Recycled Tire Rubber – Hybrid GTR Binders and Dry Added GTR – How to use them in Asphalt Pavement Mixtures

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FOREWORD

Traditional mix design procedures, Marshall, Hveem and Superpave, have been used to design mixtures containing wet process ground tire rubber (GTR) modified binders as well as asphalt mixtures containing dry added GTR. However, volumetric mixture designs alone may not provide mixtures with desired overall performance. The Balanced Mix Design (BMD) approach may be an acceptable alternative for design and evaluation of GTR modified systems. Addition of GTR, specifically with asphalt rubber (AR) binders, may raise the optimum binder content and impact mechanical property results in dense-graded asphalt (DGA) mixtures, regardless of mix design methodology. This is the reason AR is commonly used in gap-graded mixtures such as stone matrix asphalt (SMA) and open-graded mixtures such as open-graded friction courses (OGFC). This phenomenon may not hold true with mixtures designed with terminal blend rubber modified binder (RMB), hybrid GTR, or dry added GTR.

Depending on GTR loading, RMB, hybrid GTR, and dry added GTR may yield GTR modified systems suitable for gap-graded mixtures (SMA), open-graded (OGFC) mixtures, and DGA mixtures. This technical report provides a review and update on use of RMB, hybrid GTR, and dry added GTR in production of asphalt mixtures. Consideration for responsible use of GTR to promote sustainability in DGA, SMA, and OGFC asphalt pavements is given. Additional detailed information can be obtained from Federal Highway Administration (FHWA) publication FHWA-HIF-14-015, 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.

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16. Abstract

Addition of ground tire rubber (GTR) to asphalt binder and mixture is an asphalt mixture practice in asphalt production that consumes about 16.5 percent of the total ground tire rubber (GTR) market today. Modification of asphalt binders and mixtures 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. Dense-graded asphalt (DGA), stone-matrix asphalt (SMA) and open-graded friction course (OGFC) with asphalt rubber (AR), terminal blend rubber modified binder (RMB), hybrid GTR, and dry addition of GTR can be designed with standard Marshall, Hveem, and Superpave mixture design methods. This report presents a review and update of the various mixture design processes for use in designing DGA, SMA, and OGFC mixtures with RMB, hybrid GTR, and dry added GTR in production of asphalt pavements. The objective is to provide knowledge for resource responsible use of RMB, hybrid GTR, and dry added GTR to ensure engineering performance in asphalt pavements and inform environmental benefits through life cycle assessment. The scope of this report is limited to use of GTR from whole scrap tires through size reduction and grinding to the particle size range defined by industry as GTR. The report includes information related to design of DGA, SMA, and OGFC mixtures using RMB, hybrid GTR, and dry added GTR and testing of mixtures containing 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
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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LIST OF ABBREVIATIONS AND SYMBOLS

Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
AR	asphalt rubber
ARGG	asphalt rubber gap-graded
BMD	balanced mix design
CE	civil engineering
DGA	dense-graded asphalt
DOT	Department of Transportation
FHWA	Federal Highway Administration
GTR	ground tire rubber
HWTT	Hamburg Wheel-Track Testing
JMF	job mix formula
LCA	life-cycle assessment
NCHRP	National Cooperative Highway Research Program
OBC	optimum binder content
OGFC	open-graded friction course
PG	Performance Grade
PTSi	Paragon Technical Services, Inc.
RAP	reclaimed asphalt pavement
RMB	rubber-modified binder
RTR	recycled tire rubber
SBS	styrene-butadiene-styrene
SMA	stone matrix asphalt
TGA	thermo-gravimetric analysis
UNR	University of Nevada, Reno
U.S.	United States
USTMA	U.S. Tire Manufacturers Association
VMA	voids in the mineral aggregate
VTM	voids in total mixture

Symbols

G_{mb}	mixture specific gravity
V_{be}	effective binder volume
V_{GTR}	total volume of GTR
$V_{GTR\text{-}Inert}$	volume of inert filler
$V_{GTR\text{-}Polymer}$	volume of functional polymer
V_{sb}	bulk stone volume
V_T	total volume

INTRODUCTION

In 2019, markets for scrap tires were consuming just over 3.3 million tons (205.9 million scrap tires), or 75.6 percent, of the estimated 4.5 million tons (272.4 million scrap tires) of scrap tires generated annually. (1) Estimates are that only about 15.2 percent, of the scrap tires generated, approximately 684 thousand tons (41.4 million scrap tires) are disposed of in landfills. The ground tire rubber (GTR) market is reported to represent approximately 1.1 million tons of total scrap tire consumption or about 66 million scrap tires. (1) GTR is commonly used as a modifier for asphalt binders in highway construction (e.g., asphalt mixtures and maintenance products). GTR-modified asphalt pavements represent 16.5 percent, or approximately 180 thousand tons (11.0 million scrap tires) of the United States GTR market annually. (1)

Recycling of waste rubber from tires involves reduction of tire rubber into smaller particle size referred to as reduced size rubber or crumb rubber. The ground rubber market further grinds crumb rubber into two classes according to particle size: "ground" rubber (referred to herein as GTR) which is 2.0 mm (10 mesh) or smaller and "coarse" rubber which is larger than 2.0 mm (10 mesh). (2) While GTR has, at times, been referred to as "crumb rubber," in order to maintain consistency with previous publications (3) and limit confusion of terminology, this report adheres to use of "GTR" as the terminology to describe reduced size rubber (less than 2.0 mm (10 mesh)) typically used in modification of asphalt binders and asphalt mixtures.

Currently, there are two primary processes of incorporating GTR into asphalt binders and mixtures, referred to as either "wet" or "dry" The wet process blends GTR and asphalt with one of two technologies, asphalt rubber (AR) and rubber modified asphalt binder (RMB). RMB technology may also be referred to as "terminal blend." Conventional RMB consists of GTR modified asphalt binder containing only GTR as the binder modifier. A more "terminal blend" technology referred to herein as "hybrid GTR" utilizes a combination of GTR and other modifiers such as Styrene-Butadiene-Styrene (SBS). Dry process technologies, in contrast to the wet process technologies, incorporate 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.

AR is generally produced on-site at the asphalt mixture plant with a prescribed reaction time prior to mixing the GTR-modified asphalt binder with aggregate. AR technology is a batch process consisting of blending from 10 to 22 percent GTR, by weight, with asphalt binder. The typical GTR particle size is a maximum of around 1.5mm or (15 mesh). Processing temperatures range from 175°C to 190°C (≈ 350°F to 375°F) allowing the GTR and asphalt binder to react for from 30 to 60 minutes before introduction into the asphalt mixture production process.(6,7,8,9,10,9,10) This process is typically 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 asphalt mixture 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.

RMB and hybrid GTR, alternative wet process technologies to the AR technology, are produced at the asphalt binder supply terminal and shipped to the asphalt mixture production plant to be mixed with aggregate as with conventional asphalt binders and polymer modified asphalt binders. As stated, RMB technology is also commonly referred to as "terminal blend." (11) RMB or terminal blended GTR-modified asphalt is produced in a similar manner to AR, except that production occurs in fixed blending facilities with smaller sized GTR particles and generally lower GTR dosage rates. Generally, RMB consists of blending from 5 to 15 percent GTR of a size range from 600 µm to 420 µm (30 mesh to 40 mesh) with asphalt binder at temperatures ranging from 175°C to 190°C (≈ 350°F to 375°F) and allowing them to react for from 60 to 120 minutes prior to transfer to large storage tanks. Once the GTR and asphalt binder are mixed, and specification properties are achieved, 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. Production and processing of hybrid GTR technology is identical to RMB utilizing GTR of a similar particle size. However, hybrid GTR formulations typically have lower GTR content, in the range of 3 to 8 percent, plus an additional synthetic polymer modifier such as SBS added at a rate from 1 to 2 percent. Hybrid GTR asphalt binders are stored and shipped in the same manner as RMB, and polymer modified asphalt binders.

Dry addition technologies of GTR typically incorporate GTR of a particle size ranging from 600 to 420 µm (30 mesh to 40 mesh). Dry added GTR concentration is generally less than the upper limits of AR and RMB technologies with dry GTR maximums at approximately 10 percent by weight of the asphalt binder. This 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. Dry processes often contain additional additives such as polymers or waxes to provide improved mixing and compaction characteristics. (12,13) In some cases, these additives are believed to do more for improving mixing and compaction than modifying the base asphalt binder.(14)

Potential benefits of GTR modified asphalt binders and asphalt mixtures, in addition to reuse of waste tires, are longer lasting roads, reduced maintenance, and improved life-cycle costs.

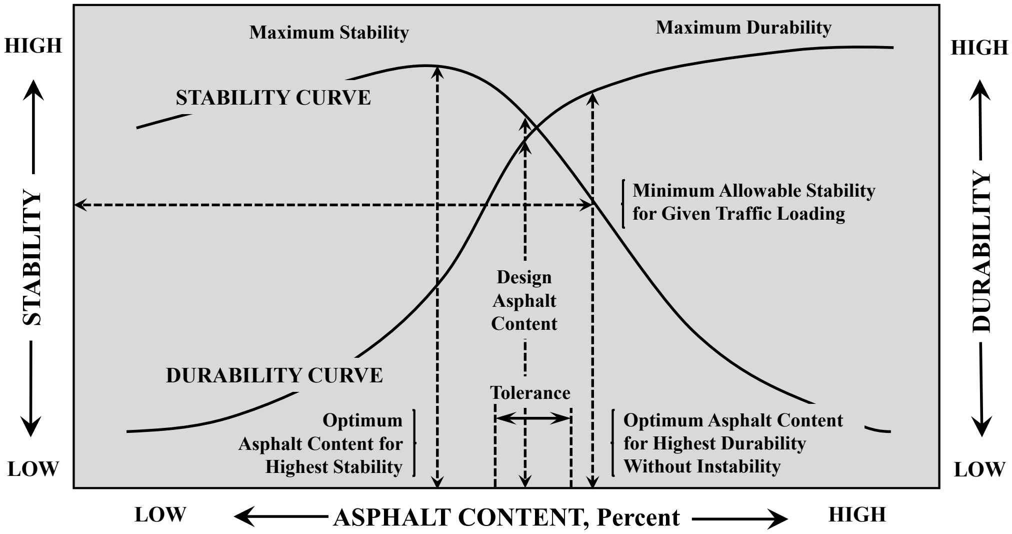
BACKGROUND

Modern GTR use in paving began in the early 1960s with a highly elastic AR modified chip seal developed for the city of Phoenix, Arizona.(4) This work expanded into larger chip seal projects along with other crack relief interlayers, and open-graded surface course (OGFC) applications.(15) In the following two decades, 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, earlier versions of dry mixture addition of GTR to asphalt mixtures had only limited success compared to the dry process GTR technologies employed today.

Interest in GTR modified asphalt pavements since the early 1960's can be credited to successful production and use of AR and RMB binders in improved performance asphalt mixtures. Even dry added GTR, having limited success in the past, has recently been employed to recycle GTR by dry addition of rubber in the hot mix asphalt mixture with greater success than previously observed. Research on GTR-modified asphalt binders over the last 50 years has shown favorable impacts of GTR modification. In fact, GTR ranks second among the most common asphalt polymer modifiers, just behind styrene-butadiene-styrene (SBS) block copolymers.

Three general asphalt mixture types are used for production of GTR-modified asphalt pavements: dense-graded, gap-graded, and open-graded.(16) Traditional Marshall, Hveem and Superpave mix design procedures have been used with modifications to test methods and design criteria to design mixtures containing AR, RMB, hybrid GTR, and dry addition of GTR.(17,18,19,20,21) It should be noted that volumetric mixture designs alone may not provide mixtures with desired overall performance with all of the GTR modification modes presented. A Balanced Mix Design (BMD) approach incorporating performance testing, discussed later in this report, may be more appropriate for design and evaluation of some GTR modified technologies. (22,23,24)

Regardless of design method or application, design of asphalt mixtures is a balancing act combining selection of aggregates and asphalt binder proportioned to provide desired performance. Asphalt mixtures are designed to provide workability necessary to construct an in-place pavement resistant to permanent deformation, fatigue, low-temperature cracking, and moisture damage, as well as provide a skid resistant smooth riding durable surface. Of primary importance in achieving the overall performance goal, or effective asphalt mixture design is asphalt binder content. As presented in Figure 1, asphalt binder content is an important factor in design of all asphalt mixtures. Excess asphalt binder content may lead to stability issues, or mixtures susceptible to permanent deformation, while insufficient asphalt binder content can be a cause of durability issues such as premature pavement cracking.



Source: Paragon Technical Services, Inc. (22)

Figure 1. Balanced asphalt mixture design for balanced performance.

Most State DOTs use the Superpave method as specified in the American Association of State Highway and Transportation Officials (AASHTO) R 35, *"Standard Practice for Superpave Volumetric Design for Asphalt Mixtures"* (20) and AASHTO M 323, *"Standard Specification for Superpave Volumetric Mix Design"* (21) to identify the optimal aggregate blend and optimum asphalt binder content. A few still rely on earlier methods such as the Hveem and Marshall methods of mixture design or employ local modifications or adjustments to AASHTO standards. Use of the AASHTO standards listed here are not Federal requirements.

However, the public's concern typically is not about design of asphalt mixture but about a smooth, comfortable ride and desirable performance over an extended pavement life at a competitive price and minimal environmental footprint. Material selection and mixture design are important elements in meeting these demands.

MIXTURE TYPES

Dense-Graded

Depending on GTR content and asphalt binder compatibility, AR, RMB, and hybrid GTR binders may have much higher viscosities than typical polymer modified binders. The overall effects of GTR-modified asphalt binder in dense graded asphalt (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 or intermediate/low temperature performance. Additionally, in some fine-graded dense asphalt mixtures, reduction of the fine aggregate portion may help facilitate 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.

Addition of GTR, specifically using AR, RMB, and hybrid GTR binder technologies, generally increases optimum asphalt binder content and lowers laboratory stability results in DGA mixtures, regardless of mix design method. AR, RMB, and hybrid GTR binders have higher viscosity relative to conventional asphalt binder preventing close packing of aggregate, so more binder is needed to get the same level of air voids in compacted mixture. This is typically not the case with dry added GTR in DGA. Since asphalt binder contents in DGA mixtures with dry added GTR are designed with a target binder content, the GTR, which is not counted as part of the binder, has minimal effect on binder viscosity or voids in total mixture (VTM).

High viscosity AR binder produced with larger GTR particles and higher GTR loadings (15 mesh at greater than 10 percent loading) is typically not used in DGA, unless the DGA gradation is opened up to provide room for the rubber particles. Otherwise there may not be sufficient void space to accommodate enough of the AR binder to significantly improve performance of the resulting pavement. (25) However, dense gradations may be well suited for use with AR binder produced with smaller GTR particles and lower GTR loadings. AR used in DGA mixtures is typically with reduced GTR particle size and concentration (30 mesh at a maximum of 10 percent loading). (26)

RMB technology and hybrid GTR binder are also used in DGA. Reduced GTR particle size and concentration (30 mesh at a maximum of 10 percent loading) of these asphalt binders can allow for substitution of the AR, RMB, or hybrid GTR binder in place of the standard asphalt and modified asphalt binder into dense-graded mixture. Use of AR, RMB, or hybrid GTR binders, with higher GTR concentration (greater than 10 percent) in DGA is not common but may occur. This typically involves selection of an aggregate gradation with higher voids in the mineral aggregate (VMA) to make room for swollen GTR particles. Even with AR of smaller particle size and lower content and RMB, fine graded dense mixtures may lack sufficient void space to accommodate the GTR modified asphalt binder. Considering that rubber particles may swell as much as five times their original size (3), if these soft swollen particles bridge aggregate-aggregate interaction, compaction may be an issue. (10,27) Increasing the VMA through removal of some of the fine aggregate to create space can accommodate the GTR modified asphalt binder allowing significant void space to provide improved performance of the resulting mixture. The asphalt binder supplier should provide information on the handling, storage, and mixture production temperatures for AR, RMB, or hybrid GTR binders.

Gap-Graded

Stone-matrix asphalt (SMA) is often used in place of dense-graded mixtures with AR technology. Other examples of gap-graded mixtures, asphalt rubber gap-graded (ARGG) mixtures, are also used. (28) The AR binders are usually at higher GTR concentrations (15 percent to 22 percent). RMB, hybrid GTR, and dry added GTR may be used in gap-graded mixtures as well, though they may have lower GTR concentrations (8 percent to 15 percent).

The SMA mixtures typically have a higher coarse aggregate content with asphalt binder contents greater than six percent. The mixture design procedures for gap-graded and SMA mixtures are similar to those used for dense-graded mixtures. Marshall or Superpave mix design methods have been used with design air voids varying based on agency specifications. Gap-graded mixtures typically involve removal of a portion of the fine aggregates to allow room for the rubber particles and/or inert material within the gradation. Gap-graded and SMA mixtures with AR binders, RMB, hybrid GTR, and dry added GTR are typically designed to have binder contents greater than 6 percent.

SMA mix designs typically have coarse stone-on-stone contact allowing for higher asphalt binder contents. GTR modified SMA mixtures are typically stiffer than conventional dense-graded mixtures and may involve higher temperatures and more mixing time. Asphalt binder drain-down can be an issue with these mixtures. Stabilizing additives, typically cellulose fibers can be incorporated to aid in prevention of the tendency of drain-down due to higher asphalt binder contents. Addition of GTR as an asphalt binder modifier may help prevent drain-down; however, State DOTs may also require use of fibers in SMA mixtures.

Open-Graded

Open-graded asphalt mixtures, such as OGFC, consist of hot-mix asphalt mixtures designed to have very high air voids, compared to conventional DGA, to aid in drainage of water through the mixture, as well as to reduce tire-pavement noise. Increased air voids are provided through use of a higher percentage of coarse aggregate. A relatively low surface area of the coarse aggregate fraction results in a significantly higher asphalt binder film thickness with only slightly higher asphalt binder content.

Modified asphalt binders are typically used to improve the asphalt binder's ability to bind and stabilize the coarse aggregate structure. OGFC mixtures represent one of the most common uses of AR binders and RMB, especially with higher GTR concentrations (15 percent to 22 percent); however, lower concentrations (10 percent to 15 percent) and hybrid GTR binders have also been employed.

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. As with SMA mixtures, binder stabilizing agents may be used to reduce asphalt binder drain down. Higher viscosity provided by GTR-modified asphalt binder can reduce drain down due to thicker films.

BINDER STABILIZING AGENTS

In some cases, binder stabilizing agents, most often fibers, have the potential of reinforcing and improving cohesion and tensile strengths of asphalt mixtures. These agents permit higher asphalt content than in conventional asphalt mixtures without significant drain-down issues. These benefits are especially important for SMA and OGFC mixtures. Thicker asphalt binder films provided by increased asphalt binder content enhance the durability of these mixtures. Oil extenders may also be added to the finder formulation, typically in the base binder, to aid in incorporation of the GTR into the binder formulation for enhancement of viscosity.

Most often, fibers such as cellulose, mineral, polypropylene, and polyester can be used at a mixture addition level of 0.1 percent to 0.4 percent, depending on the stabilizing agent and mixture type. Though use levels of binder stabilizing agent may be low, there is a significant effect on mixture properties with respect to binder viscosity, drain-down resistance, and mixture durability. These additives are generally added at the mixture production plant. Incorporation and effects on mixture placement can sometimes lead to a desire to forego addition of these binder stabilizing agents. However, consideration of improvement in drain-down resistance as well as mixture durability is important. AASHTO TP 108 *Abrasion Loss of Asphalt Mixture Specimens,* commonly referred to as the "Cantabro Mass Loss Test," a method developed to evaluate the cohesiveness and durability of OGFC mixtures. This test has also been used to evaluate dense-graded and gap-graded mixtures as well. (29) AASHTO TP 108 is a voluntary standard; its use is not a Federal requirement.

MIXTURE DESIGN CONSIDERATION

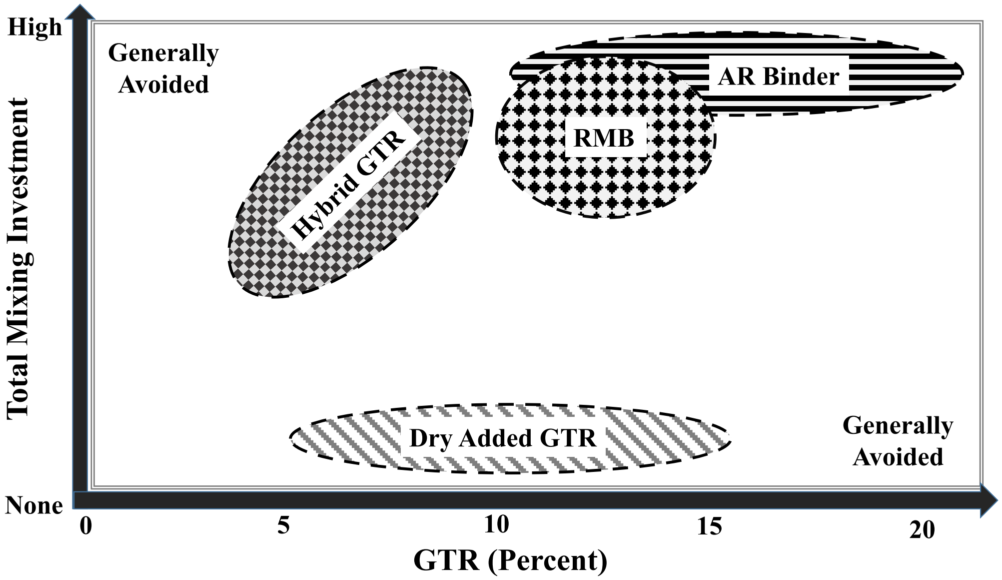
GTR modified asphalt binders are dispersions of GTR particles into asphalt binder. When GTR particles are dispersed in hot asphalt binder they absorb lighter components of the asphalt binder thereby swelling particles to as much as five times original size. (27) A number of factors affect the interaction between GTR and asphalt binder. They include blending time, blending temperature, relative surface area (particle size and texture), as well as compatibility between GTR and asphalt binder.

Due to vulcanization, GTR is a thermoset polymer, more specifically a thermoset elastomer. This means that GTR does not melt at normal modified asphalt binder or modified asphalt mixture processing temperatures. When polymers dissolve, the first step is a swelling process called solvation. Linear and branched polymers further dissolve in a second step; however, cross-linked polymers, like GTR, remain in a swollen condition. Swelling due to solvation causes the GTR to form a gel-like material in the asphalt binder. (3,8,27,29,30) Dispersion and solvation are primarily responsible for the increased stiffness and elastic nature imparted to asphalt binder from GTR modification. The effect of GTR on asphalt binder is highly dependent on proper dispersion and solvation in the asphalt binder. These GTR modified asphalt binder properties directly affect asphalt mixture performance.

Volumetric Properties

A number of factors influence GTR particle-asphalt interaction, a number of which are interrelated. When GTR modified asphalt binder or GTR is introduced into an asphalt mixture, several factors should be considered by the mixture designer. The most obvious of these factors is the amount or loading of GTR incorporated, as illustrated on the horizontal axis of Figure 2. Other factors are related to how much investment would be involved in incorporating the GTR into the final asphalt mixture, as illustrated on the vertical axis of Figure 2. Investment relates to incorporation of GTR into asphalt mixture as a function of: 1) GTR particle size; 2) processing conditions (agitation/mixing level); 3) processing temperature; and 4) processing time. Generally, smaller particle sizes processed at higher temperatures for longer times, under higher shearing conditions, result in greater incorporation of GTR's performance properties into an asphalt mixture. All of these factors directly affect asphalt mixture performance, irrespective of the asphalt mixture design method employed. The amount of GTR is the only factor that can be accounted for with volumetric principles during asphalt mixture design.

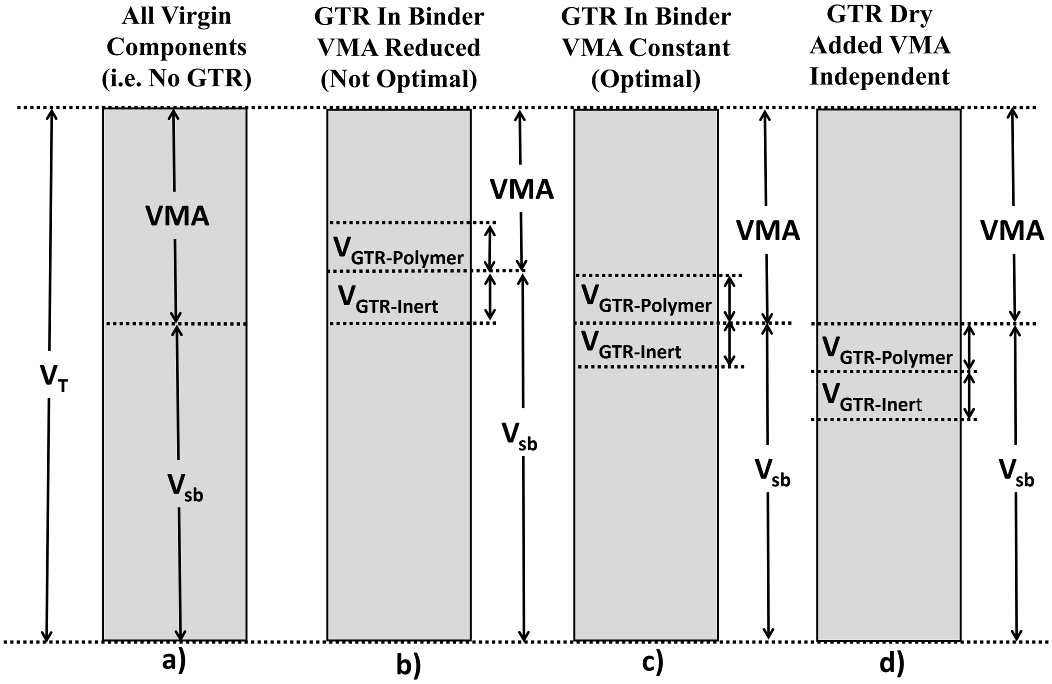
The area in the lower right portion of Figure 2, labeled "Generally Avoided," results from possible lack of success of earlier dry processes. These processes may have used too much GTR or GTR with too large particle size.



Source: Paragon Technical Services, Inc.

Figure 2. Space diagram of GTR use in asphalt mixtures.

Figure 3 is a simplified phase diagram showing volumetric conditions of interest relative to GTR modified asphalt mixture design with a total volume (V_T). Figure 3a is a reference case with no GTR or other recycled material, which is the scenario for which volumetric asphalt mixture design was originally developed. In pure form, an asphalt mixture's total volume is defined by the bulk volume occupied by stone (or equivalent inert material) that is denoted by (V_{sb}), plus the voids in mineral aggregate (VMA). V_{sb} encompasses asphalt binder absorbed into aggregates, while VMA encompasses air volume, asphalt binder volume, and any ingredients within the asphalt binder that are deemed to be asphalt binder. A key item for asphalt mixture design consideration is how to evaluate the non-asphaltic components, especially in the presence of higher GTR loadings.



Source: Paragon Technical Services, Inc.

Figure 3. Phase diagram of GTR volumetric conditions.

Several recent publications have discussed characterizing GTR as a two component-post consumer polymer system having functional polymer and filler, where functional polymer is that portion of the GTR that is reclaimed polymer serving to modify the asphalt binder through the dispersion and solvation process discussed. (3,27,31,32) If the total volume of GTR in an asphalt mixture is denoted, V_{GTR}, the functional polymer can be denoted $V_{GTR\text{-}Polymer}$ and the filler can be denoted $V_{GTR\text{-}Inert}$, Figure 3b. In this consideration $V_{GTR\text{-}Polymer}$ is essentially equivalent to the effective binder volume (V_{be}). GTR cannot be added into any asphalt mixture without volume being available. GTR is a fairly ineffective material per unit volume by comparison to typical modifiers. So, asphalt mixture designers should be aware of how much volume is going to be needed per unit of GTR. The specific gravity of GTR is typically in the 1.1 g/cm^3 to 1.2 g/cm^3 range, and for a simplistic discussion, half of GTR's volume could be considered functional polymer and the other half as filler.

For illustration, take an asphalt mixture with a bulk mixture specific gravity (G_{mb}) of 2.300 g/cm^3 and total volume (V_T) of 100 cm^3. If 5 percent asphalt binder were used that contained 10 percent GTR, 1 cm^3 of the total volume is occupied by GTR. In this example, $V_{GTR\text{-}Polymer}$ and $V_{GTR\text{-}Inert}$ are both 0.5 cm^3. $V_{GTR\text{-}Polymer}$ would be part of VMA as polymers such as SBS are considered part of the asphalt binder in conventional calculations (e.g., Figure 3c). When calculating VMA, $V_{GTR\text{-}Inert}$ should not be considered as part of VMA (e.g., Figure 3b and Figure 3c). Asphalt mixture designers can use a specific gravity of 1.15 g/cm^3 for GTR and an even distribution of functional polymer and inert filler for calculations as default values. Considering $V_{GTR\text{-}Inert}$ as part of the asphalt binder would overestimate actual VMA. This example illustrates that the asphalt mixture would have 0.5 percent less VMA than desired. Figure 3d depicts dry added GTR where none of the GTR volume is considered as part of VMA as the VGTR-Inert is only modestly activated by the dry addition process.

Considering the previous discussion, baghouse fines do not count as part of VMA; similarly, inert filler component of GTR should not count as part of VMA. Inert components of GTR are not affected by being incorporated into the asphalt binder. Some methods consider them part of the aggregate (V_{sb}) when dry added to an asphalt mixture, but consider them part of VMA when blended into the asphalt binder. If the inert components are considered part of VMA, effective binder may be reduced by the volume of the inert components leading to less-than-optimal effective asphalt binder content. A common practice for some projects has become to increase design asphalt binder content by 0.2 percent to 0.3 percent to address lean asphalt mixture concerns and early age cracking with GTR modified systems. Increasing asphalt binder by these levels is restoring the 0.5 percent VMA loss exampled earlier. A more direct and systematic method for accounting for $V_{GTR\text{-}Inert}$ is to remove this volume via calculation when determining VMA and applying existing specifications during mix design.

Asphalt mixture designers should be aware that more detailed characterization methods are available to evaluate GTR components (e.g., thermo-gravimetric analysis (TGA) methods). (31,33) On a mass basis, GTR is only about 40 percent functional polymer (values ranged from 40 to 55). (33) If direct measurements of specific gravity or functional polymer levels are available for a GTR source, they could be considered by the asphalt mixture designer, but if they are not, use of realistic estimates is more desirable than neglecting GTR's actual composition.

Binder specific design considerations

How does the information presented, in consideration of Figure 2, Figure 3, and the related discussion, affect mixture design with the different GTR technologies? The VMA discussions presented are applicable to any GTR design. It is important to note that typical mixture design parameters such and mixing and compaction temperatures are generally higher for GTR modified asphalt mixtures relative to conventional asphalt mixtures. Asphalt plant mixing generally occurs between 145°C to 175°C (293°F to 347°F) and compaction occurs at a minimum of 135°C (275°F). Mixture with dry added GTR may be designed in the laboratory with lower temperatures. However, using field construction temperatures during laboratory mix design could yield mixture performance more representative of actual pavement.

For reference and facilitation of discussion of binder specific design considerations, a summary of the GTR processing technologies discussed is presented in Table 1. Presented for each processing technology are a description, common names, typical GTR particle sizes and content, and typical blending conditions and reaction times.

Table 1. Summary of GTR processing technologies.

Technology	Description	Other Names for the Technology	Typical Rubber Particle Size and Content	Typical Blending Conditions and Reaction Time
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 10 percent by weight of the total blend and has reacted in the asphalt binder sufficiently to cause swelling of the rubber particles." (3)	• McDonald Process • Arizona Crumb Rubber • Wet Process Rubber • Recycled Tire Rubber Modified Bitumen (RTR-MB) • Asphalt Rubber Binder (ARB) • Bitumen Rubber Binder • Crumb Rubber Binder Batch Blending	AR technology is a batch process consisting of blending from 10 to 22 percent GTR, by weight, with asphalt binder. GTR particle size for AR is from 600 µm (30 mesh) to a maximum of around 1.5mm or (15 mesh).	Processing temperatures range from 175°C to 190°C (≈ 350°F to 375°F) allowing the GTR and asphalt binder to react for from 30 to 60 minutes before introduction into the asphalt mixture production process.
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." (3)	• Terminal Blend • Terminal Blended Rubberized Asphalt (TBRA) • Recycled Tire Rubber Modified Bitumen (RTR-MB) • Rubber Modified Binder (RMB) • Hybrid Rubber Binder Wright Process	RMB technology consists of blending from 5 to 15 percent GTR by weight of asphalt binder. GTR particle size for RMB is from 600 µm to 420 µm (30 mesh to 40 mesh)	Processing temperatures range from 175°C to 190°C (≈ 350°F to 375°F) allowing them the GTR to react for from 60 to 120 minutes prior to transfer to storage tanks awaiting delivery to asphalt mixture production facilities in the same manner as conventional and polymer modified asphalt binders.
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. Processing aids or co-modifiers are often used in addition to GTR." (3)	• Dry process rubber Belt add modifier (BAM)	Dry addition technology incorporates dry GTR at approximately 10 percent by weight of the asphalt binder content. This equates to approximately 0.5 percent by weight of mixture or 10 pounds of GTR per ton of asphalt mixture. GTR particle size for Dry addition is from 600 to 420 µm (30 mesh to 40 mesh).	Blending and reaction times and conditions (time and temperature) for dry added GTR are dependent on the operating and production parameters for the mixture type and location for which the asphalt mixture is being produced. Asphalt plant mixing generally occurs between 145°C to 175°C (293°F to 347°F).

Source: Paragon Technical Services, Inc.

AR Binders

AR binders use the most GTR per unit volume and are also the most mixing investment intensive method of rubber use in asphalt mixes (Figure 2). Typical particle size is 15 mesh with 10 to 22 percent GTR. Finer particles such as 30 mesh or even as fine as 80 mesh can be and have been used. (25,26), AR binder production is often performed at the asphalt plant site, which is one of the factors leading to its high total mixing investment.

RMB

As presented in Figure 2, the amount of GTR tends to be on the low to middle range of the stated GTR for AR binders, however, the mixing investment tends to be high due to the mixing and storage facilities used to support RMB production and supply.

Design of RMB mixtures is more straightforward from traditional perspectives as design with RMB is identical to design of mixture with conventional and polymer modified asphalt binder. As with AR binders, GTR particle size and amount used are important factors to consider when using RMB binder. GTR particle size for RMB is typically smaller, at around 30 mesh, compared to the 15 mesh GTR used in AR binders. Additionally, if more than 10 percent GTR is used in DGA it may be fine graded asphalt mixtures may become a challenge and thus involve gradation adjustments at higher GTR levels. Higher amounts of GTR in SMA and OGFC mixtures typically do not cause issues but drain-down is always an important factor to consider.

Hybrid GTR Binders

The previous VMA discussion, with respect to volumetric properties, are applicable to any mixture design with GTR modified asphalt binders. Designers may consider this in addition to the following discussion when considering hybrid formulations containing GTR and SBS. Researchers have provided data on hybrid polymer modification that can be referenced for more specific assessments. (34,35)

Designing an asphalt mixture with a hybrid asphalt binder for asphalt pavements is potentially a more sustainable alternative. The engineering benefits and use of hybrid asphalt binders considered in this report can inform life-cycle assessment (LCA) studies to quantify the environmental benefits within a context sensitive application. Hybrid binders with 1 percent to 2 percent SBS and 3 percent to 8 percent GTR typically allow for high temperature grading increases and for use any mixture gradation category including fine graded DGA. 6SMA and OGFC mixtures can be designed as normal. There are currently some State DOTs specifying hybrid GTR binders. (36,37,38)

As seen in Figure 2, the amount of GTR tends to be low and mixing investments tend to be high with hybrid binders. This makes their use in design more straightforward from traditional perspectives though as noted earlier sustainability implications are a motivating factor in this family of mixes.

The Cantabro Mass Loss Test (29,39) and American Association of State Highway and Transportation Officials AASHTO T324 *"Standard Method of Test for Hamburg Wheel-Track Testing of Compacted Mixtures"* (40) have shown promise in evaluating DGA with hybrid binder mixtures, and they can be useful tools for optimizing mixture proportions. Neither test is a Federal requirement.

Dry Added GTR

As previously stated, dry process GTR modified asphalt mixtures have been designed using standard Marshall 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. The dry added GTR may be composed of just GTR or combinations of GTR with other modifiers or additives.

When designing a mixture with dry added GTR, none of the GTR volume is considered part of VMA as the $V_{GTR\text{-}Inert}$ portion is only modestly activated in a dry added process. Referring to Figure 2 and aforementioned discussions, use in this manner provides minimal mixing of the GTR with virgin binder and heating of the GTR as the GTR is only in a mixing drum for a very limited time. Asphalt mixture designers may consider use of finer ground GTR in dry add applications (e.g., 30 mesh to 80 mesh). (10,12) Otherwise, dry added asphalt mixture designs can follow conventional procedures.

Laboratory stability and stiffness values of dry process modified asphalt mixtures are generally lower than values of conventional asphalt mixtures. (33,34) As stated, there is minimal agitation in the dry added GTR process, which may not allow the reaction time to provide the desired viscosity increase.

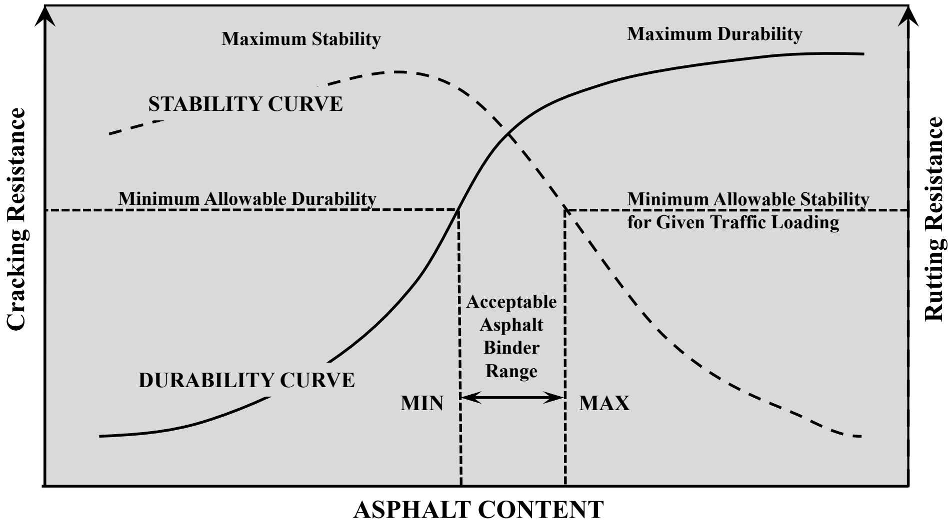
MIXTURE DESIGN WITH PERFORMANCE TESTS

Mixture design discussion thus far has been mostly limited to design based on volumetric properties—combining select quality appropriate aggregates and asphalt binder properly proportioned to provide desired performance. Performance testing has been mostly limited to indirect tensile properties and moisture damage evaluation. As a result, improved rutting resistance of asphalt pavements since introduction of the Superpave mixture design method, which relied on volumetric properties alone to provide performance, has in some areas resulted in mixtures that are prone to cracking. Evolution of the nature of asphalt binder (e.g. use of re-refined engine oil bottoms (REOB), vacuum gas oil (VGO), or bio-oils to soften standard grades) with increased use of innovative and recycled materials (e.g., reclaimed asphalt pavement, reclaimed asphalt shingles, recycling agents, synthetic polymers, and post-consumer polymers such as GTR) creates an opportunity for agencies to incorporate more in-depth testing for rutting and cracking and look beyond volumetric asphalt mixture design.

Balanced Mixture Design

BMD is "an asphalt mix design using performance tests on appropriately conditioned specimens that address multiple modes of distress taking into consideration mix aging, traffic, climate, and location within the pavement structure." (23) Specifically, BMD incorporates two or more mixture performance tests focused on stability (permanent deformation/rutting) and durability (cracking), assessing how well mixtures resist these common distresses, to design a mixture for an intended application and owner service requirements. The BMD approach considers rutting and cracking distresses by setting a maximum asphalt binder content to exceed the rutting criteria and a minimum asphalt binder content to meet an established cracking criterion as shown in Figure 4. (22, 23, 24)

Using BMD can enhance the probability that asphalt mixtures will withstand deterioration from rutting, cracking, and moisture damage. The ultimate goal of the BMD is to provide the optimal combination and proportions of asphalt binder, aggregate, and other mixture components or additives to meet the performance criteria to resist deformation and cracking types for a given level of traffic, climate, and pavement structure.



Source: Paragon Technical Services, Inc. (22)

Figure 4. Balanced mixture design approach.

The terms design asphalt binder content and optimum asphalt binder content are often used interchangeably. However, these parameters are not necessarily equal, as there can be many design asphalt binder contents but only one optimum asphalt binder content. Designers typically aim to design as closely as possible to the optimum asphalt binder content to produce the optimum mix based on intended application, the project’s performance requirements, and economics. It is this premise that drives the quest for using performance tests in a BMD approach.

The Association of State Highway and Transportation Officials (AASHTO) PP 105-20 Standard Practice for Balanced Design of Asphalt Mixtures describes four approaches (A through D) for a BMD process. (41) This is a voluntary standard; its use is not a Federal requirement.

- ***Approach A—Volumetric Design with Performance Verification.*** This approach starts with the current volumetric mixture design method (i.e., Superpave, Marshall, or Hveem) for determining an optimum binder content (OBC). The mixture is then tested with selected performance tests to assess its resistance to rutting, cracking, moisture damage, and other distresses at the OBC. If the mixture design meets the performance test criteria, the job mix formula (JMF) is established and production begins; otherwise, the entire mixture design is repeated using different materials (e.g., aggregates, binders, recycled materials, and additives) or mixture proportions until all of the volumetric and performance test criteria are satisfied.
- ***Approach B—Volumetric Design with Performance Optimization.*** This approach is an expanded version of Approach A. It also starts with the current volumetric mixture design method (i.e., Superpave, Marshall, or Hveem) for determining a preliminary OBC. Mixture

performance tests are then conducted on the mixture design at the preliminary OBC and two or more additional contents. The binder content that satisfies all of the cracking, rutting, moisture damage, and other distress criteria is identified as the final or target OBC. In cases where a binder content does not exist in which all the performance test criteria are met, the entire mixture design process should to be repeated using different materials (e.g., aggregates, binders, recycled materials, and additives) or mixture proportions until all of the performance criteria are satisfied.

- ***Approach C—Performance-Modified Volumetric Design.*** This approach begins with the current volumetric mixture design method (i.e., Superpave, Marshall, or Hveem) to establish initial component material properties, proportions, and binder content. The performance test results are then used to adjust either the initial binder content or the mixture component properties or proportions (e.g., aggregates, binders, recycled materials, and additives) until the performance criteria are satisfied. For this approach, the final design is primarily focused on meeting performance test criteria and may not have to meet all volumetric criteria.
- ***Approach D—Performance Design.*** This approach establishes and adjusts mixture components and proportions based on performance analysis with limited or no State Department of Transportation (DOT) requirements for volumetric properties. The State DOT may set minimum requirements for binder quality and aggregate properties. Once the laboratory test results meet the performance criteria, the mixture volumetric properties may be checked for use in production.

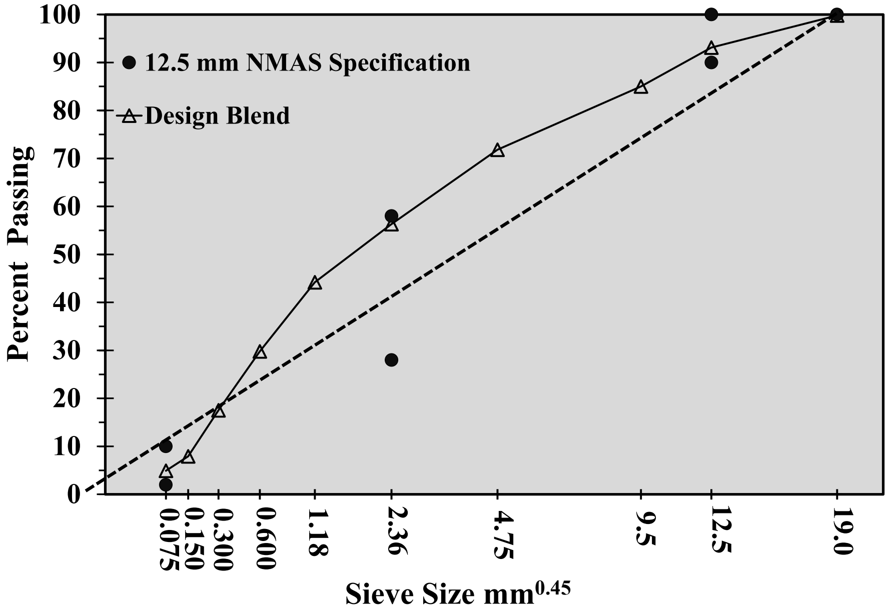
Chapter three of NCHRP Project 20-07/Task 406 (23) provides comprehensive information on the development and state of practice of asphalt mixture performance testing. Limitations of volumetric mixture design methods are discussed as well as refinements of the Superpave mixture design procedure. A state-by-state state-of-the-practice overview provides information on State DOTs using BMD and preferred performance test methods of each DOT. While there is not a specific discussion of mixtures containing GTR modified asphalt binders or dry added GTR, chapter three also provides discussion of performance testing of mixtures containing polymer modified asphalt binders which may offer aide in BMD of mixtures containing the GTR alternative. With GTR modified mixtures, applicable performance tests criteria may be different than for conventional DGA mixtures.

BMD Example and Considerations

DGA is a common mixture type used in asphalt pavement construction. It is widely used as base course, binder course, and surface course. This suggests that DGA could offer the greatest opportunity for increased use of GTR modified binders and reuse of discarded tires. SMA and OGFC mixtures may be somewhat more favorable to GTR because the gradations are more open allowing for easier incorporation of GTR into the mixture matrix. SMA and OGFC are specialty surface mixtures, with limited use compared to DGA. DGA may present a mixture design challenge for reasons discussed. Difficulty in mixture design can arise due to lack of sufficient room for GTR in the mixture matrix, leading to insufficient effective binder to provide the desired resistance to permanent deformation.

For illustration purposes, GTR modified DGA mixture performance characteristics will be considered. In this illustration, a DGA mixture typically considered to be restrictive of using GTR modified technologies is chosen. For example, a DGA mixture gradation on the fine side of the maximum density line, generally avoided with respect to GTR modified asphalt binders, is selected. (8,9,10) "Mix Design Considerations," discussed previously, will be addressed as well as performance testing in accordance with the BMD approach. In this illustration only Hamburg Wheel-Track Testing (HWTT) testing to assess rutting and mixture beam BBR testing to indicate cracking performance will be presented. BBR was selected for this discussion due to existing data pertaining to the GTR topic. (43) A number of cracking tests are available for evaluation of low temperature performance of asphalt mixtures in the BMD approach. State DOTs may have a preferred method based on experience and testing capability. Common methods include: the semicircular bending (SCB) test, Illinois Flexibility Index test (I-FIT) and indirect tensile asphalt cracking test (IDEAL-CT).

A Wisconsin DOT (WIDOT) E1-12.5mm nominal maximum aggregate size (NMAS) fine graded DGA mixture incorporating GTR modified binders and limestone aggregates was selected to prepare mixtures for subsequent rut testing via HWTT and mixture beam BBR testing. These tests were chosen to bracket the BMD rutting and cracking design parameters discussed. Figure 5 presents the aggregate gradation for the mixture.



Source: Paragon Technical Services, Inc.

Figure 5. E1-12.5mm NMAS aggregate gradation bands.

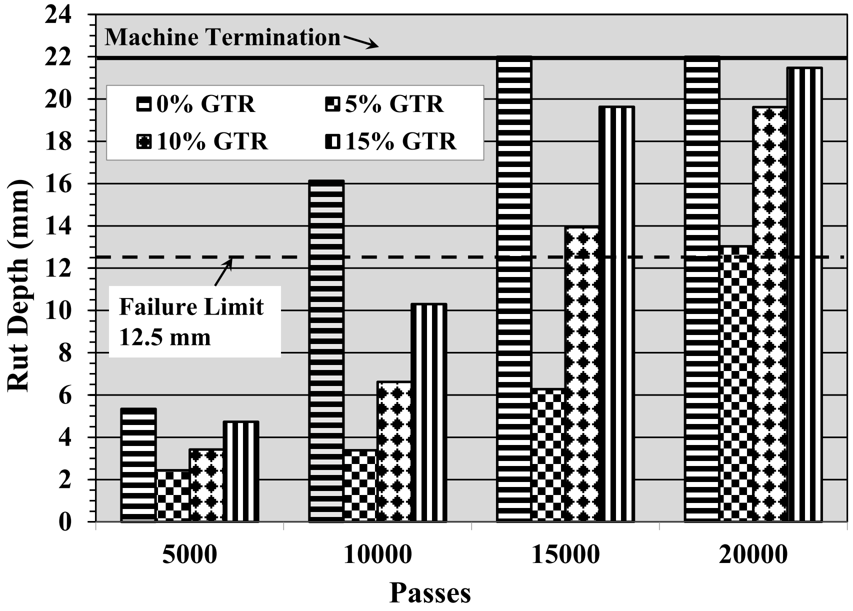
Four asphalt binder combinations were used in the illustration: a neat PG 67-22 as the base asphalt binder and three, laboratory prepared, RMB modified asphalt binders containing, 5 percent, 10 percent and 15 percent, 30 mesh GTR. Asphalt binder grading results per voluntary AASHTO M 320 and AASHTO M 332 binder grading are presented in Table 2.

Table 2. Binder grades for RMB modified asphalt binders.

Binder	AASHTO M 320 Grade	AASHTO M 332 Grade
PG 64-22	PG 64-22	PG 64S-22
5 percent GTR (30 mesh)	PG 70-22	PG 64H-22
10 percent GTR (30 mesh)	PG 76-22	PG 70E-22
15 percent GTR (30 mesh)	PG76-22	PG 70E-22

Source: Paragon Technical Services, Inc.

HWTT rutting results are presented in Figure 6. The PG64-22 dense mixture rutted the most as expected. However, HWTT results for the mixtures with GTR modified binders are not what is typically expected, considering the PG grading results presented. The mixture containing 5 percent GTR modified binder performed better than both the mixture containing 10 percent and the mixture containing 15 percent GTR modified binder. These results prompted verification testing to support the results observed. Results of verification testing supported the original findings leading to the most likely answer that issues were volumetric in nature.



Source: Paragon Technical Services, Inc.

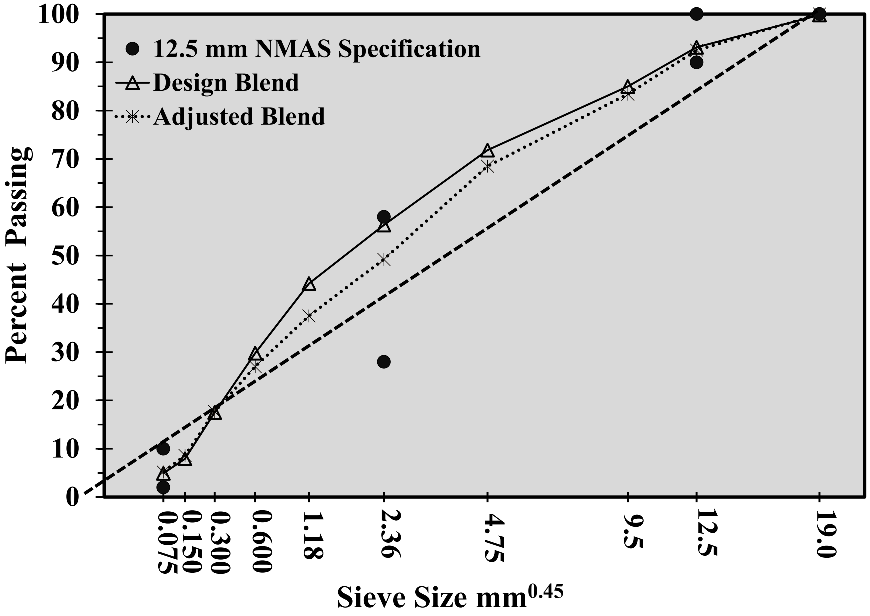
Figure 6. HWTT results for Design Blend RMB (30 mesh GTR) modified asphalt binders.

As presented, V_{be}, the volume of binder not absorbed by aggregates, is believed to be important in this discussion. Inadequate V_{be} is believed to be a key factor in Figure 6. Having insufficient effective binder to provide the desired resistance to permanent deformation has also been observed by others. (42)

A gradation adjustment was made to allow for non-bituminous components of the modified binder and to allow for additional need for adequate effective binder. (42) Essentially 50 percent of a blend sand component was removed. The equivalent value of material was split between the materials (excluding RAP) and recombined. An additional amount of blend sand was added back to the +No 8 screen. This gradation was fairly close to the original but allowed room in the gradation on the No 8, 16, and 30 screens. Figure 7 presents the original design blend and adjusted blend gradations.

No additional binder was added, however, as discussed as much as 0.2 percent to 0.3 percent could be added to account for non-bituminous components in the RMB to avoid lean asphalt mixtures.

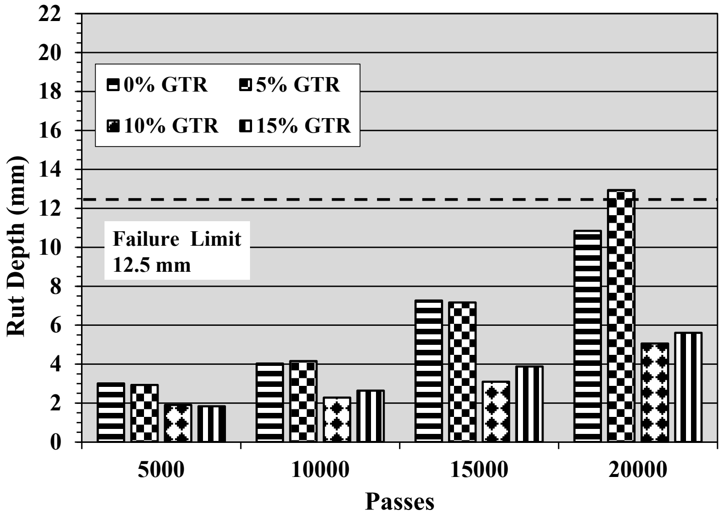
DGA gradation adjustments with GTR modified asphalt designs is not a novel concept; general practice has been to avoid mixtures on the fine side of the maximum density line. (42) Due to the presence of the rubber particles and non-bituminous components in the GTR modified asphalt binder, the aggregate gradation for dense-graded mixtures should be maintained on the course side of the gradation band. Some suggest avoidance of gradations that plot between the maximum density line and the upper limit of the gradation band. (42)



Source: Paragon Technical Services, Inc.

Figure 7. Design and Adjusted Blend E1-12.5mm NMAS aggregate gradations.

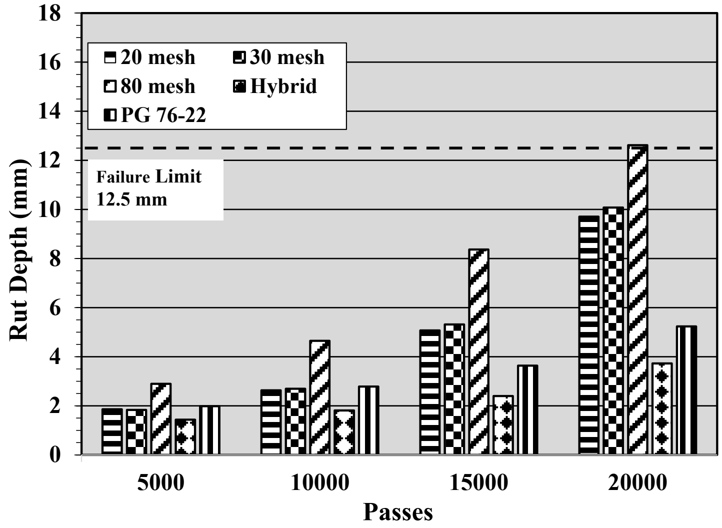
HWTT rutting results for the mixtures prepared with the adjusted blend gradation are presented in Figure 8. HWTT performance of all mixtures, including the PG64-22 dense mixture, improved with the adjusted gradation. Mixtures with the adjusted blend gradation containing the 5 percent, 10 percent, and 15 percent RMB binders exhibited performance trends expected and typical of the binder grades reported. These results are supportive of the BMD approach stated objectives.



Source: Paragon Technical Services, Inc.

Figure 8. Adjusted Blend HWTT results for RMB (30 mesh GTR) modified asphalt binders.

Figure 9 presents HWTT results for five mixtures prepared with the original design blend gradation (unadjusted) and the asphalt binders listed in Table 3. Note that three of the GTR binders contain the same amount of GTR (10 percent), but the GTR particle size is 20 mesh, 30 mesh, and 80 mesh. Indications are that these asphalt binder formulations are more adaptable to fine graded DGA with gradations such as the original design blend gradation. The maximum rut depth at 20,000 passes for the Hybrid and PG76-22 binder mixture were 3.7mm and 5.2mm, respectively. This is a considerable improvement over the failing results exhibited by the original design blend mixtures made with both the non-modified PG64-22 and the RMB binders. Results also demonstrate improved performance of hybrid GTR binders made with GTR and SBS.



Source: Paragon Technical Services, Inc.

Figure 9. Design Blend HWTT results for RMB (20, 30 and 80 mesh), Hybrid GTR (GTR plus SBS), and PG 76-22 (SBS) modified asphalt binders.

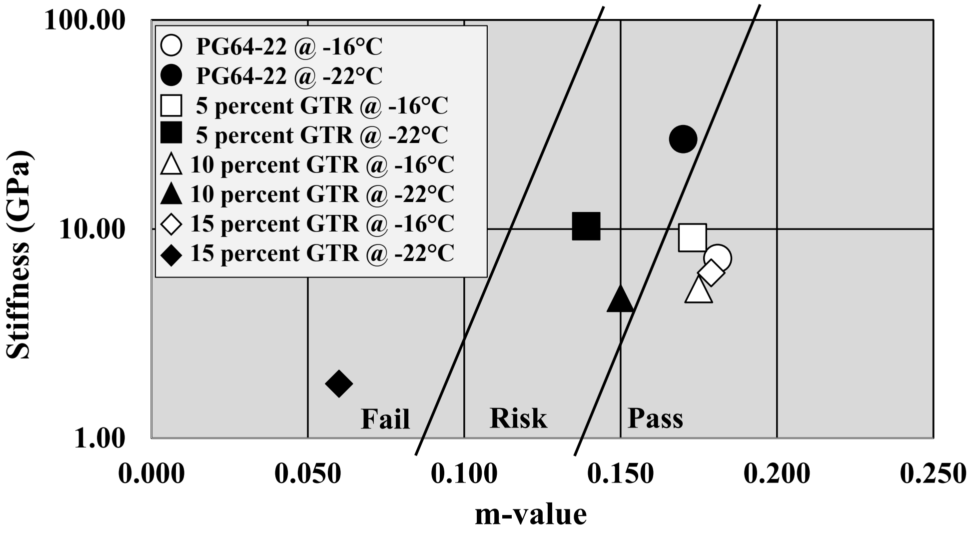
Table 3. Binder grades for RMB, Hybrid GTR (GTR plus SBS), and PG 76-22 (SBS) modified asphalt binders.

Binder	AASHTO M 320 Grade	AASHTO M 323 Grade
10 Percent GTR (20 mesh)	PG 76-22	PG 64V-22
10 Percent GTR (30 mesh)	PG 76-22	PG 64V-22
10 Percent GTR (80 mesh)	PG 76-22	PG 64V-22
PG 76-22	PG 82-22	PG 70E-22
Hybrid GTR	PG 76-22	PG 64E-22

Source: Paragon Technical Services, Inc.

Figure 10 shows BBR mixture beam stiffness versus m-value data, at 60 seconds loading tested at -16°C and -22°C, for beams made with the binders listed in Table 3. (44) Testing reported was performed at -16°C and -22°C as opposed to the normal 10°C grade offset for asphalt binder testing. Testing at actual pavement temperatures produced data more depictive of low temperature pavement performance and the testing at higher temperatures of -6°C and -12°C did not provide adequate differentiation. The GTR modified asphalt binders were produced with PG64-22 and 30 mesh GTR at the percentages indicated. BBR mixture beam testing generally shows the contribution of the binder characteristics to low temperature performance in mixtures. Low temperature characteristics are influenced by source binder performance, as BBR mixture beams prepared with both modified and unmodified binders often have similar stiffness at a given test temperature.

For example, in this illustration the neat PG64-22 mixture and the mixtures made with 5, 10 and 15 percent GTR tested at -16°C all exhibit similar performance with respect to stiffness and m-value. This is not the case with the mixtures tested at -22°C. as the BBR testing appears to differentiate the asphalt mixtures. The neat PG64-22 mixture exhibits expected higher stiffness due to reduction in test temperature with only a slight change in m-value. The mixture beams containing the 5, 10 and 15 percent GTR modified binders exhibit little to no stiffness increase with temperature reduction and more change in m-value. Mixture beams prepared with asphalt binder modified with the 5 percent GTR binder show a slight increase in stiffness along with reduction in m-value. Mixture beams prepared with asphalt binder having higher loadings of GTR at 10 and 15 percent each show decreases in stiffness as well as reduction in m-value. In a BMD approach, these data should be cause for consideration of mixture design adjustment as the mixture beams tested at -22°C seem to either fall in or near the “Risk” or “Fail” zones. What is the source of this response?

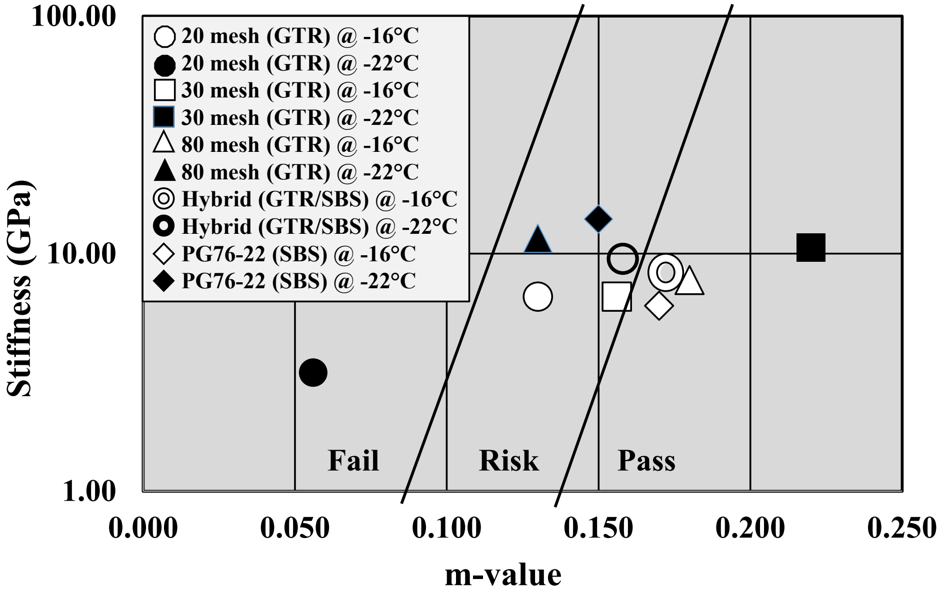


Source: Paragon Technical Services, Inc.

Figure 10. Design Blend Mixture BBR $S_{(60)}$ vs. m-value$_{(60)}$ data at -16°C and -22°C.

Data presented reveal a loss of stiffness and relaxation with reduction in temperature for the mixture beams tested. These characteristics are good indications that the mixture beams with low stiffness and poor relaxation character would possibly be more prone to low temperature cracking. At first glance it appears that addition of GTR in the binder may limit the mixtures of sufficient binder to provide the desired performance. This supports the earlier discussion of V_{be} and the function of inert fillers in GTR used to modify asphalt binder. An alternative for the BMD designer could be to evaluate these mixtures at the suggested increased binder contents of 0.2 to 0.3 percent. While possibly not as stiff as the neat PG64-22 binder, additional binder may provide adequate improvement in performance to increase both stiffness and relaxation performance. As mentioned, other standard specimen mixture cracking tests being used by State DOTs could be used to verify these results.

As was done with HWTT testing, five mixtures were prepared with the original design blend gradation (unadjusted) and the asphalt binders listed in Table 3. Figure 11 presents BBR mixture beam stiffness versus m-value data, at 60 seconds loading tested at -16°C and -22°C. These data indicate that the mixtures should have better durability than those shown in Figure 10. Of primary concern is the mixture containing the 20 mesh GTR modified binder. The smaller GTR particles (30 mesh and 80 mesh) in samples prepared with GTR modified binders do not exhibit loss of stiffness and do present acceptable relaxation properties. As with the previous example, the BMD designer might evaluate these mixtures at the suggested increased binder contents of 0.2 to 0.3 percent.



Source: Paragon Technical Services, Inc.

Figure 11. Design Blend Mixture BBR $S_{(60)}$ vs. m-value$_{(60)}$ data at -16°C and -22°C, (20, 30 and 80 mesh), Hybrid GTR (GTR plus SBS), and PG 76-22 (SBS) modified asphalt binders.

This illustration uses the mix design considerations presented in addition to Approach A of AASHTO PP 105-20 to address design of a RMB mixture using an aggregate structure that would normally not be considered for a GTR modified asphalt mixture.(41) Further testing and design using Approach B of AASHTO PP 105-20 could be beneficial in optimizing aggregate structure, asphalt binder formulation, and asphalt binder content.(41) The same procedure is applicable to design of mixtures containing other GTR modified asphalt binders whether AR, hybrid GTR, or dry added GTR. Use of PP 105-20 is not a Federal requirement.

SUMMARY

Addition of GTR to asphalt binder and mixtures is an accepted mixture practice in asphalt production and consumes about 16.5 percent, or approximately 180 thousand tons (11.0 million scrap tires), of the total United States GTR market today. Modification of asphalt binders with GTR 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, currently ranks second among the most common asphalt polymer modifiers behind SBS copolymers.

This technical report provides a review and update on the use of available GTR modified asphalt technologies in production of asphalt mixtures. The objective is to provide knowledge for resource responsible use of AR, RMB, hybrid GTR, and dry added GTR to ensure engineering performance in asphalt pavements and inform environmental benefits through life cycle assessment.

This report is limited to discussion of GTR from whole scrap tires through size reduction and grinding, to the particle size range defined by industry as GTR. Included is information related to design of DGA, SMA, and OGFC mixtures using AR, RMB, hybrid GTR, and dry added GTR and discussion of testing of mixtures containing GTR-modified asphalt binders, as well as additional considerations for GTR-modified asphalt mixture designs.

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