# Resource Responsible Use of Recycled Tire Rubber in Asphalt Pavements

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U.S. Department of Transportation
**Federal Highway Administration**

## FOREWORD

Pneumatic tires are designed to fulfill fundamental functions throughout their useful lives like cushioning, damping, transmitting of torque (driving and braking), dimensional stability, abrasion resistance, efficient rolling resistance, and durability. Lacking the ability to recycle old tires into new tires, there are several common repurposing methods to effectively reuse rubber. Recycling of rubber from old tires may include but is not limited to: tire-derived fuel, ground tire rubber, and civil engineering applications. GTR is the second highest consumer of recycled tire rubber. This informational brief provides a review and update on the various GTR processes used in production of asphalt pavements. It presents the most recent waste tire data along with a historical perspective of GTR use as a modifier for asphalt binders and as an additive in asphalt mixtures. Consideration for responsible use of GTR is given to promote sustainable use of GTR in asphalt pavements. Additional detailed information can be obtained from Federal Highway Administration (FHWA) publication FHWA-HIF-14-015 on The Use of Recycled Tire Rubber to Modify Asphalt Binder and Mixtures.

The FHWA has an ongoing Accelerated Implementation and Deployment of Pavement Technologies (AIDPT) Program, which includes the deployment of innovative technologies to improve pavement performance and reduce agency risk. This report was prepared under *Development and Deployment of Innovative Asphalt Pavement Technologies* Cooperative Agreement with the University of Nevada, Reno.

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16. Abstract

Addition of ground tire rubber (GTR) to asphalt binder and mixture is an accepted asphalt mixture practice in asphalt production that consumes about 12 percent of the total GTR market today. Modification of asphalt binders with GTR is well established and can provide high performance pavements that aid in reduction of the number of waste tires disposed of in landfills and elsewhere. This informational brief presents a review and update of the various processes for use of recycled tire rubber (RTR) in production of asphalt pavements. The objective is to provide knowledge for resource responsible use RTR to promote sustainable use in asphalt pavements. RTR is available in a variety of physical forms including: whole tires, stamped items, chunks, shreds, chips, crumb, and ground. The scope of this report is limited to use of RTR from whole scrap tires through size reduction and grinding, to the particle size range defined by industry as GTR. The report also includes information related to specifications and testing of GTR-modified asphalt binders, as well as additional considerations for GTR-modified asphalt mixture designs.

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| SI* (MODERN METRIC) CONVERSION FACTORS | | | | |
|---|---|---|---|---|
| **APPROXIMATE CONVERSIONS TO SI UNITS** | | | | |
| **Symbol** | **When You Know** | **Multiply By** | **To Find** | **Symbol** |
| | | **LENGTH** | | |
| in | inches | 25.4 | millimeters | mm |
| ft | feet | 0.305 | meters | m |
| yd | yards | 0.914 | meters | m |
| mi | miles | 1.61 | kilometers | km |
| | | **AREA** | | |
| $in^2$ | square inches | 645.2 | square millimeters | $mm^2$ |
| $ft^2$ | square feet | 0.093 | square meters | $m^2$ |
| $yd^2$ | square yard | 0.836 | square meters | $m^2$ |
| ac | acres | 0.405 | hectares | ha |
| $mi^2$ | square miles | 2.59 | square kilometers | $km^2$ |
| | | **VOLUME** | | |
| fl oz | fluid ounces | 29.57 | milliliters | mL |
| gal | gallons | 3.785 | liters | L |
| $ft^3$ | cubic feet | 0.028 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.765 | cubic meters | $m^3$ |
| | | NOTE: volumes greater than 1000 L shall be shown in $m^3$ | | |
| | | **MASS** | | |
| oz | ounces | 28.35 | grams | g |
| lb | pounds | 0.454 | kilograms | kg |
| T | short tons (2000 lb) | 0.907 | megagrams (or "metric ton") | Mg (or "t") |
| | | **TEMPERATURE (exact degrees)** | | |
| °F | Fahrenheit | 5 (F-32)/9 or (F-32)/1.8 | Celsius | °C |
| | | **ILLUMINATION** | | |
| fc | foot-candles | 10.76 | lux | lx |
| fl | foot-Lamberts | 3.426 | candela/$m^2$ | cd/$m^2$ |
| | | **FORCE and PRESSURE or STRESS** | | |
| lbf | poundforce | 4.45 | newtons | N |
| lbf/$in^2$ | poundforce per square inch | 6.89 | kilopascals | kPa |
| **APPROXIMATE CONVERSIONS FROM SI UNITS** | | | | |
| **Symbol** | **When You Know** | **Multiply By** | **To Find** | **Symbol** |
| | | **LENGTH** | | |
| mm | millimeters | 0.039 | inches | in |
| m | meters | 3.28 | feet | ft |
| m | meters | 1.09 | yards | yd |
| km | kilometers | 0.621 | miles | mi |
| | | **AREA** | | |
| $mm^2$ | square millimeters | 0.0016 | square inches | $in^2$ |
| $m^2$ | square meters | 10.764 | square feet | $ft^2$ |
| $m^2$ | square meters | 1.195 | square yards | $yd^2$ |
| ha | hectares | 2.47 | acres | ac |
| $km^2$ | square kilometers | 0.386 | square miles | $mi^2$ |
| | | **VOLUME** | | |
| mL | milliliters | 0.034 | fluid ounces | fl oz |
| L | liters | 0.264 | gallons | gal |
| $m^3$ | cubic meters | 35.314 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.307 | cubic yards | $yd^3$ |
| | | **MASS** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.202 | pounds | lb |
| Mg (or "t") | megagrams (or "metric ton") | 1.103 | short tons (2000 lb) | T |
| | | **TEMPERATURE (exact degrees)** | | |
| °C | Celsius | 1.8C+32 | Fahrenheit | °F |
| | | **ILLUMINATION** | | |
| lx | lux | 0.0929 | foot-candles | fc |
| cd/$m^2$ | candela/$m^2$ | 0.2919 | foot-Lamberts | fl |

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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## LIST OF ABBREVIATIONS AND SYMBOLS

### Abbreviations

| | |
|---|---|
| AASHTO | American Association of State Highway and Transportation Officials |
| AR | asphalt rubber |
| BR | butyl rubber |
| Caltrans | California DOT |
| CE | civil engineering |
| CRA | Crumb Rubber Asphalt |
| DGA | dense-graded asphalt |
| DOT | Department of Transportation |
| EPDM | ethylene propylene diene monomer |
| FDOT | Florida DOT |
| FHWA | Federal Highway Administration |
| GDOT | Georgia DOT |
| GTR | ground tire rubber |
| ISTEA | Intermodal Surface Transportation Efficiency Act |
| MSCR | Multiple Stress Creep and Recovery |
| NAPA | National Asphalt Pavement Association |
| NCHRP | National Cooperative Highway Research Program |
| NHS | National Highway System |
| NR | natural rubber |
| NYSDOT | New York State DOT |
| OGFC | open-graded friction course |
| PEMD | performance engineered mixture design |
| PG | Performance Grade |
| PRC | Public Resources Code |
| PTSi | Paragon Technical Services, Inc. |
| RAP | reclaimed asphalt pavement |
| RMB | rubber-modified binder |
| RPA | Rubber Pavements Association |
| RTR | recycled tire rubber |
| RUMAC | Rubber Modified Asphalt Concrete |
| SBR | styrene butadiene rubber |
| SBS | styrene-butadiene-styrene |
| SMA | stone matrix asphalt |
| TDF | Tire-derived fuel |
| UNR | University of Nevada, Reno |
| U.S. | United States |
| USTMA | U.S. Tire Manufacturer Association |
| VDOT | Virginia DOT |
| VMA | voids in the mineral aggregate |
| VTM | voids in total mixture |

**Symbols**

| | |
|---|---|
| $V_{be}$ | effective binder volume |

## INTRODUCTION

The Federal Highway Administration (FHWA) established the FHWA Recycled Materials Policy regarding sustainable infrastructure in 2006.[(1)] The FHWA policy states that recycling and reuse can offer triune benefits of engineering, economic and environmental impact (figure 1). Comparatively, sustainability is often described as being made up of the three components of environmental, social, and economic needs, collectively referred to as the "triple-bottom line." Within this discussion it is understood that in-service asphalt pavement performance affects every facet of the FHWA policy. Pavements with longer service lives should involve less maintenance and are environmentally friendly from the perspective that they involve less greenhouse gas; generating attention per unit of use. Furthermore, pavements with longer service lives are more economical, and more efficiently serve public needs (e.g., less congestion due to recurring maintenance and construction activities), which increases social well-being.

This document presents a review and update of the various processes for use of recycled tire rubber (RTR) in production of asphalt pavements. The objective is to provide knowledge for resource responsible use of RTR to promote sustainable use in asphalt pavements. RTR is available in a variety of physical forms including: whole tires, stamped items, chunks, shreds, chips, crumb, and ground. The scope of this report is limited to use of RTR from whole scrap tires through size reduction and grinding, to the particle size range defined by industry as ground tire rubber (GTR).

Recycling is the process of converting waste materials into new materials or objects. It is an alternative to conventional waste disposal that can save material and reduce environmental impact. Recycling of rubber from waste tires, commonly referred to as RTR, more specifically as GTR, into asphalt pavements is an attractive alternative addressing engineering, economic and environmental issues

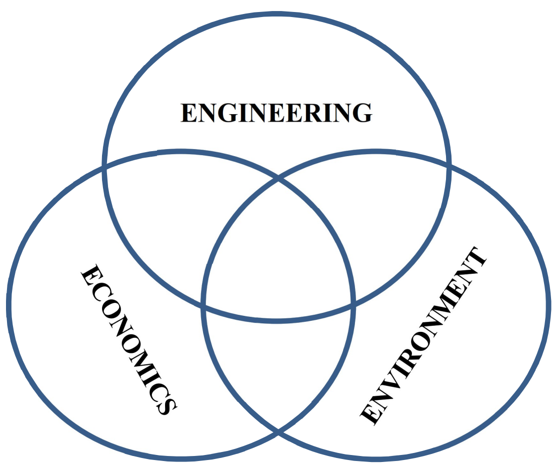


**Figure 1. Chart. Triune benefits of recycling and reuse.**(Source Paragon Technical Services, Inc. (PTSi))

## BACKGROUND

### *Waste Tire Issue*

Large amounts of polymers, such as natural rubber (NR), synthetic styrene butadiene rubber (SBR), ethylene propylene diene monomer (EPDM) rubber, and butyl rubber (BR), collectively referred to as rubber, are used in production of pneumatic tires for passenger cars, trucks, airplanes, etc. Table 1 shows a breakdown of typical tire components. When these tires are not serviceable and discarded, only about 1 percent or less rubber has been lost due to abrasion wear. Almost the entire amount of original rubber from a waste tires is discarded, which necessitates a very long time for natural degradation. Disposal of waste polymers is a serious environmental concern as polymeric materials do not decompose easily. This poses two major challenges: waste of valuable rubber and environmental pollution due to disposal of waste tires.(2,3) Currently, scrap tires are used in several productive and environmentally safe applications.(4)

**Table 1. Typical components of tires.(Source PTSi)**

| Component | Typical Range |
|---|---|
| Natural rubber (NR) | 14 to 27 percent |
| Synthetic rubber | 14 to 27 percent |
| Carbon black | 28 percent |
| Steel, fabric | 14 to 15 percent |
| Processing oils and additives | 16 to 17 percent |

In 2017, markets for scrap tires were consuming just over 3.4 million tons, or 81.4 percent, of the estimated 4.2 million tons of scrap tires generated annually.(5) Table 2 is a summary of scrape tire usage. The three largest scrap tire markets in 2017 are shown in figure 2 and were:

- Tire-derived fuel (TDF), 50.9 percent, consisting of cement kiln, pulp and paper, and industrial boiler applications.
- GTR, 29.7 percent, in asphalt, automotive, molded/extruded products, playgrounds/mulch, and sports surfacing applications.
- Civil engineering (CE), 9.3 percent, including tire shreds used in road and landfill construction, septic tank leach fields and other construction applications.

The GTR market is reported at slightly more than 1.0 million tons or about 62 million scrap tires. GTR-modified asphalt pavements represent 11.7 percent, or approximately 119 thousand tons (7.2 million scrap tires) as shown in figure 3.

**Table 2. 2017 scrap tire usage according to the U.S. Tire Manufacturer Association (USTMA).[5]**

| Market or Disposition | Thousands of Tons | Millions of Tires | % of Total to Market |
|---|---|---|---|
| Tire-Derived Fuel (TDF) | 1,736.3 | 105.9 | 50.9 |
| *Cement Kilns* | *805.9* | *49.2* | *23.6* |
| *Pulp & Paper* | *503.1* | *30.7* | *14.8* |
| *Industrial Boilers* | *427.3* | *26.1* | *12.5* |
| Ground Tire Rubber (GTR) | 1,013.3 | 61.8 | 29.7 |
| Civil Engineering (CE) | 316.0 | 19.3 | 9.3 |
| Exported | 109.8 | 6.7 | 9.3 |
| Electric Arc Furnace | 39.2 | 2.4 | 3.2 |
| Reclamation Projects | 44.0 | 2.7 | 1.2 |
| Agricultural | 7.1 | 0.4 | 1.3 |
| Baled Tires/market | 14.6 | 0.9 | 0.2 |
| Punched/ Stamped | 22.5 | 1.4 | 0.4 |
| Other | 108.5 | 6.6 | 0.7 |
| Total to Market | 3,411.3 | 208.1 | 100.0 |
| Generated | 4,189.2 | 255.6 | – |
| % to Market/Utilized | 81.4% | 81.4% | – |
| Landfill Disposal | 646.8 | 39.5 | – |
| % Managed (Includes Markets, Baled, and Landfill) | 96.9% | 96.9% | – |

– indicates not applicable.

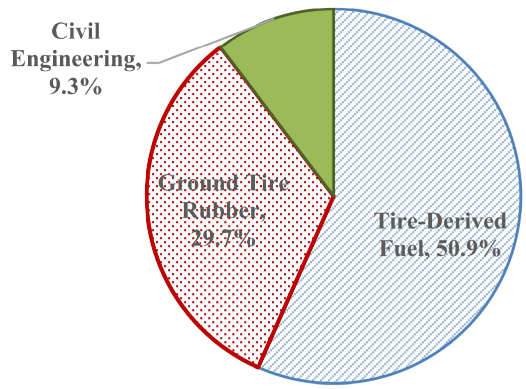


**Figure 2. Chart. 2017 largest scrap tire markets.(Source PTSi)**

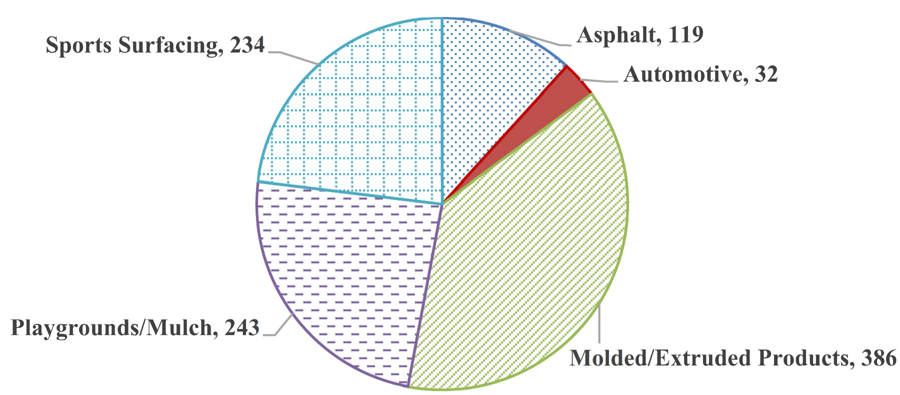


**Figure 3. Chart. 2017 GTR market distribution, in thousands of tons.(Source PTSi)**

Recycling of waste rubber from tires into GTR involves grinding or reduction of tire rubber into smaller particle size, which results in an increase in surface area. The rubber grinding industry classifies GTR according to particle size as rubber which is 2.0 mm (10 mesh) and smaller. The typical sizes of GTR used in modified asphalt binders and mixtures for pavement construction range from about 1.5 mm (1500 µm) down to 420 µm (15 mesh to 40 mesh), with limited use sizes as small as 177 µm (80 mesh) and 125 µm (120 mesh). Grinding processes for production of GTR are well developed and widely used. The most common grinding processers are ambient grinding and cryogenic grinding. A third method, wet grinding has been used, but is not as common.(6)

### *Historical Perspective*

Research on GTR-modified asphalt binders over the last 50 years has shown favorable impacts of GTR modification. GTR ranks second among the most common asphalt polymer modifiers, behind styrene-butadiene-styrene (SBS) block copolymers. Modern GTR use in paving began in the early 1960s with a highly elastic asphalt rubber (AR) modified chip seal developed for the city of Phoenix, Arizona.(7) The work expanded into larger chip seal projects along with other crack relief interlayers, and open-graded surface courses. Initial growth of AR applications included chip seal surface treatments, interlayers, and AR open-graded friction courses (OGFCs).(8) During the two decades following, AR materials increased as they proved useful in various pavement maintenance functional applications including asphalt pavement, but by far the greatest utilization during this time frame was maintenance applications.

During this same timeframe, versions of dry mixture addition of GTR to asphalt mixtures posed more of an issue than dry processes employed today. These systems were collectively referred to as Rubber Modified Asphalt Concrete (RUMAC) by Buncher.(9) RUMAC technology typically used GTR particles of 10 mesh or greater and was commonly added at 3 percent by weight of mixture. Trademarked dry processes (e.g., PlusRide™ and TAK™ technologies) were intended to act as a flexible aggregate rather than modify the asphalt binder. PlusRide™, developed in Sweden in 1960 and licensed in the U.S. in 1978, used 3 percent "coarse" rubber by weight of mix, with a maximum particle size of 6.3 mm (3 mesh) and approximately 65 percent larger (by weight) than 2.0 mm (10 mesh) added directly into the heated aggregate prior to addition of the asphalt binder. The TAK™ system, the first form of a generic dry process GTR in the U.S., attempted to modify both mixture and asphalt binder by using 1 to 3 percent of a combination of GTR particles larger than 10 mesh and less than 10 mesh with the larger particles believed to be an aggregate modifier and the smaller particles believed to modify the asphalt binder.(10–12) In 1995, Buncher reported the new generic dry addition system to be used by four States (Arkansas, Iowa, Kansas and Oklahoma) with only one (Kansas) using the concept successfully for an extended period.(9) The use of ultra-fine 177 µm (80 mesh) particle size GTR is attributed to the improved performance of the new generic dry concept used in Kansas. While presented to provide background information, these technologies using the dry process are no longer marketed for use in the current U.S. GTR-modified asphalt market.

The late 1980s and early 1990s were a time of heightened interest in GTR. Chapter 599 of the New York State Laws of 1987 were amended requiring investigation and reporting on the technical and financial implications of mandating addition of GTR to paving materials used in public works (13). In response, the New York State Department of Transportation (NYSDOT) commissioned a study in 1989.[13] Also, in 1989, GTR interest in asphalt mixtures was shown by the Florida DOT (FDOT), which initiated a study in response to action by the Florida legislature in passing Senate Bill 1192 on Solid Waste Management.[14] Rouse Rubber Industries developed a non-proprietary continuous blending method called the Florida generic wet process. It was first used in Florida in 1989 with fine ground, 177 μm (80 mesh), GTR. The Florida generic wet process was reported to eliminate perceived drawbacks of the AR technology.[15,16]

During the period from 1989 to 1991, several agencies constructed projects to evaluate GTR-modified asphalt. In 1990, the Virginia DOT (VDOT) began construction of four test sections of GTR-modified asphalt concrete.[17] Dense-graded, gap-graded surface asphalt mixes, and a base mix were constructed. In 1991 an investigation was conducted by the Joint Highway Research Project Engineering Research Station at Purdue University and the Georgia DOT (GDOT) that included construction of a GTR test section.[18,19] Also, in 1991, Section §1038(d) of the Intermodal Surface Transportation Efficiency Act (ISTEA) required States to use a minimum amount of crumb rubber from recycled tires in asphalt surfacing placed each year beginning with the 1994 paving season.[20] The ISTEA caused a surge of interest in GTR technology, prompting several thorough literature reviews.[9,21–24]

In 1994, a catalog and software database of publications was developed by the University of Nevada, Reno (UNR) under the National Cooperative Highway Research Program (NCHRP).[25] The database began with the bibliography developed by Dr. Jon Epps as part of NCHRP Synthesis 198: Uses of Recycled Rubber Tires in Highways.[26] Synthesis 198 lists 232 publications that had appeared before December 31, 1993, with the catalog listing an additional 469 publications entered into the database up to June 30, 1994. The university was to continue updating both the catalog and database regularly; however, currency extended only to 1996, after which existing documents were transferred to the Rubber Pavements Association (RPA), resulting in a database containing up to 1,000 publications. This is the largest single source for literature on GTR. Information is available through the RPA at its website.[27]

The ISTEA mandate was lifted in 1995 under section 205(b) of the National Highway System (NHS) Designation Act, though a significant number of GTR pavement sections had already been placed and national research was fostered. Many States discontinued use of GTR after the mandate was lifted. However, agencies such as Florida, Texas, and Rhode Island continued GTR use at that time. In 2005, the State of California Public Resources Code (PRC) section 42700-42703 (PRC 42703) legislated the use of GTR.[28] PRC 42703 states that the DOT shall require the use of crumb rubber in lieu of other materials at specified levels for State highway construction or repair projects that use asphalt as a construction material (not a Federal requirement). Current use levels are set at not less than 11.58 pounds of GTR, on an annual average, per metric ton of the total amount of asphalt paving materials. As of January 2015, any material may be used meeting the definition of asphalt containing GTR with respect to product type specification and annual use levels.

During the 1990s continuing into the 2000s, studies were conducted by several agencies utilizing various GTR-modified materials. Similar findings were reported by Alaska, Arizona, South Carolina, Louisiana, California and Colorado.[29–35] Common themes were: improved asphalt binder properties of GTR-modified asphalt binders, and improved mixture performance with respect to deformation resistance, fatigue cracking, thermal cracking, reflective cracking, aging properties, design thickness, as well as noise reduction.

### *Current Usage of GTR-Modified Binders and Mixtures*

A review of State DOT published specifications revealed that only twelve States currently publish specifications allowing GTR-modified asphalt binders for use in construction of asphalt pavements. The States are shared in figure 4.

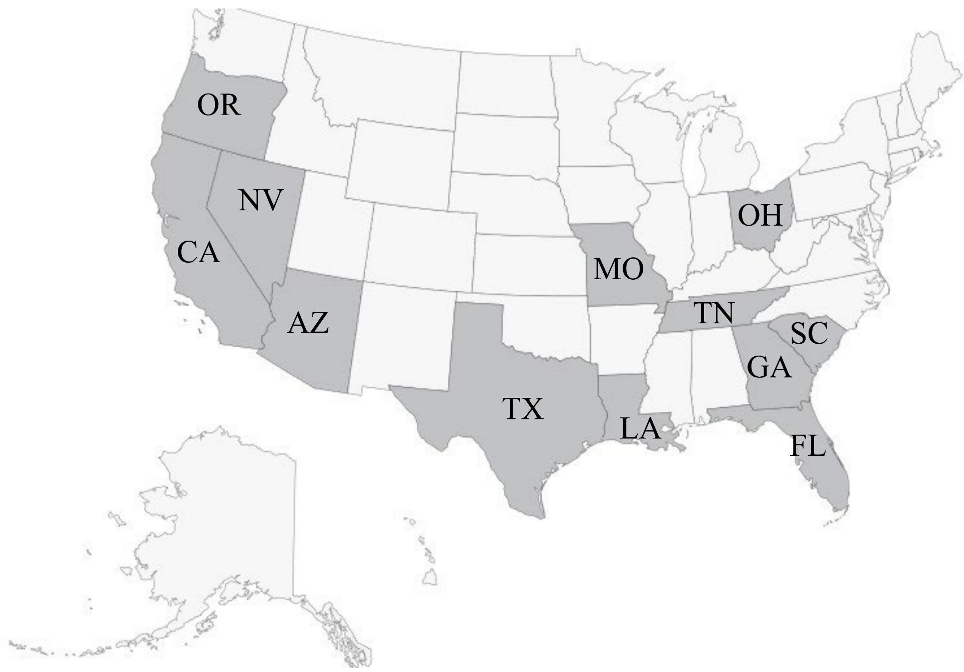


**Figure 4. Map. States allowing GTR-modified usage in current specifications.(Source PTSi)**

The National Asphalt Pavement Association (NAPA) recently reported that twenty-one producers from eleven States indicated using GTR in some asphalt mixtures.(36) The distribution among States is summarized in table 3. The 20 thousand tons of GTR used reported by NAPA is about 17 percent of the 119,000 lbs of GTR reported by the USTMA to be used in modified asphalt binders.(5) The NAPA report did not include use of GTR in surface treatments, such as chip seals, which is a major source of consumption. NAPA reported that approximately 59 percent of the total asphalt mixture tonnage using GTR was in California, which mandates widespread use of GTR in asphalt pavements (not a Federal requirement).(28)

California is by far the largest user of GTR-modified asphalt binder, with usage being directed by PRC 42703. The California DOT (Caltrans) requires (not a Federal requirement) that: GTR be derived from automobile and truck tires only; GTR-modified binders be homogeneous; GTR-modified binders may not contain visible rubber particles; and GTR-modified binders contain a minimum of 10 percent GTR.

Arizona, the second largest user of GTR-modified asphalt binders, has two different specifications.(37) One is a Crumb Rubber Asphalt (CRA) specification for GTR-modified asphalt binder produced using AR technology with a minimum of 20 percent GTR by weight of asphalt binder. The second is a Performance Grade (PG) specification (AASHTO M 320, a private, voluntary standard) for hybrid GTR-modified asphalt binder, produced by the rubber-modified binder (RMB) technology with minimum of 8 percent GTR and 2 percent SBS.[38] The Arizona PG specifications are designated as PG 64-28 TR+, PG 70-22 TR+, and PG 76-22 TR+.

**Table 3. Reported tons of GTR used in 2018.**[Source PTSi]

| State | Tons of GTR Used | % of Total Tons of GTR Used |
|---|---|---|
| Arizona | 4,303 | 21.4 |
| Arkansas | 5 | <0.1 |
| California | 13,412 | 66.7 |
| Delaware | 10 | <0.1 |
| Florida | 136 | 0.7 |
| Georgia | 378 | 1.9 |
| Illinois | 750 | 3.7 |
| Massachusetts | 710 | 3.5 |
| Michigan | 55 | 0.3 |
| Missouri | 260 | 1.3 |
| Texas | 98 | 0.5 |
| **Total** | **20,117** | **100.0** |

Louisiana, while not listed in the NAPA survey, is also a substantial user of GTR-modified asphalt binders. Louisiana allows both wet process technologies, in all mixture types, specifying a maximum GTR concentration of 10 percent, with particles no larger than 30 mesh. GTR-modified asphalt binders are graded according to AASHTO M 320, a private, voluntary standard, and designated as PG 76-22M with Multiple Stress Creep and Recovery (MSCR) percent recovery used as a plus test.

Several States have recently placed evaluation projects with both wet and dry process GTR-modified asphalt binders and mixtures. Since 2007, dry-process projects referred to by the suppliers as “chemically engineered rubber” technology have been constructed in Georgia, Illinois, Indiana, Louisiana, Maryland, Missouri, Oklahoma, Texas, Virginia, and Wisconsin. These projects account for approximately 5 million total tons of dry-process GTR since 2007 (information on these projects is available online).[39] Liberty Tire and Lehigh Industries report placement of Dry Process projects, referred to as “dry-mix” technology, in Michigan and Ohio. GTR consumption on these projects was not published.[40,41]

### *Rubber-Modified Asphalt Processes and Technologies*

Asphalt binder for production of asphalt mixtures is usually used in neat form without additives; however, it can be modified through addition of non-bituminous components or other processing methods in order to provide products with improved physical properties for desired performance, or mode of application. Asphalt modification is not new technology. Asphalt technologists have used modification methods to improve properties of asphalt binder for about as long as asphalt binder has been used in construction of pavements. Modification techniques are primarily dependent on the desired performance of the final product. Typical methods include, but are not limited to, four general classifications: addition of special fillers or extending agents, chemical modification, air oxidation and polymer modification.[42] The main topic of this document relates to polymer modification using GTR polymers.

GTR and SBS are similar in that they both contain styrene and butadiene; however, that is about as far as the similarities extend. GTR is a thermoset elastomer, due to sulfur cross-linking (vulcanization), and maintains properties somewhat consistently through heating and cooling. SBS is a thermoplastic elastomer, meaning that it can be softened by heat and cooled in a reversible physical process. GTR modification can range from as little as 5.0 percent to as much as 20.0 percent of the total asphalt binder weight, depending on the properties being targeted. Compared to SBS modified asphalt binders this would be equivalent to SBS loadings of from about 1.5 percent to 6.0 percent to achieve equivalent properties. Note from table 1 that the composition of GTR is not pure polymer (rubber), while SBS is pure polymer. On a mass percent basis, GTR is about 0.4 percent polymer and 0.6 percent inert material. A simplified assumption is that 1.0 to 1.5 percent SBS equates to about 3.0 to 4.0 percent GTR as effective asphalt binder modifier. This assumption depends highly on compatibility with the asphalt binder being modified. The effect of thermoplastic elastomers, for example SBS, and thermoset elastomers, such as GTR, on asphalt binders is highly dependent on proper dispersion and solubility in asphalt binders. Dispersion and solvation are primarily responsible for the elastic nature imparted to asphalt binders from thermoplastic and thermoset elastomer polymer modification.

Figure 5 presents a chronology of GTR uses in asphalt binders and mixtures in the U.S. Currently there are two primary processes of incorporating GTR into asphalt binders and mixtures referred to as either the “wet” or “dry” process. The wet process blends GTR with asphalt with one of two technologies. It is done either on-site at the asphalt mixture plant or at the asphalt binder supply terminal, with a prescribed reaction time prior to mixing the GTR-modified asphalt binder with aggregate. The dry process incorporates GTR directly into the asphalt mixture during production. This is usually done by adding the GTR directly to the aggregate in the asphalt plant mixing drum prior to introducing the asphalt binder.

Despite successes, GTR usage has been limited to specific pavement types and regions. Limited growth in use of GTR-modified asphalt pavements, since the early 1960s can be credited to successful construction of asphalt pavements with improved reduced permanent deformation, fatigue cracking, thermal cracking, reflective cracking, and improved aging properties, and noise reduction (with some mixture types).[9,43,44] These results are primarily observed using GTR-modified asphalt binders produced via wet process technologies: “asphalt rubber” (AR), sometimes referred to simply as the “wet process” and “rubber-modified binder” (RMB) also referred to as “terminal blend.”

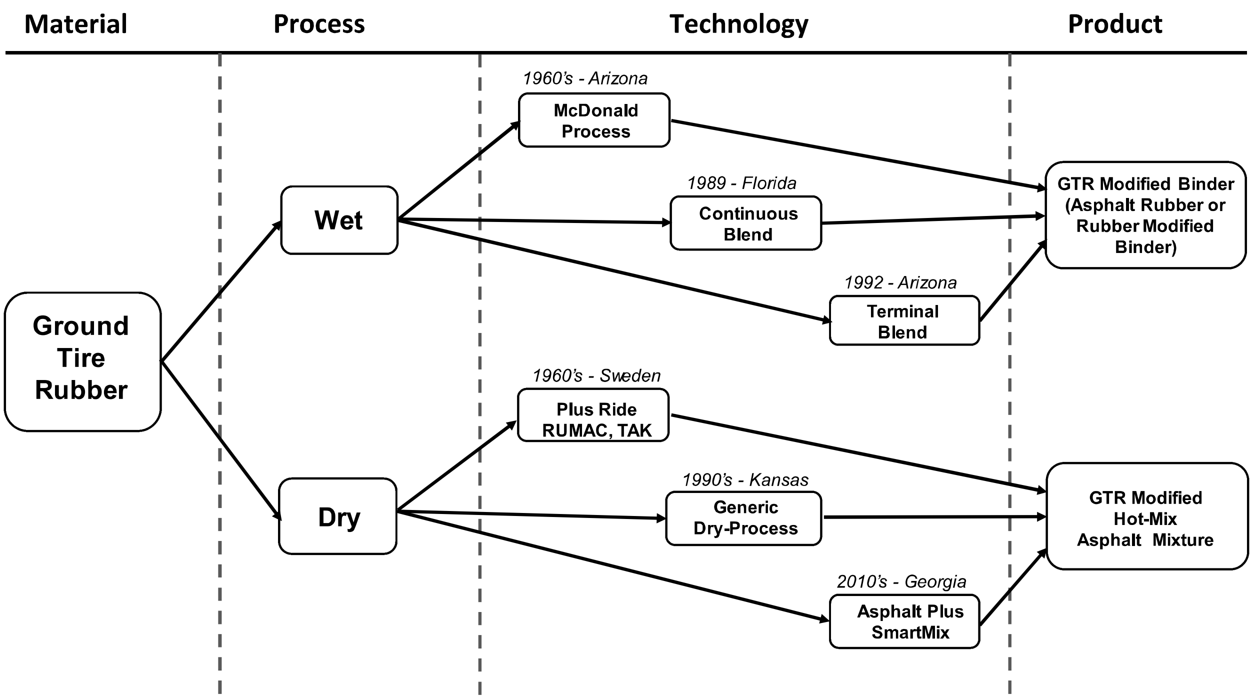


**Figure 5. Chart. Primary methods of incorporating GTR into asphalt binders and mixtures.**(Source PTSi)

### *Wet Process–AR Technology*

Production of the AR technology is a batch wet process consisting of blending from 10 to 22 percent GTR by weight of asphalt binder. The typical GTR particle size is a maximum of around 1.5mm or (15 mesh). Processing temperatures range from 175 to 190°C (≈ 350 to 375°F) allowing the GTR and asphalt binder to react for 30 to 60 minutes before introduction into the asphalt mixture production process.(7,23–24,45–48) This process is normally performed entirely at the asphalt mixture production plant using portable rubber mixing facilities where GTR is brought to the job site in bulk or super-sacks and blended with asphalt binder available at the mix production plant. The portable rubber mixing facilities integrate extensive equipment including a feed system for the GTR, a blending tank and separate storage tank(s), as well as a heating, metering, and emissions capture systems. Figure 6 is a schematic illustrating the production equipment and process.(49)

The term "reaction" is used to describe the change in asphalt binder properties when GTR is added to asphalt binder. This change in properties is more physical, due to swelling of the rubber particles, than chemical, and depends on proper dispersion of rubber particles and solubility in the asphalt binder.(45–48) Fully reacted particles may swell as much as three to five times their original size.(50). As the GTR particle swells asphalt viscosity generally increases and stabilizes when the swelling nears a maximum. Changes in properties are not only a result of GTR particle swelling, but also because the asphalt binder is giving up lighter oils through absorption into the rubber, all in a process of phase inversion.(51,52)

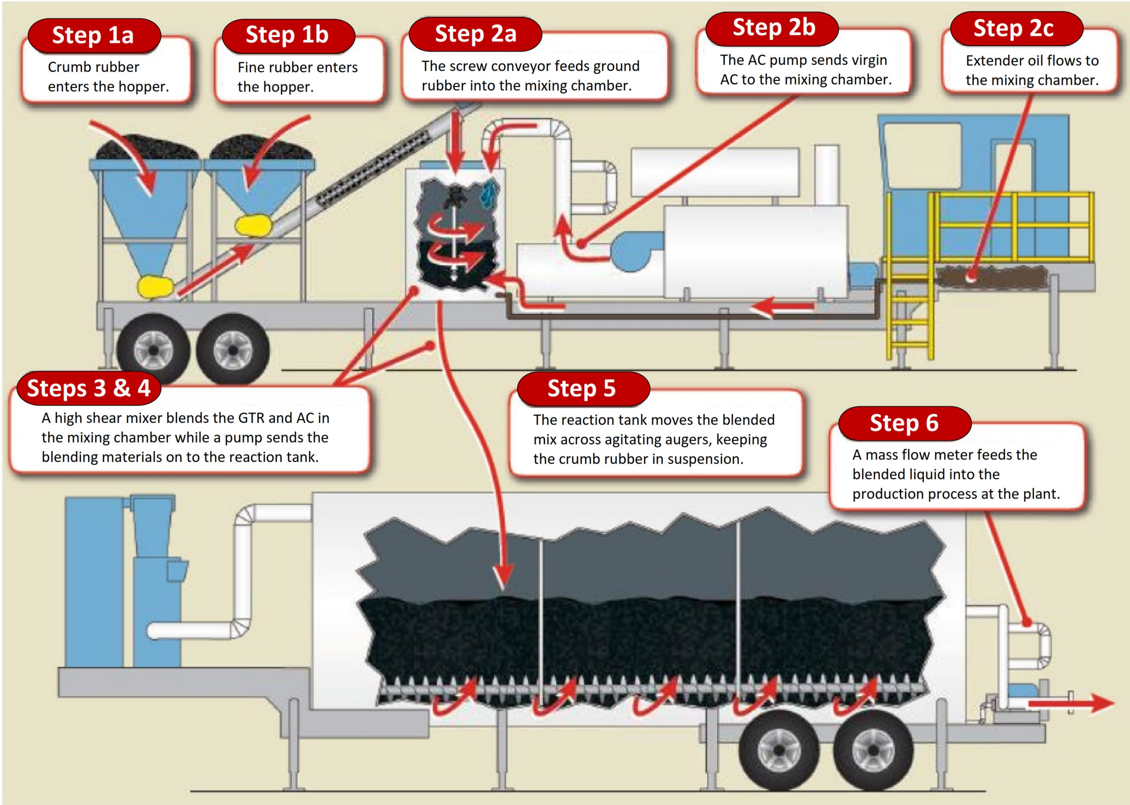


**Figure 6. Chart. Portable AR mixing facility.**[49]

As previously discussed, depending on temperature, GTR particle size—typically 1.5mm (15 mesh) down to 420 µm (40 mesh), dispersion efficiency and shear, the reaction time with the AR process is typically 30 to 60 minutes. However, reaction time may be reduced through improved dispersion and finer GTR particles, smaller than 420 µm (40 mesh). Time to fully react is reported to be a direct function of GTR relative surface area, prompting use of finely ground GTR, e.g. 177 µm (80 mesh) in some asphalt binders.[53–56]

### *Wet Process–RMB Technology*

The alternative version to the wet process with the AR technology is the RMB technology. The RMB technology is commonly referred to as "terminal blend."[57] RMB or terminally blended GTR-modified asphalt is produced in a similar manner to AR, except that production occurs in fixed blending facilities, or terminal. RMB generally consists of blending from 5 to 15 percent GTR of a size range from 600 µm to 177 µm (30 to 80 mesh) with asphalt binder at temperatures ranging from 175 to 190°C (≈ 350 to 375°F) and allowing them to react for at least 60 minutes prior to transfer to large storage tanks. Once mixed, the RMB is stored at elevated temperatures awaiting delivery to asphalt mixture production facilities in the same manner as conventional and polymer modified asphalt binders. Note that 600 µm to 420 µm (30 to 40 mesh) are more typical sizes for GTR in RMB, which is commonly referred to as "30 minus rubber."

Proprietary technologies for production of RMB eliminate the need for portable on-site blending units, used in the AR technology, while providing tank storable GTR-modified asphalt binders for asphalt mixture production. Early versions of these products—FLEXOCHAPE and ECOFLEX—allowed the GTR-modified asphalt binder to be blended at refineries or asphalt terminals like conventional asphalt binders, without modification at the mix plant.[12,58,59] Compared to AR at 20 percent GTR by weight of asphalt binder, these processes used only 10 percent and were only used sparsely in the U.S. during the early 1990s.[60] In the middle 1990s a few, recently expired, U.S. patents were issued to Neste/Wright Asphalt Products Company of Channelview Texas for a wet process technology referred to in the industry as the "Wright Process." This technology is a wet process RMB in which approximately 10 percent GTR is added to asphalt and processed at elevated temperature for extended periods to provide a GTR-modified asphalt binder that is storage stable for asphalt mixture production.[61–63] The advent of the Wright technology spawned development of several RMB technologies, making terminal blend RMB one of the preferred production technologies of GTR-modified asphalt binders.[64,65] Arizona now prefers terminal blended rubber, RMB, over AR even though AR has been the staple of their GTR-modified pavements program.[66] Terminal produced RMB binders has also led to production of hybrid asphalt binders of GTR combined with synthetic polymers such as SBS, as well as improvements in testing and certification of GTR-modified asphalt binders.[67]

### *Dry Process*

Today's accepted technology of the dry process is a modified version of Buncher's "new generic dry" system.[68] Typical GTR particle size is in the range of 600 to 420 µm (30 to 40 mesh). GTR concentrations are considerably less at approximately 10 percent by weight of the asphalt binder, which equates to approximately 0.5 percent by weight of mixture or 10 pounds of GTR per ton of asphalt mixture. GTR is typically brought to the job site in bulk or super-sacks and added through the reclaimed asphalt pavement (RAP) collar along with RAP. Today's dry processes often contain additional additives such as polymers or waxes to provide improved mixing and compaction characteristics.[65,69] These additives are believed to do more in improving mixing and compaction than function as a property modifier of the base asphalt binder.[70] More recently, Liberty Tire has introduced a treated GTR technology. This technology incorporates what is referred to as "Reacted Rubber Particle Technology" to provide a dry process for mixture modification.

A presumed drawback with the wet process technologies is that they are batch processes involving special blending equipment to react the GTR with asphalt at elevated temperatures for a specific duration, which can lead to delays at the asphalt mix plant. Therefore, some suppliers promote that a significant cost savings can be recognized by adding GTR to the asphalt mixture in a dry process, versus the wet process, due to reduction in processing and materials handling.[9,22,71]

A second factor believed to drive the cost of the AR technology higher than the dry process(es) is a belief that, once blended, the AR has a shelf life limited to 24 hours.[12,46–48] This is primarily due to higher concentrations of GTR used in the AR technology, often upwards of 20 percent, and continued swelling of the GTR in mixtures stored at elevated temperature causing asphalt mixture producers alarm if an unexpected shutdown should occur at the production plant or jobsite. Stroup-Gardiner reported that the cost to modify asphalt mixture with the dry process versus the wet process, assuming the same size and concentration of GTR, is about one-third.[72] Production time of dense-graded asphalt (DGA) mixture with AR was reported to be slower than the dry process with the AR technology. An average increase of 60 percent to production of dense graded mixture as compared to a 20 percent increase with the dry process.

### *Summary of Technologies*

A summary of the wet process technologies discussed is presented in table 4. Recall the wet process is defined as: "methods that blend ground tire rubber (GTR) with asphalt binder before incorporating the asphalt binder into asphalt paving materials. Although most wet process asphalt rubber (AR) binders involve agitation to keep the scrap tire rubber evenly distributed throughout the asphalt binder, some rubber modified binders (RMBs) may be formulated in a wet process manner so as not to need agitation."

A summary of the dry process technologies discussed is presented in table 5. Recall the dry process is defined as: "any method that mixes the ground tire rubber (GTR) with the aggregate before the mixture is charged with asphalt binder. This process only applies to hot mix asphalt production."

**Table 4. Summary of wet process GTR technologies and name.**[Source PTSi]

| Technologies Included in This Process | Technology Definition | Other Names of the Technology |
| --- | --- | --- |
| **Asphalt Rubber (AR)** | "An asphalt binder in various types of flexible pavement construction including surface treatments and asphalt mixtures consisting of a blended asphalt binder, ground tire rubber (GTR), and certain additives in which the rubber component is at least 15 percent by weight of the total blend and has reacted in the asphalt binder sufficiently to cause swelling of the rubber particles." | • McDonald Process<br>• Arizona Crumb Rubber<br>• Wet Process Rubber<br>• Recycled Tire Rubber Modified Bitumen (RTR-MB)<br>• Asphalt Rubber Binder (ARB)<br>• Bitumen Rubber Binder<br>• Crumb Rubber Binder<br>• Batch Blending |
| **Rubber Modified Binder (RMB)** | "A version of the wet process where ground tire rubber (GTR) is blended with asphalt binder at the refinery or at an asphalt binder storage and distribution terminal and transported to the asphalt mix plant or job site for use. These blends may contain from 5 to 12 percent GTR by total asphalt binder mass. Some hybrid RMB binders may contain polymers such as styrene-butadiene-styrene (SBS) in addition to GTR." | • Terminal Blend<br>• Terminal Blended Rubberized Asphalt (TBRA)<br>• Recycled Tire Rubber Modified Bitumen (RTR-MB)<br>• Rubber Modified Binder (RMB)<br>• Hybrid Rubber Binder<br>• Wright Process |

**Table 5. Summary of dry process GTR technologies and name.**(Source PTSi)

| Technologies Included in This Process | Technology Definition | Other Names of the Technology |
|---|---|---|
| **Dry Process** | "A process where hot-mix asphalt mixture is modified with ground tire rubber (GTR) using GTR as an aggregate/binder modifier which is incorporated into the aggregated prior to mixing with asphalt binder producing a GTR-modified hot-mix asphalt mixture. GTR used in this technology is generally less than 0.6mm (30 mesh)." | • Dry process rubber<br>• Belt add modifier (BAM) |

## SPECIFICATIONS AND TESTING OF GTR-MODIFIED ASPHALT BINDERS

### *Wet Process*

Purchase specifications for GTR-modified asphalt binders primarily include test results to characterize stiffness of the asphalt binder with respect to expected end use conditions complimented by tests to ensure safety, consistency and retention of properties with aging. Since GTR-modified asphalt binders are non-homogeneous, dispersed rubber particles tend to confound conventional characterization by penetration (AASHTO M 20 *Standard Specification for Penetration-Graded Asphalt Cement*, a private, voluntary standard) and absolute viscosity (AASHTO M 226 *Standard Specification for Viscosity-Graded Asphalt Cement*, a private, voluntary standard).[73–75] Therefore, non-standard procedures have been used to attempt to quantify the physical properties of GTR-modified asphalt binders.

Specifications from different agencies may vary in format and extent of the specification, but they generally have common components describing the type of product or process, materials (including specifications and test methods), construction requirements, methods of measurement and basis for payment. For example, agencies specifying modified asphalt binders with AR technology tend to follow empirical specifications based on their experiences. Common physical attributes of AR binders under consideration for asphalt mixture applications included viscosity at high temperature to ensure mixing and compaction characteristics, consistency at high and moderate temperatures to address properties at pavement surface temperatures, elasticity and low temperature characteristics.

The Superpave asphalt binder specification (AASHTO M 320 *Standard Specification for Performance-Graded Asphalt Binder*, a private, voluntary standard) encourages wider use of rheology-based testing of GTR-modified asphalt binders using the wet process and either the AR or RMB technology.[38] Minor adjustments may facilitate Superpave asphalt binder testing of GTR-modified asphalt binders using the RMB technology with particles less than 30 mesh. An example is increasing the standard DSR plate-plate testing gap from 1 mm to 2 mm. For GTR-modified asphalt binders using the AR technology with larger particles, greater than 30 mesh, alternative concentric cylinder (cup and bob) testing fixtures are available to conduct rheological testing of a wider gap up to 9.5 mm.[76–78] Rheology testing of wet-process GTR-modified asphalt binders whether with standard 1 mm gap, increased gap, or alternative geometries allows adherence to standard Superpave asphalt binder grade parameters in AASHTO M 320 (a private, voluntary standard) as well as new specifications such as MSCR (AASHTO M 332 *Standard Specification for Performance-Graded Asphalt Binder Using Multiple Stress Creep Recovery (MSCR) Test*, a private, voluntary standard).[79]

Regardless of process, GTR-modified asphalt binders are generally less sensitive to temperature than conventional asphalt binders, thereby improving asphalt pavement performance.[46,47] Higher relative stiffness at high operating temperatures is desired and is increased by addition and reaction of GTR, while desired lower relative stiffness at low operating temperatures is generally achieved by use of lower viscosity base asphalt binder or adding extender oils to soften the base asphalt binder. The base asphalt binder for GTR modification in the AR and RMB technologies is typically one or two grades lower than the standard asphalt binder used for asphalt paving in a specific region. For example, if the climatic/traffic PG asphalt binder recommended by AASHTO M 320 (a private, voluntary standard) is a PG 76-22, the base asphalt binder for GTR modification is most likely a PG 64-22 or perhaps even a PG 58-22. In the case of AASHTO M 332 (a private, voluntary standard) this would mean that PG-S grades are modified with GTR to achieve -H, -V, and -E grades. As stated, results show improved high temperature properties with added GTR. Low temperature improvements are not as prevalent but can be obtained with the combination of a softer asphalt binders and GTR concentration.

While stiffness is the primary measure of the difference between conventional asphalt binder and GTR-modified asphalt binder, other empirical and physical properties have historically been evaluated, such as changes in softening point, penetration, elasticity, flexibility, and ductility.[9,80] At the urging of some suppliers, agencies have implemented solubility as an added parameter for GTR-modified asphalt binders. This should be considered with caution as tire rubber is not totally soluble in any solvent and solubility has no indication as to the performance of an asphalt binder. For the most part solubility only serves to differentiate commercial technologies.

### *Dry Process*

Specification and certification of mixtures modified with GTR using the dry process is not as straightforward as when the wet process is used. Some agencies have specified the GTR-modified asphalt binder be evaluated and certified via asphalt binder extraction, recovery, and subsequent testing of recovered asphalt binder when the dry process is used. This approach raises concern as to whether the recovered asphalt binder represents the GTR-modified asphalt binder in the mixture. Testing of extracted asphalt binder from the dry process poses one of two, possibly both, concerns: was all the GTR recovered from the mixture and/or does solvent interaction incorporate rubber and asphalt binder in a manner not achieved in the in-place mixture. Specification of the mixture using the dry process is more appropriately based on mixture testing schemes such as performance engineered mixture design (PEMD) approach.[81]

## ASPHALT MIXTURE CONSIDERATIONS

Three general asphalt mixture types are used for production of GTR-modified asphalt pavements: dense-graded, gap-graded, and open-graded.[82] Standard mixture design procedures, Marshall, Hveem and Superpave, have been used with modifications to test methods and design criteria to design mixtures containing GTR-modified asphalt binders using both wet process technologies and dry process technologies.[83–86] Volumetric mixture designs alone may not provide mixtures with desired overall performance. The aforementioned PEMD approach to mixture design may be more appropriate for design and evaluation of GTR-modified systems.

In the U.S., predominate use of GTR-modified asphalt pavements has been in warmer climates. Issues with compaction and raveling of mixtures in colder climates and in late season paving has led some to believe that GTR-modified materials may not perform well in cold climates. Some trial projects with GTR-modified materials have exhibited early cracking, as well as issues with permanent deformation. An important factor to consider with respect to these concerns is effective binder volume ($V_{be}$). $V_{be}$ is an important factor in volumetric design of all asphalt mixtures. Excess asphalt binder content may lead to mixtures susceptible to permanent deformation, while insufficient asphalt binder content can be a cause of premature cracking. For DGA mixtures designed with GTR-modified asphalt binders premature cracking has been a concern. In fact, Crawley reported test section mixture exhibiting early cracking indicative of mixture with low asphalt binder content.[87] Synonymous to excess asphalt binder is excess filler content in asphalt mixtures because excess filler may also yield mixtures susceptible to permanent deformation. To better understand how GTR modification affects $V_{be}$, a review of GTR composition is necessary. Recall that GTR is not pure polymer (rubber) and on a per mass percentage basis GTR is only about 0.4 percent polymer, functional as a binder modifier, and 0.6 percent inert material. Baumgardner (2015) and the FDOT specifications report that the typical functional asphalt binder modifier (polymer) content of GTR is in the range of 40 to 55 percent.[52,88] Therefore, the remaining inert materials are neither polymer nor asphalt. Considering this, an assumed minimum functional asphalt binder modifier content of 40 percent can be utilized to calculate the necessary increase in asphalt binder content needed to meet volumetric demand.

For example, consider a design binder content of 5 percent, designed with conventional asphalt binder. Substituting GTR-modified asphalt binder containing 10 percent GTR would involve an increase in asphalt binder content of 0.3 percent. So, 5 percent asphalt binder with 10 percent GTR modification having 40 percent functional binder modifier would yield only 94 percent effective asphalt binder in the GTR-modified asphalt binder. To ensure 5 percent asphalt binder in the mixture, the total asphalt binder should be increased to 5.32 percent. This, and the fact that GTR absorbs light fractions of virgin binder, has prompted some States to make it common practice in specifications and design of asphalt mixtures containing GTR-modified asphalt binders to arbitrarily increase design asphalt binder content by as much as 0.2 to 0.3 percent to address concerns of lean mixtures and subsequent early cracking. A simple way of looking at this is to recognize that at a given total asphalt binder content, a neat asphalt binder results in a higher $V_{be}$ than a GTR-modified asphalt binder at the same total asphalt binder content. This is logical because a portion of the GTR modifier is an inert material. Another way of presenting the same concept is simply to view a portion of the GTR modifier as a filler, that does not contribute to $V_{be}$. Thus, for a given aggregate source and gradation, more total binder is needed for a mixture designed with GTR-modified asphalt binder to provide the same $V_{be}$. This concept is very simple but has not been well recognized when designing mixtures with GTR-modified asphalt binders.

### *Wet Process*

**Dense-Graded Mixtures**

Addition of GTR, specifically the wet process using AR and RMB technologies, generally raises optimum asphalt binder content and lowers laboratory stability results in dense-graded asphalt mixtures, regardless of mix design methodology. This is a result of AR binder having higher viscosity relative to conventional asphalt binder preventing close packing of aggregate, there-by needing more binder to get the same level of voids in total mixture (VTM).

GTR used in DGA mixtures is typically in the form of AR binder technology with reduced GTR concentration (maximum 10 percent) or RMB technology of a similar GTR concentration. Reduced GTR concentration of these asphalt binders, with well incorporated GTR particles, allow for substitution of the RMB or AR binder in place of the standard asphalt binder into the mixture. Use of AR binders, with higher GTR concentration, in DGA is not common but may occur. This involves selection of an aggregate gradation with higher voids in the mineral aggregate (VMA) to make room for swollen GTR particles. Recalling that rubber particles may swell as much as five times their original size, if these soft swollen particles bridge aggregate-aggregate interaction, compaction may be an issue.[2,48,89] The supplier should provide information and recommendations on the handling, storage, and mixture production temperatures for RMB and AR binder.

Depending on GTR content and asphalt binder compatibility, AR and RMB binders may have much higher viscosities than typical polymer modified binders. The overall effects of GTR-modified asphalt binder in DGA mixtures may vary based on binder compatibility, aggregate, and overall gradation. This may involve slightly increased binder contents in the mixture to produce similar design air voids. Additionally, in some fine-graded dense asphalt mixtures, reduction of the fine aggregate portion may help compensate for increased asphalt binder content. Directly substituting the GTR-modified asphalt binder for a polymer modified asphalt binder may not always provide the same mix properties. Product specific mix designs and mixture performance testing should be considered to better evaluate the expected mixture performance.

**Gap-Graded Mixtures**

Gap-graded asphalt mixtures are typically used in place of dense-graded mixtures with AR technology at higher GTR concentrations (15 to 22 percent). A portion of the fine aggregates is removed to allow room for the rubber particles within the gradation. Gap-graded mixes with AR binders are designed to have binder contents in the 6 to 8 percent range. As stated, Marshall, Hveem, or Superpave mix design methods have been used for mixture design, with design air voids varying based on agency specifications. For example, Arizona agencies design these mixes for 5 percent air voids and California designs for 3 to 4 percent air voids. The specified VMA is also significantly higher because of the high binder contents.

**Open-Graded Mixtures**
Open-graded asphalt mixtures represent one of the most common uses of wet process GTR-modified asphalt binder, especially with high GTR concentration AR technology. These OGFC mixtures are used to promote rapid drainage of water from the pavement surface to reduce splash and spray, as well as to reduce tire-pavement noise. Design processes for these mixtures typically involve using a standard open-graded gradation band and specified minimum asphalt binder content. An asphalt binder drain down test is used to make sure the asphalt binder does not flow off the aggregate during normal production, placement, and compaction operations. Binder stabilizing agents such as cellulose fibers may be used to aid in resistance to asphalt binder drain down. Additionally, higher viscosity provided by GTR-modified asphalt binder serves to lessen issues with drain down due to thicker films; therefore, higher GTR content and a more compatible binder/GTR may help increase viscosity.

### *Dry Process*

Dry process GTR-modified asphalt mixtures have been designed using standard Marshall, Hveem, and Superpave methods, but the criteria for selecting optimum asphalt binder content are different than typically used with these methods. Typically, laboratory designed asphalt mixtures are prepared by pre-blending heated dry aggregate and rubber followed by addition of asphalt binder. Laboratory stability and stiffness values of dry process modified asphalt mixtures are significantly lower than values of conventional mixtures. As previously stated, there is concern that the dry added GTR may lack enough reaction time to provide the desired viscosity increase. This has led some suppliers and agencies to discuss evaluation of hybrid versions of dry process GTR modification. Hybrid dry process technology is currently being proposed that combines 10 percent concentration of GTR based on asphalt binder volume—as well as lower loadings of GTR (e.g. 5 percent of asphalt binder volume)—with SBS-modified asphalt binders to produce AASHTO M 332 (a private, voluntary standard) PG H, and V grades.

## DISCUSSION

One should note parallels of recycling GTR with recycling of RAP as ingredients in sustainable asphalt pavements. Use of RAP has successfully reduced virgin binder demand as GTR has successfully been used to modify asphalt binder.

Widespread interest in the use of RAP occurred in the early 1970's and was driven by factors such as raw material shortages, increased asphalt binder prices, and pavement disposal restrictions. Over the next few years, this interest dissipated as a lack of understanding of RAP's properties and how to properly utilize these properties to produce asphalt mixtures with adequate performance was lacking.[90] Few engineering driven limits were placed on early RAP usage. Today, RAP use is accepted as a sustainable paving practice that can produce mixtures with good performance, but there are engineering based limits. Howard et al. performed a literature review related to RAP that documents several projects where RAP contents in excess of 25 percent have been successfully used.[91]

Considering GTR's use in asphalt pavements and studying parallels to the history of RAP characterization and performance, one can see that early on there were three primary hypotheses taken with RAP: 1) RAP is an inert black rock; 2) RAP binder is fully re-livened and fully blends with virgin binder; 3) RAP binder is partially re-livened and partially blends with virgin binder. Hypothesis 3 has been shown to be more reasonable over the past several years. Today it is understood that there are numerous factors affecting how RAP performs in mixtures including: binder properties (RAP and virgin), temperature and time factors associated with mixing and transport, mixing energy, and additives (e.g., rejuvenators). Every one of these categories of factors apply to GTR. For example, virgin binder properties affect incorporation of GTR, mixing temperature and time affect dispersion of GTR, and so forth.

Too much RAP or too much GTR can be used if there is not a framework for that quantity of material to be successful in the mixture. Simply placing large quantities of GTR into a mix, but not providing suitable conditions for the GTR to successfully contribute to positive performance is environmentally conscious only when looking back at the landfill, not when looking forward to pavement performance. A lesson can be learned from RAP's history; RAP and GTR are black, but they are not inert. Lessons and experience from RAP's past can benefit GTR's future and help to advance GTR to an efficiently used post-consumer polymer at a faster rate than if the industry did not have the experiences from RAP to draw from. While obvious, the paving industry occasionally needs to be reminded that the same approach to similar problems often leads to the same result.

GTR has been used regionally for approximately 50 years, and modification has ranged from as little as 5 percent to as much as 20 percent of the total binder weight. AR has generally been restricted to use in more gap or open-graded mixtures such as stone matrix asphalt (SMA) and OGFC, with terminally blended RMB and dry-process GTR being expanded to use in DGA mixture applications. Restricted GTR usage has been attributed to volumetric limitations resulting from GTR particle size and content. For example, using GTR-modified asphalt binder with conventional loadings of 10–20 percent of total binder weight and particle sizes ranging from 1.5 mm–420 µm (15–40 mesh) in DGA mixtures creates a dilemma of too much rubber that is too big for the limited binder space available in DGA. Considering that DGA is the most commonly used asphalt mixture it is obvious that DGA presents an opportunity for greater use of GTR nationwide. Lower GTR loadings such as 5 percent in wet processed binders or 5 pounds of rubber per mix ton in dry-process mixtures may provide alternatives suitable for DGA mixture applications. Innovative alternatives using lowered loadings of GTR combined with synthetic polymers, such as SBS, may also provide suitable performance.

GTR can be used to close the price gap between standard grade asphalt binders and modified asphalt binders such as in the case of hybrid binders(67,92). For example, take a PG 67-22 base asphalt binder that was modified to a PG 76-22 with 3 percent SBS. Assuming a 1:1 replacement of GTR effective polymer with SBS (a simplified assumption), 3.0 percent SBS and somewhere around 10 percent GTR should modify the PG 67-22 to PG 76-22.

Aside from simplifying assumptions for discussion purposes, 1 to 2 percent SBS and 3 to 8 percent GTR are reasonable ranges of dosages that should work well in hybrid polymer modification systems(67,92). At these loadings, there is still enough SBS to provide the consistent and desirable behaviors the industry has relied upon for several years, while also getting performance benefits from GTR, reducing binder costs, and being environmentally conscious (i.e., improving engineering, economic and environmental benefits). SBS/GTR loadings in this range are going to be useable in almost any type of DGA (coarse or fine graded), SMA, or

OGFC mixture an entity needs, as the issues documented herein and elsewhere aren't expected at lower total GTR loadings. The maximum amount of SBS replacement should be set with the idea of limiting GTR loadings so that mixture performance is improved and more consistent over time. A hybrid approach with better performance is also likely to increase the approximately 12 percent share of GTR used in asphalt paving.

## SUMMARY

Pneumatic tires are designed to fulfill fundamental functions throughout their useful lives like cushioning, damping, transmitting of torque (driving and braking), dimensional stability, abrasion resistance, efficient rolling resistance, and durability. Lacking the ability to recycle old tires into new tires, there are several common repurposing methods to effectively reuse rubber. Recycling of rubber from old tires may include but is not limited to: TDF, GTR, and CE applications. GTR is the second highest consumer of RTR with uses in:

- Molded and extruded products.
- Playground and mulch applications.
- Sports surfacing.
- Asphalt binder modification.
- Automotive uses.

Addition of GTR to asphalt binder and mixture is an accepted asphalt mixture practice in asphalt production and consumes about 12 percent of the total GTR market today. Modification of asphalt binders with GTR is well established and can provide high performance pavements that aid in reduction of the number of waste tires disposed of in landfills and elsewhere. GTR, as a post-consumer polymer, ranks second among the most common asphalt polymer modifiers behind SBS copolymers. Growth in use of GTR-modified asphalt pavements can be credited to successful construction of high-performance asphalt pavements primarily using GTR-modified asphalt binders produced via two versions of the wet-process: "asphalt rubber," (AR) commonly simply referred to as the "wet process" and "rubber-modified binder" (RMB) also referred to as "terminal blend." A second process known as the dry-process addition of GTR to asphalt mixtures is somewhat in its infancy with current technologies. Current dry-process technologies have generated promising reports from some agencies. Some have also expressed concern with long-term mixture performance, non-load related cracking and low temperature performance. This is likely due to a lack of recognition that with the dry-process effective binder content has to be closely considered. Because GTR contain 0.6 percent inert filler, the total binder content of a GTR-modified asphalt mixture has to be higher than the total binder content with a conventional or SBS-modified asphalt binder.

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## APPENDIX: GLOSSARY OF TERMS

***A***

**Ambient grinding**
A method of processing recycled tire rubber where reduced size scrap tire rubber is ground or processed at or above ordinary room temperature. Ambient processing typically provides irregularly shaped, torn particles with relatively large surface areas.

**Ambient Ground Rubber**
Result of processing where recycled tire rubber is ground or processed at or above ordinary room temperature.

**Asphalt**
A dark brown to black cementitious material, solid or semisolid in consistency, composed predominately of bitumen which occurs in nature or are obtained as residua in petroleum refining.

**Asphalt-rubber**
An asphalt binder in various types of flexible pavement construction including surface treatments and hot mixes consisting of a blend of asphalt cement, reclaimed tire rubber, and certain additives in which the rubber component is at least 15 percent by weight of the total blend and has reacted in the hot asphalt cement sufficiently to cause swelling of the rubber particles.

**Asphalt-rubber asphalt concrete (ARAC)**
Consists of asphalt-rubber binder hot mixed with a gap graded aggregate. The resultant mixture is placed as a final wearing surface or base support layer. It is generally placed from 1-2 inches (25 to 50 mm) in thickness.

**Asphalt-rubber friction course (ARFC)**
Asphalt-rubber friction course which consists of asphalt-rubber hot mixed with an open graded aggregate. The resultant mixture is placed as a final wearing course. It is generally placed 0.5 to 1.0 inch (12.5 to 25 mm) in thickness.

**Asphalt-rubber gap graded mix**
Consists of asphalt rubber binder hot mixed with a gap-graded aggregate. The resulting mixture is placed as a final wearing surface or base support layer. It is generally placed from 1–2 inch (25 to 50 mm) in thickness.

**Asphalt-rubber Type 1**
Asphalt and crumb rubber from scrap tires only and no other additives, modifiers or extenders.

**Asphalt-rubber Type 2**
Consists of a maximum of 85 percent asphalt combined with a minimum of 15 percent rubber. The rubber portion consists of 75 percent crumb rubber from scrap tires and 25 percent from a high natural rubber source. An extender oil is added to the combination of asphalt and rubber.

The amount of extender oil is generally about 2 percent of the total mixture. Type 2 is primarily used in California.

**Automobile tires**
Tires with an outside diameter less than 26 inch (660 mm) used on automobiles, pickups, and light trucks.

***B***

**Bitumen**
Dark brown to black cement-like residuum obtained from distillation of suitable crude oils. Outside the U.S., bitumen is the liquid asphalt binder (asphalt cement in the U.S.) comprised of any of various natural substances, consisting mainly of hydrocarbons.

***C***

**Course rubber**
"Course" rubber or course tire rubber is one of two classes of particle sizes in the crumb tire rubber market, derived from the recycling of scrap tires, which is larger than 2.0 mm (10 mesh), with a maximum size of 12.75 mm (0.5 inch).

**Continuous-blend Rubber Modification (CRM)**
A general term for ground tire rubber (GTR) modified asphalt binder using reduced size (80 mesh) GTR as a paving asphalt binder modifier. Finer grind GTR than that of the conventional asphalt rubber (AR) process and asphalt binder are continuously blended and stored in tanks.

**Cryogenic/Cryogenic grinding**
A method of processing recycled tire rubber where reduced size scrap tire rubber is ground or processed by freezing the scrap tire rubber and crushing the rubber to the desired particle size. The process uses liquid nitrogen to freeze the scrap tire rubber until it becomes brittle and then uses a hammer mill to shatter the frozen rubber into smooth particles with relatively small surface area. This method is sometimes used to produce reduced size scrap tire rubber prior to grinding at ambient temperatures.

***D***

**Dense-graded aggregate**
Refers to a continuously graded aggregate blend typically having particle size distribution that upon compaction results in air voids between aggregate particles that are relatively small, expressed as a percentage of the total volume occupied by the material. Used to make hot-mix asphalt concrete with conventional or modified asphalt binders.

**Devulcanized rubber**
The term used to describe rubber that has been subjected to treatment by heat, pressure, or the addition of softening agents after grinding to alter physical and chemical properties of the recycled material during reclaiming. Technically a misnomer since vulcanization is irreversible.

**Dry Process**
A process where hot-mix asphalt mixture is modified with ground tire rubber (GTR), using GTR as an aggregate/binder modifier which is incorporated into aggregate prior to mixing with asphalt binder, producing a rubber modified hot-mix asphalt concrete. GTR used in this process is generally less than 0.6 mm (30 mesh).

***E***

**Extender oil**
A low-gravity material, typically aromatic oil, used to promote the reaction of the asphalt cement and the recycled tire rubber modifier.

***G***

**Gap-graded aggregate**
Aggregate that is not continuously graded for all size fractions, typically lacking or low on one or two of the finer sizes. Used to promote stone-to-stone contact in hot-mix asphalt concrete. This type of gradation is most frequently used to make rubberized asphalt concrete-gap graded mixtures. Referred to in Arizona as asphalt-rubber asphalt concrete (ARAC) and in California as rubberized asphalt concrete gap-graded (RAC-G) paving mixture.

**Ground tire rubber (GTR)**
"Ground" rubber or ground tire rubber is one of two classes of particle sizes in the crumb tire rubber market, derived from the recycling of scrap tires, which is 2.0 mm (10 mesh) and smaller.

***H***

**Hot-mix asphalt (HMA)**
Result of mixing asphalt and aggregate at elevated temperature and placing the resultant mix as the asphalt pavement.

**High natural rubber**
Scrap rubber product that includes natural rubber or isoprene and a rubber hydrocarbon. Sources of high natural rubber include scrap tire rubber from some types of heavy truck tires, scrap from tennis balls, and mat rubber.

***I***

**Interaction**
Commonly used term for the interaction between asphalt binder and crumb rubber modifier when blended together at elevated temperatures. The reaction is more appropriately defined as polymer swell. It is not a chemical reaction. It is a physical interaction in which the crumb rubber absorbs aromatic oils and light fractions (small volatile or active molecules) from the asphalt binder, and releases some of the similar oils used in rubber production into the asphalt binder.

***O***

**Open-graded aggregate**
Aggregate gradation that is intended to be free draining. Consisting mostly of two or three sizes of aggregate particles with few fines and 0 to 4 percent by mass passing the No. 200 (0.075 mm) sieve.

**Open-graded friction course (OGFC)**
Friction course typically used on high speed roadways, asphalt to provide relatively thin surface or wearing courses with good frictional characteristics that quickly drain surface water to reduce hydroplaning, splash, and spray.

***P***

**Performance Grade (PG)**
A form of American Association of State Highway Transportation Officials (AASHTO) specified grading of asphalt by the climatic zone such that the asphalt meets the needed properties for the climatic zone.

***R***

**Rubber Asphalt Foundation (RAF)**
Rubber Asphalt Foundation located in Scottsdale, Arizona.

**Reaction**
The interaction between asphalt cement and crumb rubber modifier (CRM) when blended together at a certain temperature for a certain period. The reaction, more appropriately defined as polymer swell, is not a chemical reaction. It is the absorption of aromatic oils from the asphalt cement into the polymer chains of the crumb rubber.

**Recycled tire rubber (RTR)**
Reduced size rubber obtained by processing used automobile, truck, or bus tires (essentially highway or "over the road" tires).

**Rubber Pavements Association (RPA)**
Rubber Pavements Association located in Tempe, Arizona.

**Rubber Aggregate**
Crumb rubber modifier added to hot mix asphalt mixture using the dry process which retains its physical shape and rigidity.

**Rubber-modified asphalt**
General term that refers to a broad family of asphalt binder products that contain ground tire rubber (GTR). Also used to describe wet-process terminal blended recycled tire rubber (GTR) modified asphalt binders.

**Rubber-modified asphalt concrete**
Hot mix asphalt concrete mixture with dense graded aggregates using a rubberized asphalt type of asphalt binder. (Note: The ground tire rubber (GTR) percentage is generally low (5 to 10 percent) and is generally the finer mesh (30 mesh size or smaller).

**Rubber-modified asphalt technologies**
Term used to refer to any technology that uses ground tire rubber (GTR) in asphalt pavements.

**Rubber-modified binder (RMB)**
Synonymous with terminal blend. A version of wet process where ground tire rubber (GTR) is blended with hot asphalt binder at the refinery or at an asphalt binder storage and distribution terminal and transported to the asphalt concrete mixing plant or job site for use. These blends may contain from 5 to 12 percent GTR by total asphalt binder mass. Some hybrid terminal blend asphalt binders may contain polymers such as styrene-butadiene-styrene (SBS) in addition to GTR

**Rubberized asphalt**
Refers to a broad family of asphalt binder products that contain ground tire rubber (GTR). Terminology often used for virtually any asphalt binder that contains some amount of ground tire rubber derived from scrap tires.

**Rubberized asphalt concrete (RAC)**
Caltrans terminology for a material produced for hot mix applications by mixing asphalt-rubber or rubberized asphalt binder with graded aggregate. RAC may be dense-, gap-, or open-graded.

***S***

**Sieve Sizes**
Sieve sizes various nomenclature in accordance with ASTM E11.

| Sieve Designation | | Nominal Sieve Opening |
|---|---|---|
| Standard | U.S. Alternative | |
| 25 mm | 1 inch | 1.00 inch |
| 19 mm | 3/4 inch | 0.750 inch |
| 12.5 mm | 1/2 inch | 0.500 inch |
| 9.5 mm | 3/8 inch | 0.375 inch |
| 6.4 mm | 1/4 inch | 0.250 inch |
| 4.75 mm | No. 4 | 0.187 inch |
| 2.36 mm | No. 8 | 0.0937 inch |
| 2 mm | No. 10 | 0.0787 inch |
| 1.68 mm | No. 12 | 0.0661 inch |
| 1.18 mm | No. 16 | 0.0469 inch |
| 0.8 mm | No. 20 | 0.0331 inch |
| 0.6 mm | No. 30 | 0.0234 inch |
| 0.4 mm | No. 40 | 0.0165 inch |
| 0.3 mm | No. 50 | 0.0117 inch |
| 0.15 mm | No. 100 | 0.0059 inch |
| 75 micron | No. 200 | 0.0029 inch |

**Stress-absorbing membrane (SAM)**
A stress absorbing membrane used primarily to mitigate reflective cracking of an existing distressed asphalt or rigid pavement. It is usually associated with an asphalt-rubber binder sprayed on an existing pavement surface at 0.60 gallons per square yard (2.9 liters per square meter) and immediately followed by an application of a uniform pre-coated aggregate, which is then rolled, embedding the aggregate into the asphalt binder layer. The nominal thickness normally ranges between 1/4 and 3/8inch (6 and 9 mm).

**Stress absorbing membrane interlayer (SAMI)**
A stress absorbing membrane is a ground tire rubber (GTR) modified asphalt membrane interlayer beneath an overlay designed to resist the stress strain of reflective cracks and delay propagation of cracking through the overlay. The term SAMI has also been used to include an interlayer of GTR-modified asphalt chip seal (SAMI-R), fabric (SAMI-F), or fine unbound aggregate.

***T***

**Terminal blend**
A version of wet process where ground tire rubber (GTR) is blended with hot asphalt binder at the refinery or at an asphalt binder storage and distribution terminal and transported to the asphalt concrete mixing plant or job site for use. These blends may contain from 5 to 12 percent GTR by total asphalt binder mass. Some hybrid terminal blend asphalt binders may contain polymers such as styrene-butadiene-styrene (SBS) in addition to GTR.

**Thermoplastic**
Substances (especially polymers) that soften or become plastic on heating and harden or return to original condition on cooling and can repeat these processes

**Thermoset**
Substances (especially polymers) that solidify or "set" irreversibly when heated. This property is usually associated with a crosslinking reaction as in the case with vulcanized rubber.

**Truck tires**
Tires with an outside diameter greater than 660 mm (26 inches) and less than 60 inches (1520 mm) used on commercial trucks and buses.

***V***

**Vulcanization**
A physiochemical change resulting from cross-linking of the unsaturated hydrocarbon chain of polyisoprene (rubber) with sulfur, usually with the application of heat.

**Vulcanized rubber**
A crude or synthetic rubber that has been subjected to treatment by chemicals (primarily sulfur), heat and/or pressure to improve physical properties and performance. The odor of recycled tire rubber (RTR) is associated with the use of sulfur in the vulcanized rubber.