Comparing Effects of Crumb Rubber and Synthetic Polymers on Hot Mix Asphalt Performance

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ABSTRACT. *One of the most widely used bitumen additives is styrene-butadiene-styrene (SBS) polymer. Addition of this polymer has been shown to improve asphalt binder properties; however, there has been growing uncertainty about the future supply of SBS due to the fluctuation of prices in crude oil versus natural gas. This uncertainty has caused a need to find alternate modification techniques. In addition to introducing other new synthetic polymers, a concept with growing popularity in many parts of the world is the addition of recycled ground tire rubber (GTR). GTR is a vastly available resource produced from used vehicle tires. Modification with GTR however is not accepted yet within the PG (Performance Grading) system. Several highway agencies remain skeptical and believe that superior pavement performance incorporating GTR is only applicable in specific climates. This study is intended to summarize findings of important past studies regarding the degree of digestion of GTR in asphalt binder. Also mechanical performance and aggregate structure evaluated by image analysis of GTR mixtures are compared to unmodified mixtures as well as mixtures produced with SBS-modified (elastomeric polymer) and plastomeric-modified binders. Results indicate that GTR-modified binder has the capacity to meet and even exceed the performance of some more widely used synthetic polymer-modified asphalt binders. The GTR-modified mixtures show a lesser degree of plastic deformation, specifically at increased stress levels. The results are encouraging and confirm the potential of successful use of GTR to deliver good performance at reasonable cost with less risk of supply shortages experienced with other additives.*

KEYWORDS: *Ground Tire Rubber, Modification, Asphalt Binder and Mixture Performance, Image Analysis, Internal Aggregate Structure*

1. Introduction

In recent years the efforts to obtain improved binder characteristics have led to the evaluation, development and use of a wide range of asphalt binder modifiers which aim to enhance the performance of the base binder and hence, improve pavement performance (Nicholls, 1998). Lab and field studies have shown that crumb rubber modification of asphalts can improve the binder properties, and improvements have been observed in field studies of crumb rubber modified pavements (Mehta et al., 2002; Oliver, 2000; Brown et al., 1997, Bahia and Davies, 1994). There are many reasons to use rubber modified binders in asphalt pavements. In general, these modified binders have better performance properties than those of the base binders. These improved properties are the result of the interactions between the Ground Tire Rubber (GTR) particles and the binder. In addition to binder performance properties, the use of GTR promotes sustainable environmental stewardship by using millions of scrap tires. Since its initial use many decades ago, several state and local government agencies are using the rubber modified binders in asphalt pavements. With new specifications, research, and technical services, increased usage of these materials can be realized.

Ground tire rubber (GTR) is obtained by mechanical shearing or grinding tires into small particle sizes. The purpose of using GTR-modified binders is to improve hot mix asphalt (HMA) resistance to cracking and rutting failures under traffic loading and environmental conditions. Blending crumb rubber into an asphalt binder is believed to improve its elastic and energy absorption properties, which are directly related to the binder's resistance to cracking and rutting failures. However, the optimum methods for working with GTR as an additive to asphalt remain unclear. It has been reported that the mechanism by which some crumb rubbers change the binder properties is different from that of most polymer modifiers (Leite et al., 2001). The polymer disperses completely into the asphalt and results in changes to the molecular structure of the asphalt. Crumb rubber keeps its general physical shape and behaves as flexible particulate filler in the binder. Additional investigation to assist in developing optimum methods of processing and blending GTR are needed for the widespread use of the material. Reaction time between GTR and asphalt binders while blending, and the design of GTR-modified binders to yield full potential at a given percentage are not standardized and there are varying opinions about the best practice to achieve desired properties.

This study focused on the evaluation of using GTR to modify asphalt binders at high temperatures. The study investigates the variability in properties as the time exposed to elevated temperatures increases and the potential for material degradation during this extended period. Multiple percentages of GTR were used to modify the same base binder, and each of these percentages was prepared at a range of reaction times. Each binder was then characterized using current Superpave procedures.

To compare performance of GTR modification with other types of modifications, mixtures were produced using a common base binder for the region in which this study was conducted. Mixtures incorporating the neat/unmodified binder, elastomeric polymer-, plastomeric polymer-, and GTR-modified binders were subjected to repeated creep testing to determine if the elastic or plastic effects of corresponding binders could be observed. GTR mixes could then be compared to the polymer-modified to determine the elastic versus plastic effects of GTR. In addition to mechanical testing, two-dimensional image analysis was performed on the mixtures to characterize internal aggregate structure. This characterization allows for quantification of the structure to determine if the decreased solubility of GTR influences the aggregate structure within the mix, whether positively or negatively.

2. Materials

2.1. Binders and GTR

GTR can be produced by various methods of grinding (ambient versus cryogenic) and can meet various size distributions. These two factors (grinding type and size) are known to affect the surface area of rubber particles, which in turn can affect the rate and extent of interaction with the asphalt binders. GTR with a wide range of maximum rubber particle size has been used in asphalt concrete modification. However it is logically expected that for dense graded mixtures the GTR with maximum size of passing No. 30 mesh (0.6 mm) is perhaps the largest that can or should be used to avoid interference with the aggregate structure and load carrying skeleton. It is also observed that the ambient grinding is more widely used than cryogenic at this time. In ambient grinding of materials, a varying particle size distribution can be achieved and the maximum particle size can be selected. Although the maximum particle size is a controlled variable, to obtain a smaller maximum size a once ground tire rubber can be passed through the grinding process subsequent times. This clearly results in increased costs associated with a smaller particle size, as reducing the size results in a minimum of twice the time invested. For this reason, GTR of particle size passing No. 30 mesh is considered as optimum and was thus used in the study. It is also assumed that if No. 30 rubber can be tested using standard Superpave practice for modified binders, while resulting in meaningful data, smaller particle sizes should also produce acceptable results. All GTR-modification was completed using the wet process, which was a modification of the asphalt binder, and then adding the modified binder to aggregate for production of mixtures (as opposed to using the dry process, which would consist of adding the GTR particles to the dry aggregate allowing it to act as a surrogate aggregate and is then blended with the asphalt to produce a mix). The wet process was selected as this will simulate a similar procedure to other binder modification, resulting in a modified product that can be characterized in the binder phase prior to incorporation in a mix.

Two base binders (PG 64-16, and PG 64-22) were used in this study. These binders, in addition to be tested as unmodified binders, were modified with minus No. 30 GTR, elastomeric polymer, and plastomeric polymer. These modified binders were produced in the laboratory and also compared to a commercially available Tire Modified Asphalt Concrete terminal blend material, MAC-10TR, which is produced by incorporating 10% GTR in a pressurized vessel allowing for elevated temperatures and pressures. This results in complete solubility of the GTR. The polymer modifiers were used at percentages found to result in a single and double grade bump of the high temperature grade (to a PG 70-16 and PG 76-16, or PG 70-22 and PG 76-22, respectively). GTR was initially incorporated at 10 and 20% to cover the range currently used by the limited suppliers and contractors accepting of GTR products and later prepared at a percentage that would result in a similar grade to the alternate modifiers.

To study effect of reaction time, each percentage of GTR was prepared at 45, 65, and 85 minutes of blending/reaction time and later with the additional time of 360 minutes. The true-grade of each combination of percentage and reaction time was determined to see how the high temperature grading is affected by each factor. Reaction times for GTR-modification were measured following a 15 minute period dedicated for incremental introduction of the rubber particles into the binder. The terminal blend material was reheated and blended for 10 minutes to ensure homogeneity prior to pouring.

2.2. Mixtures

In addition to testing of the modified asphalt binders, aggregate gradations were selected for production and testing of dense-graded asphalt concrete mixtures. Two gradations were used, fine and coarse, which were determined by matching the broadest range allowed by Wisconsin Department of Transportation (WisDOT section 460, 2010) specifications. The fine and coarse grain-size distributions can be seen in Figure 1 accompanied by WisDOT control points. Aggregates were washed prior to batching for precise control over the volume of mineral filler in each mixture, and it can be seen in Figure 1 that mineral filler (minus 0.075mm) was adjusted to match between the two gradations, eliminating any significant influence of varying mastic properties.

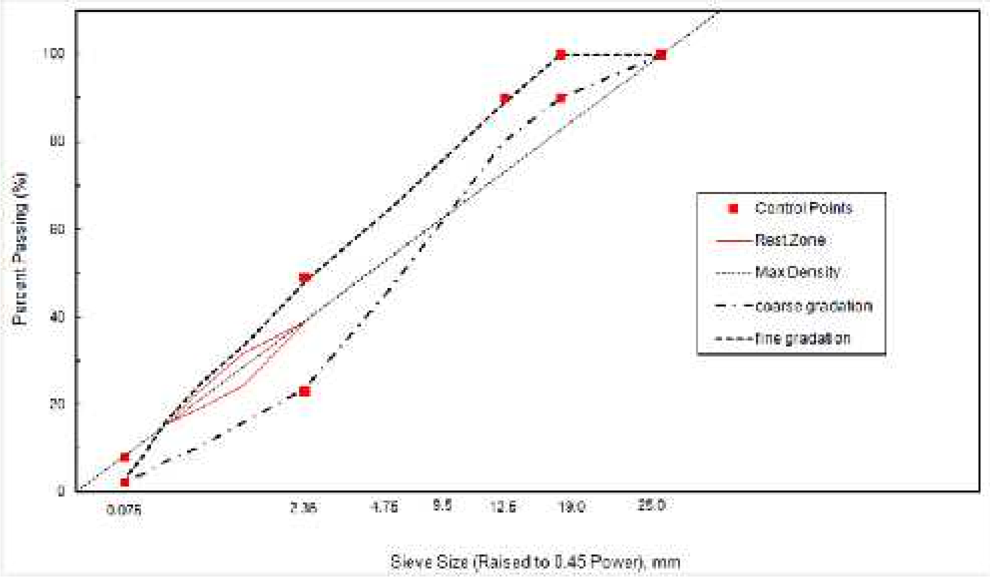

Figure 1. *Fine and coarse gradations used for mixtures.*

The coarse and fine gradations were each combined with the four binders individually to determine an appropriate mix design. This was done by compacting samples at predetermined intervals anticipated to span above and below the optimum asphalt content which is defined by Superpave mix design as the asphalt content which results in 96 percent theoretical maximum density, or four percent air voids, after a specified number of gyrations for compaction. Finally, the optimum asphalt content was selected 4.6% and 5.5% for fine and coarse gradation respectively to meet the criteria.

3. Testing Procedures

3.1. Binders

Binders used in this study were graded based on standard Superpave protocol. Also, advanced rheological testing using the Repeated Creep and Recovery (RCR) test, and the Multiple Stress Creep and Recovery (MSCR) test were conducted at temperatures of 46, 58, and 70ºC. The repeated creep tests (RCR) were performed at a constant stress of 0.10, 3.20, and 10.00 kPa and the loading cycles included 1-s loading followed by a 9-s rest period. A total of 1000 creep and recovery cycles were performed on RTFO aged binders. One thousand cycles test was selected to capture full behavior of modified binder over a long range of time. The standard MSCR test described in the AASHTO TP70 standard “Standard Method of Test for Multiple Stress Creep Recovery (MSCR) Test of Asphalt Binder Using a Dynamic Shear Rheometer (DSR)” was followed, which consists of 10 cycles of 0.1 kPa stress creep and recovery, followed immediately by another 10 cycles of 3.2 kPa stress creep and recovery. Accumulated strain, non-recoverable creep compliance, Jnr, and the percent recovery, R%, are reported over the test period for each binder.

The Jnr and the percent recovery are two of the parameters calculated from the measured strain under different stress cycles and the average of that is reported (AASHTO TP70). Non-recoverable creep compliance (Jnr) is presently being viewed as the most appropriate rheological parameter for evaluating the propensity of an asphalt binder to resist permanent deformation or rutting in the pavement wheel paths. The duration of the creep interval, the duration of the recovery interval, the number of loading cycles and, of course, the entity of the applied shear stress unequivocally cooperate to the control of Jnr. In other words, Jnr depends on the mechanical history of the experiment. In addition, R% is the representative of elastic behavior of binder under loading.

Rotational Viscosity (RV) testing was conducted at both 135^{o}C (Superpave Volumetric Mix Design, AASHTO M323) as well as 175^{o}C as indicated by ASTM D 6114 (Standard Specification for Asphalt-Rubber Binder). Material was brought to the desired test temperature within 30 minutes and the spindle (SC4-27) was inserted and rotated for an additional ten minutes to ensure equilibration of the material. Data was then collected for approximately three minutes at six second intervals.

The initial testing of GTR-modified asphalt binders was conducted in the same manner as testing of the neat binder. For a more complete understanding of GTR-modified asphalt binder behavior between these two periods of data collection as well as beyond, a time sweep covering over five hours was used for data collection beyond the 30 minute ramp to test temperature and 10 minute equilibration time in an attempt to more accurately identify when a constant viscosity is observed as well as possible cause for the initially observed reduction.

3.2. Mixtures

Mechanical testing of mixtures was conducted in accordance with standard protocol for repeated creep testing, commonly known as flow number (AASHTO TP79). The flow number is defined as the number of cycles required for the sample to begin exhibiting tertiary creep, or flow, which is more clearly defined as the number of cycles that corresponds to the minimum rate of change in permanent axial strain of the specimen under a repeated load test. When plotting the total accumulated strain versus number of cycles, a distinct primary (I), secondary (II), and tertiary (III) zone are identified on the creep curve as seen in Figure 2. The transition from secondary to tertiary creep corresponds to the minima of the rate of change of axial strain as shown in Figure 3.

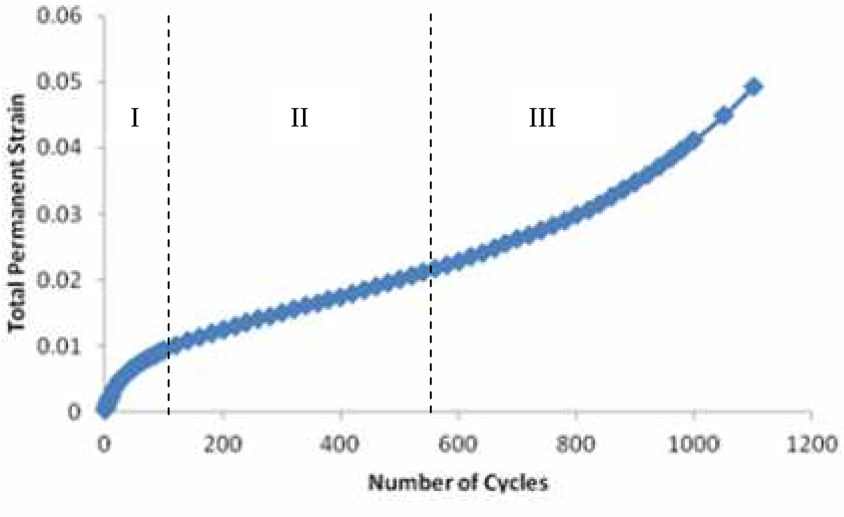

Figure 2. *Typical creep curve for HMA mixture.*

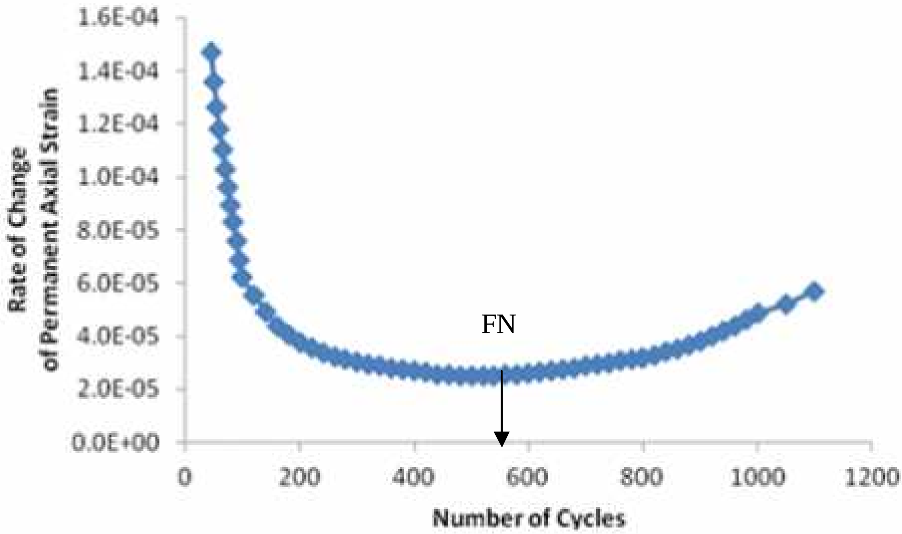

Figure 3. *Plot of rate of change of permanent axial strain versus cycles.*

The flow number test consists of repeatedly loading a sample under stress control, with a 0.1 second pulse of a prescribed stress, followed by a 0.9 second rest period. This cyclic haversine compressive loading is intended to simulate repeated passing of traffic/vehicles over the roadway, and when testing for resistance to permanent deformation, is continued until failure occurs. Failure is defined by clearly exceeding the transition from secondary to tertiary creep and when the sample has lost the capacity to withstand the prescribed stress. The test is performed on a 100 mm diameter specimen of 150 mm in height, produced by cutting and coring a gyratory specimen. Specimens for this study were compacted to a consistent air void content or density by targeting 6.5 + 0.5 percent air voids. Asphalt mixture testing was conducted at 46^{o}C. The 7-day high temperature is chosen since this research is focused on resistance to permanent deformation, which is a consequence of high temperatures and heavy loads. Heavy loads can be seen as arbitrarily defined, for this reason mixture testing was conducted at two stress levels, 50 and 150 psi (345 and 1034 kPa) intended to span the average stress level found in field measurements.

3.3. Image Analysis

This study utilized iPas (Image Processing & Analysis System) software to determine the internal structure of HMA. The software was used to quantify aggregate proximity index (API). The viewing level can then be zoomed in iPas to determine the approximate diameter of remaining aggregate in the image. This was done for both the coarse and fine gradations, resulting in aggregate equal to or greater than a diameter of 0.6 mm remaining in the processed image. In order to account for an equivalent percent retained for each gradation, a minimum aggregate size of 0.6 mm was selected for images of fine gradation and 2.36 mm for coarse gradation. This was combined with an SDT of 0.15 mm (determined from median filter selection and image resolution) for analysis of API.

4. Results

4.1. Binders

The GTR-modified binders were tested to investigate the time dependency of viscosity. The results of a five hour time sweep for viscosity of 10% GTR with a reaction time of 65 minutes at temperatures of 135 and 175^{o}C can be seen in Figures 4 and 5, respectively.

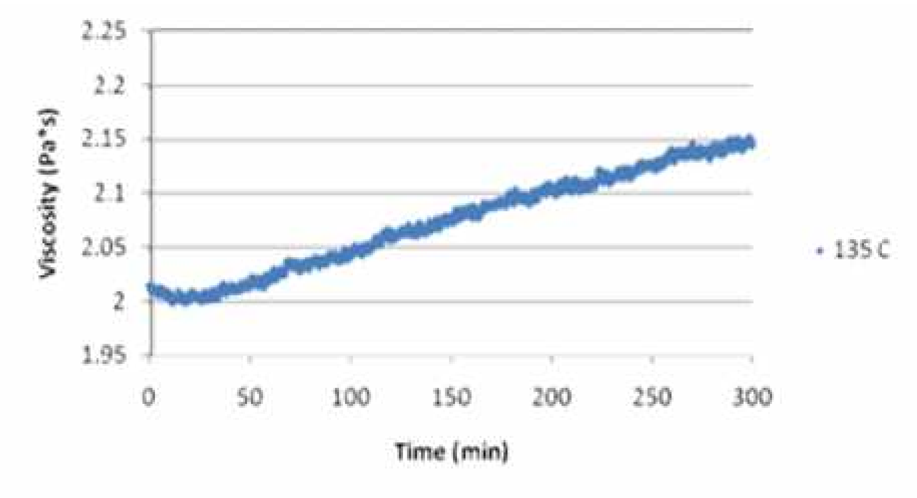

Figure 4. *Viscosity of GTR-modified asphalt binder with 10% GTR and blending time of 65 minutes at 135^{o}C.*

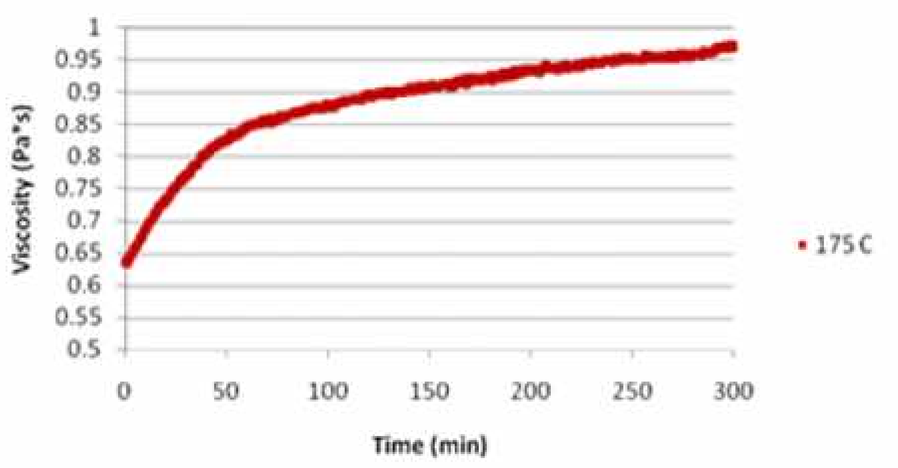

Figure 5. *Viscosity of GTR-modified asphalt binder with 10% GTR and blending time of 65 minutes at 175°C.*

The results indicate that reaction time has a major effect on viscosity of GTR-modified binders. It should be mentioned that it was observed that there is a possibility for segregation of rubber particles during the early reaction times but, after a certain period of time, a rapid increase in viscosity takes place, which is indicative of reaction/swelling of the rubber. Figure 4 depicts this behavior as it shows an initial decrease followed by a short period of stable viscosity readings. However, at times longer than 30 minutes a rapid increase in viscosity is observed.

Data in Figures 4 and 5 also indicate a difference in behavior at different temperatures, and as seen in Figure 5, when the testing temperature is increased from 135 to 175°C, the initial decrease and stable region were no longer seen, yet the same perpetual increase in viscosity was identified at both temperatures. To support this hypothesis of swelling of the rubber particles, the terminal blend material was tested at 135 and 175°C, as terminal blend material is said to be fully reacted prior to shipment. Results of viscosity testing of terminal blend asphalt binder with 10% GTR can be seen in Figure 6. It should be noted however that the viscosity of the terminal blend rubber is much lower than the GTR modified binder. It can only be speculated that this is due to the degradation of the rubber due to long reaction time, or that the terminal blend has less GTR than 10 %.

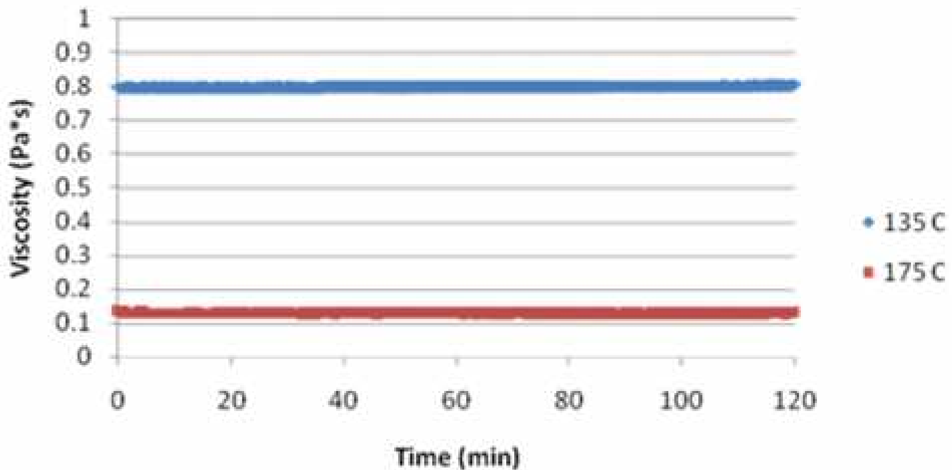

Figure 6. *Viscosity of terminal blend asphalt-rubber binder with 10% GTR.*

These observations of changing properties with extended periods of time at elevated temperatures match that of the previous studies reviewed. Such studies (Zanzotto and Kennephol, 1996; Bullin et al., 1996; and Glover et al., 2000) indicate that this change in properties could actually lead to elimination of the benefits of GTR modification. The studies suggest that the change in properties is not only due to the swelling of the rubber particles, but that there is degradation of the rubber itself which is leading to a diminishing positive influence of adding the GTR to the asphalt binder.

The increase in viscosity readings, as observed in Figure 5, show that though the increase continued for times approaching more than 5 hours, a reduced rate of change was observed after approximately one hour. The decrease in rate suggested a constant reading could be reached.

4.2. PG Grading and Advanced Creep Testing Results

The PG-grading temperatures of the rubber modified binders ranged from 64 to 82oC. It can be seen in Table 1 as well as Figure 7 that 10% GTR provided an average increase of three grades (+18^{o}C change) from the original binder (referred to as three grade bumps), whereas the terminal blend material only provided two grade bumps for the same amount of GTR. The change indicates an increase of approximately two degrees improvement in grade per 1% GTR for laboratory blended binders. Results show that 2% SBS results in a single grade bump and addition of a cross-linking agent at manufacturer’s specifications increases the true grade temperature by a couple degrees but still does not cross the threshold of the next PG. Thus, true-grade testing indicates that 2% SBS (polymer) provides one-grade bump and the addition of a cross-linking agent at additional cost does not change the PG grade of the material. Similarly, 10% GTR provides roughly a three-grade bump which indicates that for the binder used in this study, a 3-4% GTR can give one grade bump. In other words, GTR content required for one grade bump is twice that required for the SBS polymer, though the virgin polymer has a significant cost associated with it whereas the GTR is a secondary use of a disposed material.

Table 1. *True-grade of materials as defined by pass/fail temperature resulting in a |G*|/sinδ measurement of 1.00 kPa.*

Binder	Average	COV	PG Grade	Grade Shifts
Neat	67.3	0.2%	64	0
10GTR_45min	84.5	1.0%	82	3
10GTR_65min	84.3	0.7%	82	3
10GTR_85min	83.7	0.5%	82	3

10GTR_360min	81.9	0.8%	76	2
Terminal Blend	78.8	0.1%	76	2
Neat + 2% ELASTOMER	73.0	0.1%	70	1
2% ELASTOMER + XL*	75.4	0.0%	70	1

*XL = cross linking agent

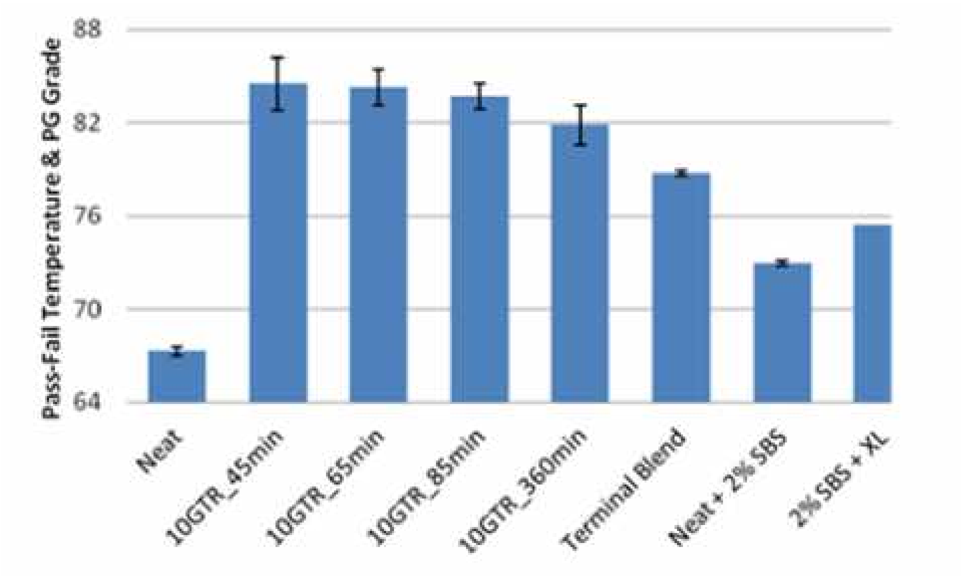

Figure 7. *Pass/fail temperatures of laboratory blended materials.*

Performance distinction can also be made using the MSCR test results as seen in Figures 8 and 9. Figure 8 shows the comparison of 10% GTR laboratory blends versus the terminal blend material with the same percentage of rubber by mass as well as the neat binder. It is clearly seen in the figure that at each stress level, the neat binder exhibits the least recoverable strain per cycle, and though the terminal blend resists a small portion of the strain seen by the neat binder at given stress levels (indicated by a vertical shift of the curve), the terminal blend also shows similar response in terms of permanent versus recoverable strain per cycle of loading (indicated by parallel curves). When looking at the 10% GTR blends produced using 45, 65, and 85 minutes blending times, all show some improvement by lowering the strain exhibited at each stress level, though 65 minutes appears to be far superior to 45 and 85 minutes. The shortest blending time of 45 minutes shows slight decrease in strain and a slight increase in recoverable strain per cycle, but a significant difference is seen when blending time is increased to 65 minutes, clearly seen in Figure8. The strain is decreased by nearly an order of magnitude and a majority of total strain per cycle can be seen as recoverable rather than permanent. The trend of increase did not continue for the 85 minute blending time as the results for the 85 minute blending time appears to revert the material response back near what was seen for the 45 minute blend, which does not differ a great deal from the neat binder and terminal blend.

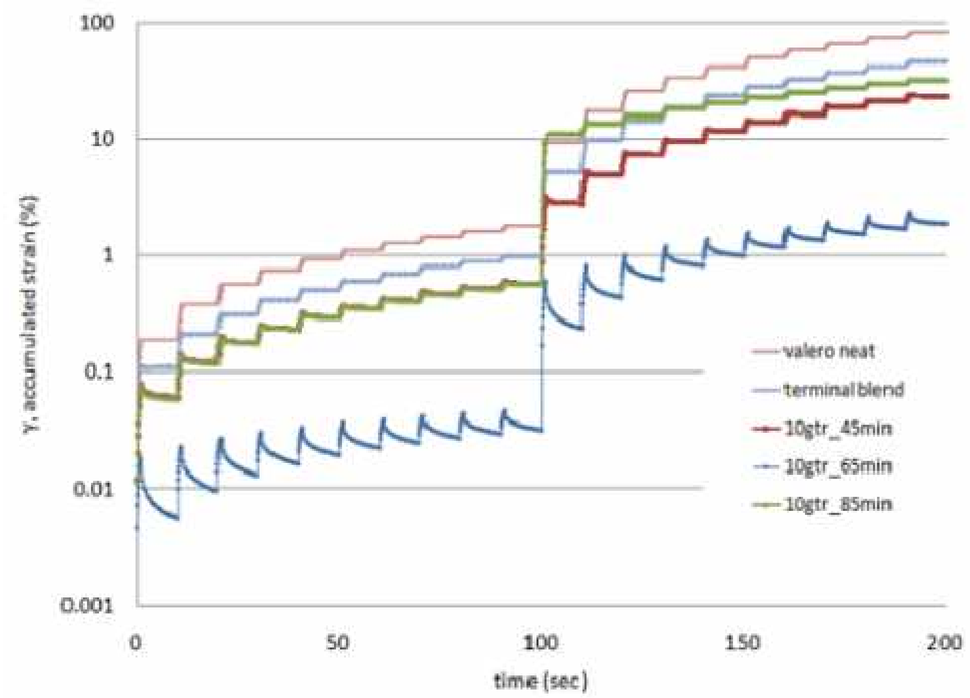

Figure 8. *Accumulated strain vs. time in MSCR test at 58^{o}C for neat binder, terminal blend and 10% GTR laboratory blends.*

Figure 9 includes the results for the 20 % GTR blends. When 20% rubber was used, blending times did not show a significant difference in response, but it did show a significant improvement in recoverability as compared to the neat binder and the terminal blend. In fact, the grouping of the three blending times for 20% GTR is nearly the same response shown by the 65 minute blend time when 10% GTR was used.

To study effect of base binder source a PG 64-22 binder was added to the study and modified with the three different additives. Three trial blends of the elastomeric (linear styrene-butadiene-styrene block copolymer), plastomeric modifier (polyethylene) and ground tire rubber (GTR) were produced and the true grade was determined. The targeted grades include two grade bumps (PG 76 from PG 64). After several trial blends, modifier quantities resulting in similar high-temperature Performance Grade (PG) were achieved. The required percentage of each modifier and resulting grade can be seen in Table 2.

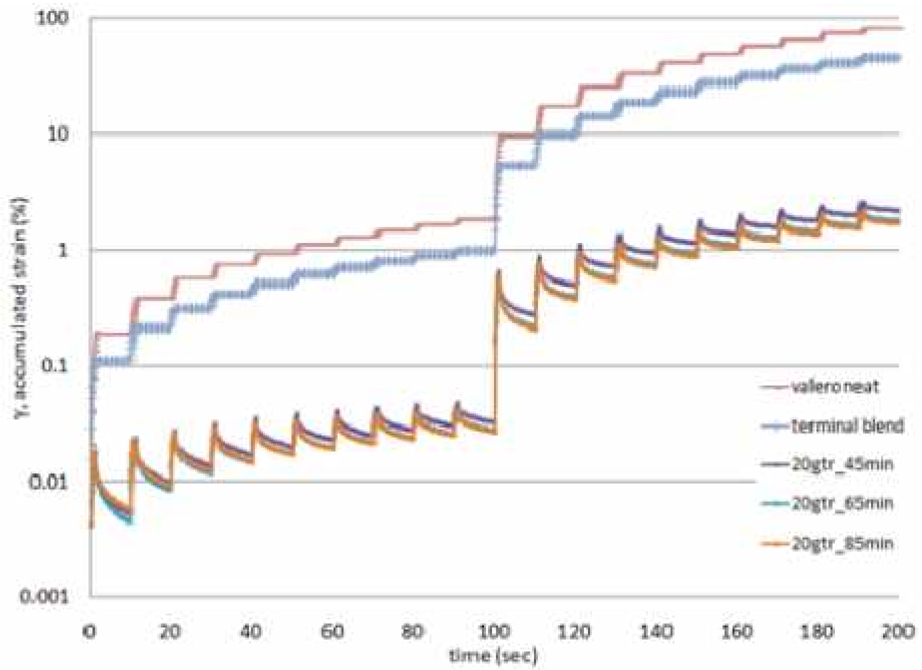

Figure 9. *Accumulated strain vs. time in MSCR test at 58oC for neat binder, terminal blend and 20% GTR laboratory blends.*

Table 2. *Percent modifier used to get high-temperature grade for modified binders.*

Modifier	Percent by weight	True Grade (^{o}C)
Elastomer	3.2	77.88
Plastomer	4.7	78.08
GTR	7.1	77.87

The Repeated Creep test offers valuable information about the susceptibility of asphalt mixtures to rutting when changes in temperature occur (Bahia et al., 2001; Delgadillo, 2008; Centeno et al., 2008). The Repeated Creep test has the capability of measuring the permanent deformation and elastic recovery of asphalt binder under different levels of stress (Bahia et al., 2001). This fact is important because when using this test as a complement to an asphalt characterization like specification SUPERPAVE, it is possible to establish differences between rutting performance of modified asphalts. Therefore, data for binder testing was collected from Repeated Creep and Recovery (RCR) and Multiple Stress Creep and Recovery (MSCR) tests on the various binders at different temperatures. Table 3 shows the summary of MSCR results at three temperatures for neat and modified binders.

Table 3. *MSCR results for neat and modified binders at three temperatures.*

Temperature	46 °C				58 °C				70 °C			
MSCR Parameters	Jnr (1/kPa)		%R		Jnr (1/kPa)		%R		Jnr (1/kPa)		%R	
Stress Level (Pa)	100	3200	100	3200	100	3200	100	3200	100	3200	100	3200
Neat	0.083	0.083	25.9	24.6	0.701	0.724	8.1	5.9	4.103	4.423	3.0	0.5
Plastomer	0.006	0.009	75.0	66.8	0.04	0.085	72.1	47.7	0.156	0.839	73.3	13.8
Elastomer	0.013	0.013	64.6	65.0	0.116	0.118	45.8	42.4	0.677	0.791	28.2	20.0
GTR	0.019	0.017	57.7	61.8	0.154	0.169	41.0	35.7	0.801	1.002	25.8	12.3

The comparison of binders' performance as shown in Table 3 shows that the behavior of new neat base binder is very similar to old base binder. Also it can be seen from the above table that the behavior of different modified binders are very similar. The Jnr values are increasing, while R% values are decreasing, when stress level or temperature are increased. The values for Jnr and R% for all three modified binders are relatively similar when compared to effects of temperature. Although the GTR modified binders give slightly higher Jnr and slightly lower %R values, it can be concluded that GTR modification can have similar behavior as other modifiers. Furthermore, the values compared to the neat asphalt show clearly that GTR modification has significant effect on improving rutting resistance and elastic behavior of neat binder at broad range of temperatures.

In addition to the MSCR testing, Repeated Creep and Recovery (RCR) test was conducted to see more complete creep behavior of binders. RCR tests were done at three stress levels (100, 3200 and 10000 Pa) to observe effect of stress levels on binder behavior. Moreover because this data will be compared to mixture results, it was necessary to have a wide range of binder behavior at different stress levels.

RCR tests were conducted at the same temperature as mixture testing. Table 4 summarizes the results of RCR test at three stress levels for neat and modified binders.

Table 4. *RCR results for neat and modified binders at three different stress levels.*

Temperature	46 °C					
MSCR Parameters	Jnr (1/kPa)			%R		
Stress Level (Pa)	100	3200	10000	100	3200	10000
Neat	0.081	0.086	0.109	26.3	23.7	19.0
Plastomer	0.003	0.012	0.028	93.2	68.4	44.0
Elastomer	0.018	0.019	0.015	60.6	57.1	64.2
GTR	0.018	0.023	0.013	65.8	58.2	65.2

The RCR results show that GTR is a good candidate for modifying binder especially at high stress levels. It can be seen from Table 4 that GTR modified binder has a very stable trend at different stress levels and it shows the least stress sensitivity. Furthermore, it can be observed that GTR has significant impact on elastic recovery of neat binder and it is appropriate to give more flexibility to pavement to recover the deformation under traffic. Changing stress levels did not have a large influence on the behavior of GTR modified binder when normalized for the effect of stress and it proves GTR suitability to use under heavy traffic level to modify neat binders.

4.3. Results of Mixtures

Flow number (FN) testing was conducted for both fine and coarse gradations of limestone using each of the four binders at stress levels of 344 and 1034 kPa. Mixture testing was conducted at a temperature of 46^{o}C. A summary of the test results for limestone mixtures is shown in Table 5.

The fine gradation consistently had a greater FN than the coarse gradation for each of the binder types and at both stress levels. The FN values show consistent reduction when the stress level was increased. The mixtures modified with the GTR show significantly higher FN values when compared to the mixtures with the neat binder. The improvement due to the use of the 10 % GTR show improvements ranging between 60% increase in FN to as high as 110% increase, depending on stress used and gradation.

Table 5. *Summary of Flow Number (FN) results for mixtures with different gradations and binders.*

	FN (Cycles) at 46°C	
Stress (kPa)	**345**	**1034**
Neat-Coarse	450	100
Neat-Fine	730	150
GTR-Coarse	690	160
GTR-Fine	1575	240
Plastomer-Coarse	3000	210
Plastomer-Fine	50000+	400
Elastomer-Coarse	1050	260
Elastomer-Fine	3150	430

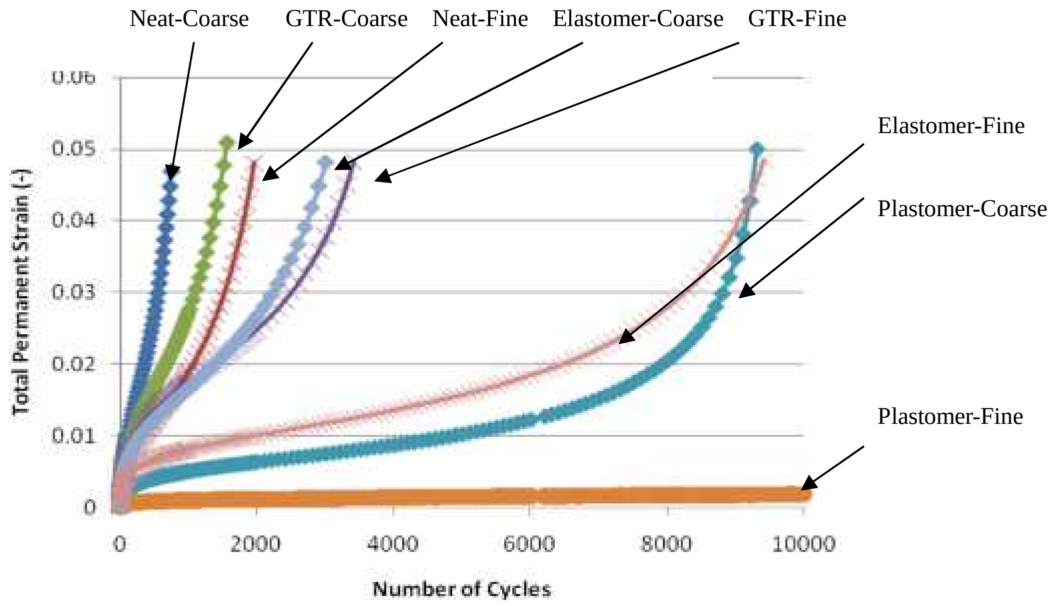

Figure 10. *FN results for limestone mixtures at 345 kPa.*

The mixtures modified with the GTR were however not as favorable as the mixtures with plastomers and Elastomers. The mixtures with plastomer modification exhibited higher FN than those with elastomeric and GTR modifiers at the lower stress level; In fact, the fine gradation with plastomeric binder did not exhibit tertiary flow within a 50000-cycle loading duration. However, this ranking was slightly changed at the increased stress level. It can be seen that at high stress level of 1034 kPa, the elastomer and plastomer show very similar FN values. Such results suggest that there may be a shift in the component that governs mixture performance when changing from low to high stress. An example of the results obtained from FN testing at 344 kPa is shown in Figure 10. As shown in the plots, the plastomer with coarse gradation is performing similarly to the elastomer with fine gradation.

It can be seen from Figure 10 and Table 5 that GTR-modification improves the performance beyond that of the unmodified binder, but falls short of elastomer and plastomer modified binders. This holds true regardless of stress level or gradation. Because of the decreased solubility of the GTR particles, the GTR-modified binder may be considered a unique modification when compared to the virgin polymers. Consequently, it is necessary to investigate internal structure of the mixes to determine if this solubility characteristic is altering the structure in such a way that may be limiting the GTR mixes from performing to the level of the elastomer and plastomer polymers.

4.4. Image Analysis

The iPas software is capable of taking and image of asphalt mixture and determining the number of proximity zones between aggregates, as shown in Figure 11. The proximity is defined by the user to represent a specific distance between aggregate boundaries as defined using a user specific filtering scheme (Coenen et al., 2012).

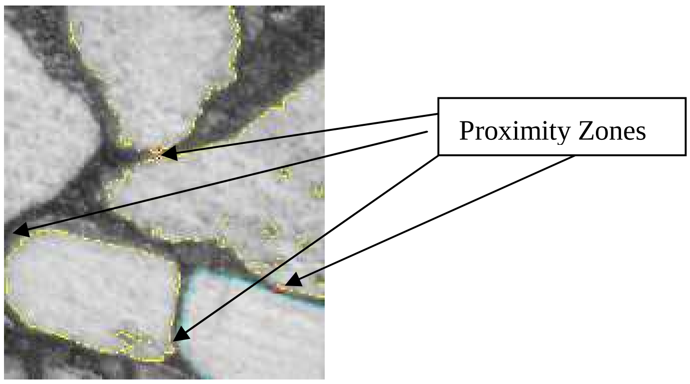

Figure 11. *Example of using iPas imaging software to determine Aggergate Proximity zones.*

A total of six images for each specimen were analyzed. These six images come from opposing faces of three physical cuts that divide the specimen into four equi-volume slices based on the dimensions of the cut and cored samples Locations of the slices can be seen in Figure 12.

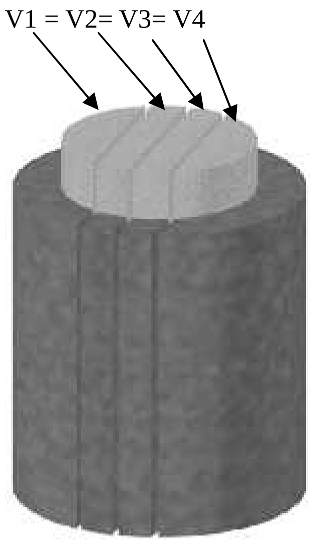

Figure 12. *Location of slices/cuts of gyratory specimen for imaging.*

The Aggregate Proximity Index (API) per 100 square centimeters (API/100cm2) was used to represent the internal aggregate structure of each mix type. This information is shown in Table 6.

Table 6. *Average Aggregate Proximity Index (API)/100cm^2 for limestone mixes.*

Mix Type	API/100cm2
Coarse_Neat	64
Coarse_GTR	80
Coarse_Plastomer	103
Coarse_Elastomer	114
Fine_Neat	280
Fine_GTR	291
Fine_Plastomer	298
Fine_Elastomer	301

It can be seen in Table 6 that the binder modification type has a significant effect on the API values, and that API of modified binders are higher than the neat binder in both gradations. Indeed fine gradation (LSF) mixtures consistently show greater API values than coarse gradation (LSC) Furthermore, the ranking of the API within each gradation is similar to that obtained from mechanical testing of the mixtures at 1034 kPa. Figures 13 and 14 represent results of correlation between API values and FN for a single minimum aggregate size of 2.36 and 0.6, respectively. When observing a single minimum aggregate size, the relationship between internal aggregate structure (API) and mixture rutting performance (FN) becomes quite clear. Note that the minimum aggregate sizes selected for Figures 13 and 14 represent approximately 75% of the total aggregate within each gradation. It is clear in Figure 13 that 75% of the total aggregate for the coarse gradation is representative and can capture the relationship between performance and aggregate structure.

A better correlation could be achieved by using a smaller aggregate size. A smaller aggregate size (i.e., 0.3 mm) should be used for fine-graded mixes and a minimum aggregate size resulting in an equivalent percent passing be used for coarse-graded mixes. However, this cannot be accomplished with the resolution used in this study. It is suggested that future work increase image resolution from 1200 dpi to a minimum of 2400 dpi to account for a minimum of nearly 85% of total aggregate in each mix.

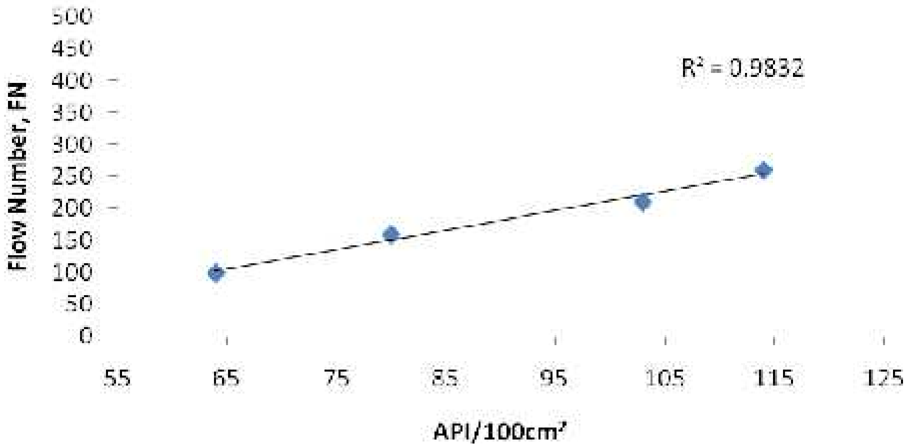

Figure 13. *FN at 1034 kPa versus API for coarse mixes with minimum aggregate size selected as 2.36 mm.*

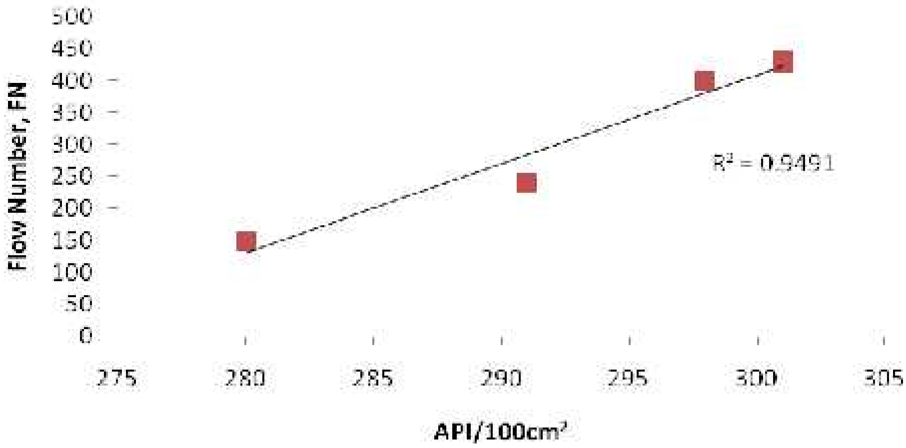

Figure 14. *FN at 1034 kPa versus API for fine mixes with minimum aggregate size selected as 0.6 mm.*

Additional mixtures using the same asphalt binders were prepared at different densities to validate the concept that performance is partially governed by internal structure at more than one density. The additional mixtures were prepared using the same aggregate source, gradations, and one of the four original asphalt binders, while only the density was altered during compaction. The additional coarse-graded mix was produced using the GTR-modified binder and was compacted to a lower relative density, resulting in an increased percentage of air voids. Additional fine-graded mixes were produced using the GTR-modified binder as well as the unmodified/neat binder. The fine-graded GTR mix was compacted to result in a lower density, whereas the neat binder was combined with the fine-graded aggregate and compacted to a greater density. Two replicates of each mix were tested for mechanical performance and specimen preparation for image analysis (i.e., physical slicing of the specimen, scanning, etc.) was performed as previously discussed.

Figures 15 and 16 show the previously presented mixtures separated by gradation, with the addition of the alternate density mixes. It can be seen in these figures that there is a good correlation between the internal aggregate structure and the resistance to permanent deformation conducted at the higher stress level of 1034 kPa. The GTR-modified mixes are not outliers from this relationship, indicating that the level of solubility of a GTR modifier in binders does not significantly affect or rearrange the internal aggregate structure nor reduce the improvements provided by the modifier over the neat binder.

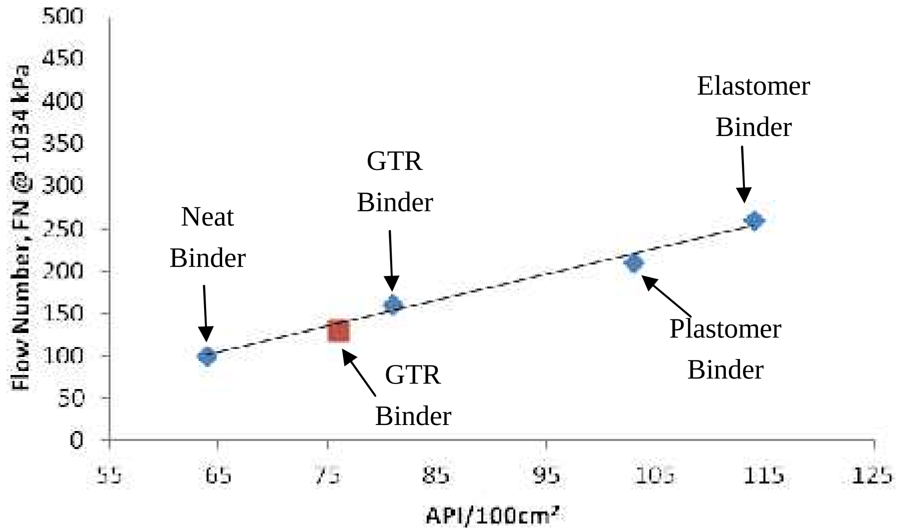

Figure 15. *FN at 1034 kPa versus API for coarse mixes with minimum aggregate size selected as 2.36 mm with additional mix density.*

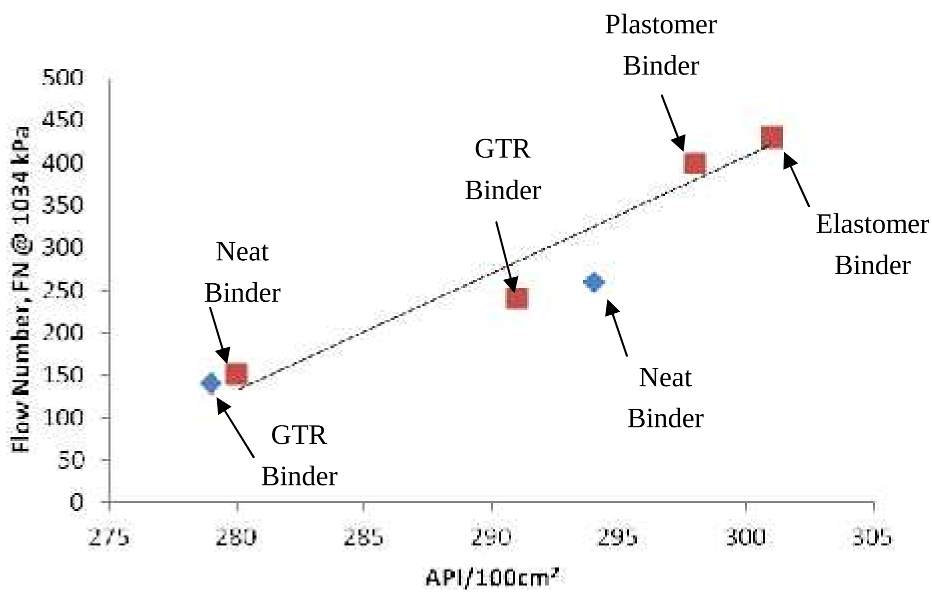

Figure 16. *FN at 1034 kPa versus API for fine mixes with minimum aggregate size selected as 0.6 mm with additional mix density.*

5. Summary of Findings

This study included limited types of modifiers and aggregate gradations. The following summary represents the main findings of the study.

- The results presented in this paper clearly indicate that GTR-modification of asphalt binders has the potential to improve the rutting resistance of mixtures. However it is clear that the GTR modification used in this study at 10 % addition of No. 30 mesh rubber, although showed equivalent PG grading, is not sufficient to produce equivalent mixture performance compared to that of using virgin polymer modifiers. It appears that higher percentages of rubber are needed. Therefore, relying on PG grading to determine needed rubber amount to produce equivalent mixture performance is not sufficient. Mixture evaluation is a better method.
- The binder testing results indicate that properties of GTR modified binders vary depending on amount of GTR used and reaction period. Thus, the comparison to the use of virgin polymers in modification is complex and requires further qualification. There is the potential that GTR amount and method of reaction could lead to results that are equivalent or even superior to the performance of virgin polymers. Furthermore, when considering the cost and environmental benefits of using GTR, additional benefits from the use of GTR modification should be considered.
- State of the art internal structure image characterization of HMA samples has shown that the reduced levels of solubility of GTR do not result in aggregate structure that is significantly different from that of mixtures produced with unmodified or virgin polymer modifiers.
- This study has shown that stress level is important in rutting characterization, and that a transition in rutting resistance may take place between stresses of 344 to 1034 kPa. Results suggest that binder properties play a significant role in dictating pavement performance at lower stress levels but aggregate structure becomes more significant as stress is increased.
- Results also distinguished between coarse and fine gradations and indicate that binder modification could have more significant effect on aggregate structure for mixtures produced with coarse gradation. This finding indicates that binder modification may be extremely beneficial in

performance of stone matrix asphalt (SMA), which utilizes coarse and gap graded aggregate gradations.

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