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1. INTRODUCTION

Each year the United States generates approximately 290 million scrap tires. Of these 290 million tires, approximately 80.4 percent are recycled or reused in fuel, agricultural or civil engineering markets leaving 27 million tires left to be placed in landfills or stockpiles. Currently, about 12 million scrap tires each year are being converted into ground tire rubber for modifying asphalt cements (*1*).

The utilization of scrap tire rubber in asphalt started in the mid-1960s when ground rubber was placed in asphalt surface treatments, such as chip seal applications. Later on, in the 1970's, crumb rubber modified (CRM) asphalt chip seals were used as a stress absorbing membranes interlayer (SAMI). Its use extended to hot mix asphalt (HMA) and has continued to evolve due to the rubber's enhancement of mixture performance including improved rutting resistance, thermal reflective crack resistance, and resistance to fatigue cracking. Some other benefits reported include reduction in maintenance, smooth ride, good skid resistance, and noise reduction *(2, 3, 4, 5).*

In terms of environmental issues, the disposal of scrap tires is a major waste management concern due to used tires being placed in scrap tire piles. Additionally, some studies have shown that the addition of ground tire rubber (GTR) does not contribute significantly to any increase in undesirable compounds such as CO_2 emissions *(6).*

Arizona, California, Florida, and Texas have successfully developed and specified the most rubberized asphalt products. It was reported that together, these states recycled over 35.6 million tires in asphalt paving applications from 1995 to 2001 *(7, 8).*

While environmental stewardship is important, some state agencies and/or contractors are investigating GTR-modified asphalt binders as a substitute for using polymers such as styrene-butadiene-styrene (SBS) in asphalt binders. If GTR-modified binders can perform equivalently to polymer modified binders, state agencies and contractors will have additional tools they can use if another polymer shortage occurs.

One challenge associated with using GTR asphalt is that crumb rubber can vary in size and grinding method. These methods include but are not limited to the crackermill, granulator, micromill, and cryogenic processes. A brief description of each of these methods follow (*9*):

- Crackermill process – The crackermill process is the most common method of producing crumb rubber. The grinding of the scrap tire is controlled by the spacing and speeds of the drums. The rubber is reduced in size by tearing as it moves through a rotating corrugated steel drum. This process typically generates particles which have large surface areas and are irregularly shaped. Typically, this process occurs at ambient temperatures.
- Granulator process – The granulator process uses revolving steel plates to shred the tire rubber. The resulting particles are cubical with low surface areas.
- Micromill process – Micromilling reduces the size of the crumb rubber particles beyond that of a granulator or crackermill. Water is mixed with the crumb rubber to form a

slurry which is then forced through an abrasive disk to further reduce the particle size. The crumb rubber is then retrieved and dried.

- Cryogenic process – Liquid nitrogen is used to increase the brittleness of the crumb rubber in the cryogenic process. Once the rubber is frozen, it can be ground to the desired size. Cryogenic hammer mills are typically used to make -30 mesh (600 µm) GTR. Cryogenic turbo mills are typically used to make GTR -40 mesh (400 µm) to -300 mesh (50 µm). GTR with a significant fraction of -140 mesh (105 µm) is also referred to as micronized rubber powder (MRP).

While some research has been conducted tying these components to asphalt binder properties, agencies and contractors are still unsure as to how the choice of crumb rubber type will ultimately influence the overall performance of the binder and mixture.

1.1 Objective and Scope

The objective of this research was to assess how rubber properties affect the properties of an asphalt binder. This objective was completed by blending eleven unique crumb rubber samples with a singular asphalt binder at a singular loading of 10 percent rubber. Two of the selected rubbers were additionally tested at 15 percent loading. These fourteen GTR asphalt binders were then tested using the performance grade (PG), multiple stress creep recovery (MSCR), cigar tube test, and softening point methodologies.

1.2 Organization of Report

This report is divided into five chapters. The second chapter includes the methodology used for characterizing the GTR and GTR-modified binders. The third chapter characterizes the eleven unique rubber sources used in this study in terms of particle size and chemistry. The fourth chapter presents the results of tests conducted on the rubber-modified asphalts while the fifth chapter assesses how adding polymer and Vestenamer affect GTR-modified asphalt binders. The final chapter presents the conclusions and recommendations based on the aforementioned testing results.

2. METHODOLOGY

The following section of this report describes the testing methodology used to quantify the properties of the fourteen GTR-modified binders developed for this study. Each of the eleven crumb rubber products was originally characterized for particle size and chemical compositions before it was blended with a standard performance graded (PG) 67-22 asphalt binder at either 10 or 15 percent loading. The GTR binders were then tested for performance grade, creep recovery, particle separation, and softening point.

2.1 RO-TAP Particle Size

Ro-tap testing was conducted to determine the particle size of the eleven crumb rubber products used in the study. The testing was conducted according to Lehigh Technologies testing methodology using approximately 100 grams of crumb rubber. The ground rubber was mixed with Flow-aid, a product used to ease the movement of the crumb rubber through the sieves (Figure 1). Additionally, the Flow-aid is -#200 material; therefore, it did not affect the test results on the +#200 sieves.

Figure 1 Rubber and Flow-Aid mixture.

A set of sieves was chosen based on the estimated particle size of the sample. The zero screen was designated as the sieve where 99.9 percent of the material should pass. The designation sieve corresponded to the sieve where at least 90 percent of the materials pass. Additional sieves were placed below the estimated designation sieve to further characterize the size of the rubber materials. Two rubber balls were placed on each sieve to aid the material in passing through the sieves without accruing material degradation (Figure 2).

The GTR and Flow-aid mixture was then poured into the top sieve and placed with the stack of sieves in the Ro-tap machine (Figure 3). The samples were agitated for at least 10 minutes and for a maximum of 20 minutes based on the estimated particle size of the product. The smaller the particle size, the longer the material was agitated in the Ro-tap.

Figure 2 Rubber balls in sieves.

Figure 3 RO-TAP Device.

Upon completion of agitation, each sieve was checked for fiber. Any accrued fiber was removed from the sieve and weighed. Fiber has been speculated to affect dynamic shear rheometer results causing increased variability; however, as described later, the rubber samples which included fiber did not have increased testing variability.

Additionally, any rubber material adhering to the rubber balls on each sieve was brushed from the balls back to the sieve. The mass of the material on each sieve was quantified. The weights on each sieve and weight in the bottom pan were then quantified as *z* and used in Equation 1.

$$x = y - (z - 100) \qquad \text{(Equation 1)}$$

where: x = weight of the rubber in the pan
y = everything in the bottom of the pan, including the Flow-aid
z = the mass of all the sieve contents

z did not deviate from the original mass sample by more than 2 grams. The particle size was ultimately determined by quantifying the last sieve where 90 percent or more GTR particles pass through the sieve. This mesh size designation was consistent with ASTM D5603-01; however, this specification has no provision for 16 mesh material or specific cuts of rubber such as the -80/+140. Therefore, the specification has limitation. The RO-TAP data were also assessed for mean particle size.

2.2 Thermogravimetric Analysis (TGA)

TGA testing was conducted to analyze the crumb rubber for its makeup using ASHM E1131-03. The test determines the percent extractible, polymer, carbon black, and ash in each crumb rubber source. Testing was completed in a Perkin-Elmer TGA devicee. A testing sample was placed in the testing device and the temperature ramped to 325°C at 10°C per minute in a nitrogen environment. The percent of material lost at this temperature was calculated and deemed to be extractibles. The temperature in the chamber was increased at a ramp of 10°C per minute in nitrogen until it reached the target temperature of 530°C where the temperature was held constant for 10 minutes. After the temperature was held constant, the percent material lost was calculated. The material lost in this temperature range was classified as polymer. The temperature was then increased again at 10°C per minute to 850°C in an oxygen environment where the percent loss quantified the percent carbon black in the crumb rubber sample. The remaining material was considered ash.

2.3 Specific Surface of GTR Samples

Quantachrome was contracted by the project sponsors to quantify the surface area of each GTR material incorporated in the study. The methodology quantified the surface area of each rubber source by determining the physical absorption on Krypton for each GTR sample.

To conduct this test, approximately a 1 to 3 gram sample of rubber was transferred to a testing cell which was connected to a degassing unit. In ambient conditions, a vacuum was used to remove the gas from the cell for 16 hours. The cell was removed from the degassing unit and the sample was weighed. Multipoint Brunauer-Emmett-Teller (BET) testing was then conducted using an ultra-high purity Krypton gas at relative pressures of 005, 0.075, 0.10, 0.15, 0.20, 0.25, and 0.30 at a bath temperature of 77.35 °K. The surface area is calculated by assessing the volumetric changes between the gas adsorbed or desorbed and the amount of gas required to fill the space around the sample in conjunction with Equation 2.

$$S = W_m NA/M \qquad \text{(Equation 2)}$$

Where: S = surface area (m^2/g)
W_m = monolayer capacity
N = Avogadro number
A = cross-sectional area of Krypton
M = molecular weight of Krypton

2.4 GTR-Modified Binder Blending

Prior to blending, the virgin binder was heated in a 275°F oven until fluid enough to pour (approximately 3 hours). While heating, the binder was stirred with a glass rod every 30 minutes. Once heated, the binder was proportioned into pre-weighed cans and set aside until needed for blending.

The amount of GTR needed for each sample was calculated based on the final weight of the asphalt binder and GTR blend to ensure a representative sample, a significant portion of GTR was poured onto a tray and the material was manually blended to ensure homogeneity. The required weight of GTR was then split from this homogeneous pile.

Each can of binder was heated for 30 minutes at 275 °F prior to being blended. A heating mantle was used to ensure the temperature of the binder and rubber sample remained constant during blending. The target temperature of the GTR and binder mixture during blending was 163°C. This was monitored through the use of a thermometer probe.

The GTR sample for each blend was added at a constant rate during the first two minutes of blending. While adding the GTR, the stirring paddle was set at 700 RPM to help prevent rubber particles from being blown outside the system. Once all the GTR was added, the blender was set to 1000 RPM and the material blended for 30 minutes. To ensure that each blend received the same style of blending, the blender propeller was placed at a depth to ensure a one inch vortex (Figure 4) during blending. Immediately after blending, a small portion of the GTR binder was poured into an aluminum tube for separation testing according to ASTM D7173-11 using ¾ inch tubes instead of the specified 1 inch tubes. The rest of the material was covered and set aside for at least four hours at room temperature for further testing.

This blending process was more extreme than typically used at most plants; however, the blending methodology was provided by project sponsors.

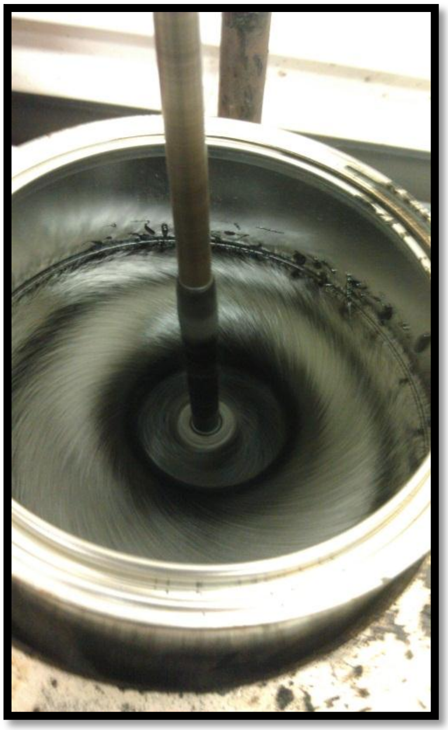

Figure 4 Sample Vortex

2.5 Performance Grade

Prior to testing, the pre-blended cans of GTR binder were placed in a 163°C oven for 30 minutes and then blended at 1000 RPM for 10 minutes. Again, the temperatures of the samples were monitored with a lab thermometer and the target mixing temperature of 163°C was held constant through the use of the heating mantle.

The 13 GTR binders were then tested and graded according to AASHTO M320-10.
The standard 1 mm Dynamic Shear Rheometer (DSR) gap was initially used on all 14 blends. Past research (*10, 11*) has suggested using a 2mm DSR gap to improve the repeatability of PG testing on DSR results. However, only the binder modified with the largest particle sizes was inconsistent in its critical temperature analyses; therefore, a 2 mm gap was used to test the only -16 "powderizers" blend. The variability of the testing was reduced using this procedure for that one binder.

2.6 Multiple Stress Creep Recovery

In addition to the PG grading of the GTR binders, the performance grade of the 14 GTR binders was also determined in accordance with AASHTO M19-10. The multiple stress creep recovery (MSCR) test was performed of the rolling thing film oven (RTFO) aged material in accordance with AASHTO TP 70-09. Testing was conducted at 64°C which is the average 7-day maximum pavement design temperature in Auburn, Alabama. The same (RTFO) aged specimen used in the DSR was used for MSCR testing. The MSCR results measure the non-recoverable creep compliance. The acceptable non-recoverable creep compliance at 3.2 kPa and percent differences for varying levels of traffic as specified in AASHTO MP19-10 are given in Table 1.

Table 1 Requirements for Non-Recoverable Creep Compliance (AASHTO MP 19-10)

Traffic Level	Max $J_{nr3.2}$ (kPa^{-1})	Max J_{nrdiff} (%)
Standard Traffic "S" Grade	4.0	75
Heavy Traffic "H" Grade	2.0	75
Very Heavy Traffic "V" Grade	1.0	75
Extremely Heavy Traffic "E" Grade	0.5	75

Note: The specified test temperature is based on the average 7-day maximum pavement design temperature.

2.7 Separation Tubes

The separation tube test procedure is performed to determine the tendency of an asphalt modifier to separate from the asphalt binder during static heated storage. If a modified asphalt binder shows a tendency to separate during storage, this must be taken into account either by providing some sort of agitation or stirring or by re-formulating the binder. Testing was conducted in accordance with ASTM D7173-11, *Standard Practice for Determining the Separation Tendency of Polymer from Polymer Modified Asphalt*.

Immediately after the blending was performed, 50 ± 0.5g of the hot asphalt binder was then poured into a cylindrical aluminum tube which was closed on one end and supported vertically in a rack. Once filled, the open end of the tube was sealed to prevent air from reaching the sample. The tube and rack were placed in an oven at 163 ± 5°C and allowed to condition for 48 ± 1 hr.

After the conditioning was completed, the tube assembly was removed from the oven and immediately placed in a freezer at 10 ± 10°C for at least 4 hours. Once frozen, the tube was removed from the freezer and cut into three equal portions. The middle portion was discarded and the top and bottom portions were placed in separate 3oz tins and heated until sufficiently fluid that asphalt binder flows from the metal tubing. The two asphalt binder samples were then stirred thoroughly and used for comparative testing to determine if the asphalt binder in the top and bottom portions of the tube were significantly different in terms of critical high temperature grading in the DSR.

2.8 Softening Point

The Ring-and-Ball softening point test (ASTM D36-09) measures the temperature at which an asphalt binder begins to flow at elevated service temperatures. It was used here in conjunction with the separation tube procedure to determine if there was a difference in properties of the asphalt binder from the top and bottom portions of the separation tube. A difference in the softening point values of the upper and lower portions of the tube would indicate that the modifier had separated from the asphalt binder during the storage period.

The softening point test was performed by heating the asphalt binders obtained from the top and bottom portions of the aluminum separation tube and pouring them into two small brass rings.

The asphalt binders and rings were allowed to cool at room temperature for at least 30 minutes. The asphalt binder was then trimmed flush with the top of the rings.

A ring holder assembly (Figure 5) was placed in a fluid bath along with two steel balls where they were allowed to condition to a starting temperature of 5 ± 1°C for 15 minutes. A bath of distilled water was chosen for this study based on the expected softening point (between 30 and 80°C) of the material being tested. Other fluid options exist for materials with higher softening points.

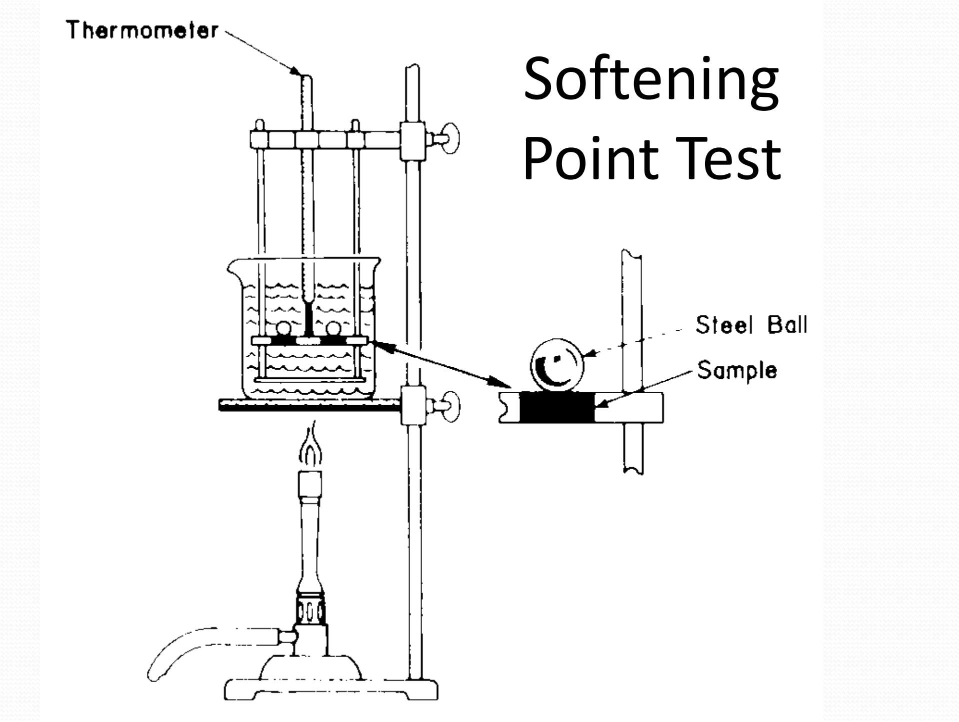

Figure 5 Ring-and-Ball Softening Point Apparatus

After the conditioning period, the steel balls were placed on top of the asphalt binder in the rings. The bath was heated at a rate of 5°C/min until the asphalt binder softened to the point that the balls drop and touch the bottom plate of the assembly. The temperature at which each ball touches the plate was recorded as the softening point for the asphalt binder in that ring. Softening points were considered different if they vary by more than 1.2°C between samples tested by the same operator.

3. RUBBER PARTICLE CHARACTERIZATION

Twelve unique rubber sources were included in this research study. These rubber products are listed in Table 2 as well as descriptions of the product.

Table 2 Rubber Products Used in Study

Manufacturer	Product Name	Grinding Temperature	Tire Type	Mesh Size
Lehigh Technologies, Inc.	MD-402-TR	Cryogenic	Truck Tire (TT)	-40
Lehigh Technologies, Inc.	MD-400-TR	Cryogenic	TT	-40
Lehigh Technologies, Inc.	MD-400-AM	Ambient	TT	-40
Lehigh Technologies, Inc.	MD-180-TR	Cryogenic	TT	-80
Lehigh Technologies, Inc.	MD-105-TR	Cryogenic	TT	-140
Liberty Tire	Cryohammer	Cryogenic	Passenger Car (PC)	-30
Liberty Tire	Crackermill	Ambient	TT	-30
Lehigh Technologies, Inc.	-80/+140	Cryogenic	TT	-80/+140
Liberty Tire	-30 Fine	Ambient	PC + TT	-30
Liberty Tire	-30	Ambient	PC + TT	-30
Liberty Tire	-20	Ambient	PC + TT	-20
Liberty Tire	-16 Powderizers	Ambient	PC + TT	-16

3.1 RO-TAP Particle Size

Each rubber product initially was characterized for particle size using the RO-TAP procedure previously described in section 2.1. The results of this analysis are shown in Table 3. As can be seen, the coarsest rubber particles were the Liberty Powderizers with 30 percent retained on the #20 sieve. The finest rubber particles were a found in the MD-105-TR where 77.3 percent of the rubber particles passed the #200 sieve. Most of the products ranged in size from 30 to 60 mesh materials with few exceptions. It should also be noticed that three products (MD-402-TR, Liberty Powderizers -16, and Liberty -20) had trace amounts of fiber which were extracted from their particle size distribution.

Table 3 RO-TAP Results

Product	Mesh Size	Percent Retained on Sieve #, %													Fiber Content,%
		14	16	20	30	40	60	80	100	120	140	170	200	Pan	
MD-402-TR	-40	--	--	--	--	0.0	15.8	53.0	--	--	--	--	--	32.1	0.025
MD-180-TR	-80	--	--	--	--	--	0.0	1.2	12.5	28.3	15.5			42.7	--
MD-105-TR	-140	--	--	--	--	--	--	--	--	0.0	0.4	5.0	17.3	77.3	--
-80/ +140	-80/+140	--	--	--	--	--	--	2.5	16.5	57.8	11.6	--	--	11.6	--
MD-400-TR	-40	--	--	--	0.0	1.5	33	49.7	--	--	--	--	--	16.1	--
Powderizers – 16	-16	0.0	0.0	29.3	21.2	6.6	--	--	--	--	--	--	--	43.1	0.01
-20	-20	--	--	0.0	7.8	37.5	32.6	10.8	--	--	--	--	--	11.2	0.034
Cryohammer	-30	--	--	0.0	0.3	16.8	50.5	16.8	--	--	--	--	--	15.6	--
-30	-30	--	--	--	0.0	25.5	49.6	15.0	--	--	--	--	--	9.9	--
-30 Fine	-30	--	--	--	0.0	12.3	40.5	22.2	--	--	--	--	--	25.0	--
Crackermill	-30	--	--	--	--	12.6	45.4	18.9	--	--	--	--	--	23.1	--
MD-400-AM	-40	--	--	0.0	0.0	6.0	56.0	33.0	5.0	--	--	--	--	--	--

While engineers commonly refer to rubber particles mesh size using the mesh with 90 percent passing, there is a current trend in the rubber industry to refer to particles by the mean particle size which is more representative of the actual particle sizes included in the product. Table 4 provides both the mesh and mean particle size for the products evaluated in this study.

Table 4 RO-TAP Results

GTR	Mesh Size	Mean Particle Size, microns	Grinding Temperature
MD 402 TR	-40	180	Cryogenic
MD 400 TR	-40	180	Cryogenic
MD 400 AM	-40	180	Ambient
MD 180 TR	-80	105	Cryogenic
MD 105 TR	-140	50	Cryogenic
Liberty Cracker Mill	-30	250	Ambient
Cryo-Hammer	-30	250	Cryogenic
-80/140	-80/+140	125	Cryogenic
-30 Liberty	-30	250	Ambient
-30 Fines Liberty	-30	250	Ambient
-20 Liberty	-20	250	Ambient
-16 Powderizers	-16	600	Ambient

3.2 TGA

TGA testing was conducted to quantify the makeup of each ground rubber product according to ASTM E1131-03. In this test, the percent extractibles, polymer, carbon black, and ash were calculated for each of the eleven crumb rubber sources. The results are given in Table 5. As can be seen, most of the crumb rubber products had extractibles which fell within a 4 percent band, polymer contents which varied by no more than 6.5 percent, carbon black differences of 4.7 percent maximum, and ash contents within 1.7 percent of each other. Therefore, while there was some deviation in the test results of the ground rubber sources, most of the particles have similar makeups. The 6.5 percent difference in polymer content of some rubber sources could be inflated when used at 10 to 15 percent loading. This would theoretically give one modified binder an additional 0.65% polymer than another which could influence both high and low temperature critical temperatures.

Table 5 TGA Results

Product	Percent Material, %				Mesh	Grinding Temperature
	Extractibles	Polymer	Carbon Black	Ash		
MD-402-TR	6.78	58.11	30.13	4.80	-40	Cryogenic
MD-400-TR	7.35	57.95	29.86	4.70	-40	Cryogenic
MD-400-AM	10.17	56.10	28.36	5.18	-40	Ambient
MD-180-TR	8.79	54.48	30.88	5.67	-80	Cryogenic
MD-105-TR	10.97	52.43	30.17	6.26	-140	Cryogenic
Cryohammer	10.37	51.89	31.40	6.20	-30	Cryogenic
Crackermill	8.11	52.78	29.35	9.63	-30	Ambient
-80/ +140	8.67	53.73	32.31	5.31	-80/ +140	Cryogenic
-30 Fine	7.73	58.46	27.56	5.96	-30	Ambient
-30	9.69	52.29	31.54	6.36	-30	Ambient
-20	9.86	54.36	30.65	5.03	-20	Ambient
-16 Powderizers	9.49	55.53	28.43	6.44	-16	Ambient
Maximum	10.97	58.46	32.31	6.44		
Minimum	6.78	51.89	27.56	4.70		

3.3 Surface Area

The surface area of each rubber product was characterized by Quantichrome using the BET procedure previously described in conjunction with Krypton gas. The surface area for each rubber product is given in Table 6. As seen, the product with the smallest surface area was the cryo-hammer material produced by Liberty Tire. The material with the highest surface area was the MD 105 TR. This material was cryogenically ground and had the smallest particle size.

Table 6 Surface Area

GTR	Mesh	Grinding Temperature	Surface Area (m2/g)
MD 402 TR	-40	Cryogenic	0.407
MD 400 TR	-40	Cryogenic	0.079
MD 400 AM	-40	Ambient	0.400
MD 180 TR	-80	Cryogenic	0.275
MD 105 TR	-140	Cryogenic	0.751
Liberty Cracker Mill	-30	Ambient	0.104
Cryo-Hammer	-30	Cryogenic	0.044
-80/140	-80/ +140	Cryogenic	0.104
-30 Liberty	-30	Ambient	0.056
-30 Fines Liberty	-30	Ambient	0.114
-20 Liberty	-20	Ambient	0.092
16 Powderizers	-16	Ambient	0.079

4. GTR-MODIFIED BINDER CHARACTERIZATION

While it was important to characterize the particle sizes and makeup for each crumb rubber product, it is even more critical to understand how each crumb rubber product will affect the properties of the asphalt binder it is modifying. Therefore, all eleven crumb rubber product were blended with a standard PG 67-22 asphalt binder at a loading rate of 10 percent. Two of the crumb rubber products (Cryo-hammer and -20 Liberty) were blended at loading rates of 15 percent to determine how the additional 5 percent rubber affected the binder properties. These two products were chosen at the discretion of the sponsors. Each of the fourteen rubber-modified binders was then analyzed for performance grade, multiple stress creep recovery grade, and separation potential via the separation tubes and softening point procedure.

4.1 Performance Grade Testing

The GTR-modified asphalt binders were tested and graded according to AASHTO M 320-10. Detailed results are provided in Appendix A. Table 7 summarizes the true grade and performance grade of each blended binder. All of the rubber products were tested using a 1 mm gap in the DSR with the exception of the -16 Powderizers. This product was the largest in size and showed signs of the GTR particles affecting the DSR test results. In order to get a more accurate reading of the GTR-modified binder properties, a 2 mm gap was used to characterize this product in addition to the 1 mm gap.

Table 7 Modified Binder Performance Grades

Rubber Product	Grinding Temp	Mesh Size	Loading. %	True Grade	Performance Grade
Base Binder	NA	NA	0%	70.0 – 25.4	70 – 22
MD-402-TR	Cryo	-40	10%	79.0 – 23.0	76 – 22
MD-400-TR	Cryo	-40	10%	80.4 – 24.2	76 – 22
MD-400-AM	Ambient	-40	10%	82.1 – 20.8	82 - 16
MD-180-TR	Cryo	-80	10%	81.2 – 25.4	76 – 22
MD-105-TR	Cryo	-140	10%	77.9 – 25.6	76 – 22
Cryo-Hammer	Cryo	-30	10%	82.2 – 23.2	82 – 22
Cryo-Hammer	Cryo	-30	15%	86.7 – 19.3	82 – 16
Crackermill	Ambient	-30	10%	82.8 – 23.1	82 – 22
-80/140	Cryo	-80/+140	10%	83.6 – 24.9	82 – 22
-30 Liberty Fines	Ambient	-30	10%	79.8 – 20.4	76 – 16
-30 Liberty	Ambient	-30	10%	80.7 – 23.6	76 – 22
-20 Liberty	Ambient	-20	10%	83.1 – 24.6	82 – 22
-20 Liberty	Ambient	-20	15%	87.9 – 21.3	82 – 16
-16 Powderizers (2 mm gap)	Ambient	-16	10%	84.7 – 21.8	82 – 16
-16 Powderizers (1mm gap)	Ambient	-16	10%	76.3 – 21.8	76 – 16

The base binder used in this study had a true grade of PG 70.0 – 25.5. A dosage rate of 10% was used for each rubber product in attempt to modify the base binder to a PG 76 – 22. All fourteen CRM blends had a PG critical high temperature of at least 76°C. Additionally, the two rubber blends which were tested at both 10 and 15 percent loading had higher critical temperatures when loaded at 15 percent.

Both grinding method and particle size seemed to make no difference on the critical high temperature of the blended binder. Figure 6 graphically shows the relationship between GTR particle size and critical high temperature of the blended binders. The best relationship that could be developed has a low R^2 value of 0.19 suggesting particle size did not really influence the true grade of the binder; however, outliers were not removed from the data set. Using an average value of the GTR-modified asphalt binders with ambient #30 mesh material did not improve the goodness-of-fit.

The grinding temperature seemed to have little effect as both cryogenically and ambiently ground particles were blended with a PG 67-22 binder to achieve the PG 76-22 performance grade. Additionally, both ambient and cryogenic crumb rubber products were able to modify the PG 67-22 binder to a PG 82-22 binder at 10 percent loading. To further support this point, a one-sided *t*-test was used to statistically compare the high temperature grade of the four GTR-modified asphalt binders using ambiently ground 30 mesh material to the GTR-modified asphalt binder using 30 mesh cryogenically ground rubber products. The ambient 30 mesh GTR-modified binders had an average critical high temperature grade of 81.6°C while the GTR-modified binder with 30 mesh cryogenically ground rubber had a critical high temperature grade of 82.2°C. There was no evidence of a statistical difference (*p*-value = 0.509) between the 30 mesh between the GTR-modified asphalt binders using ambiently or cryogenically ground #30 mesh material.

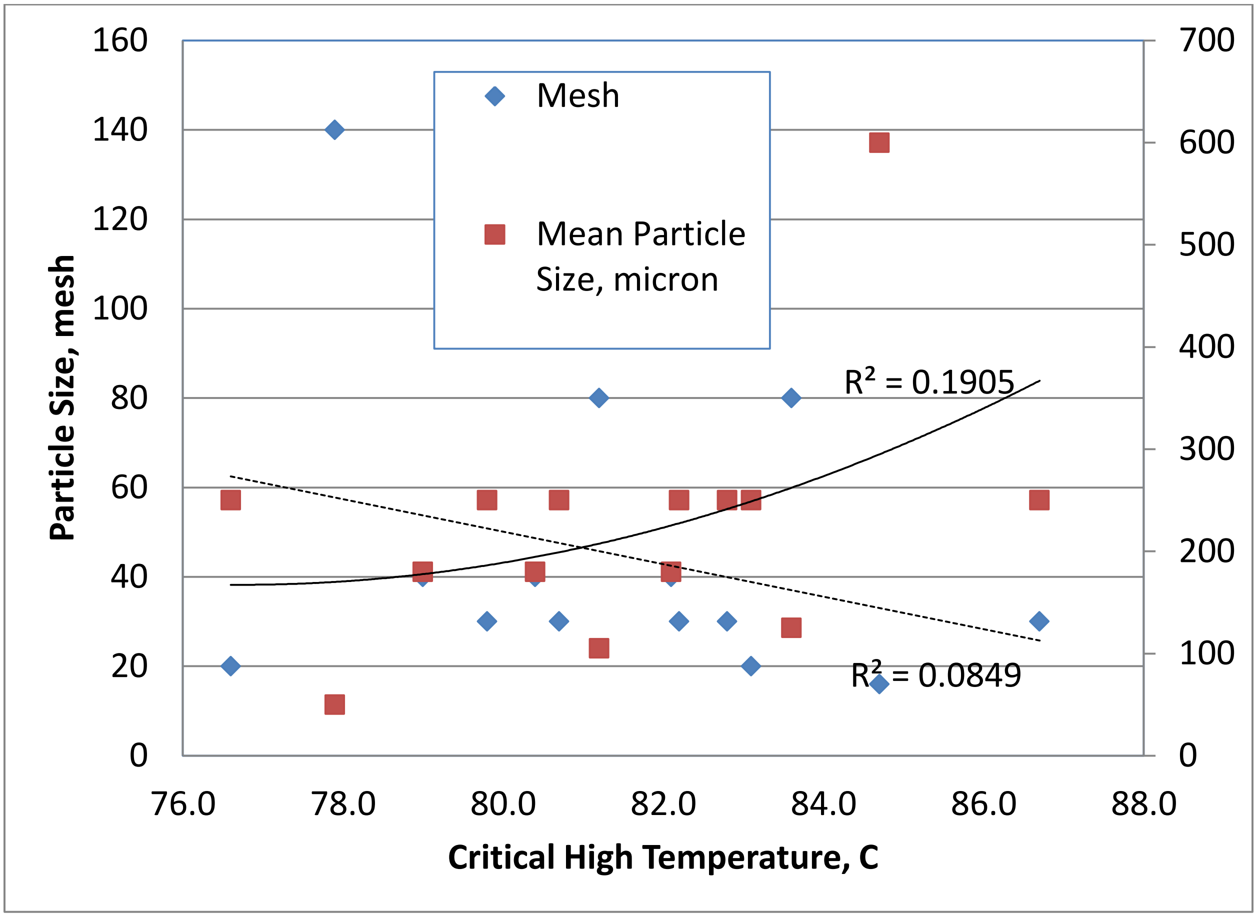

Figure 6 Particle size versus critical high temperature.

The General Linear model (α = 0.05) was attempted to statistically assess if particle size, grinding temperature, tire type, surface area, polymer content, and loading rate statistically affected the critical high temperature grade of the rubber modified binder (Table 8). Using surface area and polymer content as covariates due to the nature of the data, none of the factors were statistically significant in explaining the high temperature grade of the modified binder. This could be due to the unbalanced nature of the dataset. While none of the variables were statistically significant, the model only explained 68 percent of the total variability. The two factors which explained the most variability in the model were mean particle size (28.5 percent) and surface area (21.2 percent).

Table 8 High Temperature Grade ANOVA Table

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Surface Area*	1	20.10	0.95	0.95	0.06	0.826
Polymer*	1	0.79	0.22	0.22	0.01	0.915
Loading Rate	1	0.53	1.22	1.22	0.08	0.803
Mean Particle Size	5	27.04	17.82	3.56	0.24	0.916
Tire Type	2	12.53	12.93	6.47	0.43	0.700
Temperature	1	3.59	3.59	3.59	0.24	0.674
Error	2	30.25	30.25	15.13		
Total	13	94.84				

*Covariate

Four of the fourteen GTR blends failed to meet the critical low temperature specification of -22°C. Of the four materials which did not meet this specification, two were rubber-binder blends which used 15 percent rubber, and one of the other rubber modified asphalt used the crumb rubber with the largest particle sizes. The fourth product which graded at -16°C was the -30 Fines produced by Liberty. In each of the four cases, the m-value caused the rubber blend to fail the low temperature criterion. A possible solution for three of the GTR blends could be to reduce the amount of GTR added to the binder. The -16 Powderizers, 15% -20 Liberty, and 15% Cryo-Hammer blends are all relatively close to passing the -22°C grade and have a large margin over the 76°C target. A slight reduction in the GTR for these materials should achieve a passing low temperature grade while still maintaining the desired PG 76. As can be seen from the table, the 10% -20 Liberty and 10% Cryo-Hammer meet the -22°C requirements. The -16 Powderizers are only 0.2°C below the -22°C grade and have over an 8°C margin above the 76°C grade. It should only take a small decrease in this GTR to achieve the target grade. The -30 Liberty Fines may also benefit from a decrease in GTR percentage, but it may prove difficult to obtain the -22°C grade without dropping below the PG 76°C for the high grade.

Figure 7 shows the relationship between particle size and critical low temperature. While the relationship was stronger than the relationship for critical high temperature ($R^2 = 0.3615$), the relationship is not robust enough to draw any strong conclusions about the relationship between particle size and critical low temperature. The goodness-of-fit for this relationship was reduced due to the number of #30 crumb rubber sources with differing low temperatures. Using the mean particle size did not improve the relationship (Figure 8).

While it is difficult to determine if there is a difference in the effect of grinding method on low temperature binder performance, the only blends which failed the -22°C criterion at 10 percent loading used an ambient grind. All the binder blends using cryogenically ground materials passed this specification.

The General Linear model ($\alpha = 0.05$) was used to assess if particle size, grinding temperature, tire type, surface area, polymer content, and loading rate statistically affected the critical low temperature grade of the GTR-modified binders (Table 9). Using surface area and polymer content as covariates due to the nature of the data, again, none of the factors were statistically significant in explaining the low temperature grade of the modified binder. However, unlike the high temperature critical temperature, approximately 92 percent of the model variability was explained by factors. The two factors which had the most influence on the low temperature grade were the mean particle size (34.6 percent) and loading rate (21.3 percent). The effect of loading rate was evident as changing from 10 to 15 percent loading always increased the critical high temperature by at least one binder grade.

Table 9 Low Temperature Grade ANOVA Table

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Surface Area*	1	4.996	0.430	0.430	0.21	0.690
Polymer*	1	3.66	6.567	6.567	3.24	0.214
Loading Rate	1	10.323	9.209	9.209	4.54	0.167
Mean Particle Size	5	16.766	14.563	2.913	1.44	0.459
Tire Type	2	3.567	8.825	4.412	2.17	0.315
Temperature	1	5.353	5.353	5.353	2.64	0.246
Error	2	4.058	4.058	2.029		
Total	13	48.472				

*Covariate

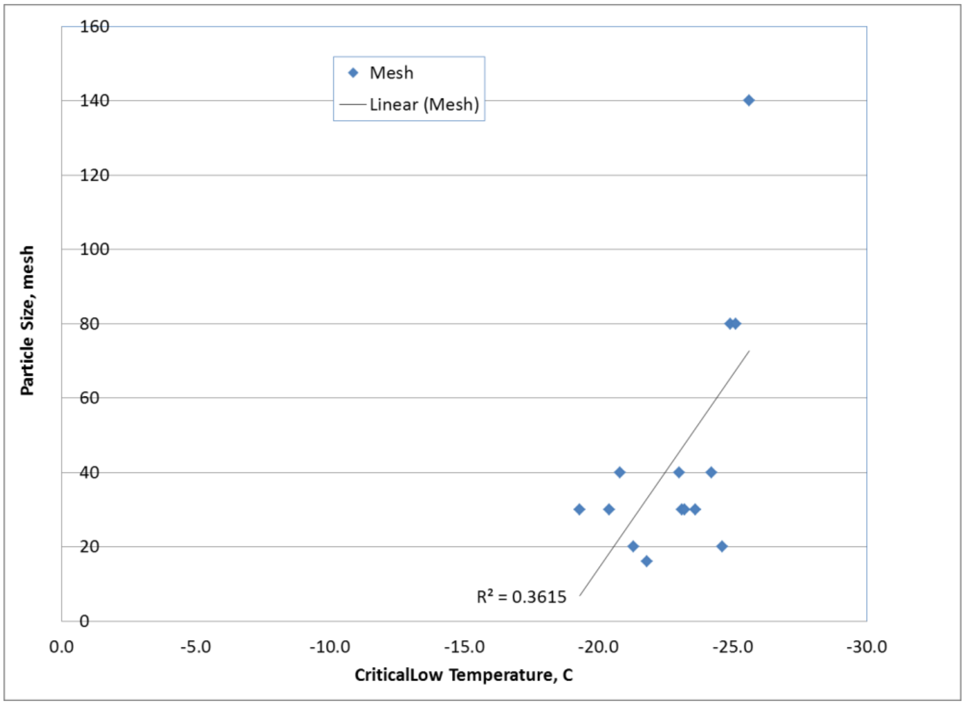

Figure 7 Particle size versus critical low temperature

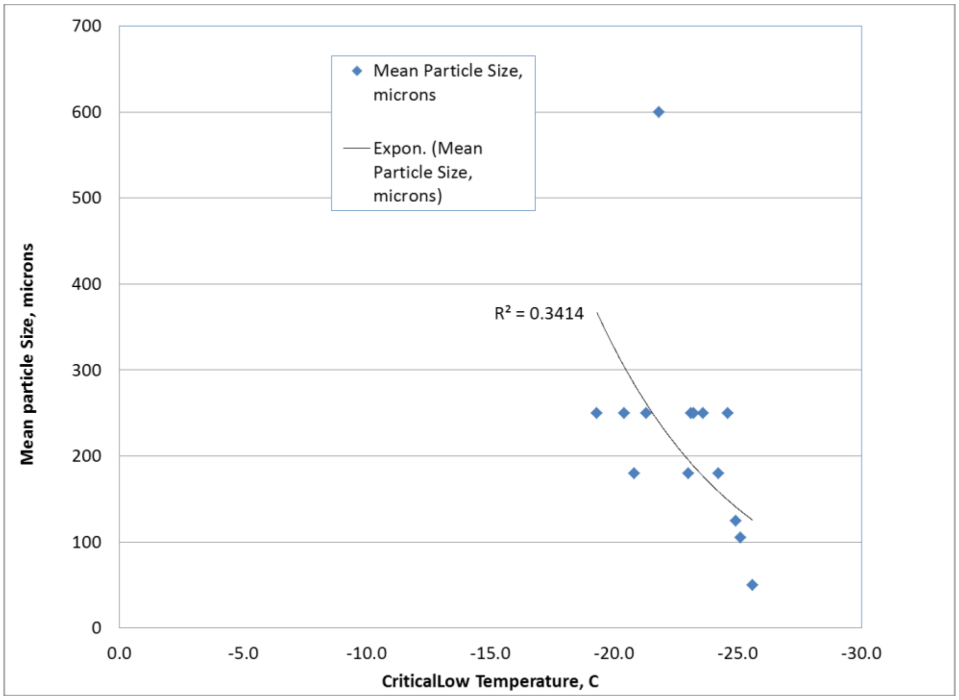

Figure 8 Particle size versus critical low temperature using mean particle size

4.2 Multiple Stress Creep Recovery

To determine the performance grade in accordance with AASHTO M 19-10, the MSCR test (AASHTO TP 70-09) was conducted at 64^{o}C(the average 7-day maximum pavement design temperature for Auburn, Alabama) to determine the non-recoverable creep compliance for all the binders. The same RTFO aged specimen utilized in the dynamic shear rheometer (DSR) test according to AASHTO T 315-09 was used in the MSCR test. Table 10 summarizes the MSCR testing results. The base binder was graded as an “H” for heavy trafficking.

Ten of the modified rubber binders met the requirements for the highest trafficking level “E”. The “E” stands for extremely high traffic or trafficking of greater than 30 million equivalent single axle loads (ESALs) and standing traffic. When compared to the PG grades, all ten modified binders had critical high temperatures greater than 76°C.

Four of the rubber modified binders (-20 Liberty at 10 and 15 percent loading, cryo-hammer at 15 percent loading, and -16 powderizers using 1 mm DSR gap) exceeded the maximum allowable J_{nr} difference of 75 percent due to extremely low J_{nr} values at 0.1 kPa. However, while these blends did not meet the “E” specification, the $J_{nr0.1}$ and $J_{nr3.2}$ results suggest they should have adequate resistance to permanent deformation under those conditions.

Table 10 Modified Binder MSCR Results

Rubber Product	Grinding Temp	Mesh Size	Loading Rate, %	J_{nr}			% Recovery		Traffic Level
				0.1 kPa^{-1}	3.2 kPa^{-1}	% Diff	0.1 kPa^{-1}	3.2 kPa^{-1}	
Base Binder	NA	NA	0%	1.150	1.353	17.68	12.99	5.616	“H”
MD-402-TR	Cryo	-40	10%	0.178	0.202	13.52	42.90	36.69	“E”
MD-400-TR	Cryo	-40	10%	0.139	0.166	19.19	51.23	43.55	“E”
MD-400-AM	Ambient	-40	10%	0.123	0.160	57.18	46.88	30.53	“E”
MD-180-TR	Cryo	-80	10%	0.175	0.201	14.90	44.66	38.02	“E”
MD-105-TR	Cryo	-140	10%	0.273	0.344	26.08	36.86	24.50	“E”
Cryo-Hammer	Cryo	-30	10%	0.150	0.201	34.21	50.59	36.68	“E”
Cryo-Hammer	Cryo	-30	15%	0.062	0.1949	216.2	68.87	44.72	”E”*
Crackermill	Ambient	-30	10%	0.122	0.183	50.88	59.46	42.73	“E”
-80/140	Cryo	-80/+140	10%	0.123	0.190	46.39	58.44	41.87	“E”
-30 Liberty Fines	Ambient	-30	10%	0.092	0.127	37.68	61.62	49.58	“E”
-30 Liberty	Ambient	-30	10%	0.201	0.233	15.95	43.56	36.42	“E”
-20 Liberty	Ambient	-20	10%	0.086	0.159	85.81	69.16	46.45	”E”*
-20 Liberty	Ambient	-20	15%	0.030	0.193	554.0	85.94	50.43	”E”*
-16 Powderizers (2 mm gap)	Ambient	-16	10%	0.088	0.122	39.41	63.03	50.44	“E”
-16 Powderizers (1mm gap)	Ambient	-16	10%	0.096	0.720	652.5	95.20	66.45	”E”*

* Did not meet Jnr % difference requirement (≤75%)

4.3 Separation Tubes

Separation tubes were used in conjunction with the DSR to determine if particle size and grinding method affected the overall separation of the GTR particles from the asphalt binder. The amount of separation was quantified by the difference in the critical high temperature of the modified binder removed from the top half of the separation tube compared to the critical temperature grade of the modified binder removed from the bottom half of the separation tube. The results are shown in Table 11.

There currently is no consensus pass/fail criterion for this testing methodology; therefore, one can only rank the performance of the modified binders. Using this methodology, the MD-180-

TR had the smallest difference between the critical high temperatures for the asphalt binder in the top and bottom of the tubes. The mixture which had the greatest difference was the -16 powderizers. No trend was noticed when comparing the mesh rubber size to the different in critical high temperatures; however, there was a strong trend between separation and mean particle size (Figure 10). The finer the mean particle size, the less separation occurred.

To statistically assess this hypothesis, the GLM (α = 0.05) was used to assess the variability of the test results in terms of particle size, grinding temperature, loading rate, surface area, and polymer content (Table 12). Using the GLM, the only factor which statistically influenced the separation results was particle size. Smaller particles showed less separation. Over 86 percent of the model variability was explained using this term alone. The second most influential factor was surface area; however, it only accounted for 7.8 percent of the data. Overall, the model had less than one percent error.

Table 11 Modified Binder Separation Tube DSR Results

Rubber Product	**Grind Temp**	**Mesh Size**	**Loading Rate, %**	**Critical High Temperature, °C**			
				Top	*Bottom*	*Absolute Difference*	*% Difference*
MD-402-TR	Cryo	-40	10%	82.75	102.7	19.95	24.11
MD-400-TR	Cryo	-40	10%	81.79	102.6	20.81	25.44
MD-400-AM	Ambient	-40	10%	86.1	99.9	13.8	13.9
MD-180-TR	Cryo	-80	10%	74.98	81.56	6.58	8.78
MD-105-TR	Cryo	-140	10%	79.93	92.53	12.6	16.61
Cryo-Hammer	Cryo	-30	10%	77.71	102.1	24.39	23.89
Cryo-Hammer	Cryo	-30	15%	79.85	110.5	30.65	38.40
Crackermill	Ambient	-30	10%	77.04	102.4	25.36	32.90
-80/140	Cryo	-80/+140	10%	78.87	97.52	18.65	23.65
-30 Liberty Fines	Ambient	-30	10%	85.63	97.07	11.44	11.79
-30 Liberty	Ambient	-30	10%	76.67	103.6	26.93	35.12
-20 Liberty	Ambient	-20	10%	75.84	101.7	25.86	34.10
-20 Liberty	Ambient	-20	15%	94.3	107.4	13.1	12.20
-16 Powderizers (1mm)	Ambient	-16	10%	79.78	197.5	117.72	147.56

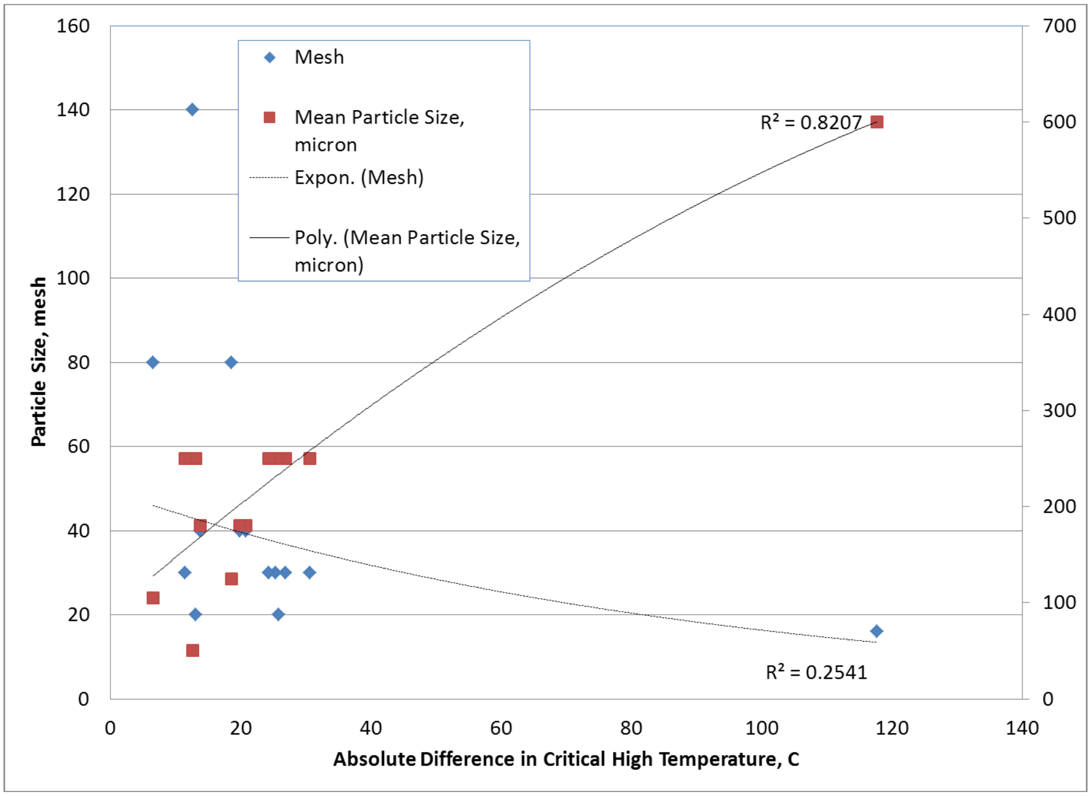

Figure 9 Particle size versus difference in separation tube critical high temperatures.

Table 12 DSR Separation Different ANOVA Table

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Surface Area*	1	753.73	0.13	0.13	0.00	0.962
Polymer*	1	108.26	116.96	116.96	2.58	0.250
Loading Rate	1	281.86	14.97	14.97	0.33	0.624
Mean Particle Size	5	8343.08	7608.22	1521.64	33.55	0.029
Tire Type	2	6.51	25.80	12.90	0.28	0.779
Temperature	1	54.35	54.35	54.35	1.20	0.388
Error	2	90.72	90.72	45.36		
Total	13	9638.51				

*Covariate

4.4 Softening Point

The softening point test was conducted according to AASHTO D36-09 to determine if the rubber particles separated when mixed with the asphalt binder, and the results are presented in Table 13. The current specification states that if the top and the bottom of the separation tubes have softening points greater than 2°C, the binders are considered different materials and separation will have occurred. Using this standard, only the MD-105-TR did not separate. All of the other modified binders had softening points which differed by more than 2°C.

While most of the rubber particles seemed to settle in the asphalt binder, the research team wanted to determine if the particle size or grinding technique influenced the amount of separation. It should be noted that the one particle size which did not separate in the separation tubes had the smallest particle size. Figure 10 shows the relationship between particle size and softening point differences. Using the developed relationship and a maximum allowable temperature difference of 2°C, the data suggest that particle sizes larger than 100 mesh may have a tendency to separate from the asphalt binder. It should also be noted that only one product had a particle size less than 80 mesh. This suggests that contractors using larger particle sizes will need agitation systems to ensure the rubber and binder stay blended.

To statistically assess this hypothesis, the GLM ($\alpha = 0.05$) was used to assess the factors which had the most influence on the softening point results (Table 14). None of the variables were statistically significant; however, mean particle size (30.5 percent) and surface area (22.9 percent) explained the most variability in the model. The smaller particles with larger surface areas were less susceptible to settling than the larger particles with smaller surface areas.

Table 13 Modified Binder Separation Tube Softening Point Results

Rubber Product	**Mesh Size**	**Loading Rate, %**	**Softening Point, °C**			
			Top	*Bottom*	*Absolute Difference*	*% Difference*
MD-402-TR	Cryo	-40	59.7	77.2	17.5	25.6
MD-400-TR	Cryo	-40	61.7	73.3	11.6	17.2
MD-400-AM	Ambient	-40	62.2	71.4	9.2	13.8
MD-180-TR	Cryo	-80	58.6	63.0	4.4	7.2
MD-105-TR	Cryo	-140	60.6	61.1	0.5	0.8
Cryo-Hammer	Cryo	-30	59.7	70.7	10.3	15.9
Cryo-Hammer	Cryo	-30	61.9	75.0	13.1	19.1
Crackermill	Ambient	-30	58.9	66.7	7.8	12.4
-80/140	Cryo	-80/+140	61.4	78.0	16.6	23.8
-30 Liberty Fines	Ambient	-30	62.8	72.8	10.0	14.7
-30 Liberty	Ambient	-30	58.9	72.5	13.6	20.7
-20 Liberty	Ambient	-20	58.9	69.4	10.5	16.4
-20 Liberty	Ambient	-20	66.4	73.3	6.9	9.9
-16 Powderizers	Ambient	-16	59.2	69.7	10.5	16.3

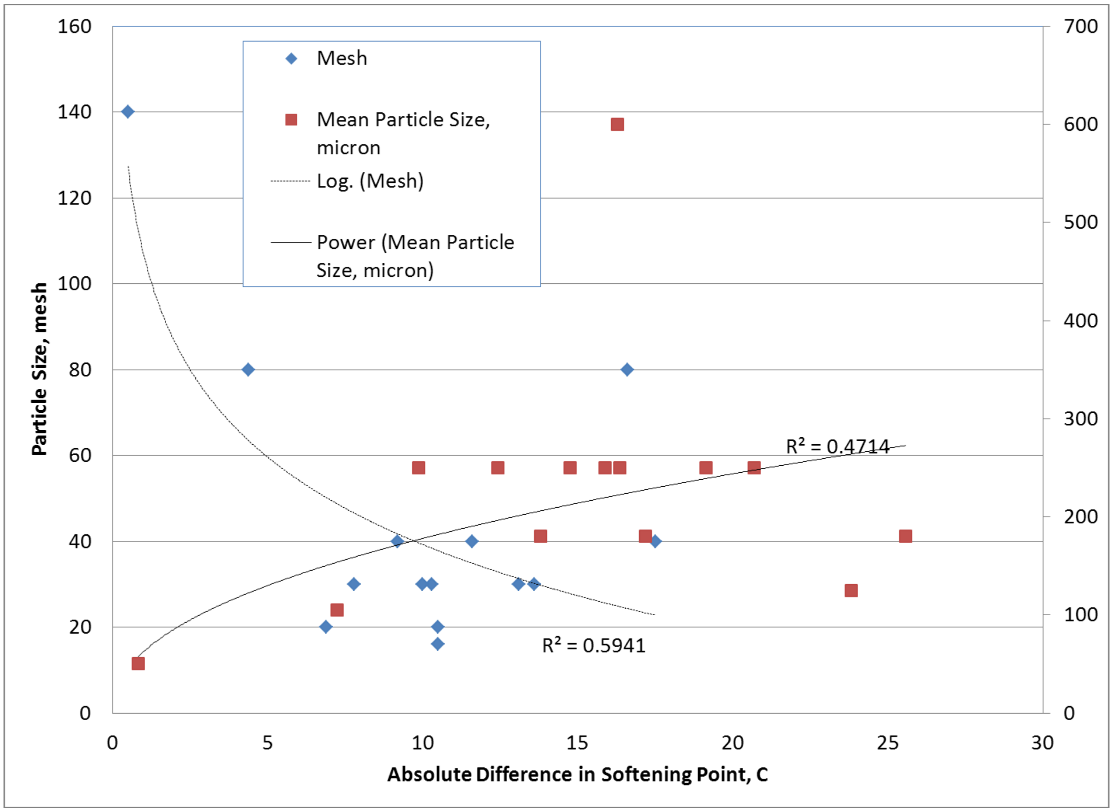

Figure 10 Particle size versus difference in softening points

Table 14 Softening Point Separation Different ANOVA Table

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Surface Area*	1	59.91	16.17	16.17	1.52	0.343
Polymer*	1	49.33	6.69	6.69	0.63	0.510
Loading Rate	1	0.57	4.22	4.22	0.40	0.593
Mean Particle Size	5	79.80	123.75	24.75	2.33	0.327
Tire Type	2	13.47	22.48	11.24	1.06	0.486
Temperature	1	37.47	37.47	37.47	3.53	0.201
Error	2	21.24	21.24	10.62		
Total	13	261.78				

*Covariate

5. EFFECT OF ADDITIVES ON RUBBER-MODIFIED BINDERS

Two common additives used in conjunction with GTR binders are polymer and Vestenamer. Polymer-modified GTR binders are typically termed “hybrid” binders as they include both GTR and SBS as modifiers. As an additional effort, the research team wanted to determine how Vestenamer and polymer affected the PG and MSCR grades of an asphalt rubber binder as well as the separation of the binder and rubber particles using the softening point test.

5.1 Materials

The rubber-modified binders using 10% #30 Liberty and 10% MD-400-TR were modified with Vestenamer at a dosage rate of 0.5 percent by weight of binder. The material was mixed with the binder using instructions provided by the project sponsor.

In addition to the Vestenamer modified binder, a polymer modified GTR binder was developed and provided by Blacklidge Emulsions, Inc. The binder used 40 mesh ambient ground rubber and SBS. Due to the proprietary nature of the binder, the exact percentages of each material cannot be disseminated in this report.

5.2 Performance Grade

The performance grades of the three modified rubber binders were determined using the methodology outlined in Section 2.5 of this report. The results are given in Table 15. As can be seen, using the Vestenamer slightly increased the high and low true grades of the binder. In effect, it made the binder slightly stiffer than the rubber-modified binders without the Vestenamer. This was only critical (i.e. decreased the performance grade) of the MD-400-TR modified binder at the low temperature.

The hybrid binder graded as a PG 82 -22. While there is no control binder to see how the polymer changed the performance grade results, one does see that both the true grade and performance grade of the binder are similar to other GTR-only modified binders.

Table 15 Performance Grades of Rubber Modified Binders with Additives

Rubber Product	Mesh Size	Grind Temp	Loading Rate. %	Additive	True Grade	Performance Grade
#30 Liberty	-30	Ambient	10%	None	80.7 – 23.6	76 - 22
				Vestenamer	82.3 – 22.4	82 - 22
MD 400 TR	-40	Cryo	10%	None	80.4 – 24.2	76 – 22
				Vestenamer	81.8 – 19.5	76 - 16
Blacklidge Hybrid	-40	Ambient	NA	Polymer	82.8 – 23.5	82 - 22

5.3 Multiple Stress Creep Recovery

MSCR testing was conducted as described in Section 2.6 of this document on the two GTR-modified binders with Vestenamer and the hybrid binder. The results are given in Table 16. All three binders met the criterion for the heaviest trafficking level “E.” In respect to the control binders (non-Vestenamer binders) the additive slightly reduced the J_{nr} values for both binders at both stress magnitudes. This suggests the Vestenemer adds some measure of elasticity to the binder. Overall, none of the additives should affect the rutting resistance of the binders.

Table 16 MSCR Results of Binders with Additives

Rubber	**Mesh Size**	**Grind Temp**	**Loading Rate, %**	**Additive**	**J_{nr}**			**% Recovery**		**Traffic Level**
					0.1 kPa^{-1}	**3.2 kPa^{-1}**	**% Diff**	**0.1 kPa^{-1}**	**3.2 kPa^{-1}**	
MD-400-TR	-40	Cry	10%	None	0.139	0.166	19.19	51.23	43.55	"E"
				Vestenamer	0.091	0.157	71.65	62.44	41.37	"E"
-30 Liberty	-30	Ambient	10%	None	0.201	0.233	15.95	43.56	36.42	"E"
				Vestenamer	0.092	0.118	28.84	57.66	48.44	"E"
Blacklidge Hybrid	-40	Ambient	NA	Polymer	0.196	0.240	22.31	57.91	50.03	"E"

5.4 Softening Point

The softening point test on separation tube binder was the final test run on binders containing the additives. The methodology described in Section 2.7 of this report was used to assess capacity of polymer and Vestenamer for reducing the separation potential of GTR-modified asphalt binders. If the softening point of the binder in the top of the tube deviated from the softening point of the binder in the bottom of the tube, the rubber was assumed to have separated from the asphalt.

The results of the softening point tests are shown in Table 17. As seen, all three rubber binders with additives showed some signs of separation. However, the Vestenamer made the MD-400-TR have a higher degree of separation while the product made the -30 Liberty material separate less. While numerous factors such as particle size and grinding method could influence this, the testing matrix was not robust enough to determine what caused the differences in the test results.

Table 17 Softening Points of Rubber Binders with Additives

Rubber Product	**Mesh Size**	**Grind Temp**	**Loading Rate, %**	**Additive**	**Softening Point, °C**			
					Top	*Bottom*	*Absolute Difference*	*% Difference*
MD-400-TR	-40	Cryo	10%	None	61.7	73.3	11.6	17.2
				Vestenamer	77.6	114.3	36.7	38.2
-30 Liberty	-30	Ambient	10%	None	58.9	72.5	13.6	20.7
				Vestenamer	92.0	104.5	12.5	12.5
Blacklidge Hybrid	-40	Ambient	NA	Polymer	80.4	94.2	13.8	13.8

6. SUMMARY AND CONCLUSIONS

Based on the results of this research, the following conclusions can be drawn.

- All fourteen modified binders met the criterion for high temperature grade classification of PG 76. Additionally, five of the eleven blends loaded at 10 percent and both blends using 15 percent loading met the criterion of a PG 82 binder.
- Surface area and particle size of the rubbers had the most influence on increasing the critical high temperature grade of the modified binder. Grinding temperature (ambient versus cryogenic) had little to no influence on the results due to additional surface area of the -#40 cryogenically ground material.
- Four of the fourteen asphalt blends using rubber particles did not meet the -22°C PG specification. Both of the mixtures using 15 percent rubber loading were graded as -16°C binders.
- Polymer content and grinding method had little influence on the low temperature properties of the modified binders. Loading rate and particle size had the most influence; however, strong relationships were not developed due to the scatter of the data.
- While four of the modified binder blends did not meet the percent difference Jnr specification for the MSCR test, twelve of the binders were graded for the highest level of trafficking at 64°C. Low $Jnr_{0.1}$ values artificially inflated the percent difference of the four binders which did not pass that portion of the MSCR specification. These binders are expected to resist rutting in the field.
- Eighty-seven percent of the variability in DSR data from the separation tubes was explained by the particle size of the rubber. The larger particle sizes showed greater discrepancies between the high temperature grades of the binder from the top of the tube compared to the bottom of the tube.
- Only one modified binder passed the softening point requirements. This binder had the smallest particle size of any of the rubber products analyzed in the study. Particle size and surface area explained the most variability in the model.
- Using a hybrid binder is appropriate for increasing the MSCR and PG grade of a virgin binder; however, incorporating polymer into a GTR-modified binder does not prevent settling.
- Vestenamer slightly stiffens an asphalt binder at both the high and low critical temperatures. It can be used in conjunction with GTR mixtures; however, it will not always prevent GTR and asphalt binder separation.
- The loading rate (10 percent) was arbitrarily chosen for this study and using less than 10 percent rubber could modify binder properties enough to meet a PG 76 criterion. These data support the idea of states moving to a performance grade specification for binders instead of specifying raw materials.

Using the previous stated conclusions, the following recommendations are made:

- Ground tire rubber should be considered an appropriate asphalt binder modifier to achieve critical high temperature performance in mixtures.
- Ambient and cryogenically ground GTR performed equivalently in terms of binder modification and separation. Specifications should not distinguish between the two types of materials when the GTR is -#30 or smaller.
- Ten percent rubber is an appropriate level of loading for increasing a PG 67-22 binder to a PG 76-22. Increasing the rubber content of the binders increased the critical low temperature grade of the modified material. To achieve a similar performance grade, one might need to use a binder which has a lower virgin critical temperature (i.e. -28°C).
- When using GTR particle sizes larger than 100 mesh, continuous agitation systems should be used to prevent separation of the rubber particles and asphalt binder.
- When GTR is used in asphalt mixtures, contractors should be aware GTR asphalt mixtures will swell if they are removed from gyratory compactor molds too quickly due to the dilation of the rubber. Samples should be allowed to cool in the molds before they are measured for volumetric properties.

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APPENDIX A: PERFORMANCE GRADE RESULTS

Superpave Asphalt Binder Grading Summary
AASHTO M320

Sample ID: **1: -80 / 140**

Original Binder				
Test, Method			**Test Results**	**Specification**
Rotational Viscosity @ 135^{o}C, AASHTO T 316, PaS			1.425	≤ 3 PaS
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, ^{o}C	G*, kPa	Phase Angle δ, ^{o}	G* / sinδ, kPa	
82	1.14	81.8	1.16	≥ 1.00 kPa
88	0.66	82.9	0.67	
Rolling Thin Film (RTFO) Aged Binder, AASHTO T 240				
Mass Change, %			-0.164	≤ 1.00%
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, ^{o}C	G*, kPa	Phase Angle δ, ^{o}	G* / sinδ, kPa	
82	3.34	70.5	3.549	≥ 2.20 kPa
88	1.915	74.35	1.988	
Pressure Aging Vessel (PAV) Aged Binder, AASHTO R28				
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, ^{o}C	G*, kPa	Phase Angle δ, ^{o}	G* sinδ, kPa	
19	7091	36	4168	≤ 5,000 kPa
16	9864	34.2	5543	
Bending Beam Rheometer (BBR) AASHTO T313				
Test Temperature, ^{o}C				
-12	Stiffness, Mpa		89	≤ 300 Mpa
	m-value		0.322	≥ 0.300
-18	Stiffness, Mpa		188	
	m-value		0.276	
True Grade	83.6	-24.9		
PG Grade	82 -	22		

Superpave Asphalt Binder Grading Summary
AASHTO M320

Sample ID: **2: MD-180-TR**

Original Binder				
Test, Method			**Test Results**	**Specification**
Rotational Viscosity @ 135^{o}C, AASHTO T 316, PaS			0.825	≤ 3 PaS
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, ^{o}C	G*, kPa	Phase Angle δ, ^{o}	G* / sinδ, kPa	
76	1.71	83.2	1.73	≥ 1.00 kPa
82	0.92	85.3	0.92	
Rolling Thin Film (RTFO) Aged Binder, AASHTO T 240				
Mass Change, %			-0.183	≤ 1.00%
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, ^{o}C	G*, kPa	Phase Angle δ, ^{o}	G* / sinδ, kPa	
82	3.33	72.5	3.50	≥ 2.20 kPa
88	1.86	76.8	1.91	
Pressure Aging Vessel (PAV) Aged Binder, AASHTO R28				
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, ^{o}C	G*, kPa	Phase Angle δ, ^{o}	G* sinδ, kPa	
22	6161	38.9	3965	≤ 5,000 kPa
19	8604	37	5177	
Bending Beam Rheometer (BBR) AASHTO T313				
Test Temperature, ^{o}C				
-12	Stiffness, Mpa		112	≤ 300 Mpa
	m-value		0.325	≥ 0.300
-18	Stiffness, Mpa		234	
	m-value		0.276	
True Grade	81.2	-25.1		
PG Grade	76 -	22		

Superpave Asphalt Binder Grading Summary
AASHTO M320

Sample ID: 3: MD-400-TR

Original Binder				
Test, Method			**Test Results**	**Specification**
Rotational Viscosity @ 135^{o}C, AASHTO T 316, PaS			1.425	≤ 3 PaS
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, ^{o}C	G*, kPa	Phase Angle δ, ^{o}	G* / sinδ, kPa	
76	1.55	83.9	1.55	≥ 1.00 kPa
82	0.85	85.5	0.85	
Rolling Thin Film (RTFO) Aged Binder, AASHTO T 240				
Mass Change, %			-0.215	≤ 1.00%
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, ^{o}C	G*, kPa	Phase Angle δ, ^{o}	G* / sinδ, kPa	
82	3.71	70.6	3.938	≥ 2.20 kPa
88	2.131	74.8	2.209	
Pressure Aging Vessel (PAV) Aged Binder, AASHTO R28				
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, ^{o}C	G*, kPa	Phase Angle δ, ^{o}	G* sinδ, kPa	
16	8715	33.7	4829	≤ 5,000 kPa
13	12050	32	6383	
Bending Beam Rheometer (BBR) AASHTO T313				
Test Temperature, ^{o}C				
-12	Stiffness, Mpa		89	≤ 300 Mpa
	m-value		0.316	≥ 0.300
-18	Stiffness, Mpa		179	
	m-value		0.273	
True Grade	80.4	-24.2		
PG Grade	76 -	22		

Superpave Asphalt Binder Grading Summary
AASHTO M320

Sample ID: **4: MD-402-TR**

Original Binder				
Test, Method			**Test Results**	**Specification**
Rotational Viscosity @ 135^{o}C, AASHTO T 316, PaS			1.3	≤ 3 PaS
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, ^{o}C	G*, kPa	Phase Angle δ, ^{o}	G* / sinδ, kPa	
76	1.36	84.6	1.37	≥ 1.00 kPa
82	0.73	85.8	0.73	
Rolling Thin Film (RTFO) Aged Binder, AASHTO T 240				
Mass Change, %			-0.236	≤ 1.00%
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, ^{o}C	G*, kPa	Phase Angle δ, ^{o}	G* / sinδ, kPa	
82	3.35	73.3	3.501	≥ 2.20 kPa
88	1.88	77.2	1.928	
Pressure Aging Vessel (PAV) Aged Binder, AASHTO R28				
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, ^{o}C	G*, kPa	Phase Angle δ, ^{o}	G* sinδ, kPa	
22	5192	36.9	3118	≤ 5,000 kPa
19	7233	35.2	4165	
Bending Beam Rheometer (BBR) AASHTO T313				
Test Temperature, ^{o}C				
-12	Stiffness, Mpa		96	≤ 300 Mpa
	m-value		0.306	≥ 0.300
-18	Stiffness, Mpa		186	
	m-value		0.27	
True Grade	79.0	-23.0		
PG Grade	76 -	22		

Superpave Asphalt Binder Grading Summary
AASHTO M320

Sample ID: **5: MD-105-TR**

Original Binder

Test, Method	**Test Results**	**Specification**
Rotational Viscosity @ 135^{o}C, AASHTO T 316, PaS	1.425	≤ 3 PaS

Dynamic Shear Rheometer AASHTO T 315

Test Temperature, ^{o}C	G*, kPa	Phase Angle δ, ^{o}	G* / sinδ, kPa	
76	1.20	82.9	1.21	≥ 1.00 kPa
82	0.66	83.7	0.66	

Rolling Thin Film (RTFO) Aged Binder, AASHTO T 240

Mass Change, %	-0.174	≤ 1.00%

Dynamic Shear Rheometer AASHTO T 315

Test Temperature, ^{o}C	G*, kPa	Phase Angle δ, ^{o}	G* / sinδ, kPa	
82	2.14	76.92	2.192	≥ 2.20 kPa
88	1.198	79.9	1.217	

Pressure Aging Vessel (PAV) Aged Binder, AASHTO R28

Dynamic Shear Rheometer AASHTO T 315

Test Temperature, ^{o}C	G*, kPa	Phase Angle δ, ^{o}	G* sinδ, kPa	
19	7319	36.4	4339	≤ 5,000 kPa
16	10390	34.4	5864	

Bending Beam Rheometer (BBR) AASHTO T313

Test Temperature, ^{o}C			
-12	Stiffness, Mpa	93	≤ 300 Mpa
	m-value	0.317	≥ 0.300
-18	Stiffness, Mpa	183	
	m-value	0.289	

True Grade	77.9	-25.6
PG Grade	76 -	22

Superpave Asphalt Binder Grading Summary
AASHTO M320

Sample ID: **6: -30 Liberty**

Original Binder				
Test, Method			**Test Results**	**Specification**
Rotational Viscosity @ 135°C, AASHTO T 316, PaS			1.4	≤ 3 PaS
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, °C	G*, kPa	Phase Angle δ, °	G* / sinδ, kPa	
76	1.61	82.9	1.62	≥ 1.00 kPa
82	0.87	84.8	0.87	
Rolling Thin Film (RTFO) Aged Binder, AASHTO T 240				
Mass Change, %			-0.23	≤ 1.00%
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, °C	G*, kPa	Phase Angle δ, °	G* / sinδ, kPa	
82	3.00	73.2	3.128	≥ 2.20 kPa
88	1.689	77.1	1.733	
Pressure Aging Vessel (PAV) Aged Binder, AASHTO R28				
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, °C	G*, kPa	Phase Angle δ, °	G* sinδ, kPa	
19	7989	34	4471	≤ 5,000 kPa
16	10810	32.5	5805	
Bending Beam Rheometer (BBR) AASHTO T313				
Test Temperature, °C				
-12	Stiffness, Mpa		94	≤ 300 Mpa
	m-value		0.309	≥ 0.300
-18	Stiffness, Mpa		193	
	m-value		0.276	
True Grade	80.7 -23.6			
PG Grade	76 - 22			

Superpave Asphalt Binder Grading Summary
AASHTO M320

Sample ID: 7: -20 Liberty

Original Binder				
Test, Method			**Test Results**	**Specification**
Rotational Viscosity @ 135^{o}C, AASHTO T 316, PaS			1.887	≤ 3 PaS
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, ^{o}C	G*, kPa	Phase Angle δ, ^{o}	G* / sinδ, kPa	
82	1.09	81.5	1.10	≥ 1.00 kPa
88	0.63	83.1	0.64	
Rolling Thin Film (RTFO) Aged Binder, AASHTO T 240				
Mass Change, %			-0.237	≤ 1.00%
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, ^{o}C	G*, kPa	Phase Angle δ, ^{o}	G* / sinδ, kPa	
82	3.23	69.2	3.46	≥ 2.20 kPa
88	1.929	72.6	2.022	
Pressure Aging Vessel (PAV) Aged Binder, AASHTO R28				
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, ^{o}C	G*, kPa	Phase Angle δ, ^{o}	G* sinδ, kPa	
16	9057	33.1	4942	≤ 5,000 kPa
13	12410	31.5	6476	
Bending Beam Rheometer (BBR) AASHTO T313				
Test Temperature, ^{o}C				
-12	Stiffness, Mpa		92	≤ 300 Mpa
	m-value		0.315	≥ 0.300
-18	Stiffness, Mpa		176	
	m-value		0.28	
True Grade	83.1	-24.6		
PG Grade	82 -	22		

Superpave Asphalt Binder Grading Summary
AASHTO M320

Sample ID: 8: -16Powder

Original Binder				
Test, Method			**Test Results**	**Specification**
Rotational Viscosity @ 135^{o}C, AASHTO T 316, PaS			1.6	≤ 3 PaS
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, ^{o}C	G*, kPa	Phase Angle δ, ^{o}	G* / sinδ, kPa	
94	0.94	36.2	1.60	≥ 1.00 kPa
100	0.89	28.34	1.87	
Rolling Thin Film (RTFO) Aged Binder, AASHTO T 240				
Mass Change, %			-0.227	≤ 1.00%
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, ^{o}C	G*, kPa	Phase Angle δ, ^{o}	G* / sinδ, kPa	
94	2.65	45.72	3.696	≥ 2.20 kPa
100	2.131	39	3.384	
Pressure Aging Vessel (PAV) Aged Binder, AASHTO R28				
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, ^{o}C	G*, kPa	Phase Angle δ, ^{o}	G* sinδ, kPa	
19	6852	35.1	3935	≤ 5,000 kPa
16	9509	33.3	5226	
Bending Beam Rheometer (BBR) AASHTO T313				
Test Temperature, ^{o}C				
-6	Stiffness, Mpa		55	≤ 300 Mpa
	m-value		0.33	≥ 0.300
-12	Stiffness, Mpa		102	
	m-value		0.299	
True Grade	76.3	-21.8		
PG Grade	76 -	16		

Superpave Asphalt Binder Grading Summary
AASHTO M320

2mm gap

Sample ID: **8: -16Powder**

Original Binder				
Test, Method			**Test Results**	**Specification**
Rotational Viscosity @ 135^{o}C, AASHTO T 316, PaS			1.6	≤ 3 PaS
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, ^{o}C	G*, kPa	Phase Angle δ, ^{o}	G* / sinδ, kPa	
82	1.28	82.1	1.29	≥ 1.00 kPa
88	0.73	83.6	0.74	
Rolling Thin Film (RTFO) Aged Binder, AASHTO T 240				
Mass Change, %			-0.227	≤ 1.00%
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, ^{o}C	G*, kPa	Phase Angle δ, ^{o}	G* / sinδ, kPa	
88	2.18	72.8	2.282	≥ 2.20 kPa
94	1.288	76.1	1.327	
Pressure Aging Vessel (PAV) Aged Binder, AASHTO R28				
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, ^{o}C	G*, kPa	Phase Angle δ, ^{o}	G* sinδ, kPa	
19	6852	35.1	3935	≤ 5,000 kPa
16	9509	33.3	5226	
Bending Beam Rheometer (BBR) AASHTO T313				
Test Temperature, ^{o}C				
-6	Stiffness, Mpa		55	≤ 300 Mpa
	m-value		0.33	≥ 0.300
-12	Stiffness, Mpa		102	
	m-value		0.299	
True Grade	84.7	-21.8		
PG Grade	82 -	16		

Superpave Asphalt Binder Grading Summary
AASHTO M320

Sample ID: **9: Liberty Cracker Mill**

Original Binder				
Test, Method			**Test Results**	**Specification**
Rotational Viscosity @ 135^{o}C, AASHTO T 316, PaS			1.99	≤ 3 PaS
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, ^{o}C	G*, kPa	Phase Angle δ, ^{o}	G* / sinδ, kPa	
82	1.07	82.1	1.08	≥ 1.00 kPa
88	0.61	83.9	0.61	
Rolling Thin Film (RTFO) Aged Binder, AASHTO T 240				
Mass Change, %			-0.193	≤ 1.00%
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, ^{o}C	G*, kPa	Phase Angle δ, ^{o}	G* / sinδ, kPa	
82	3.21	69.7	3.42	≥ 2.20 kPa
88	1.899	73.4	1.98	
Pressure Aging Vessel (PAV) Aged Binder, AASHTO R28				
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, ^{o}C	G*, kPa	Phase Angle δ, ^{o}	G* sinδ, kPa	
16	10020	33.9	5594	≤ 5,000 kPa
19	7186	35.6	4186	
Bending Beam Rheometer (BBR) AASHTO T313				
Test Temperature, ^{o}C				
-12	Stiffness, Mpa		99	≤ 300 Mpa
	m-value		0.306	≥ 0.300
-18	Stiffness, Mpa		199	
	m-value		0.273	
True Grade	82.8	-23.1		
PG Grade	82 -	22		

Superpave Asphalt Binder Grading Summary
AASHTO M320

10%

Sample ID: **10: Liberty Cryo-Hammer**

Original Binder				
Test, Method			**Test Results**	**Specification**
Rotational Viscosity @ 135^{o}C, AASHTO T 316, PaS			1.675	≤ 3 PaS
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, ^{o}C	G*, kPa	Phase Angle δ, ^{o}	G* / sinδ, kPa	
82	1.01	82.8	1.02	≥ 1.00 kPa
88	0.58	84.2	0.58	
Rolling Thin Film (RTFO) Aged Binder, AASHTO T 240				
Mass Change, %			-0.193	≤ 1.00%
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, ^{o}C	G*, kPa	Phase Angle δ, ^{o}	G* / sinδ, kPa	
82	3.14	72.5	3.294	≥ 2.20 kPa
88	1.793	76.4	1.84	
Pressure Aging Vessel (PAV) Aged Binder, AASHTO R28				
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, ^{o}C	G*, kPa	Phase Angle δ, ^{o}	G* sinδ, kPa	
16	9482	33.2	5186	≤ 5,000 kPa
19	6777	34.95	3883	
Bending Beam Rheometer (BBR) AASHTO T313				
Test Temperature, ^{o}C				
-12	Stiffness, Mpa		100	≤ 300 Mpa
	m-value		0.307	≥ 0.300
-18	Stiffness, Mpa		184	
	m-value		0.273	
True Grade	82.2	-23.2		
PG Grade	82 -	22		

Superpave Asphalt Binder Grading Summary
AASHTO M320

15%

Sample ID: **11: Liberty Cryo-Hammer**

Original Binder				
Test, Method			**Test Results**	**Specification**
Rotational Viscosity @ 135°C, AASHTO T 316, PaS			2.912	≤ 3 PaS
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, °C	G*, kPa	Phase Angle δ, °	G* / sinδ, kPa	
82	1.52	81.2	1.54	≥ 1.00 kPa
88	0.88	82.8	0.89	
Rolling Thin Film (RTFO) Aged Binder, AASHTO T 240				
Mass Change, %			-0.259	≤ 1.00%
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, °C	G*, kPa	Phase Angle δ, °	G* / sinδ, kPa	
88	2.76	73.6	2.88	≥ 2.20 kPa
94	1.641	77.4	1.682	
Pressure Aging Vessel (PAV) Aged Binder, AASHTO R28				
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, °C	G*, kPa	Phase Angle δ, °	G* sinδ, kPa	
16	10310	32.1	5471	≤ 5,000 kPa
19	7744	33.4	4262	
Bending Beam Rheometer (BBR) AASHTO T313				
Test Temperature, °C				
-6	Stiffness, Mpa		46	≤ 300 Mpa
	m-value		0.338	≥ 0.300
-12	Stiffness, Mpa		302	
	m-value		0.269	
True Grade	86.7	-19.3		
PG Grade	82 -	16		

Superpave Asphalt Binder Grading Summary
AASHTO M320

15%

Sample ID: **12: -20 Liberty**

Original Binder				
Test, Method			**Test Results**	**Specification**
Rotational Viscosity @ 135^{o}C, AASHTO T 316, PaS			4.050	≤ 3 PaS
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, ^{o}C	G*, kPa	Phase Angle δ, ^{o}	G* / sinδ, kPa	
82	1.63	79.5	1.66	≥ 1.00 kPa
88	0.98	80.4	1.00	
Rolling Thin Film (RTFO) Aged Binder, AASHTO T 240				
Mass Change, %			-0.259	≤ 1.00%
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, ^{o}C	G*, kPa	Phase Angle δ, ^{o}	G* / sinδ, kPa	
88	3.20	68.8	3.43	≥ 2.20 kPa
94	1.955	72	2.06	
Pressure Aging Vessel (PAV) Aged Binder, AASHTO R28				
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, ^{o}C	G*, kPa	Phase Angle δ, ^{o}	G* sinδ, kPa	
16	10500	31.4	5471	≤ 5,000 kPa
19	7645	33.1	4172	
Bending Beam Rheometer (BBR) AASHTO T313				
Test Temperature, ^{o}C				
-6	Stiffness, Mpa		43	≤ 300 Mpa
	m-value		0.324	≥ 0.300
-12	Stiffness, Mpa		85	
	m-value		0.297	
True Grade	87.9	-21.3		
PG Grade	82 -	16		

Superpave Asphalt Binder Grading Summary
AASHTO M320

Sample ID: **13: -30 Fines Liberty**

Original Binder				
Test, Method			**Test Results**	**Specification**
Rotational Viscosity @ 135°C, AASHTO T 316, PaS			1.725	≤ 3 PaS
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, °C	G*, kPa	Phase Angle δ, °	G* / sinδ, kPa	
76	1.44	82.8	1.45	≥ 1.00 kPa
82	0.80	84.4	0.80	
Rolling Thin Film (RTFO) Aged Binder, AASHTO T 240				
Mass Change, %			-0.256	≤ 1.00%
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, °C	G*, kPa	Phase Angle δ, °	G* / sinδ, kPa	
82	3.65	69.2	3.90	≥ 2.20 kPa
88	2.13	73.2	2.23	
Pressure Aging Vessel (PAV) Aged Binder, AASHTO R28				
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, °C	G*, kPa	Phase Angle δ, °	G* sinδ, kPa	
13	10900	32.4	5835	≤ 5,000 kPa
16	7959	33.9	4434	
Bending Beam Rheometer (BBR) AASHTO T313				
Test Temperature, °C				
-6	Stiffness, Mpa		54	≤ 300 Mpa
	m-value		0.324	≥ 0.300
-12	Stiffness, Mpa		109	
	m-value		0.291	
True Grade	79.8 -20.4			
PG Grade	76 - 16			

Superpave Asphalt Binder Grading Summary
AASHTO M320

Sample ID: **MD-400-AM**

Original Binder				
Test, Method			**Test Results**	**Specification**
Rotational Viscosity @ 135°C, AASHTO T 316, PaS			1.887	≤ 3 PaS
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, °C	G*, kPa	Phase Angle δ, °	G* / sinδ, kPa	
82	1.00	84.1	1.01	≥ 1.00 kPa
88	0.58	85.3	0.58	
Rolling Thin Film (RTFO) Aged Binder, AASHTO T 240				
Mass Change, %			-0.281	≤ 1.00%
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, °C	G*, kPa	Phase Angle δ, °	G* / sinδ, kPa	
88	2.15	73.5	2.24	≥ 2.20 kPa
94	1.281	76.7	1.32	
Pressure Aging Vessel (PAV) Aged Binder, AASHTO R28				
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, °C				
Test Temperature, °C	G*, kPa	Phase Angle δ, °	G* sinδ, kPa	
19	7520	32.2	4008	≤ 5,000 kPa
16	9903	31.3	5144	
Bending Beam Rheometer (BBR) AASHTO T313				
Test Temperature, °C				
-6	Stiffness, Mpa		53	≤ 300 Mpa
	m-value		0.323	≥ 0.300
-12	Stiffness, Mpa		102	
	m-value		0.294	
True Grade	82.1	-20.8		
PG Grade	82 -	16		