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Rheological Characterization of Ground Tire Rubber Modified Asphalt Binders with Parallel Plate and Concentric Cylinder Geometries

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Abstract: Recently, scrap tire rubber-modified asphalt binders and pavements have been the preferred choice of state DOTs and parties involved due to the desirable engineering, as well as economic and environmental impacts. Rheological and mechanical properties of rubber modifications have been the main focus of researchers for the last couple of decades. This paper investigates the rutting potential, fatigue cracking resistance, and continuous performance grade (CPG) changes of waste tire rubber-modified, original, and aged asphalt binders. The CPG of asphalt binders is determined at high, intermediate, and low temperatures. A Delta T Critical comparison of the binder was carried out to establish a relationship between measured parameters. Linear amplitude sweep (LAS) tests at equi-stiffness temperatures were conducted to discover the fatigue life of all binders while the multiple stress creep recovery test is performed to assess the high-temperature rutting performance of asphalt binders as per the Superpave performance grading system at accepted regional (58 °C) as well as high PG temperatures. In addition, parallel-plate geometry and concentric cylinder geometry were used with the Multiple Stress Creep Recovery (MSCR) test to discover the impact of discrete particles available in crumb/ground tire rubber-modified asphalt binders as per standards. The results show that rubber modifications improved the base binder's rutting resistance and continuous PGs without adversely affecting the fatigue cracking resistance. Based on the mathematical expressions developed, 2.71%, 7.82%, 12.94%, and 18.05% (by weight of binder), GTR modifications improved the high PG of the modified binders one, two, three, and four grade bumps, respectively. Similar linear correlations with R^2 0.872 and 0.6 were established for continuous low and intermediate PGs, respectively. MSCR test results revealed that both 9% and 20% GTR modifications were achieved to enhance the H-grade traffic level of the original binder to E-grade.

Keywords: ground tire rubber; parallel plate geometry; concentric cylinder geometry; MSCR; LAS; continuous performance grade; Delta T Critical

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1. Introduction

Asphalt modifications to enhance the load and weather-related performance of pavements have been a common practice used by agencies nowadays. Ground tire rubber (GTR) has been one of the most applied asphalt modifiers even though there are many virgin and recycled asphalt modifiers in the market. The modified asphalt costs more than the original one, and the actual price changes depending on the amount as well as on the type of the modifier. Based on the literature, rubber-modified asphalts can cost 10% to 30% higher than conventional ones [1–4] while polymer-modified asphalts can cost twice as much [5]. However, the life cycle cost of modified asphalts, in general, is lower due to enhanced performance and fewer maintenance cycles required [6,7]. Rubberized asphalt can achieve as good as or even better performance than pricey polymer-modified binders, making GTR a cost-effective alternative to polymers [8–10].

Around one billion scrap tires are generated globally every year [11]. The state of California produces over 50 million waste tires by itself [12]. When they are not properly discarded in landfills, the scrap tires are stockpiled or illegally dumped on the land, creating fire hazards or housing for disease-carrying mosquitos, insects, and rodents [13]. To overcome such issues, state DOTs are searching for alternative ways to handle waste scrap tires. In one attempt, California state law obligates Caltrans to use GTR in 35% of all its asphalt paving projects. Moreover, it requires at least 20% rubber in the asphalt binder used in surface courses [12]. As a result of all these requirements, it is estimated by the California Department of Resources Recycling and Recovery (CalRecycle, Sacramento, CA, USA) that more than 35,000 tons of crumb rubber were integrated into paving activities in 2018. In addition, less than 25,000 waste scrap tires are anticipated in the stockpiles of California [14].

Other than the above-mentioned engineering, economic, and environmental benefits, some other added-value benefits of using GTR in asphalt pavements can be found in the literature. Some of them can be listed as reducing tire pavement interaction noise [15,16], decreasing tire wear [17], providing better ride quality [18], increasing longevity [19], softening stiff binders in high RAP pavements [20], improving aging properties [21], decreasing ice retention [22], and increasing resistance to reflective cracking [23]. This study aims to fill the gap in the literature by investigating the rheological and mechanical properties of wet-process GTR-modified asphalt binders at various percentages using the CPG and recently introduced binder performance tests such as Delta T Critical, LAS, and MSCR. As the state DOTs have been in the transition phase to a new binder grading system, this paper intends to establish an understanding between the old Superpave high-temperature specification AASHTO M320 and the new MSCR specification AASHTO M322 for GTR-modified asphalt binders. It also examined one of the main concerns regarding the use of parallel plate geometry for binders with discrete particles, such as rubber-modified binders, by comparing it with concentric cylinder geometry. The findings and correlations between various parameters studied can serve as the basis for future researchers and binder modifiers in this field.

2. Objectives and Scope

There were a few objectives of this study. The major objective was to evaluate the rutting potential and fatigue cracking resistance of GTR-modified asphalt binders along with the continuous low-, intermediate-, and high-performance grades. Another objective was to establish correlations between the percent GTR modifier and all three continuous grading temperatures. Yet, another objective was to investigate the impact of testing geometry for binders with discrete particles as per specifications. For this purpose, MSCR tests of modified and original binders were conducted by using both testing geometries, namely parallel-plate and concentric cylinder. The scope of the study covered 3%, 6%, and 9% GTR modification of the original PG58-28 binder along with the commonly used 20% GTR modification in rubberized asphalt pavements. The performance of the modified asphalt binders relative to the original binder was tested using Delta T Critical, LAS, and MSCR tests along with fundamental Superpave binder tests.

3. Materials and Methods

Asphalt binders with an original PG58-28 commonly used in the Midwest region of the United States was selected as the base binder for all modifications and testing. Basic information regarding the original asphalt binder is provided in Table 1.

GTR particles are produced at ambient temperature with the cracker mill process (CMP), which is the most common GTR production technique. CMP uses shredded tire pieces instead of full-size tires. Before shredding and further size reduction, fiber reinforcements and steel belting are removed from the tire bodies using a series of fiber and steel separators. In this process, scrap tire pieces pass between rotating corrugated steel drums for size reduction. The spacing and the differential speed of the drum pairs control the tearing of the scrap tires. GTR produced with this process has irregular shapes with larger surface areas. Particle sizes can be achieved over a range of 425 microns to 4.75 mm. Mesh size #20 acquired with the cracker mill process at ambient temperature is utilized in this study. According to the sieve analysis results, almost 100% of the GTR particles passed the #16 sieve, a little less than 50% were able to pass the #30 sieve, and only 2.3% of the rubber particles were retained in the #100 sieve.

Table 1. Basic properties of the original/neat/base binder.

Property	Value	Unit
Continuous High Grade	60.1	°C
Continuous Intermediate Grade	17	°C
Continuous Low Grade	−29.1	°C
Viscosity at 135 °C & 170 °C	285 & 68	cP
$\lvert G^* \rvert$ at 10 °C & 70 °C	3,470,167 & 238	Pa
Phase Angle at 10 °C & 70 °C	62.6 & 88.8	degrees
Flash Point	312	°C

Ground Tire Rubber Modification Process

There are various GTR modification methods in the literature. The modification method applied in this study is adapted from one of the GTR manufacturers in the industry, which is similar to the ones researchers have been using in the literature as well [24]. In this process, only low-shear mixing is used. It was conducted using a benchtop blender with a boat motor-type propeller as shown in Figure 1a–c, which illustrates the 20-mesh size ground tire rubber particles used in this research and a sample of a GTR-modified asphalt binder in a concentric cylinder geometry, respectively.

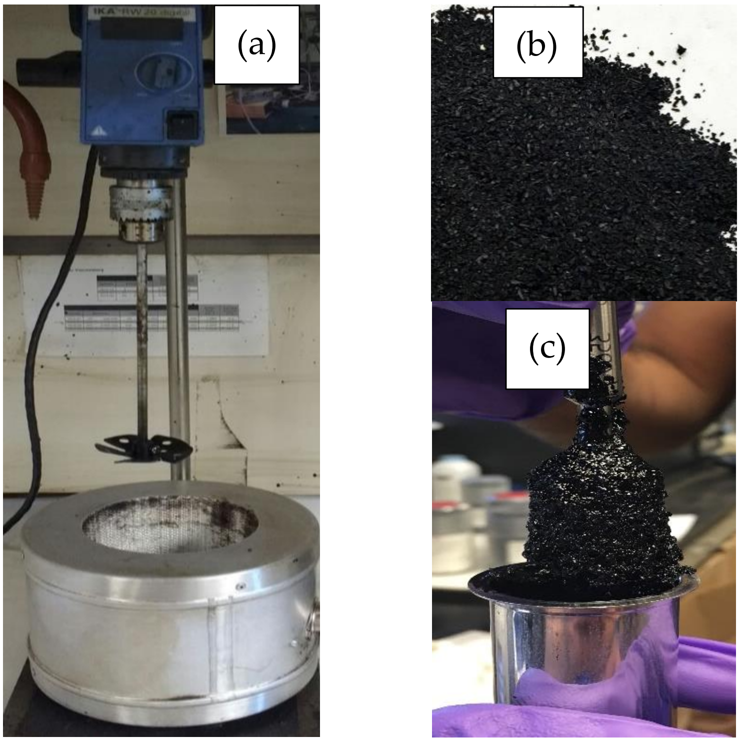

Figure 1. (**a**) Low-shear mixer with heating mantle. (**b**) GTR particles. (**c**) GTR-modified asphalt binder in a CC geometry.

Rubber particles are slowly added into the preheated asphalt binder at 180 °C while the mixer is set to rotate at 1000 rpm. The addition of the GTR is completed within 5 min. the binder–rubber blend is mixed for 60 min at the same rpm value unless a vortex is formed on the surface of the mixture. Otherwise, the speed is adjusted to ensure vortex-free surface mixing. The temperature of the mixing system is kept at around 180 °C by using an adjustable heating mantle for a gallon can. Circulatory heating oil baths and hot plates can be used as well depending on the size of the containers. It is important to leave some space in the containers to house the swollen rubber particles. Once the mixing process is completed, the GTR-modified asphalt binder is transferred to an oven at 163 °C for 16 h in an oxygen-free condition to complete the reaction between binder and rubber particles. This process is also known as static aging. At least two batches were prepared per modification for the repeatability of the modification process. The calculations showed the consistency of the modification process by providing minimal variations.

4. Tests, Results, and Discussion

PG, ΔTc, LAS, and MSCR tests and calculations were conducted to understand the relative performance of GTR-modified asphalt binders compared to each other and the original/neat binder. Statistical methods were applied to the test results to establish relationships between modifications and certain useful parameters such as continuous performance and traffic grades. All tests were carried out on a minimum of two replicates per binder batch. Hence, at least four samples per binder (either original or modified) were tested for each test type. The basic descriptive statistical values for the test results were computed and presented along with the data.

4.1. Continuous High-, Intermediate-, and Low-Performance Grade Tests and Results

The major focus of this research was to determine the change in all continuous grading temperatures of GTR-modified asphalt binders relative to the base binder as the PG is a basic step for binder classification based on AASHTO M320. The original/neat/base binder was denoted with "0%" in the test results since there were no modifiers incorporated. Similarly, the aged-base/original binder was denoted with "A-0%". The aged-base binder was prepared by only exposing the original binder to the modification process (i.e., heating and low-shear mixing) without adding any modifier to illustrate the aging effect during the binder modification process. Continuous PGs are selected in lieu of discrete PGs since they provide more information and precise data about the modifications. Additionally, they are a better fit for research that includes modifications. Asphalt binder producers, especially, use CPG values to achieve cost-effective binder modifications. In the literature, there are researchers who apply the CPGs to determine the required amount of asphalt modifiers, such as styrene-butadiene-styrene (SBS) polymers, devulcanized rubber, or their combinations to acquire the asphalt binders with desired PG values [25,26]. In addition, some other researchers benefitted the CPG concept to compare the accuracy of testing equipment [27]. The linear interpolation method stated at ASTM D7643 was implemented to determine the continuous grades even though there were other methods such as nonlinear, parabolic, and exponential curve fitting, used by researchers to calculate the continuous grades in the literature. Based on the information provided in ASTM D7643, a 3% GTR-modified binder has continuous grades of 66.2–31.32 (15.3) where 66.2 °C is the continuous high grade (CHPG), −31.32 is the continuous low grade (CLPG), and 15.3 is the continuous intermediate grade (CIPG).

The linear interpolation between the absolute highest passing and lowest failing temperatures as per ASTM D7643 was applied to the data to find the critical temperatures. There are two equations provided in the standards to determine the continuous grades. Both equations are developed based on the two-point linear relations between the test results and temperatures. Equation (1) uses the log_{10} scale for the test results and the arithmetic scale for test temperatures, and it is applicable for all test results other than the m-value, whereas Equation (2) uses the arithmetic scale for both parameters, and it is only applied to determine the m-value-based critical temperature for CLPG:

$$T_c = T_1 + \left(\frac{log_{10}(P_s) - log_{10}(P_1)}{log_{10}(P_2) - log_{10}(P_1)} \right) \times (T_2 - T_1) \tag{1}$$

$$T_c = T_1 + \left(\frac{P_s - P_1}{P_2 - P_1}\right) \times (T_2 - T_1) \quad (2)$$

where:

T_c = Continuous grading temperature, °C;
T_1 = Lower test temperature, °C;
T_2 = Higher test temperature, °C;
P_s = Required value for failing criteria based on the specifications;
P_1 = Test result at T_1;
P_2 = Test result at T_2.

Table 2 summarizes the process of determining the continuous high-grading temperature by linear interpolation method for 3% GTR-modified asphalt binder. The left part of the table gives information about the original binder measurements while the right part shows the test results for RTFO-aged binder along with some basic descriptive statistical values such as average (AVR), standard deviation (Stdev), and coefficient of variation (COV). Lastly, the bottom row provides the final continuous grading temperature (T_C-final) in degrees Celsius, which is the lower of T_C-neat and T_C-rtfo. To determine the CLPGs, RTFO-aged binders were further aged inside the pressurized aging vessel (PAV) to simulate the long-term/oxidative aging that occurs under field conditions. Before preparing the bending beam rheometer (BBR) samples, PAV-aged binders were degassed in a vacuum oven to minimize/eliminate the air bubbles introduced during the aging process. The BBR test provides the low-temperature relaxation and stiffness properties of asphalt binders. Those properties are used to examine the thermal cracking resistance of the asphalt binders. Based on the low PG of the unmodified binder, which was −28 °C, BBR tests were conducted at −12 °C, −18 °C, and/or −24 °C until the failure took place. As per the specifications, the failure occurred when either the stiffness was greater than 300 MPa or the m-value was smaller than 0.300 at the 60th second.

Table 2. Determining the continuous high grading temperature of 3% GTR-modified binder.

GTR 3% Original				GTR 3% RTFO-Aged			
	Average of Run 1	**Average of Run 2**	**AVR** [1]		**Average of Run 1**	**Average of Run 2**	**AVR** [1]
T_C-neat (°C)	64.28	63.64	63.96	T_C-rtfo (°C)	64.75	65.01	64.87
T_1 (°C)	64.0	58	Stdev [2]	T_1 (°C)	64.0	64.0	Stdev [2]
T_2 (°C)	70.0	64.0	0.46	T_2 (°C)	70.0	70.0	0.17
P_1 (kPa)	1.03	1.97	COV [3]	P_1 (kPa)	2.4	2.47	COV [3]
P_2 (kPa)	0.548	0.956	0.71%	P_2 (kPa)	1.2	1.23	0.26%
P_s (kPa)	1.0	1.0		P_s (kPa)	2.2	2.2	
T_C-final (°C)				63.96			

AVR [1]: average, Stdev [2]: standard deviation, COV [3]: coefficient of variation.

Table 3, which illustrates the process of calculating the CLPG, presents the stiffness and m-value at the 60th second recorded during BBR testing along with the application of Equations (1) and (2). The last row in Table 3 shows the continuous low temperatures (T_C), which are the absolute smallest of T_C-s and T_C-m. It is important to note that continuous low temperatures (T_C, T_C-s, and T_C-m) are not the same as continuous low PG temperatures. The CLPGs can be acquired by adding −10 °C to the calculated continuous low temperatures as stated at AASHTO M320.

The third continuous performance grade calculation was performed to discover the CIPG of the binders. Even though the CIPG is not a part of PG designation, it is found to evaluate the fatigue cracking behavior of the binders. CIPG is known to be the weakest chain of the Superpave binder performance grading. It lacks either a theoretical or a practical basis. Intermediate PG was established as the arithmetic average of the high and low PG difference plus 4 °C according to AASHTO MPI-93. As an example, for the PG 58−28 grade binder, the intermediate PG can be calculated as (58−28) + 4 = 19 °C, which does not have any mechanistic foundations. Unlike high- and low-performance grades, the intermediate PG test temperatures change at 3 °C intervals. The lower the intermediate PG is, the more flexible the asphalt binder is, and it performs better in fatigue cracking resistance.

Table 3. Continuous low-temperature grade construction of 3% GTR-modified binder.

GTR 3% Stiffness (S-Value) Based				GTR 3% Slope (m-Value) Based			
	Average of Run 1	**Average of Run 2**	**AVR**		**Average of Run 1**	**Average of Run 2**	**AVR**
T_C-s (°C)	−20.03	−20.04	−20.04	T_C-m (°C)	−20.59	−20.36	−20.48
T_1 (°C)	−18	−18	Stdev	T_1 (°C)	−18	−18	Stdev
T_2 (°C)	−24	−24	0.46	T_2 (°C)	−24	−24	0.16
P_1 (MPa)	231	230	COV	P_1 (MPa)	0.319	0.313	COV
P_2 (MPa)	501	503	1.53%	P_2 (MPa)	0.275	0.280	0.53%
P_s (MPa)	300	300		P_s (MPa)	0.300	0.300	
T_C (°C)				−20.04			

Table 4 provides the results of continuous high-, intermediate-, and low-performance grades of neat and modified binders in a summary form. It is worth re-emphasizing that the A-0% binder underwent the heating and mixing process with no modifier to simulate the impact of aging that occurred during the modifications. While it improved the CHPG by 1.8 °C, it, as expected, worsened both CIPG and CLPG by 0.9 °C and 2.2 °C, respectively. Based on the measured data, the impact of the aging was strong enough to change the PG of the base binder from 58–28 to 58–22. Regardless of the modification type and amount, the original binder DSR testing protocol became the governing testing to determine the CHPG of the binders over the RTFO-aged DSR testing protocol. Similarly, m-value-based continuous low-grading temperatures were dominant for all asphalt binders tested other than the neat and 3% GTR-modified ones.

Table 4. Results of continuous high-, intermediate-, and low-performance grades.

Modification Type	**Continuous High PG (°C)**			**Continuous Inter. PG (°C)**	**Continuous Low PG (°C)**				**CHPG-CLPG**
	CH PG	**Original PG**	**RTFO Aged**	**CIPG PAV Aged**	**CLPG**	**S-Based**	**m-Value Based**	**Δ*Tc***	**(°C)**
0%	60.1	60.1	61.2	17.0	−29.1	−29.1	−30.6	1.5	89.2
A-−0%	61.9	61.9	62.5	17.9	−26.9	−28.4	−26.9	−1.5	88.8
3% GTR	64.0	64.0	64.9	15.3	−30.0	−30.0	−30.5	0.5	94.0
6% GTR	68.6	68.6	69.3	14.2	−30.7	−31.3	−30.7	−0.6	99.3
9% GTR	72.3	72.3	74.3	14.6	−30.2	−32.4	−30.2	−2.2	102.5
20% GTR	83.7	83.7	86.4	13.9	−31.9	−34.8	−31.9	−2.9	115.6

Figure 2a demonstrates the impact of the GTR modification on CHPG. As the amount of GTR modifier increased, the CHPG of the modified binders improved as well. The 3% and 6% GTR modifications achieved a one-grade bump while the 9% and 20% GTR modifications accomplished two-grade and four-grade bumps, respectively.

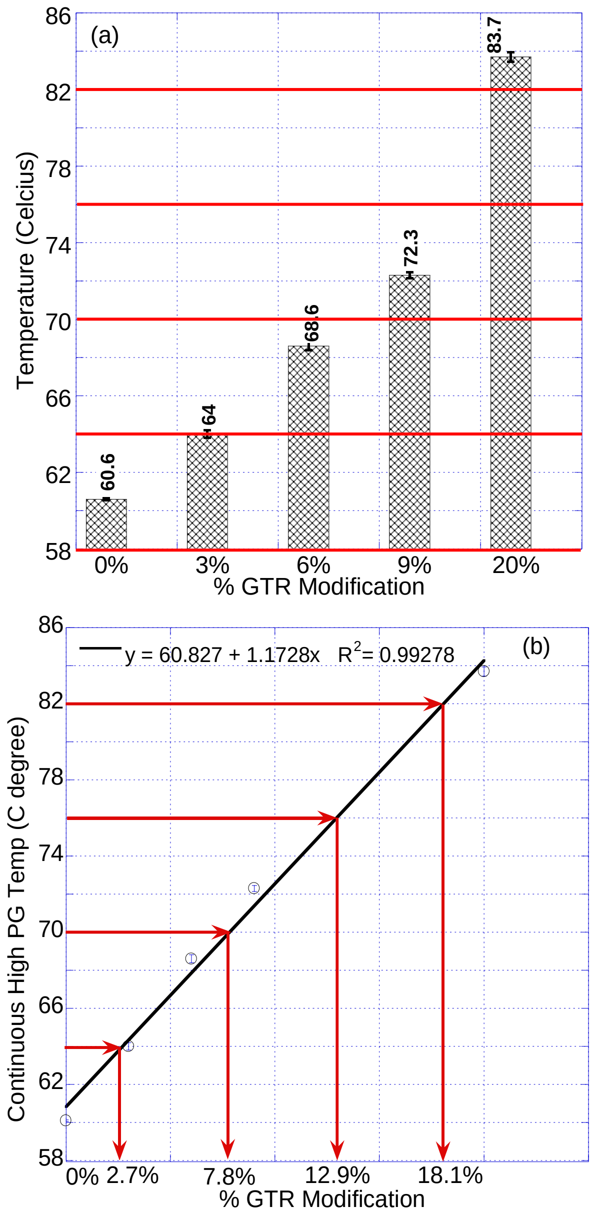

Figure 2. (**a**) Impact of GTR modification on CHPG. (**b**) Correlation between modifications and CHPG.

To determine the exact amount of GTR modifier to attain the desired grade bump, the correlation established in Figure 2b between the percent modifier and CHPG can be used. Linear correlation with R^2 of 0.993 implies a strong relationship between the parameters investigated. Based on the mathematical expression formulated during the linear curve fitting process, around 7.82% (by weight of binder) GTR is required to acquire two-grade bumps, and 12.94% rubber is needed to reach three-grade bumps.

Different modifiers are generally used to decrease the low PG or to increase the high PG of the asphalt binders. Multiple modifiers can be used simultaneously in the same asphalt binder to enhance both the high and low PGs. Even though GTR modification of the binder is generally conducted to increase the high PG of the binder to provide better resistance to rutting without adversely affecting the low and intermediate PGs, the results reveal that any GTR modification improved not only CHPGs but also CIPGs and CLPGs with a clear trend. The linear relationships between the percent modifiers and CIPG-CLPG were established to determine useful mathematical expressions.

Figure 3a,b illustrates the relationship between GTR modifications versus CLPG and CIPG, respectively. Linear correlation between percent GTR and CLPG was established with R^2 equal to 0.872. Similarly, a linear correlation between the percent GTR and CIPG was established with R^2 equal to 0.6. Despite being simple, yet reasonable, correlations for the asphalt binders, the relationship can be better represented by using different curve fitting options and by enhancing the testing matrix. Compared to the intermediate PG of the base binder, which was 19 °C, all modified binders resulted in one grade bump by lowering the intermediate PG to 16 °C. The highest improvement was attained at 20% GTR modification by lowering the CIPG 3.1 °C compared to the original binder.

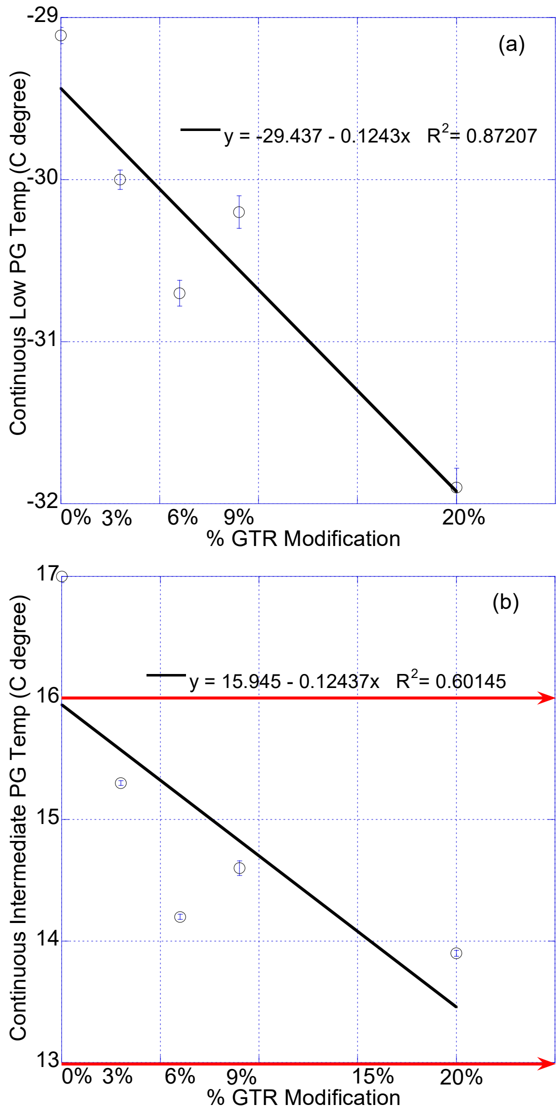

Figure 3. Linear correlations between (**a**) GTR modifications and CLPG; (**b**) GTR modifications and CIPG.

4.2. Delta T Critical (Delta Tc or ΔTc) Analysis

Delta T_C (ΔT_C-Delta T critical) was another parameter calculated during the CLPG determinations. It is used as an indicator of the impact of aging and modifiers on binder rheology [27]. It is a parameter state DOTs either have implemented or have been considering implementing into their specifications as another PG+ binder test. ΔT_C is used to understand the asphalt binders' relaxation properties, which are a sign of nonload-related cracking or aging-related embrittlement distress in the flexible pavements. The parameter is computed using the creep stiffness and rate from BBR testing for any asphalt binder including neat binders, binders with additives, modified binders, and recovered binders although it was primarily developed for neat asphalt binders [28]. However, researchers should be cautious against using ΔT_C for polymer-modified binders since it is generally accepted that polymer-modified asphalt binders show reduced laboratory aging (RTFO and PAV) due to their higher viscosities. The reduced aging can create a favorable condition for stiffness by causing lower T_C-s values [29]. There is ongoing research to investigate polymer-modified asphalt binders and their relationship with ΔT_C. Further research is needed to establish a better understanding between GTR-modified asphalt binders and ΔT_C as well since the aging characteristics, especially RTFO aging, of GTR-modified binders can show slight variations as described in the literature.

First conceptualized by Anderson et al. in 2011, ΔTc is a relatively new parameter that has been gaining popularity due to its ability to quantify the aging propensity of asphalt binders as well as to correlate it directly with certain types of pavement distress, such as block cracking [28–31]. The same procedure explained in the computation of the continuous low-grading temperature section, which is presented in Table 3, is followed to find the critical temperatures based on creep stiffness (*Tc-s*) and creep rate (*Tc-m*) at the end of the 60th second. Once these parameters are calculated, Equation (3) is used to calculate the ΔTc:

$$\Delta T_c = T_{C-S(60\text{s})} - T_{C-m(60\text{s})} \tag{3}$$

Depending on the *Tc-s* and *Tc-m* values, ΔTc can be positive or negative. $+\Delta Tc$ is an indicator of the fact that the binder's low PG is governed by the creep stiffness while $-\Delta Tc$ indicates that the low PG of the binder is controlled by the creep rate. In addition, the magnitude of the parameter provides information about the level of dominatΔTcion by stiffness or creep rate. In addition, a warning limit of −2.5 °C and a failure limit of −5.0 °C are suggested for 20-h PAV-aged asphalt binders. These limits are strongly related to the basic understanding of the parameter. As binders age, *Tc-m* increases quicker than *Tc-s* and makes the binders more m-controlled. The m-controlled binders are more brittle and less able to relax the applied stresses, hence more prone to cracking distress. Anderson et al. showed that there is a strong correlation between fatigue cracking (top-down cracking) and some other pavement distresses related to poor relaxation properties and higher negative values of ΔTc, although the ΔTc parameter was derived from the BBR testing, which was developed for thermal cracking [28,31].

ΔTc values for modified as well as the aged and original binders are provided in Table 4. As the amount of aging and GTR modification increased, the ΔTc parameter became more and more m-value controlled. While the ΔTc of the original binder 0% was 1.5 °C, it became −1.5 °C for the A-0% sample and 0.5 °C, −0.6 °C, −2.2 °C, and −2.9 °C for 3%, 6%, 9%, and 20% GTR modifications, respectively. Figure 4 illustrates two linear correlations between ΔTc and percent GTR modification. The only difference between these two correlations is the inclusion of 20% GTR modification results. The reason to construct relationships with and without the 20% GTR is the fact that not all binders have linear m-value or log-linear S-value with temperature. Moreover, as the amount of rubber modifier increases, the stiffness values become smaller. In the case of 20% GTR, the stiffness value was less than 300 MPa at any BBR temperature when Tc-m < 0.300 or Tc-m > 0.300, which was a different behavior than any other modified and original binders. Hence, it was decided to provide two linear correlations with and without a 20% GTR-modified binder. It is worth noting that the author established linear correlations for simplicity by assuming linear relationships between the m-value and temperature. Although both linear relations have strong correlations, a better curve fitting other than a linear one may be possible with the inclusion of 20% GTR modification. As can be seen from Figure 4 the first correlation with R^2 of 0.987 omitted the 20% GTR modification, and the second one with R^2 of 0.845 included it.

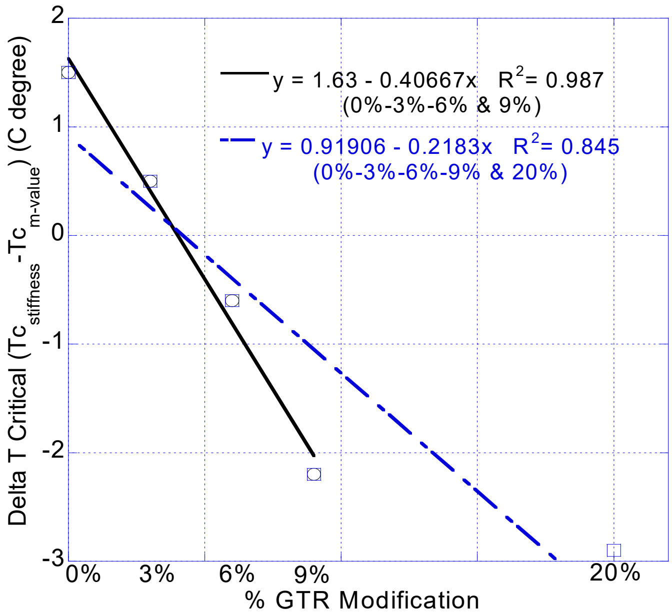

Figure 4. Linear correlations between ΔTc and percent GTR modifications.

4.3. Fatigue Cracking Resistance Test and Results

Superpave binder tests and the PG system were initially developed to find out the climatic and load-related performance of asphalt binders for certain pavement distresses. While high PG was developed for the rutting resistance, low PG was established for the thermal cracking of asphalt pavement. Similarly, the intermediate PG of the binders was created to provide information about the fatigue life of the asphalt binders. Although low and high PGs quite successfully estimated the relative performance of unmodified binders for resistance to low-temperature cracking and rutting, respectively, intermediate PG was not as successful to determine the fatigue cracking resistance of asphalt binders since it lacked any theoretical and practical fundamentals. Moreover, the recent changes in binder production practices as well as the need for binder modifications to prevent the early distress accumulation in the asphalt pavements as a result of heavier traffic volumes developed parallel to the exponentially growing world population in recent decades made Superpave binder tests obsolete and gave rise to the development of newer test methods to better understand their mechanistic behavior. In an effort, a viscoelastic continuum damaged (VECD) mechanics-based linear amplitude sweep (LAS) test was developed to determine asphalt binders' resistance to fatigue cracking. It is designed to evaluate the fatigue resistance ability of asphalt binders under cyclic loading with increasing amplitudes. LAS test can estimate the number of cycles to fatigue failure (N_f) as a function of strain developed in the asphalt pavement at a 35% reduction in initial modulus.

Theoretically, the LAS test has two parts. The first part, frequency sweep tests, is performed to acquire the undamaged rheological properties of the asphalt binders. In this stage, the sample was tested at a set of standard specified frequencies between 0.2 Hz and 30 Hz at 0.1% strain amplitude. This stage is important to derive the damage analysis parameter alpha (α). The second part of the tests is performed to determine the fatigue characteristics of asphalt binders under oscillatory shear strain-controlled mode with linearly increasing strain amplitude between 0.1% to 30% at a constant 10 Hz frequency for a total of 3100 loading cycles. The same binder specimen is used in both stages since the frequency sweep test does not create damage to the sample. LAS can be performed with 8-mm parallel-plate geometry and a 2-mm working gap using readily available DSR equipment on either RTFO- or PAV-aged asphalt binders as per AASHTO- T391 (previously TP101) specifications. In this study, PAV-aged, degassed asphalt binders were used. The same specification recommends testing temperature as the intermediate pavement temperature based on the PG grades of the binder. However, this suggestion lacks a mechanistic basis as stated in detail at CIPG calculations. According to this recommendation, base binder, 3% GTR-, 6% GTR-, 9% GTR-, and 20% GTR-modified binders would have been tested at 19 °C, 22 °C, 22 °C, 25 °C, and 28 °C, respectively. Many researchers experienced the same problem with the LAS testing temperature. They applied different methods and mechanistic approaches to establish a relation for testing temperature. Some researchers suggested using a certain temperature, such as 25 °C, as it corresponds to the local intermediate temperature of the region of interest [32], while some of them selected a typical representative intermediate temperature such as 20 °C [33]. Some others recommended the testing temperature as the average climatic PG minus 4 °C based on the linear viscoelastic range of the asphalt binders [34]. Further studies showed that the linear viscoelastic approach was suitable to select the LAS temperatures. It was suggested that LAS temperatures should be selected between the temperatures corresponding to $|G^*| < 60$ MPa at 10 Hz (approximately 2.5 MPa at 10 rad/s) to prevent excessive brittleness and adhesive failures between parallel-plate geometry of DSR and binder specimen and to $|G^*| > 60$ MPa at 10 Hz (about 25 MPa at 10 rad/s) to prevent the bulging and geometry changes [35]. Yet, some other researchers proposed using temperatures at which the iso-stiffness condition occurs, such as $|G^*| \times \sin(\delta) = 6.5$ MPa [36]. Typically, the LAS results at 2.5% and 5.0% strain levels are presented considering the pavement layer stiffness. The general approach is to use a 5.0% strain level for asphalt layers thinner than 4 inches and a 2.5% strain level for asphalt layers thicker than 4 inches [35].

In this study, the authors selected the LAS temperatures at which $|G^*| \times \sin(\delta) = 5000$ kPa. These temperatures are also known as the equi-stiffness temperatures or the temperatures equal to the CIPGs of the binders. LAS temperatures determined using this approach satisfied the linear viscoelastic range of asphalt binder tests. Visual inspections also confirmed that there was no bulging or excessive brittleness during the testing.

Figure 5 illustrates the findings of the LAS tests of GTR-modified asphalt binders as well as the original binder at different strain levels. Data analysis of the LAS test results was performed at 1%, 3%, 5%, and 8% applied strain levels. The aim of selecting numerous strain levels was to better understand the fatigue performance of thinner overlays, such as 2-inch, and thicker asphalt pavements, such as 18-inch-thick multi-lift pavements, other than only focusing on the 4-inch thickness. Analysis of LAS results revealed that 3% GTR modification shortened the fatigue life of the asphalt binder at all strain levels tested. However, as the strain level increased from 1% to 8%, the difference in fatigue life diminished. At 8% strain level, both original and 3% GTR-modified were statistically indifferent. The 6% GTR modification improved the fatigue life at smaller strain levels compared to the 3% GTR-modified binder; however, it did not enhance the fatigue life at higher strain levels. Similarly, 9% GTR modification improved fatigue life at 1% and 3% strain levels compared to 6% GTR modification. Ultimately, 20% GTR modification almost reached three times more fatigue life at a 1% strain level than the original binder. Both 20% GTR modified and original binders had almost the same fatigue life cycles at a 3% strain level. However, at higher strain levels, 20% GTR modification did not provide better fatigue life than the original binder. It can be summarized that as the GTR percentage increased, the fatigue life of the asphalt binders enhanced considerably at lower strain levels and worsened at higher strain levels.

Figure 6a–d illustrates the relationship between the number of fatigue cycles to failure and the percent GTR modification for 1%, 3%, 5%, and 8% strain levels, respectively. Linear correlations were established between the parameters investigated at four different strain levels. R^2 values of the linear relationships for all strain levels changed between 0.9 and 0.99 implying strong correlations. While there was a positive correlation between the fatigue live and GTR percentages at 1% and 3% strain levels, a negative correlation occurred between the same parameters at 5% and 8% strain levels.

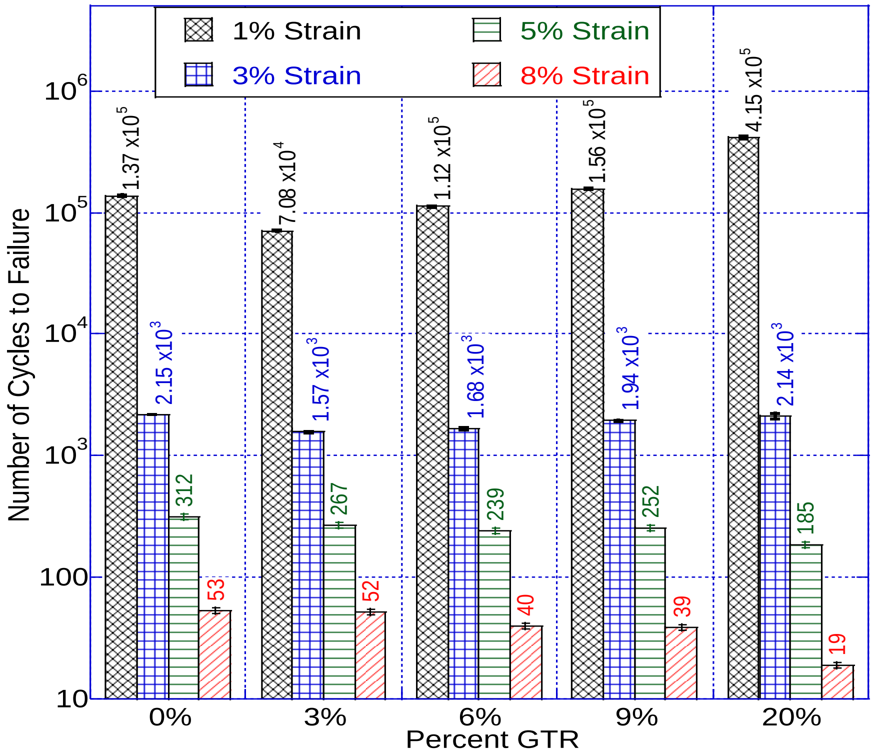

Figure 5. LAS test results for different strain levels at CIPG temperatures.

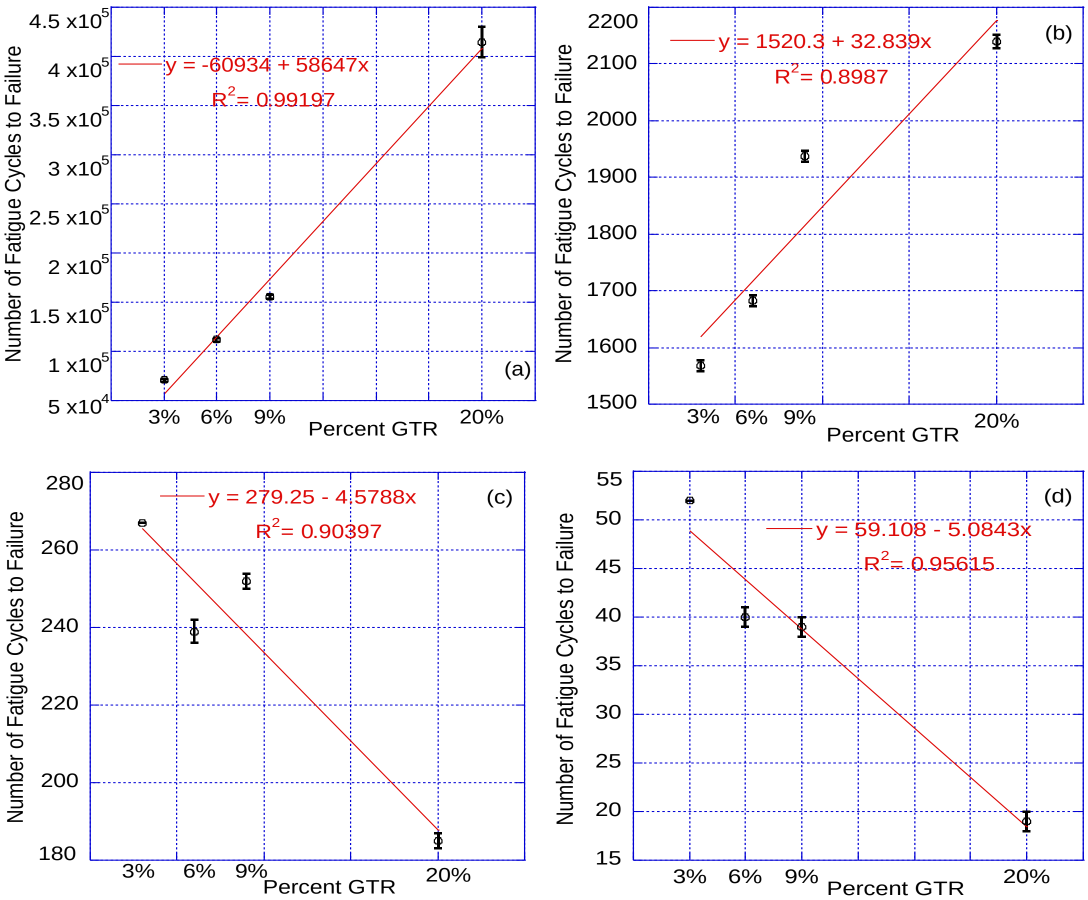

Figure 6. Fatigue life vs. GTR modification at (**a**) 1% strain, (**b**) 3% strain, (**c**) 5% strain, (**d**) 8% strain.

4.4. MSCR Rutting Resistance Test Results with Parallel Plate and Concentric Cylinder Geometries

The original Superpave performance grading system used a dissipated strain energy approach to determine the rutting performance of the asphalt binders. In this approach, the |G*|/sin (δ) parameter for original and RTFO-aged binders was limited to calculate the high PG temperature grade. The |G*|/sin (δ) parameter became inadequate to accurately assess the rutting potential of asphalt binders with the recent changes in the binder production practices and introduction of modified binders. Deficiencies related to the |G*|/sin (δ) parameter and corresponding test methods resulted in proposing novel test methods such as zero-shear viscosity, low-shear viscosity, and nonrecoverable creep compliance [37]. Further studies demonstrated that the nonrecoverable creep compliance is better correlated with the rutting performance of modified and unmodified binders [38–40]. As an alternative to PG plus tests, the MSCR test, which provides nonrecoverable creep compliance and percent recovery at multiple stress levels, was proposed to determine the high-temperature performance of the asphalt binders. Following a path with four phase evolutions between 2001 and 2014 (phase I-NCHRP Project 9-10, phase II-original MSCR test, phase III-standard MSCR test, and phase IV-modified MSCR test), the MSCR test protocol was documented at AASHTO T350 and AASHTO M332 standard specifications [37]. Similar to the LAS test to evaluate the fatigue cracking resistance of asphalt binders, the MSCR test is another mechanistic binder performance test developed to better understand the permanent deformation behavior of the original and modified asphalt binders. The test is conducted using DSR equipment with parallel plate geometry and a 1 mm gap setting at short-term aged asphalt binders. According to the MSCR testing protocol, the asphalt binder is loaded at 0.1 kPa and 3.2 kPa stress levels. The loading pattern follows a 9 s recovery after a 1 s shear creep in both stress levels. This loading pattern is repeated for 20 cycles for 0.1 kPa and 10 cycles for 3.2 kPa. The %R-percent recovery and Jnr-nonrecoverable creep compliance are the two main parameters recorded at the end of the test. MSCR grade bumping is carried out based on the traffic level, and traffic grade selection is performed using the MSCR nonrecoverable creep compliance value obtained at 3.2 kPa shear level, $J_{nr3.2kPa}$. Traffic grade is included in the binder PG by placing one of the four-grade letters next to the high PG temperature. The traffic letter grade can be S, H, V, or E according to the following criteria:

- Standard Traffic: S-grade, which occurs when 2.0 kPa^{-1} < $J_{nr@3.2kPa}$ < 4.5 kPa^{-1};
- Heavy Traffic: H-grade, which occurs when 1.0 kPa^{-1} < $J_{nr@3.2kPa}$ < 2.0 kPa^{-1};
- Very Heavy Traffic: V-grade, which occurs when 0.5 kPa^{-1} < $J_{nr@3.2kPa}$ < 1.0 kPa^{-1};
- Extremely Heavy Traffic: E-grade, which occurs when $J_{nr@3.2kPa}$ < 0.5 kPa^{-1}.

The biggest changes in the last two phases of the MSCR tests were made to the number of creep and recovery cycles as well as the testing temperatures. While the latest version of the standards states that the testing should be performed at regional high temperatures, which is 58 °C for this study, the earlier version (AASHTO MP19 and AASHTO TP70) suggested the test be conducted at the high PG of the asphalt binders. This temperature change was necessary since the modified asphalt binders would never reach the high PG temperature in regions with lower high temperatures. In this study, for a comparison reason between previous and current MSCR protocols, the tests were performed at both the regional and high PG temperatures. Figure 7a demonstrates the change in $J_{nr@3.2kPa}$ with percent GTR for both high PG temperature and regional temperature. Even though there was not a clear trend for the results acquired at high PG temperatures, the nonrecoverable creep compliance values decreased as the percent GTR modifier increased at the regional high temperature of 58 °C. Thus, the comparison hereinafter focuses on the test results obtained at 58 °C. All modifications reduced the nonrecoverable creep compliance values compared to the neat binder. While the original binder with no modifications was at the H-traffic level, both 9% and 20% GTR modifications achieved two grade bumps and reached the E-traffic level. GTR 3% modification was not able to make a difference in the traffic level, and 6% GTR modification accomplished one grade bump by bringing the traffic grade to V-level. Figure 7b demonstrates the linear correlation developed between nonrecoverable creep compliance at 3.2 kPa and the percent GTR modifications.

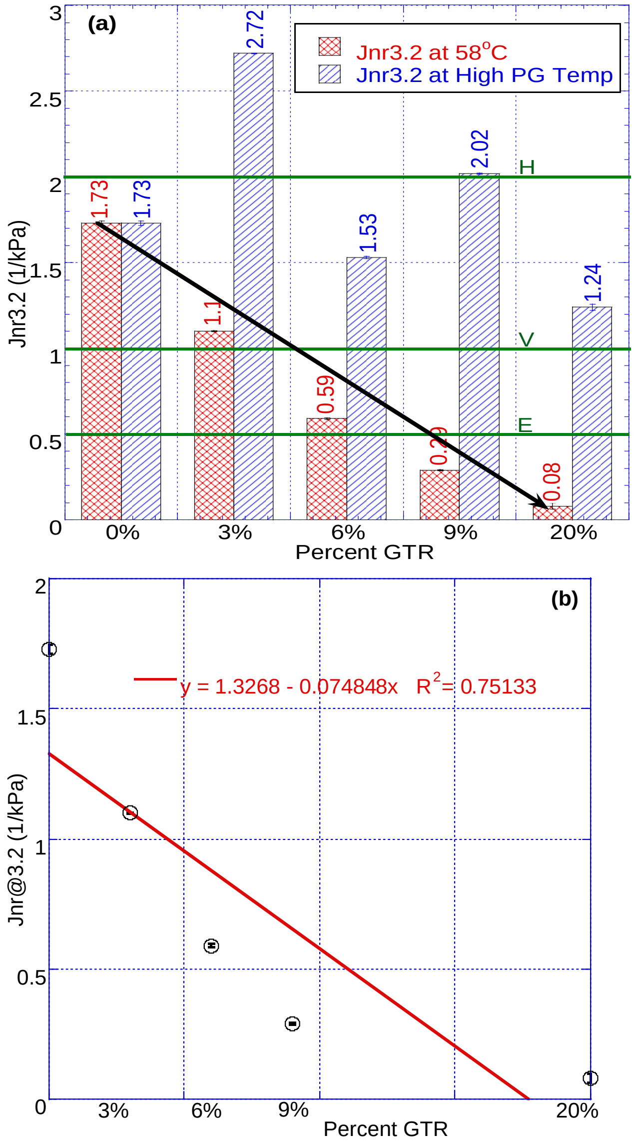

Figure 7. (**a**) Change in Jnr at 3.2 kPa as GTR modification increases at regional and high PG temperatures. (**b**) Correlation between Jnr at 3.2 kPa and GTR modifications at 58 °C.

One of the objectives of this research was to study the impact of testing geometry on the MSCR parameters. In the literature, there has been a concern regarding the testing of asphalt binders with discrete particles such as crumb rubber-modified asphalt binders, and the use of concentric cylinder geometry (a.k.a bob and cup) was promoted. In addition, AASHTO MP19 stated that the standards were not applicable for asphalt binders with undissolved distinct particles larger than 250 microns inside. To evaluate the impact of testing geometry on GTR-modified asphalt binders, MSCR tests were carried out with parallel plate (PP) and concentric cylinder (CC) setups. Figure 8a shows the correlation between nonrecoverable creep compliance values obtained at 3.2 kPa stress level for PP and CC geometries. There is almost a perfect linear fit between measured values with R^2 equal to 0.98 (0.993 with zero intercepts). This implies that either testing geometry can be used to determine the nonrecoverable creep compliance of mesh size 20 GTR-modified asphalt binder.

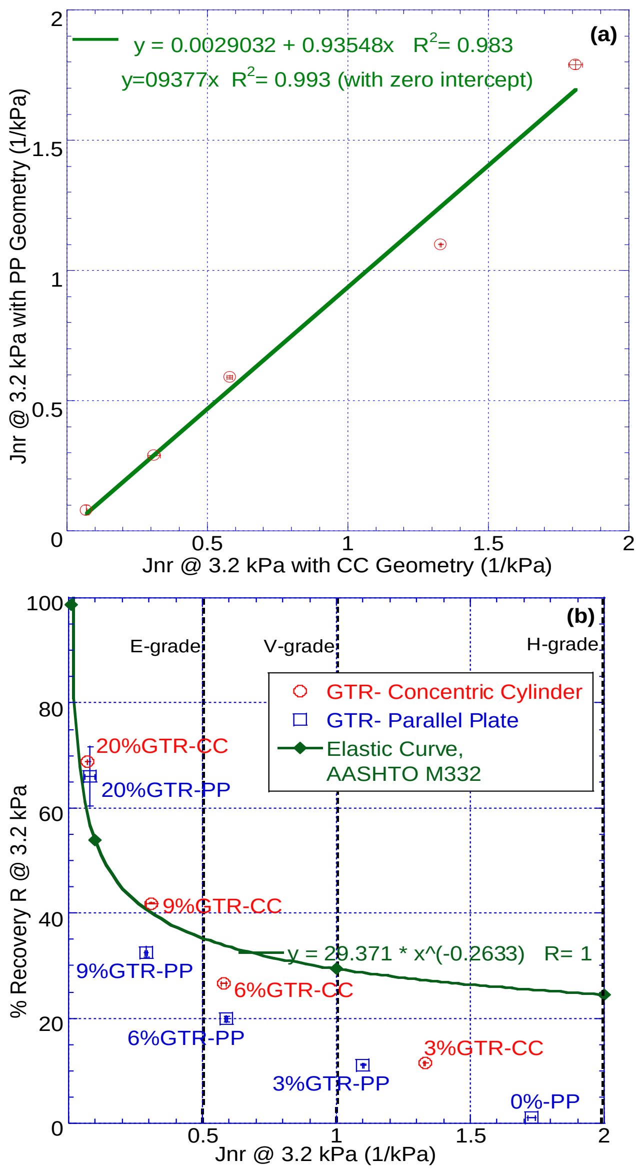

Figure 8. (**a**) Linear correlation between Jnr at 3.2 for PP and CC testing geometries. (**b**) Nonrecoverable creep compliance versus percent recovery graph for GTR modifications.

Figure 8b illustrates the nonrecoverable creep compliance and percent recovery values attained at 3.2 kPa stress level for PP and CC geometries along with the AASHTO M332 elastic curve. This graph is also known as MSCR elastic curve graph, which is mainly developed to ensure that there are enough elastic modifiers in the modified asphalt binders. According to the AASHTO T350, binders reaching above the curve have the desired quantity of elastic modifiers. $J_{nr3.2}$ values measured with PP and CC geometries were almost the same for all modified binders other than 3% GTR, and percent recovery results obtained from the CC setup were slightly higher than the PP geometry measurements for all tested binders. This resulted in 9% GTR CC measurement reaching above the elastic curve while 9% GTR PP measurement fell below the curve while it did not affect any other test outcomes. Regardless of the testing geometry, 20% of GTR modifications were able to pass the elastic curve, and none of the other modifications had enough elastic modifier to reach above the elastic curve. In addition to providing valuable information regarding the existence of elastic modifiers, the graph is an efficient way to show the traffic grade as well. Testing geometries had no impact on the traffic grade of the asphalt binders tested.

5. Discussion

PG of the asphalt binders has been major selling point for manufacturers for years based on the Superpave Binder Performance Grading system. Results of binder modification on binder performance grade studies mostly remained confidential. In general, each modifier is used to improve a certain property of the binders such as high PG, low PG, elasticity, ductility, viscosity, etc. The common practice is to use combined modifiers to enhance multiple properties, such as high and low PGs, of asphalt binders simultaneously. GTR modifications have been practiced improving the high PG of the asphalt binders mainly due to their preferable high-temperature/rutting performances [41]. On the other hand, some researchers showed that GTR modifications had an insignificant impact on the low-temperature properties [6–43]. Moreover, some other studies showed a significant decrease in the low-temperature performance of GTR-modified binders [42]. This study showed that GTR modification has a positive impact on both low and intermediate CPGs of the binders. The use of continuous PGs instead of discrete ones, which were assessed mainly in GTR modification studies in the literature, made it possible to reveal improvements in low and intermediate PGs even though the enhancements were smaller and easy to neglect when compared to high PGs. As the amount of GTR increased gradually from 3% to 20%, it was observed that all three continuous PGs improved proportionally. This study suggests further research with GTRs higher than 20%, different rubber gradations, and modification methods that have a great influence on the swelling or degradation behavior of the GTR [44,45].

ΔTc was another parameter evaluated in this study for GTR-modified asphalt binders. ΔTc is an indicator of the aging/nonload-related embrittlement in the asphalt pavements. ΔTc was initially developed for neat binders, and it has strong correlations with certain thermal crack types. However, the reduced laboratory aging of the modified binders due to higher viscosities prevents establishing strong correlations for modified binders. At this moment, the research to establish the relationship between ΔTc and polymer-modified asphalt binders has been ongoing [28,29,46]. This applies to GTR-modified asphalt binders as well. True aging of GTR-modified asphalt binders in laboratory conditions is challenging to determine, and there is further research needed to establish the guidelines. It should be noted that relations and data provided in this research for ΔTc are based on the so-called/artificial laboratory RTFO and PAV aging of GTR-modified asphalt binders. Further research may include increased aging time, pressure, temperature, or combinations thereof.

Fatigue cracking resistance of GTR-modified asphalt binders were analyzed using a VECD-based LAS test at different strain values. The fatigue life of modified binders showed an increasing trend at lower strain levels whereas they decreased at higher strain levels. This means that GTR-modified asphalt binders can perform better at low-volume or less traffic-loading roads better than high-volume roads such as interstates. The results do not necessarily follow the literatures' findings. There are many research studies showing that the addition of rubber particles improved the fatigue life of the asphalt binders [42,47–49]. However, it was also mentioned that the rubber type, size, production method, and mixing conditions have a considerable impact on the fatigue life [50,51]. It should be noted that most of the research in the literature was performed using a single LAS test temperature. In this study, LAS temperatures changed for each mixture type based on the equi-stiffness temperatures, which complies with early literature.

MSCR test results followed the results of high CPG closely as supported by earlier studies [52]. As the percent GTR increased, the nonrecoverable creep compliance values at both stress levels showed a decreasing trend, which conforms to the literature findings [52–54]. On the other hand, percent recovery values increased with growing GTR percentage. MSCR elastic curve, which is an indirect method of evaluating the elasticity of the binders, showed that only 20% GTR modification was able to provide enough elasticity to the binder. It also implies that as the rubber amount increases, binders become more elastic. One of the major concerns related to use of MSCR test with GTR modified asphalt binder was that the modified binder had larger than 250-micron discrete particles inside.

Since MSCR uses parallel-plate geometry, the gap between the plates may hinder the actual performance of rubber-modified binders under loading. In order to overcome this concern, tests were conducted using concentric cylinders in addition to parallel-plate geometry. Results showed a strong correlation between the two testing geometries by suggesting the use of either geometry for up to 20% GTR modifications. Additional research is recommended for higher than 20% GTR modifications. Furthermore, this study suggests improvements to MSCR specifications for a Jnr difference limit of 75%. Although the Jnr difference was lower than 75% for up to 9% GTR modifications, it was around 177% for 20% GTR modification. This was mainly due to the fact of insignificant nonrecoverable creep compliance at 0.1 kPa loading for heavily modified binders such as 20% GTR modification, which complies with literature findings as well [52].

6. Conclusions

Based on the data analysis and results obtained in this document, the following conclusions were compiled:

- The aging during the modification process (A-0% samples) resulted in a change in the PG of the original binder from 58–28 to 58–22. While it improved the CHPG by 1.8 °C, it worsened both CIPG and CLPG by 0.9 °C and 2.2 °C, respectively.
- A linear correlation with R^2 of 0.993 was established between CHPG and percent GTR modifications. The 3% GTR modifications achieved a one-grade bump while 9% and 20% GTR modifications accomplished two-grade and four-grade bumps. Similar to the linear correlation of CHPG, linear correlations between percent GTR and CIPG-CLPG were established as well. While the relationship for CLPG had an R^2 equal to 0.872, it was 0.6 for CIPG.
- The ΔTc parameter reduced as the artificial aging and percent GTR modification increased. Strong linear correlations between ΔTc and percent GTR modifications with R^2 value up to 0.987 were established.
- Based on the LAS test results, as the GTR percentage increased, the fatigue life of the asphalt binders enhanced considerably at lower strain levels and worsened at higher strain levels. The improvements compared to the original binder either were insignificantly small or did not exist.
- At regional high-temperature measurements, all modifications reduced the nonrecoverable creep compliance values compared to the neat binder. Compared to the original binder with no modifications, which was at the H-traffic level, both 9% and 20% GTR modifications achieved two grade bumps and reached the E-traffic level.
- Although the percent recovery values obtained with CC geometries were slightly higher than ones acquired with PP testing geometries, the difference between nonrecoverable creep compliance values was insignificant. A linear correlation between PP and CC geometries was established with R^2 equal to 0.98 (0.993 with zero intercepts), implying either testing geometry can be used to determine the nonrecoverable creep compliance.
- Only 20% of GTR modifications tested with PP and CC geometries and 9% of GTR modifications tested with CC geometry were able to pass the AASHTO M322-elastic curve. This indicates that low-percent GTR modifications do not provide enough elasticity to the asphalt binder. Moreover, the type of testing geometry may have an impact on the selection decision of the GTR-modified asphalt binders.

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