were drawn:

- Although increasing the gap height of the DSR during testing seems like a logical means of testing asphalt binders with crumb rubber, it appears that asphalt binder does “leak” out between the parallel plates when testing the asphalt binders at their failing temperature during PG grading. This was visually observed in Figures 15 to 20. How this influences the test results in the DSR is shown in Figures 9 through 14. In Figures 9 and 10, the resultant continuous high temperature PG grade decreases as the gap height increases. Although it would appear to be relatively small changes, when evaluating the information using the AASHTO T315 Precision and Bias statement, there is a clear indication that the repeatability diminishes when testing occurs at the failure PG temperature, especially at the Original aged condition (Figures 12).

- Asphalt binder testing was conducted using three test procedures to evaluate the high temperature performance: 1) Current AASHTO T315 and R29 with 1.0 mm gap height; 2) MSCR (AASHTO TP70) test procedure at 2.0 mm gap height; and 3) Cup & Bob test procedure. The test results showed that:
    - The high temperature PG grade determined at 1.0 mm gap height and the MSCR J_{nr} value determined at 64^oC at 2.0 mm gap height showed an excellent correlation to one another.
    - The (G*/sin δ) measured with the parallel plates and gap setting of 1.0 mm was approximately 15% lower than that measured by the Cup & Bob. The difference appears to be more due to the G* measurement than the phase angle measurement.
    - The MSCR J_{nr} parameter correlated best with the high temperature asphalt mixture testing than the continuous high temperature PG grade.
    - When plotting MSCR Jnr vs the MSCR % Recovery, a majority of measured results in the study fell under the recommended "modification" curve shown in Figure 28. This would indicate that although the crumb rubber provides some type of elastomeric modifications, it is not to the same magnitude as an elastomeric polymer like SBS.
- Additionally, the Elastic Recovery (ASTM D6084) and Separation Test (ASTM D7173) were also conducted on the sampled asphalt binders. The testing showed:
    - The Elastic Recovery of the CRM asphalt binders ranged between 30 and 85% with a majority of the test results falling between 60 and 80%. A good correlation was found between the Elastic Recovery (ASTM D6084) and the % Recovery from the MSCR test (AASHTO TP70). The Separation Test showed that all but two asphalt binders were prone to separation. This would indicate that the CRM asphalt binders need to be continually mixed/agitated to ensure they do not separate under heated storage.
- Asphalt mixture testing consisting of the AMPT Flow Number and Dynamic Modulus, as well as the Asphalt Pavement Analyzer (APA), were conducted on compacted samples produced with an approved NYSDOT mixture design and the different conventional and crumb rubber modified asphalt binders. The test results were compared to the asphalt binder performance parameters discussed earlier. The testing showed:
    - The AMPT Flow Number, measured at a test temperature of 50^oC, correlated well with the MSCR J_{nr} measured at a test temperature of 64^oC. A correlation ratio (R^2) of 0.84 was determined. The AMPT Flow Number did not correlate as well to the continuous high temperature PG grade of the asphalt binders, however, a determined correlation ratio of 0.76 is still showing a moderate to good correlation. Based on the testing conducted, the AMPT Flow Number correlated the best to the asphalt binder performance testing.
    - The Asphalt Pavement Analyzer (APA) correlated best to the MSCR J_{nr} parameter with a correlation ratio of 0.59. Although the trend in APA

Rutting and continuous high temperature PG grade was correct (i.e. – decreasing APA rutting with increasing high temperature PG grade), a moderate to poor correlation was found (R^2 = 0.46).
    - The Dynamic Modulus (E*) at 35°C and 1 Hz did not correlate well with any of the asphalt binder tests conducted.
- Overall, the asphalt binder test that best seems to characterize the asphalt binder modified with crumb rubber would be the MSCR test procedure conducted with a gap setting of 2.0 mm and a test temperature of 64°C (for NYSDOT environmental conditions).
- Asphalt modification with crumb rubber seems to take place via two mechanisms; 1) Elastomeric modification due to the rubber and polymers in the crumb rubber dissolving in the asphalt binder, and 2) Mechanical modification due to residual crumb rubber particles within the asphalt binder providing physical reinforcement within the liquid. This hypothesis is based on the review of multiple asphalt binder tests conducted in the study.
    - Elastic Recovery (ASTM D6084), which is currently adopted by the Northeast states to ensure proper elastomeric modification, indicated that a majority of the CRM binders meet the minimum 60% recovery specified by NYSDOT. This indicates that an elastomeric medium is present in the asphalt binder. However, when conducting the MSCR test procedure and plotting J_{nr} vs % Recovery, a majority of the test results were found to fall under the recommended elastomer, polymer modification line, even though generally low Jnr values (i.e. – greater resistance to rutting) were measured. This indicates that a stiffening is taking place with the asphalt binder, yet the stiffening may not be due entirely to the elastomeric modification and is most likely a combination of liquid modification and particulate reinforcement of the asphalt binder.

7.2 Recommendations

Based on the research conducted during the study, it is recommended that the NYSDOT implement the Multiple Stress Creep Recovery (MSCR) test procedure (AASHTO TP70-12) at a test temperature of 64°C and a gap setting of 2.0 mm to characterize the high temperature performance of the asphalt binder. The following reasons are highlighted to validate this recommendation.

1. It is not recommended to increase the gap setting of the DSR when conducted high temperature PG grading in accordance to AASHTO R29, *Grading or Verifying the Performance Grade (PG) of an Asphalt Binder*. When the gap increases beyond 1.0 mm and test temperatures are above the PG grade, a reduction in testing accuracy occurs, especially at the Original aged condition. It should be noted this testing was conducted with asphalt binders not containing crumb rubber.
2. The non-recoverable creep compliance (J_{nr}) parameter measured during the Multiple Stress Creep Recovery (MSCR) measured at 64°C and a gap setting of 2.0 mm correlated well to the AMPT Flow Number and Asphalt Pavement

Analyzer – both tests commonly used to determine the rutting susceptibility of asphalt mixtures. At the test temperature of 64^{o}C, the asphalt binder will not have the tendency to "leak" out between the parallel plates with an increase in the gap height setting, as shown earlier in Chapter 2 when conducting PG grading.

As noted above, with the test procedure correlating well to mixture rutting performance, as well as the Northeast states and industry moving towards implementing the MSCR test and AASHTO looking at allowing the gap height setting to be increased, it would make sense for the NYSDOT to consider the adoption and implementation of the MSCR test at a test temperature of 64^{o}C and gap height setting of 2.0 mm to characterize the high temperature performance of crumb rubber modified binders.

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