Performance Analysis of Asphalt Mixtures Modified with Ground Tire Rubber Modifiers and Recycled Materials

Punyaslok Rath 1,*, Joshua E. Love 2, William G. Buttlar 1 and Henrique Reis 2

1 Department of Civil and Environmental Engineering, University of Missouri, Columbia, MO 65211, USA; buttlarw@missouri.edu
2 Department of Industrial and Enterprise Systems Engineering, University of Illinois, Urbana-Champaign, IL 61801, USA; jelove2@illinois.edu (J.E.L.); h-reis@illinois.edu (H.R.)
* Correspondence: prath@mail.missouri.edu; Tel.: +1-217-974-0659

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Abstract: The usage of Ground Tire Rubber (GTR) in asphalt pavements has gained renewed interest due to its potential sustainability, economic, and performance benefits. This study focuses on asphalt mixtures designed with three different rubber modifier products including (1) a terminal-blend GTR, (2) a dry-process, chemically processed rubber product, and (3) a terminal-blend rubber-polymer hybrid product. The modifications were incorporated into Illinois Tollway’s approved Stone Matrix Asphalt (SMA) designs using (1) a base binder (PG 58-28), (2) a softer binder (PG 46-34), and (3) a softer binder with higher recycled content. Disk-shaped Compact Tension (DC(T)) test, Hamburg Wheel Tracking Test (HWTT) and Acoustic Emission (AE) tests were performed to characterize the mixtures. The fracture energy for most mixtures met the stringent criteria of 690 J/m$^2$ and the rut depths measured were less than 6 mm at 20,000 wheel passes. A Hamburg-DC(T) plot suggests that higher amounts of RAP/RAS (RAP: Reclaimed Asphalt Pavement; RAS: Reusable Asphalt Shingles) can be successfully used if a suitably soft base binder is employed.

Keywords: ground tire rubber (GTR); disk-shaped compact tension (DC(T)); rubber modifier; reclaimed asphalt pavement (RAP); reusable asphalt shingles (RAS); pavement

1. Introduction

More than 90% of roads in the United States are surfaced with asphalt. There are approximately 3500 asphalt plants in the US that produce roughly 400 million tons of asphalt mixtures annually [1,2]. The production of asphalt requires a major expenditure of natural resources, and the associated mining, refining, production and construction activities produce considerable greenhouse gas emissions [3]. In light of this, the industry has been steadily moving towards adopting more sustainable practices. Prime examples of this have been the incorporation of recycled materials such as recycled asphalt pavement (RAP), recycled asphalt shingles (RAS), and ground tire rubber (GTR) in asphalt mixtures. Using recycled content in asphalt mixtures has economic and environmental benefits by reducing the production of new asphalt and aggregates, and by preventing the recycled material from being simply placed in landfills. Additionally, recycled materials can be used in high-performing asphalt mixtures [4–14], if carefully designed.

This study describes a detailed laboratory study involving a suite of mixture performance tests performed on mixture composed of three GTR products used on the Illinois Tollway, namely:

(1) Terminal-Blend GTR; referred to as TB-GTR-1,
(2) a Dry-Process, chemically-treated rubber product; referred to as DP-GTR-1, and,
(3) a second Terminal-Blend modified asphalt product composed of a hybrid GTR and styrene-butadiene-styrene (SBS) pellet blend, referred to as TB-GTR-2.

The other study variable involved three different base binder/recycling component combinations, including:

1. a standard base binder, plus 12% RAP and 5% RAS (taken as the control treatment);
2. a softer base binder, plus 12% RAP, and 5% RAS (designed to be softer than the control);
3. a softer base binder, plus 16% RAP and 7% RAS (designed as an economical alternative to the control, having additional sustainability benefits).

The study further aimed to demonstrate the technique of pairing the Disk-shaped Compact Tension (DC(T)) test and Hamburg Wheel Tracking Test (HWTT) as bookend performance tests for mix design optimization. A first look at plotting high-recycle content, GTR-modified mixes in a Performance-Space diagram [11] is also presented, along with the key insights gained. The following section provides a brief review of the pertinent literature.

1.1. Literature Review

Rubber-modified asphalt was introduced in the U.S. in the 1960s by Charles H. McDonald who demonstrated that mixing rubber with asphalt at high temperatures leads to an increase in the binder flexibility. This modified binder not only opened the door for improved performance, but also helped address the serious environmental threat posed by mass stockpiling of scrap tires [15]. Key terms and concepts used in the GTR recycling domain are now reviewed.

1.1.1. Rubber Modification in the Asphalt Industry

The shredded rubber particles used in GTR-modified asphalt mixtures can be obtained by one of two main processes—ambient grinding or cryogenic fracture [16,17]. Once the GTR particles are obtained, the next step is to blend them into asphalt binders or mixtures. Broadly, there are two main processes for blending, i.e., dry process and wet process.

**Dry Process.** Refers to processes wherein rubber particles are added to the asphalt mixture during production. Originally, large dry rubber particles were introduced as part of the virgin aggregate combined cold feed. Recently, finer dry rubber products are generally injected at the location where RAP, RAS and/or fiber are introduced at the asphalt plant. This could either be the lower portion of drum mixer, or in a second drum, or in the pugmill, in the case of batch plants. The dry process requires a higher production temperature for effective blending of the rubber particles. The Federal Highway Administration (FHWA) recommends a production temperature between 149 and 177 °C (300 to 350 °F) [18,19]. In recent usage, crumb rubber particles in the range of 30 mesh (0.595 mm) have been used, with a common design strategy involving replacement of 1–3% of fine aggregates in the mixture [17].

**Wet Process.** The original wet process was introduced in the United States in the 1960s and is often termed ‘the McDonald process’ [8]. Wet process rubber modification involves mixing the tire rubber with a binder in mixing tanks and allowing them to react for a set time (45 to 60 min) and at a set temperature (175 to 200 °C (350 to 400 °F)) [8,16]. GTR-modified binder results when rubber absorbs asphalt binder and swells at a high temperature. The addition of rubber to form a theoretical, continuous homogenous phase with a binder will increase the viscosity of the binder blend, making it stiffer and thereby increasing the rut resistance of the mixture. At the same time, the softened rubber grains enhance the toughness of the binder system, leading to an increased resistance to various cracking forms [20]. Typically, ‘wet process GTR’ is used to denote operations, whereby GTR-modification occurs at the asphalt mixing plant.

Terminally-blended GTR denotes crumb rubber modification at an asphalt blending terminal, requiring subsequent transportation to job sites. Terminology at the California Department of
Transportation (Caltrans) refers to terminal blends as a wet-process-no-agitation binder since it supposedly does not require any agitation after its production stage [21,22]. However, researchers have reported cases of settlement in the trucks used for transportation of terminal blends, thus affecting the performance of the end product [8]. Consequently, a few state agencies have either mandated or used additional modifiers such as Vestenamer, a trans-poly-octenamer rubber (TOR) (Missouri Department of Transportation (DOT), Pennsylvania DOT), and extender oils (Caltrans, Oregon DOT, NJDOT) in an effort to avoid such constructability issues and to enhance mixture performance [23–25]. However, agencies such as the Illinois Tollway are moving towards the use of low- and high-temperature mixture performance properties to ensure that target GTR modification levels are consistently achieved [26].

Rubber-modified asphalt has been found to possess higher fracture energy at low temperatures, indicating higher resistance to thermal and block cracking [27,28]. The fatigue life of rubber-modified asphalt mixtures compares favorably to conventional asphalt mixtures [29]. Rubber modified asphalt mixtures have also been shown to provide good resistance to permanent deformation due to the elastic behavior of the rubber particles and show better resistance to moisture-induced damage [30–32]. While the earliest use of rubber asphalt was in chip seals, rubber-modified asphalt has also been used as an interlayer between pavement layers to retard reflective cracking [32–36]. Furthermore, asphalt rubber applications are not limited to a single pavement layer. GTR mixes have been simultaneously used in multiple layers in pavement systems, such as in the leveling course, in a stress-absorbing membrane interlayer (SAMI), and in the surface course [37]. Finally, GTR has been used in conjunction with other modifiers in asphalt mixtures, such as WMA (Warm Mix Asphalt) additives, recycled asphalt materials (RAP/RAS), rejuvenators, etc. [4,38,39].

Despite the reported performance benefits, GTR mixes may be unsuitable for construction that requires extensive handwork, unless a chemical coating or other additive is introduced to facilitate workability [40,41]. Furthermore, it has been reported that rubber-modified mixtures are not suitable for laying when the pavement temperature is below 13 °C (55 °F) or during rainy weather [42,43]. Finally, the manufacturing cost of rubber-modified asphalt is generally more than conventional Hot Mix Asphalt (HMA) mixtures’ costs [31]. Wet-process GTR is often priced to compete with traditional polymer-modified asphalt mixtures. This might explain its limited usage in a number of markets, where contractors have more experience in dealing with traditional polymer-modified mixes. Dry process GTR appears to provide a lower cost alternative to polymers or wet-process GTR, but its performance characteristics for use in colder climates is still in an early stage of field evaluation.

The highlighted concerns about rubber modification have led to increased research in the area of using treated rubber to modify asphalt mixtures. It has been shown that rubber can be chemically treated or “activated” before being introduced into the binder or mastic system to address issues such as draindown, workability, etc. The treated rubber products have also been shown to improve the cracking resistance of asphalt mixtures [44,45]. Memon et al. were among the first to produce chemically-modified crumb rubber asphalt (CMCRA) in the FHWA laboratories at Turner Fairbank Highway Research Centre [45]. Sousa et al. produced Reacted and Activated Rubber (RAR), wherein the researchers used a ground raw-silica based material to coat the rubber particles, which resulted in activation of the binder system leading to improved rutting performance and fatigue resistance [46]. Liu et al. used trans-polyoctenamer rubber additives (TOR) to modify crumb rubber [47], while Yu et al. used microwave irradiation to activate the surface of the crumb rubber before introducing it into the binder system [48].

1.1.2. Performance Engineered Mix Design (PEMD)

Asphalt mixture testing procedures have been largely inspired by methods developed for metals. In the 1980s, the Central Electricity Generating Board (CEGB) of England developed the first known balanced design approach to assess the effect of defects on integrity of a structure through a Failure Assessment Diagram (FAD). The assessment diagram was a locus of two-parameter points dividing the ‘acceptable’ and the ‘unacceptable’ range for a given material [49–51]. Akin to approaches like the
FAD [51], the asphalt community has recently devised several performance-engineered mixture design (PEMD) methods to assess the performance of asphalt mixtures. These are also referred to as balanced mix design methods. These PEMD approaches are often based on the results of two performance tests, usually including a high-temperature test, along with either a low- or intermediate-temperature test. It is noted that the Superpave PG (Performance Grade) binder specification [52] included high, intermediate, and low-temperature tests to control rutting and thermal cracking, respectively. The PG binder grading system uses a two-grade designation, i.e., PG 64-22, PG 70-28, etc.

PEMD systems gained momentum around the time that larger quantities of RAP were incorporated into asphalt mixtures. The addition of higher amounts of RAP (>25%), though economically advantageous, renders the mixture as stiffer unless sufficient countermeasures are taken. This typically involves the use of a softer base binder and/or a rejuvenator. However, the efficacy of these countermeasures cannot be adequately addressed through binder testing alone, since imperfect mixing of the original and recycled binder is known to occur [53]. The addition of RAP generally increases rutting resistance of the mix, while decreasing the cracking resistance [54]. Zhou et al. proposed a performance-based RAP mix design approach, which recommended choosing the final asphalt content of a mixture by optimizing the mixture performance indicators obtained via two tests—the Hamburg Wheel Track Test (HWTT) and the Overlay Tester (OT) [55]. Zhou et al. furthered their approach in 2013 by suggesting the inclusion of project-specific cracking requirements for asphalt mixtures [56]. Cooper et al. proposed a balanced mix design method by using HWTT and Louisiana’s intermediate temperature Semi-Circular Bend (SCB) test in a 2D interaction plot [57]. Buttalar et al. introduced the Performance-Space diagram, an interactive plot with Hamburg rutting results in reverse arithmetic scale on the y-axis and the DC(T) fracture energy results on the x-axis [11]. The authors demonstrated the use of the DC(T)-Hamburg plot in effectively characterizing the overall mixture performance by including variables such as aggregate type, polymer modification, recycled content, and rejuvenators in their study [11].

The remainder of this paper presents new laboratory results and field production observations for both wet and dry GTR systems, as evaluated through high and low temperature asphalt mixture performance tests. Mix designs and test sections were built in the Midwest region of the United States on the Illinois Tollway system. Until recently, high-tonnages of GTR-modified asphalt mixtures were predominant only in Arizona, California and to a lesser extent, Georgia. Thus, a high-tonnage, high profile demonstration project was deemed useful for evaluating the economics and performance of modern GTR mixtures under high traffic in harsh, Midwest climatic conditions—hot summers, cold winters, freeze-thaw cycling. This project represents another step in the Illinois Tollway’s ambitious, decade-long strategy to substantially increase pavement sustainability through maximization of recycled material content in warm-mix asphalt without sacrificing pavement durability.

2. Asphalt Mixture Modifiers and Their Evaluation

The Illinois Tollway constructed test sections using three GTR products on the Reagan Memorial Tollway (I-88) in April of 2016. The TB-GTR-1 product has been used extensively across Illinois while the DP-GTR-1 and TB-GTR-2 products were used for the first time by the Illinois Tollway. A brief product profile for each of these three systems is presented in the following paragraphs.

TB-GTR-1 is a terminally-blended product, which has been used successfully in Illinois since 2005. Over 10 million tons of hot-mix and warm-mix asphalt has been produced with this product in the Chicago area since its introduction in the last decade.

DP-GTR-1 is dry-process GTR product, manufactured by liquid surface treatment of crumb rubber. The product is shipped to the asphalt plant in 1-ton totes, and fed into a drum-mix plant using a feeder system resembling a fiber feed system. The feeder system provides agitation to break up clumps and uses pneumatic transport through a clear, flexible tube into a RAP or fiber collar located around the bottom third of the mixing drum. The GTR is activated through the elevated mixing temperatures, interaction with hot binder, and by mixing tortuosity (tumbling with aggregates). Being a dry process
rubber modifier, quality control at the plant is critical to ensure a constant level of modification. This is achieved by using a continuous loss-of-weight feed system, which usually involves mounting the feeder unit on a load measuring support system that can stream data to the plant control room.

**TB-GTR-2** is a combination of SBS (Styrene Butadiene Styrene) and chemically-treated GTR, packaged as a mixed-pellet product. This product is designed to be terminal-blended using conventional SBS high shear mixing procedures and equipment. The Illinois tollway project used a mixed pellet blend with 75% GTR and 25% SBS by weight. The chief advantage of this product is the flexibility of engineering/modification according to the requirements of the project.

Apart from estimating the performance characteristics of the new rubber modified products, this study also aimed to examine the effect of softer virgin binders and increased amounts of reclaimed asphalt on mix performance, which was incorporated into the Illinois Tollway’s approved stone matrix asphalt (SMA) surface friction, warm-mix asphalt designs. A 3-by-3 design was used, for a total of nine investigated mixtures, as shown in Table 1. The nine mixtures involved the three aforementioned GTR products (two terminal blends and one dry process product), two base binders (PG 58-28 and PG 46-34), and two recycling levels (moderate (33%) and high (47%) asphalt binder replacement (ABR), achieved with varying levels of RAP and recycled asphalt shingles (RAS)).

**Table 1.** SMA (Stone Matrix Asphalt) mixture matrix used on Reagan Memorial Tollway (I-88). All mixtures used the same base design aggregates.

<table>
<thead>
<tr>
<th>Product</th>
<th>Base Binder</th>
<th>Softer Binder</th>
<th>Softer Binder &amp; Increased ABR</th>
</tr>
</thead>
<tbody>
<tr>
<td>TB-GTR-1</td>
<td>PG 58-28 + 12%</td>
<td>PG 46-34 + 12%</td>
<td>PG 46-34 + 12% TB-GTR-1 &amp; increased ABR</td>
</tr>
<tr>
<td></td>
<td>TB-GTR-1</td>
<td>TB-GTR-1</td>
<td>TB-GTR-1</td>
</tr>
<tr>
<td>DP-GTR-1</td>
<td>PG 58-28 + 10%</td>
<td>PG 46-34 + 10%</td>
<td>PG 46-34 + 10% DP-GTR-1 &amp; increased ABR</td>
</tr>
<tr>
<td></td>
<td>DP-GTR-1</td>
<td>DP-GTR-1</td>
<td>DP-GTR-1</td>
</tr>
<tr>
<td>TB-GTR-2</td>
<td>PG 58-28 + 10%</td>
<td>PG 46-34 + 10%</td>
<td>PG 46-34 + 10% TB-GTR-2 &amp; increased ABR</td>
</tr>
<tr>
<td></td>
<td>TB-GTR-2</td>
<td>TB-GTR-2</td>
<td>TB-GTR-2</td>
</tr>
<tr>
<td>ABR * (%)</td>
<td>33.9</td>
<td>33.9</td>
<td>46.8 (47.0 for TB-GTR-2)</td>
</tr>
<tr>
<td>Virgin Binder (%)</td>
<td>4.03</td>
<td>4.03</td>
<td>3.21 (3.18 for TB-GTR-2)</td>
</tr>
<tr>
<td>Recycled Binder (%)</td>
<td>2.07</td>
<td>2.07</td>
<td>2.82</td>
</tr>
<tr>
<td>RAP, by wt. of mix (%)</td>
<td>12.1</td>
<td>12.1</td>
<td>16.2</td>
</tr>
<tr>
<td>RAS, by wt. of mix (%)</td>
<td>5.0</td>
<td>5.0</td>
<td>7.0</td>
</tr>
</tbody>
</table>

* Asphalt Binder Replacement = Percent recycled binder (RAP plus RAS) by weight of total binder.

Baseline insights regarding the rubber modifier and base binder combinations were obtained by computing the continuous Superpave PG grades of the two base binders with and without GTR modification. Table 2 gives a summary of the continuous grades measured in accordance with ASTM (American Society for Testing and Materials) D7643 standard [58] and the corresponding traditional AASHTO (American Association of State Highway and Transportation Officials) M320 grades. The testing procedures followed AASHTO M320, with the exception of DSR (Dynamic Shear Rheometer) testing at high temperatures wherein a 2 mm gap was maintained between the parallel plates to accommodate GTR particles.

The performance grades indicate that the rubber modifiers were effective in bumping up the high temperature grades. For both base binders, the DP-GTR-1 and TB-GTR-2 products resulted in almost two grade bumps—a slightly higher dosage of DP-GTR-1 would have resulted in an equal grade bump for the two products. The TB-GTR-1 product exhibited three grade bumps (almost four) for the softer binder (PG 46-34), but only one grade bump in the case of PG 58-28. This indicates the high dependency of grade modification on the base asphalt and/or in the inability of standard binder testing to properly characterize GTR-modified binders. Note that the base binder results for the TB-GTR-1 product are not available (insufficient material was available at the time of testing), and thus the relative changes in grade assume that the base binder met the PG grading requirements. There was little effect of the modifiers on the low temperature grade of the base binders. None of the modifiers changed the low
temperature grade in the case of PG 46-34. Even though DP-GTR-1 and TB-GTR-2 modifiers tended to bump the low temperature grade to $-22\,^\circ C$ from $-28\,^\circ C$ in the case of the PG 58-28 base binder, it was noted that the control binder was a borderline PG xx-28 grade according to AASHTO M320. All modifiers exhibited an improved intermediate continuous grade, which resulted in intermediate temperature not being a critical factor in determining PG grade. An important takeaway from these results is that all the modifiers resulted in an increase in the Usable Temperature Interval (UTI) of the resulting binders. This is critical because, like polymer modification, significant performance benefits are required to justify the additional cost associated with the use of modifiers such as GTR. Although promising, binder test benefits alone are probably insufficient to convince an owner-agency to begin specifying GTR as an alternative to traditional polymer modification. Favorable mixture performance test results and successful field trials are also typically needed before specifications are adjusted and widespread usage is possible.

Table 2. Summary of continuous grades of asphalt binders according to ASTM D7643 and corresponding AASHTO M320 grade.

<table>
<thead>
<tr>
<th>Base Binder</th>
<th>Modifier</th>
<th>Continuous Grade</th>
<th>Intermediate Continuous Grade</th>
<th>AASHTO M320 Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>PG 46-34</td>
<td>None</td>
<td>49.6–37.2</td>
<td>8.8</td>
<td>PG 46-34</td>
</tr>
<tr>
<td>PG 46-34</td>
<td>TB-GTR-1</td>
<td>69.3–38.2</td>
<td>7.4</td>
<td>PG 64-34</td>
</tr>
<tr>
<td>PG 46-34</td>
<td>DP-GTR-1</td>
<td>57.0–37.6</td>
<td>8.3</td>
<td>PG 52-34</td>
</tr>
<tr>
<td>PG 46-34</td>
<td>TB-GTR-2</td>
<td>62.1–34.5</td>
<td>7.9</td>
<td>PG 58-34</td>
</tr>
<tr>
<td>PG 58-28</td>
<td>None</td>
<td>59.6–28.4</td>
<td>18.7</td>
<td>PG 58-28</td>
</tr>
<tr>
<td>PG 58-28</td>
<td>TB-GTR-1</td>
<td>67.5–30.6</td>
<td>14.9</td>
<td>PG 64-28</td>
</tr>
<tr>
<td>PG 58-28</td>
<td>DP-GTR-1</td>
<td>69.5–27.2</td>
<td>17.0</td>
<td>PG 64-22</td>
</tr>
<tr>
<td>PG 58-28</td>
<td>TB-GTR-2</td>
<td>73.8–26.1</td>
<td>14.2</td>
<td>PG 70-22</td>
</tr>
</tbody>
</table>

* For TB-GTR-1 product, the base binder does not have the same continuous grade as presented here. The modified binder (blended) was directly supplied by the manufacturer and thus no results for the base binder was available.

3. Asphalt Mixtures and Testing Methods

All of the mixture blends used Illinois Tollway CM14 Quartzite aggregate (12.5 mm nominal maximum aggregate size), CM16 Steel Slag, recycled asphalt shingles (RAS), and fractionated recycled asphalt pavement (FRAP). For the non-high-recycle mixtures, the base mix design remained the same except for the source, grade of the binder, and the type of rubber modification. The blends were designed for 3.5% air voids, which is the standard specified level for Illinois Tollway SMA’s. For the high-recycle mixes, the asphalt binder replacement (ABR) level was increased from 33.8% to 47.0% by adding extra RAS into the mixes (increased from 5 to 7%, which makes a significant difference in ABR due to the high binder content in RAS, i.e., around 25% by weight). The recycled content was found to contribute 2.07% of the binder by weight of the asphalt mixture for non-high-recycle mix and 2.82% for the mixtures with high recycled content. The addition of more recycled content warranted slight adjustments in the mixture blends (see Figure 1), and thus new mix designs were developed for the high-recycle mixes. After construction, 12 field cores of 150 mm diameter were extracted from each of the nine test sections constructed tested for use in mixture testing. Table 3 summarizes the general location of the field cores on I-88, just south of DeKalb, IL, USA.

The study primarily focused on the low-temperature cracking and rutting performance of asphalt mixtures. Disk-shaped Compact Tension (DC(T)) tests and Acoustic Emission (AE) embrittlement tests were performed on both field cores and plant-compacted gyratory specimens to assess the thermal cracking response of the mixtures. To evaluate different reliability levels for protection against thermal cracking, DC(T) tests were conducted at two different temperatures, i.e., at $-12\,^\circ C$ and at $-18\,^\circ C$. The AE tests were performed using the two half-specimens resulting from each fractured DC(T) specimen after testing. Hamburg Wheel Track Testing was performed at $50\,^\circ C$, as per the standard specification (AASHTO-T324), using 20,000 wheel passes. This is commensurate for the high traffic experienced on the Illinois Tollway.
Figure 1. Aggregate gradation for high-recycle and non-high-recycle asphalt mixtures.

Table 3. Location of GTR test sections on the Reagan Memorial Tollway (I-88).

<table>
<thead>
<tr>
<th>Rubber Modifier</th>
<th>Lane</th>
<th>Mile Post Limits</th>
<th>Individual Test Section Mile Post Delineations</th>
</tr>
</thead>
<tbody>
<tr>
<td>TB-GTR-2</td>
<td>EB (Eastbound) Outer shoulder</td>
<td>65.2–66.0</td>
<td>65.2–65.5</td>
</tr>
<tr>
<td>DP-GTR-1</td>
<td>EB Inside Lane (Lane 1)</td>
<td>60.1–60.5</td>
<td>60.5–60.9</td>
</tr>
<tr>
<td>TB-GTR-1</td>
<td>EB Inside Lane (Lane 1)</td>
<td>64.4–66.2</td>
<td>64.4–64.7</td>
</tr>
</tbody>
</table>

* No TB-GTR-1 asphalt placed between Mile Posts 64.7–65.5.

3.1. Disk-Shaped Compact Tension Test (DC(T))

The DC(T) test was developed to characterize the fracture behavior of asphalt concrete materials at low temperatures. The main advantages of the DC(T) test include simple test sample configuration, which allows the test samples to be easily obtained from gyratory compacted specimens and/or from extracted field cores, and its simple standard fracture test procedure. This test has the capability of capturing the transition from a quasi-brittle to brittle fracture of the mixtures across several low test temperatures, and the ability to differentiate various mixture factors such as aggregate quality, modifiers and other additives, recycled materials, and aging level [59–65].

The DC(T) test procedure includes conditioning the fabricated specimens at the test temperature in a temperature-controlled chamber for two hours. After the conditioning, each specimen is set in the loading fixture of the DC(T) test instrument, as shown in Figure 2a. The test is conducted at a constant Crack Mouth Opening Displacement (CMOD) rate of 0.017 mm/s (1 mm/min) [66], which is measured by the clip-on gages at the crack mouth. At the testing temperature, a seating load no greater than 0.2 kN (typically about 0.1 kN) is applied before starting the test. The test is completed when the post-peak load level has reduced to 0.1 kN. A typical load-fitted CMOD curve is shown in Figure 2b. The fracture energy is obtained by measuring the area under the load-fitted CMOD curve and normalizing it by the fracture area, as shown in Equation (1) and (2),
\[ A = \int_{0}^{\delta_{\text{max}}} P(\delta) d\delta, \]  
\[ G_f = \frac{A}{bL}. \]  

where \( A \) is the area under the Load-CMOD curve, \( P(\delta) \) is the load at CMOD value of \( \delta \), \( \delta_{\text{max}} \) is the maximum CMOD value, \( G_f \) is the DC(T) fracture energy, \( b \) is the fracture area width and \( L \) is the initial fracture ligament length.

DC(T) tests were conducted on specimens obtained from plant-compacted gyratory samples and from the field cores of the nine different mixtures. Although ASTM D7313 standard recommends the test temperature to be 10 °C warmer than the virgin binder’s low temperature grade \([66]\), many states, such as Illinois, conduct the test at 10 °C warmer than the temperature corresponding to the low-temperature climate of the region obtained through LTPPBInd tool at various reliability levels. The LTPPBInd chosen PG low-temperature grade for Chicago varies from \(-22 \) °C to \(-28 \) °C at 50% and 95% reliability levels, respectively. Hence, the test temperatures chosen were \(-12 \) °C and \(-18 \) °C to further understand the low-temperature fracture susceptibility of the mixtures. A minimum fracture energy threshold of 690 J/m² was used as a minimum requirement for this high project criticality application, in accordance with suggestions in the National Pooled Fund Study on Low-Temperature Cracking Phase-II \([59]\).

**Figure 2.** Disk-Shaped Compact Tension (DC(T)) test; (a) test Loading fixture, and (b) Typical load versus crack opening displacement (CMOD) curve from DC(T) testing of asphalt mixtures at \(-12\) °C.

### 3.2. Hamburg Wheel Tracking Test

The Hamburg Wheel Tracking Device was originally developed in Hamburg, Germany, in the mid-1970s, and has been extensively used in the United States as a mixture evaluation tool \([54,67,68]\). Hamburg test results provide a good indication of both, the rutting susceptibility and the moisture sensitivity of the mixture. It does so by simulating the traffic load conditions on the cylindrical specimens of the mix. The Hamburg testing is conducted at 50 °C with the specimens immersed under a water-bath, as specified by AASHTO T-324 \([69]\). A loaded steel wheel, weighing approximately 71.7 kg tracks over the samples in the heated water bath. The deformation of the specimen is measured against the number of passes. In this study, only the rutting susceptibility of the mixtures is reported. Moisture resistance was also found to be very good, but is not reported herein for brevity.

### 3.3. Acoustic Emission Test

Acoustic emission (AE) testing is a non-destructive testing (NDT) method capable of evaluating and characterizing the thermal cracking resistance of asphalt mixtures \([60,70,71]\). When an asphalt concrete specimen is subjected to progressively lower temperatures, thermal tensile stresses develop in the binder mainly because of the thermal expansion coefficient mismatch between the binder and...
the aggregates. The AC mixture also transitions from a brittle-ductile state to a quasi-brittle state. This lowers the fracture resistance of the mixture and, when the increasing thermal stresses reach the value of the mixture fracture strength, thermal cracks develop. The formation of cracks and the subsequent crack growth through the asphalt concrete sample release strain energy in the form of transient stress waves, i.e., acoustic emissions (AE events), which can be detected (within distances) using AE piezoelectric sensors. The AE test method ‘listens’ to these events. Figure 3a describes the AE concept. The data is used to extract the embrittlement temperature information of the mixture. A typical plot from the AE test is shown in Figure 3b. The temperature corresponding to an event with the energy level above a prescribed threshold is defined as the Embrittlement Temperature, which represents the commencement of damage accumulation in the material. The embrittlement temperature is believed to be a fundamental property of asphalt mixtures, and to be independent of sample shape and size beyond the threshold of a representative sample volume [71,72]. One of the main advantages of AE testing is that it does not require any additional specimen fabrication; it can use the two broken halves of the tested DC(T) specimen. Since the mixture embrittlement temperature is much lower than the DC(T) testing temperatures, it is assumed that no detrimental effects are caused by prior DC(T) testing.

Figure 3. Acoustic Emission (AE) test method; (a) working concept of Acoustic Emission (AE) method, and (b) typical AE plot of an asphalt concrete test sample [72]. The vertical lines represent the energy of the individual events and the green line represents the cumulative number of events.

3.4. Performance-Space Diagram

As discussed in the literature review section, Buttlar et al. used the DC(T) and the Hamburg test results to develop a graphical tool that gives a holistic view of the overall performance of the mix [11]. Hamburg results are plotted on a reverse Y-axis arithmetic scale, while the DC(T) results are plotted on a standard arithmetic X-axis. The plot can be divided into the following four major parts:

- An upper-left section, where the mix will have a good rutting resistance, but poor fracture energy,
- A lower-left section, where the mix will be failing in both rutting and fracture criteria,
- A lower-right section, where the mix will have good fracture energy but poor rutting resistance, and
- An upper-right section, where the mix will have good rutting resistance as well as good fracture energy.

This is illustrated in Figure 4, where an ideal mix would lie in the upper-right corner of the performance-space diagram, which is the target performance region for SMA mixtures.
4. Experimental Results and Discussion

4.1. DC(T) Fracture Test Results

Fracture energy values of the nine mixtures were obtained at −12 °C and at −18 °C for test samples cut from extracted field cores and from gyratory compacted specimens. Three replicates were tested for each mixture, with results shown in Figures 5 and 6. All the mixtures passed the stringent DC(T) fracture energy criteria of 690 J/m² at −12 °C, chosen in accordance with Marasteanu et al. [59] for high traffic volume roads, within the margin of experimental error. Comparison of fracture energy at −12 and −18 °C show that the DP-GTR-1 and the TB-GTR-2 mixture systems have adequate protection against critical winters in the Chicago region. The TB-GTR-1 mixture system showed a more noticeable drop in the fracture energy when the lower test temperature was used. However, the mixtures still exhibited relatively high fracture energy at lower temperatures, indicating good resistance to thermal cracking in extreme cold events. During the DC(T) tests, it was noted that many specimens displayed an extended, post-peak load-CMOD curve during the test, an example of which is shown in Figure 7. This is likely caused by the toughening effect of GTR modification [73–75], and resembles the DC(T) response observed in mixtures with higher levels of polymer modification.

A comparison of fracture energy obtained from lab-compacted gyratory specimens and field cores is shown in Figure 8, revealing similar values for most mixtures. This suggests that the mixtures underwent minimal changes during transportation from plant to field and that the laboratory specimen preparation process reasonably mimicked the composition of asphalt mixture compacted in the field. Furthermore, as a general trend, it was observed that binder replacement with a softer binder in the mix increased the fracture energy and that addition of higher-recycled asphalt decreased the fracture energy. The DC(T) fracture energy results also point to the possibility of using high recycled asphalt content in mixture designs without compromising fracture energy by using a softer binder system.

Figure 9 shows the effect of the additives by grouping the fracture energies with respect to different binder types. At −12 °C, the TB-GTR-1 mixtures have the highest fracture energy values for all the binder types indicating its higher potential for improving low-temperature cracking resistance. In the other two rubber-modifier systems, DP-GTR-1 has better fracture energy in all cases except one, wherein the difference is not very high. At the test temperature of −18 °C, less difference between mix types was observed. This compression in data spread at the lower temperature is not unexpected, as the various binder components begin to approach a glassy modulus asymptote.
Figure 5. DC(T) fracture energy for Gyratory Compacted Samples tested at $-12\,^{\circ}\mathrm{C}$ and $-18\,^{\circ}\mathrm{C}$.

Figure 6. DC(T) fracture energy for test specimens cut from extracted field cores at $-12\,^{\circ}\mathrm{C}$ and $-18\,^{\circ}\mathrm{C}$.
Figure 6. DC(T) fracture energy for test specimens cut from extracted field cores at −12 °C and −18 °C.

Figure 7. Load-CMOD (Crack Mouth Opening Displacement) plot for TB-GTR-1 with PG46-34 plant-compacted gyratory obtained from DC(T) fracture test with the long-drawn-out post-peak load-CMOD curve highlighted. Tests were conducted at −12 °C.

Figure 8. Comparison of DC(T) fracture energy value for test samples obtained from gyratory compacted specimens and extracted field cores obtained at −12 °C.

Figure 9. Effect of additives on fracture energy of (a) field cores tested at −12 °C; (b) gyratory compacted specimens tested at −12 °C; (c) field cores tested at −18 °C; (d) gyratory compacted specimens tested at −18 °C.
Figure 8. Comparison of DC(T) fracture energy value for test samples obtained from gyratory compacted specimens and extracted field cores obtained at −12 °C.

Figure 9. Effect of additives on fracture energy of (a) field cores tested at −12 °C; (b) gyratory compacted specimens tested at −12 °C; (c) field cores tested at −18 °C; (d) gyratory compacted specimens tested at −18 °C.

4.2. Hamburg Wheel Tracking Test Results

The Hamburg Wheel Tracking results are shown in Figure 10. All the mixes tested experienced rut depths well below the 12.5 mm threshold at 20,000 passes, indicating excellent rut resistance. All nine mixtures also fall below the 6 mm threshold recently adopted by the Illinois Tollway for SMA mixtures. The mixtures have a strong aggregate system that includes steel slag as one of the constituents and further modification with recycled materials and rubber also imparts stiffness to the mixture leading to the low measured rut depths. The increased rut depths of the mixtures with softer binder systems (PG 46-34) show the effect of substituting the base binder with a softer binder. The addition of recycled materials to the softer binder stiffens the mixtures and lead to smaller rut depths. The TB-GTR-1 PG46-34 mixture showed the largest rut depth in the Hamburg testing, which coincides with the high fracture energy results presented in the previous section. The softer binder renders the mastic as softer, resulting in a highly elongated post-peak tail in the DC(T) fracture energy test, along with a higher rut depth in the Hamburg test.

4.3. Acoustic Emission Test Results

The embrittlement temperatures measured on the nine study mixtures are shown in Figure 11. For the gyratory compacted samples, the trend is similar to the DC(T) fracture energy results. The use of a softer binder led to a cooler embrittlement temperature, and the addition of recycled asphalt led to a warmer embrittlement temperature. This finding gravitates towards the expected results, as the addition of softer binder enhances the ductile part of the mixture and should result in cooler embrittlement temperatures. The addition of recycled content (RAP and RAS) stiffens the mixture, and hence warmer embrittlement temperatures are expected. In the case of TB-GTR-1 field cores, the embrittlement temperatures are very close to their low-temperature performance grade (PGLT), but the other two rubber-modifier systems show a warmer embrittlement temperature than the PGLT when a softer binder is used.
2.96 Gyratory Compacted Samples

Figure 10. Hamburg Wheel Tracking test results at 20,000 passes. The test was conducted at 50 °C.

Figure 11. Embrittlement temperature results from acoustic emission testing; Gyratory Compacted Samples: using test samples obtained from gyratory compacted specimens; Samples Extracted from Field Cores: using test samples cut from extracted field cores.

The field cores exhibited cooler embrittlement temperatures than the corresponding gyratory samples. This may be an indication of the difference in the thermodynamics of lab mixing versus plant
mixing, where higher thermal and mechanical energy is imparted. This additional mixing efficiency in the field could possibly result in a more homogeneous binder system (better blending of recycled binder with virgin binder), and better reaction of the GTR, particularly in the case of the dry GTR system. The AE system has been shown to yield warmer embrittlement temperatures for mixtures with significant amounts of unblended recycled materials [60], which supports the observations made herein. For the TB-GTR-2 system, less difference between lab and plant results was observed in the AE test results. This could be due to the lesser amount of GTR used in this system, and stiffer overall composition. Note that, since the AE test detects highly localized fracture events, as compared to the DC(T), which produces a single, homogenized fracture assessment per specimen, effects of recycled materials on test results may differ significantly. This appears to be the case, as Figure 8 indicated lower fracture energy in five of the nine field core samples as compared to their corresponding gyratory specimen results. This indicates a trend towards lower overall (homogenized) fracture energy with increased mixing of virgin binder and recycling components in the field. Although different trends were observed in some cases, the combination of DC(T) and AE testing provided a more complete picture of local and global fracture behavior in the mixtures investigated.

4.4. Performance-Space Diagram Plots

As seen in Figure 12, all the mixtures fall in the upper-right section of the Hamburg-DC(T) plot, indicating high resistance to thermal cracking and rutting. The arrows, or the trade-off axis, shows the relative movement of the mixtures on the plot with respect to changes in binder and recycled content. The mixtures gain fracture energy and incur higher rut depths when a softer binder is used. However, the shift still stays within the confines of the right-upper section, indicating that a higher amount of RAP/RAS could be utilized if a softer binder is used in similar mixtures. This result is consistent with the inferences made from the fracture energy results in previous sections. In addition, the alignment of the data on a relatively straight line also demonstrates the great advantage of pairing the Hamburg with the DC(T) as bookend performance tests. Designers have a graphical, intuitive tool for the optimization of mix design variables.

![Figure 12](image_url)

**Figure 12.** Performance-Space Diagram for gyratory compacted test specimens. Note that with reference to Figure 4, the horizontal axis had to be extended to accommodate the high fracture energy of rubber mixes and the vertical axis was reduced to 12.5 mm instead of 25 mm.
The performance space diagram also suggests that the three systems could likely be rendered very similar in terms for fracture energy by varying the base binder used. For instance, the DP-GTR-1 product could be shifted either to the right (to coincide with the TB-GTR-1 product) or to the left (to coincide with the TB-GTR-2 product) with the use of a softer or stiffer base binder, respectively. Following previous studies [11], the reason that the products fall on a line is that the mixtures have a similar aggregate type, aggregate structure, and volumetrics. The main variable in this study is the binder, or, more correctly, the mastic resulting from the GTR system used.

5. Conclusions

This study focused on asphalt mixtures designed with three different rubber modifier products including, (1) a terminal-blend GTR, (2) a dry-process, chemically processed rubber product, and (3) a terminal-blend rubber-polymer hybrid product. Test samples from gyratory compacted specimens and field cores were tested using the DC(T) test method to ascertain their fracture energies at two test temperatures, \(-12\, ^\circ\text{C}\) and \(-18\, ^\circ\text{C}\). Furthermore, the rut resistance of the mixtures measured with the Hamburg test and the embrittlement temperature, another low-temperature cracking susceptibility parameter, was computed using Acoustic Emission test method. The results from the performance tests can be summarized as follows:

- All test samples obtained from plant-compacted gyratory samples field cores passed the fracture energy criteria of 690 J/m\(^2\) at \(-12\, ^\circ\text{C}\), within the margin of statistical error.
- In general, the TB-GTR-1 system showed the highest fracture energy, and the largest fracture energy values were observed in all GTR systems when a softer base binder was used (PG 46-34).
- Hamburg rut depths were measured at 50 °C, and all mixtures had rut depths of less than 6 mm at 20,000 passes, indicating excellent rut resistance. None of the mixtures exhibited any moisture-related issues on visual inspection.
- Acoustic emission (AE) embrittlement testing was generally consistent with the DC(T) based fracture energy findings in the gyratory compacted specimens. Clearly, the use of softer binder led to colder embrittlement temperatures when compared to the base binder, and the addition of recycled content to the softer binder led to warmer embrittlement temperatures. The AE test was particularly sensitive to detecting microcracking events at warmer temperatures in the lab-mixed samples, which might indicate the test’s ability to detect the presence of stiff, unblended recycled content.
- The combination of passing cracking and rut test results can be attributed to the high-quality aggregate skeleton used in the Tollway SMA mixtures, along with the toughening mechanisms provided by GTR. The choice of a softer base binder was shown to be effective in balancing the effects of high recycle content using both RAP and RAS.

Furthermore, DC(T) fracture energy and Hamburg rut depths were plotted in a performance-space diagram to evaluate the overall performance of the mixtures. The conclusions and recommendations drawn from this analysis were summarized as follows:

- All mixtures had a high margin of safety in terms of rutting resistance. Thus, it is recommended that an even softer base binder could be used to further increase the fracture energy without prohibitively compromising the rutting resistance of the high recycle content (47%) mixtures.
- The performance-space diagram revealed similar performance characteristics for the two new GTR systems, DP-GTR-1 and TB-GTR-2. The TB-GTR-2 mixtures were closer to the fracture energy threshold of 690 J/m\(^2\) and had the lowest rut depths, while the DP-GTR-1 mixtures had a slightly better balance of rutting resistance and fracture energy.
- The alignment of the data on a relatively straight line demonstrated the advantage of pairing the Hamburg with the DC(T) as bookend performance tests, namely, that mixture designers can use this relationship to expedite mixture design by only running one of the tests during design
iterations. The second test can then be used to verify promising designs, thereby reducing testing expenses. The results also suggest that the three GTR systems are providing similar overall performance benefits, as they appear to move along the same line on performance-space diagram, moving right and slightly downwards as softer base (virgin) binders are used, and moving in the opposite direction as more recycled content is used.

Overall, the low-temperature cracking and rutting performance results of the three rubber-modified SMA mixtures with high recycle content is promising. Construction, economic, and environmental factors will be evaluated in a future study to further characterize these and other related GTR technologies to aid in future designs and future specification updates, as the Illinois Tollway continues its quest for increased pavement sustainability.

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**References**


10. Willis, J.R. Effect of Ground Tire Rubber Particle Size and Grinding Method on Asphalt Binder Properties; National Center of Asphalt Technology: Auburn, AL, USA, October 2012.


33. DeLaubenfels, L. Effectiveness of Rubberized Asphalt in Stopping Reflection Cracking of Asphalt Concrete (Interim Report); California Department of Transportation: Sacramento, CA, USA, January 1985.


55. Zhou, F.; Sheng, H.; Das, G.; Scullion, T. High RAP Mixes Design Methodology With Balanced Performance; Texas Department of Transportation: Austin, TX, USA, 2011.


67. Solaimanian, M.; Pendola, G.R.; Kennedy, T.W. Relationship between Aggregate Properties and Hamburg Wheel Tracking Results; Center for Transportation Research, Argonne National Laboratory: Argonne, IL, USA, 2002.


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