USE OF GROUND TIRE RUBBER (GTR) IN ASPHALT PAVEMENTS: LITERATURE REVIEW AND DOT SURVEY

FINAL REPORT

Submitted to:

Ferrella March
Environmental Programs Manager
Oklahoma Department of Environmental Quality
Land Protection Division

Submitted by:

Rouzbeh Ghabchi, Ph.D.
Musharraf Zaman, Ph.D., P.E.
Amir Arshadi, Ph.D.

School of Civil Engineering and Environmental Science (CEES)
The University of Oklahoma
Norman, Oklahoma

DEQ
OKLAHOMA
DEPARTMENT OF ENVIRONMENTAL QUALITY

September 2016

TABLE OF CONTENTS

LIST OF ACRONYMS

Crumb Rubber (CR)

Crumb Rubber Modified (CRM)

Ground Tire Rubber (GTR)

Department of Transportation (DOT)

Oklahoma Department of Transportation (ODOT)

Oklahoma Department of Environmental Quality (ODEQ)

Transportation Research Information Services (TRIS)

Transportation Research Board (TRB)

Federal Highway Administration (FHWA)

National Cooperative Highway Research Program (NCHRP)

American Society of Civil Engineers (ASCE)

Asphalt Institute (AI)

Western Research Institute (WRI)

National Center for Asphalt Technology (NCAT)

Hot Mix Asphalt (HMA)

Intermodal Surface Transportation Efficiency Act (ISTEA)

Rubber Pavement Association (RPA)

Stress Absorbing Membrane Interlayer (SAMI)

Poly (styrene-butadiene-styrene) (SBS)

Reclaimed Asphalt Pavement (RAP)

Porous European Mix (PEM)

Rolling Thin Film Oven (RTFO)

Dynamic Shear Rheometer (DSR)

LIST OF ACRONYMS (CONTINUED)

Pressure Aging Vessel (PAV)

Dynamic Shear Modulus (DSM)

Polymer Modified Asphalt (PMA)

Performance Grade (PG)

Multiple Stress Creep Recovery (MSCR)

Equivalent Single Axle Loads (ESAL)

Stone Mastic Asphalt (SMA)

Semi-circular Bend (SCB)

Indirect Tensile Strength Test (IDT)

Resilient Modulus (M_r)

Florida Department of Environmental Protection (FDEP)

Stress Absorbing Membranes (SAMs)

Conventional Dense-graded Asphalt Concrete (DGAC)

Rubber Asphalt Concrete (RAC)

New Mexico Department of Transportation (NMDOT)

Rubberized Open-graded Friction Course (ROGFC)

Open-graded Friction Course (OGFC)

Porous Friction Course (PFC)

Oregon Department of Transportation (ODOT)

Rotational Viscometer (RV)

Bending Beam Rheometer (BBR)

Direct Tension Tester (DTT)

Warm Mix Asphalt (WMA)

LIST OF FIGURES AND TABLES

LIST OF FIGURES AND TABLES (CONTINUED)

ABSTRACT

According to available statistics at least 275 million scrap tires exist in stockpiles in the U.S. The proper disposal/reusing these materials is a challenging task. Common practice of dumping scrap tires in landfills has been an environmental concern. To address this concern, national and regional environmental protection agencies have taken major initiatives to recycle scrap tires. Developing new markets for the collected scrap tires is an important element of such initiatives. Markets now exist for about 80 percent of scrap tires. The existing markets include: tire-derived fuel generation, civil engineering applications, and ground rubber applications. These applications have helped utilize up to 87% of annually generated scrap tires in the U.S. One of the major categories for recycling scrap tires is crumb rubber products. Crumb rubber is produced by finely grinding tires that can be used to modify asphalt for roadway applications. Modified rubberized asphalt is produced by blending the ground rubber with asphalt to beneficially modify its properties in highway construction. The ground tire rubber (GTR) can be used either as part of the asphalt rubber binder (also known as, asphalt rubber), seal coat, cap seal spray or joint and crack sealant, or as substitute aggregate (rubber modified asphalt concrete). Therefore, the largest single market for GTR is asphalt rubber, consuming approximately 12 million tires. Arizona and Florida Departments of Transportation (DOTs) are the leading state DOTs in asphalt rubber utilization. Texas and Nebraska are currently using greater amounts of asphalt rubber as well. South Carolina is also working on utilization of asphalt rubber in county and state roads. Other states such as New York and New Mexico that have studied this topic are in the process of using rubberized asphalt in pavements. Currently, the Oklahoma Department of Transportation (ODOT) does not allow using the rubberized asphalt in pavements. This is partially due to lack of information, laboratory test data and specifications or special provisions on the use of GTR in asphalt pavements.

The current study was undertaken in order to conduct a comprehensive literature review to summarize the available wealth of knowledge, identify research needs, and document the major findings of previous pertinent studies. More specifically, the significant findings consisting of laboratory test results, field observations, and common practices were documented. The literature review focused on the use of GTR in asphalt mixes, wet process and dry process, characterization of hot mix asphalt (HMA) mixes containing GTR and their associated performance when combined with virgin materials. Sources of literature included, but was not

limited to, Transportation Research Information Services (TRIS), Transportation Research Board (TRB), Federal Highway Administration (FHWA), National Cooperative Highway Research Program (NCHRP), and DOTs. Other sources such as society journals American Society of Civil Engineers (ASCE), Asphalt Institute (AI), Western Research Institute (WRI), and National Center for Asphalt Technology (NCAT) were also consulted. Also, national and international conferences, symposia and workshops were reviewed. Furthermore, a survey was conducted and the results of the survey were summarized and documented. In order to promote successful use of GTR in Oklahoma, it is imperative to help ODOT develop specifications/special provisions for utilizing rubberized asphalt by collecting information, common practice and specifications followed by other state DOTs. Therefore, a survey of construction specifications used by different DOTs, which allow the use of GTR in asphalt, was conducted. According to research team's experience, since the DOT practices are generally not available in the open literature, this survey found to be an effective tool for gathering data on the current practices including the methods, special provisions, and specifications associated with the use of GTR in asphalt pavement by DOTs. The survey questionnaire was prepared in close collaboration with ODOT and Oklahoma Department of Environmental Quality (ODEQ). The survey was conducted through an online data collection website, namely www.surveymonkey.com, to maximize the efficiency and productivity of the data collection process. The survey questionnaire was distributed among different DOTs with the help of ODOT Materials & Research Division.

BACKGROUND

Annual generation of scrap tires in the United States increased from 200 million in the 1980s to 300 million in the 2010s and is increasing each year since then because of the projected growing number of vehicles (Kandhal et al., 1989; Willis et al., 2012; Bairgi et al., 2015). Approximately, 80 percent of the annually generated scrap tires in the United States are recycled or reused in fuel industry, agricultural and structural engineering markets (Willis et al., 2012).


Figure 13. One of the massive scrap tire piles (Ohio Environmental Protection Agency, 2008)

For the past 50 years, when the idea of using scrap tire rubber in asphalt pavements arose, it seemed that the push to use tire rubber in asphalt pavement was primarily a means of getting rid of the piles of scrap tires as they were visually offensive and a health and fire hazard (Figure 1). In one of the earlier efforts, recycled tire rubber was added in place of binder using a system called “Plus Ride.” Larger-sized recycled rubber (often 1.25” and larger material) was added to hot mix asphalt (HMA) much like an aggregate, and the resulting mix was placed and compacted much like standard hot mix asphalt. Early efforts had elevated levels of failure because of mix design problems (including insufficient binder, compaction issues, material handling issues and non-representative distribution of rubber in aggregate), but when finer crumb rubber was combined in hot mix asphalt, researchers found that rubber-modified pavements performed at least as well as standard hot mix pavements. Although the use of recycled rubber in pavements was desirable from an environmental sustainability standpoint, the cost of rubber modification was typically higher than standard modified asphalt pavements, often without evidence of superior performance.

Crumb rubber modifier (CRM), or ground tire rubber (GTR), is recycled tire rubber that has been grounded into fine particles to be used as an asphalt modifier. In the 1990s, a Federal Highway Administration/United States Department of Transportation (FHWA/USDOT) national mandate for the use of rubber in asphalt centered on what has been called either the Wet Process or Terminal Blend Asphalt. In these methods finer mesh crumb rubber is introduced into liquid binder (often with other additives), followed by cooking and “digestion” of the rubber into the binder before use in asphalt production. Using crumb rubber in road construction projects was a result of the U.S. federal law included in the Intermodal Surface Transportation Efficiency Act (ISTEA) of 1991 (Heitzman, 1992). A lack of clear standards and deficient preparation for technology deployment (insufficient user training) created a number of problems in the field as the mandate was rolled out, ultimately resulting in the cancellation of the rubber use requirement by FHWA/USDOT. However, later on, engineers and researchers observed enhancement of mix performance, resulted from utilization of scrap tire rubber in asphalt (Heitzman, 1992; Krutz et al., 1992; Hicks et al., 1995; Kaloush et al., 2002; Huang et al., 2002; Navarro et al., 2002; Palit et al., 2004; Chiu et al, 2007). It was shown that asphalt rubber in dense-graded mixes could reduce the asphalt layer thickness by 20-50% without affecting its performance (Kirk, 1991; Hicks, 2002). A research project conducted in Brazil found that having 15% rubber in the HMA overlay binder reduces the crack development 5-6 times in comparison with conventional asphalt binder (Nunez, et al., 2005). Mashaan et al. (2012) presented an overview of use of rubber-modified binders in HMAs. Their findings indicated that use of crumb rubber modifier not only reduces pollution problems but also results in safer and smoother roads. Their study also indicated that crumb rubber modifier improves the rutting resistance and produce pavements with better durability. In a recent study conducted in India, it was shown that application of crumb rubber modifier in HMAs improves the rutting resistance and durability of the pavement (Asadi et al., 2016). Crumb rubber modification improves the temperature-susceptibility of the asphalt binder and generally bumps up both high and low performance grade temperatures (Kaloush, 2014). In terms of pavement performance, wet process CRM mixes have the potential to resist crack propagation better than other polymer-modified mixes and conventional mixes (Kaloush, 2014). Fraser (2016) showed that modification of asphalt binder with GTR increases the stiffness, maximum load capacity, and calculated strength of resulted asphalt mix compared to regular HMA. In a recent study, it was indicated that asphalt rubber modification improves the binder performance in terms of rutting and fatigue resistance by increasing the complex shear modulus and the storage modulus, and decreasing the phase angle (Al-Khateeb et al., 2015). Air voids and voids in mineral aggregates are the two key parameters in rutting performance of wet processed CRM mixes (Zhang et al., 2014). Laboratory and field studies on a gap graded mix with 20% of crumb rubber by weight of binder indicated that use of high content crumb rubber reduces the noise emitted by tire/pavement interaction by 2.5 dB(A) for vehicles driving with speed of 50 mph (Paje et al., 2013). In another research conducted on a two-lane road located in

Spain, it was concluded that wet processed CRM mix (with rubber content of 20% by weight of binder) is quieter than reference mix by around 1 dB(A) at 32 mph (Vazuez et al., 2014). Rubber Pavements Association (RPA) conducted a noise study and found that use of tire rubber in open-graded mixtures reduces tire noise by at least 50%. Shirini et al. (2016) investigated the effect of crumb rubber modification on porous asphalt performance. They indicated that although crumb rubber modification enhances the resilient modulus, skid resistance, moisture susceptibility, and rut resistance of the asphalt mix, it has negative effect on mix permeability. It was concluded that crumb rubber content of 10% is the most effective dosage with respect to overall performance of CRM mix.

History…

- *Arizona* constructed its first crumb rubber-modified hot-mix asphalt (CRM-HMA) pavement in 1975.
- In 1978, *California* placed its first rubber-modified asphalt pavement.
- *Florida* initiated CRM-HMA work in 1988.

Charles H. McDonald of the city of Phoenix Arizona, known as the inventor of asphalt rubber, developed the McDonald process (also called the wet process) for production of asphalt rubber (Scofield, 1989). Arizona, Florida, California, and Texas are the leading states in asphalt rubber utilization. Together, these states recycled almost 36 million scrap tires in asphalt pavement applications from 1995 to 2001 (Willis et al., 2012). In a study conducted for California Department of Transportation in 2005, it was reported that the number of scrap tires used per ton of HMA in states of Arizona, California, Florida, and Texas, are 4.4, 3.3, 1.9, and 4.9, respectively. The number of states where tire rubber is routinely used in asphalt pavement applications has increased significantly in past 10 years (Figure 2).

The primary application of crumb rubber-modified asphalt binder in pavement industry includes crack and joint sealants; binders for chip seals, interlayers, HMA, and membranes. Chip seals can be placed on the pavement surface or as a Stress Absorbing Membrane Interlayer (SAMI) placed between pavement layers. It was shown that the application of GTR-modified binders in interlayers and chip seals provides a longer service life in comparison with conventional asphalt binders without any GTR (Hicks et al., 2013). The gap-, open-, and dense-graded GTR-modified HMA mixes can be successfully placed as surface course (Glover et al., 2001; Willis et al., 2012).

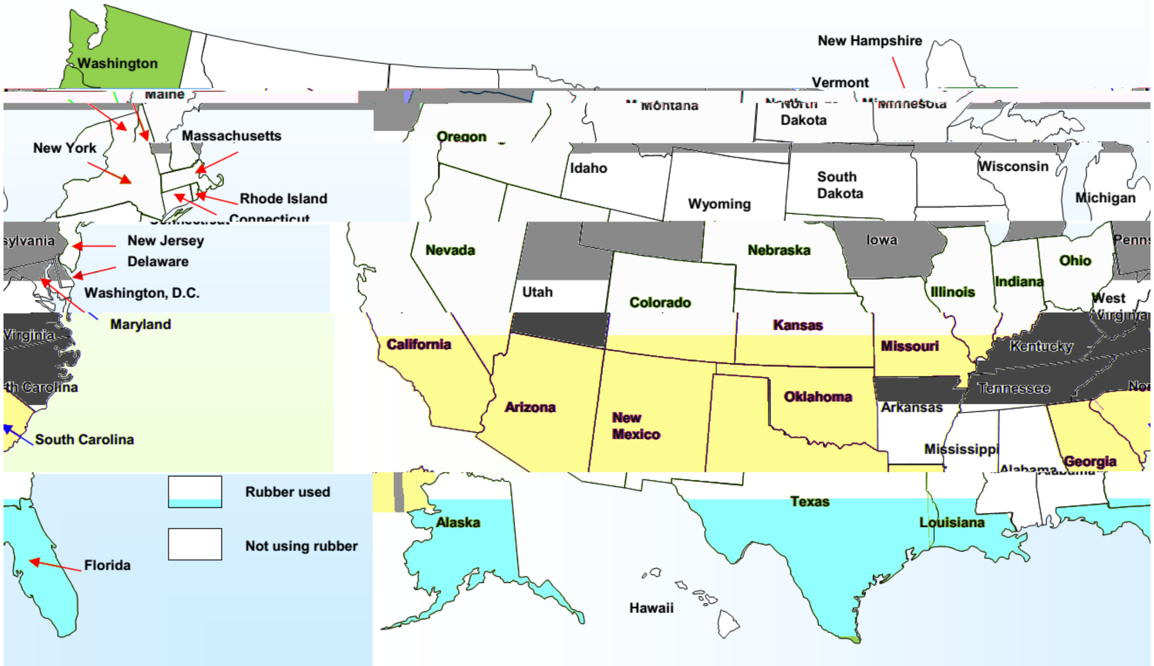


Figure 14. States where tire rubber is routinely used in asphalt (DOT, Transportation Authority, County or City) (Blumenthal, 2013)

A survey was conducted among 23 transportation agencies known to use crumb rubber in pavement construction to determine the types of applications of CRM in pavement constructions between 2006 and 2011 (Figure 3). As shown in Figure 3, the CRM materials were mostly used for surface treatments such as chip seal, fog seal and crack sealing, and in thin overlays.

PRODUCTION OF GTR-MODIFIED BINDERS AND MIXES

Although the make-up of the tires varies depending on their type (truck or passenger car) and manufacture, the basic components of different tires are almost the same (Figure 4). The general belief is that the slight variations in amount of natural and synthetic rubber do not cause differences in the performance of GTR-modified binders (USDOT, 2014).

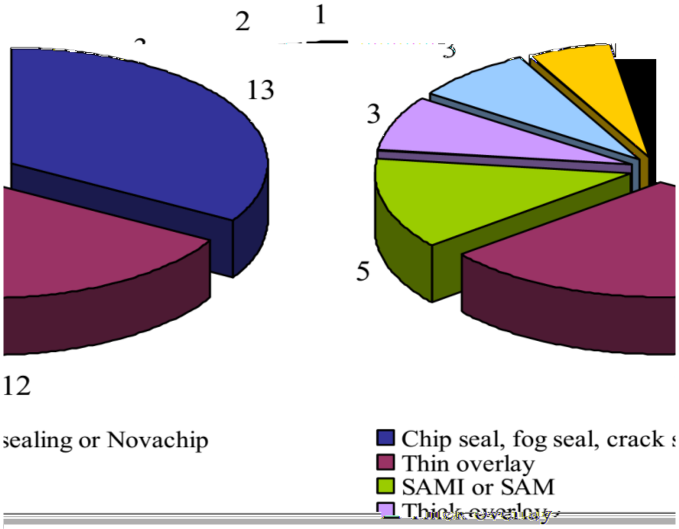


Figure 15. Types ofCRM applications used or tried by state DOTs from 2006 to 2011 (Bandini, 2011)

In order to use tire as a binder modifier or a mix additive, the steel and fiber must be removed from its structure. Magnets are usually used to remove the steel. The fiber is also removed by aspiration. The remaining tire rubber must be reduced in size to be ready for being blended with asphalt binder or asphalt mix. One of the most important factors that can significantly affect the performance of GTR-modified binder is the method used for grinding the tire rubber (Willis et al., 2012). These methods include but are not limited to ambient grinding, cryogenic grinding, granulation, and shredding (West, 1998). The ambient grinding occurs at or above ordinary room temperature by grinding the scrap tire to provide irregularly shaped particles with large surface area to promote their interaction with asphalt binder. In the cryogenic process, the liquid nitrogen is used to freeze the rubber and increase its brittleness and then a hammer mill is used to shatter the frozen rubber into smooth particles with relatively small surface area. The granular process uses revolving steel to shred the scrap tire to cubical particles with low surface area. The shredding process reduces the scrap tires to pieces smaller than 6 in^2 prior to granulation of ambient grinding. It should be noted that the two primary grinding methods are ambient and cryogenic grinding (USDOT, 2014).

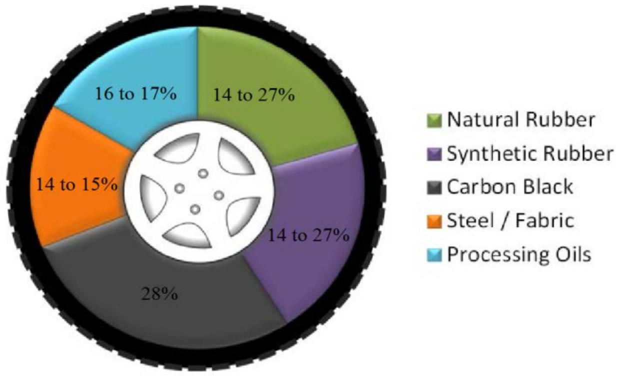


Figure 16. Components of tires (USDOT, 2014)

There are two distinct approaches for incorporating the ground tire rubber in asphalt pavements: wet process (Figure 5) and dry process (Figure 6). According to the - - FHWA-the modified binder obtained from the “wet process” is termed as “asphalt rubber” and asphalt made by using the dry process is called “rubberized asphalt” (Chesner, 1997). It should be noted that each of these processes produce GTR-modified asphalt mixes with different performance. In order to make the right choice on the type of process, understanding their differences is very important. In addition, necessary testing and inspections need to be conducted on each of these processes to ensure the success.

Use of Scrap Tire Rubber…

There are two general techniques to produce Ground Tire Rubber (GTR) modified asphalt pavement: 1- Dissolve rubber in binder as modifier, known as “wet process”, and 2- Replace a portion of fine aggregate with ground rubber, known as “dry process”.

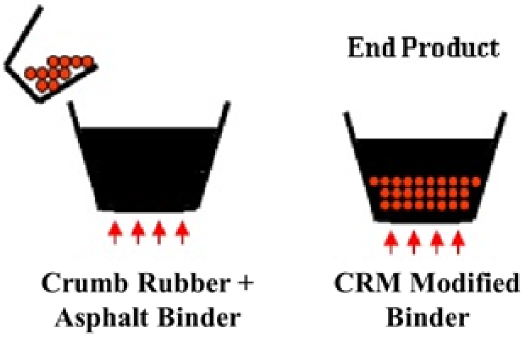


Figure 17. Wet process method (Hassan et al., 2014)

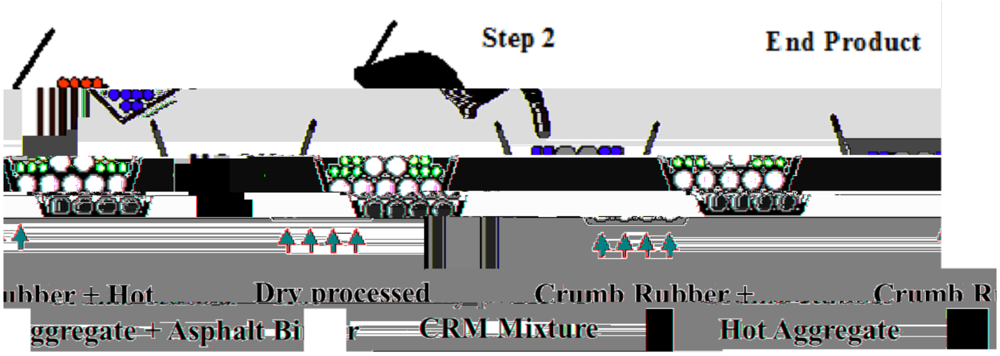


Figure 18. Dry process method (Hassan et al., 2014)

A 2011survey polled 23 agencies that have used or tried crumb rubber in pavement construction. Of those agencies polled 17 agencies have used wet process-terminal blending, nine (9) agencies use/have used wet process-on-site blending, and six (6) agencies use/have used dry process (Figure 7; Bandini, 2011).

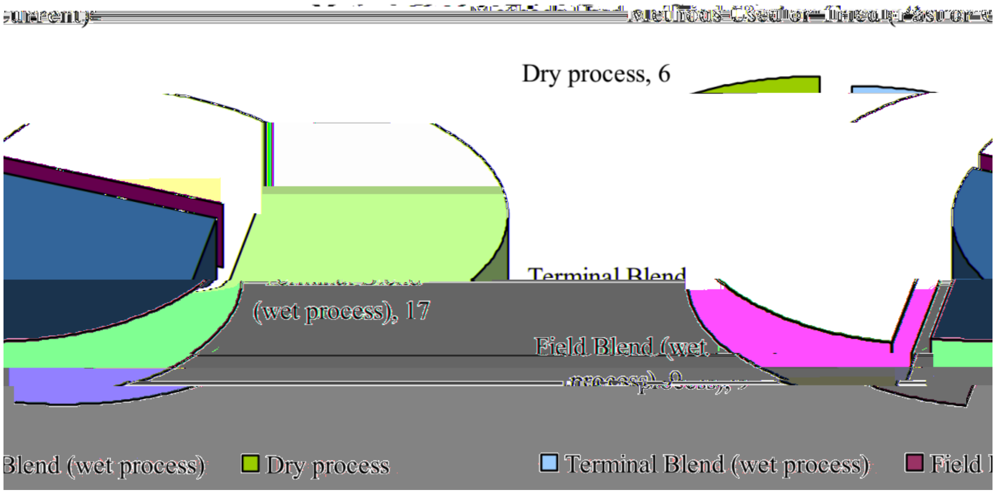
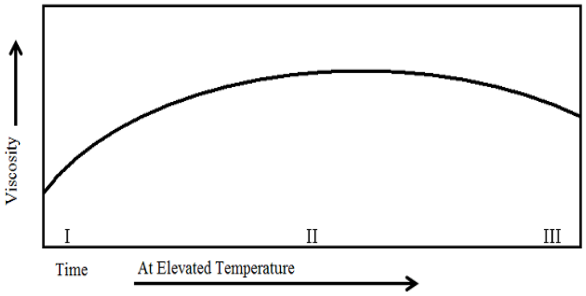
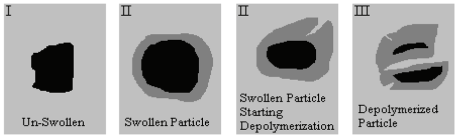


Figure 19. Production methods currently and/or formerly used or tried by state DOTs (Bandini, 2011)

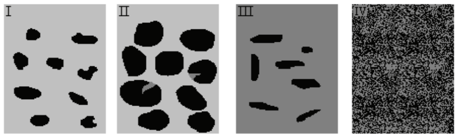
Wet Process

As noted above, wet process rubberized asphalt involves mixing of recycled tire crumb rubber into an asphalt binder in high temperature (176 ºC to 226ºC), followed by a period of cooking and digestion (hours or days) and continued agitation in order to keep the crumb rubber suspended in the binder (Hicks, 2002). Unlike polymers, the recycled tire rubber does *not* become a near-integral part of the binder. The crumb rubber used in the wet process has a higher density than the binder, allowing the rubber and binder to separate if not maintained in a turbulent environment. During heating, the crumb rubber will both soften and swell because of surface absorption of lighter binder components in the surface pores of the rubber (Artamendi and Khalid, 2006; Shen et al., 2012, 2015). The swelling process is caused by a selective removal of asphalt lighter ends from the binder while adding swollen crumb rubber to the mix matrix. This increases the viscosity of the binder, stiffens the mix and increases resistance to permanent deformation (rutting). The presence of softened rubber grains in the mix also makes the asphalt more flexible, thus increasing resistance to various forms of cracking (Peralta et al., 2012). In addition, dissolving rubber in asphalt binder increases its viscosity, allowing higher binder content to be used in the mix. Theoretically, this leads to asphalt mixes with improved fatigue resistance and durability (Huang et al., 2007). Extended reaction time decreases the binder viscosity slightly because of digestion of the rubber in the asphalt binder (Figure 8).





(b) Change of Particle Size over Time at Elevated Temperature



(a) Change of Binder Viscosity over Time at Elevated Temperature (c) Change of Binder Matrix over Time at Elevated Temperature

Figure 20. Progression of the asphalt-rubber interaction at elevated temperature (Abdeirahman, 2006)

Although some companies using the wet process have suggested that there might be some sort of material chemical exchange between the binder and the crumb rubber during heating and mixing, the assertion is controversial. The bulk of vulcanized tire rubber cannot melt at asphalt plant temperatures (149 - 205ºC), but it will decompose/oxidize in a higher-temperature (>316 ºC) environment over time. Xiao et al. (2006) suggests that there is a modest mass loss from crumb rubber over extended cooking periods in an asphalt binder, but Peralta et al. (2012) suggest that mass loss is due to splitting of the crumb rubber into finer particles and contribution of processing oils from the tire rubber. It was also observed that the depolymerization potential of recycled crumb rubber is quite low, primarily because of the strength of bonding due to vulcanization (Peralta et al., 2012).

An important question to be answered is: if the heated binder does not materially polymerize the recycled rubber, then what is the binder modification mechanism for crumb rubber in asphalt? There is ample evidence of some binder light ends (Maltenes) uptake in the surface pores of rubber grains while heated (Shen et al., 2015; Peralta et al., 2012). National Center for Asphalt Technology (NCAT) research (Hines, 2014) clearly suggests that for shorter cooking times (characteristic of dry process and Arizona Wet Process rubberized asphalt), the primary interaction between rubber and binder is mechanical in nature, not chemical. This uptake process causes two physical/mechanical changes in the asphalt binder and mix: an increase in binder viscosity and a swelling of the crumb rubber. These changes influence the performance of the binder and any produced asphalt mix. The rubber additions and withdrawal of light ends increase the $G^*/\sin\delta$ of the binder, which is a surrogate for rutting resistance. Therefore, rubberized pavements are more resistant to permanent deformation. The swelling of the crumb rubber also adds a larger flexible mass to the asphalt mix matrix, providing an increased degree of pavement flexibility (increasing the cracking resistance of the rubberized pavement). Mechanical changes aside, there appears to be little likelihood of any material chemical exchanges between the rubber and the binder during blending, transport and mixing for hot and warm mix production. Finally, there is a second change in the character and performance related to the physical presence of crumb rubber in the asphalt matrix: a typical 8 lb. crumb rubber dose rate in an asphalt mix adds roughly 40 million individual crumbs of rubber in a ton of asphalt mix. In the event that any cracking might begin in the asphalt, each crumb of rubber can help to pin cracks before they propagate.

Also, it should be noted that the properties of asphalt rubber is highly influenced by base binder composition, blending time, temperature, amount and size of ground tire rubber, and the grinding method (Bahia et al., 1994; Chesner, 1997; West el al., 1998; Leite et al., 1999; Navarro et al., 2004; Xiang et al., 2009; Hung et al., 2014). It is suggested not to use polymer-modified binders for asphalt rubber as the polymer-rubber interaction affects the durability of asphalt mixes (Airey et al., 2002). There are two methods for preparing asphalt rubber: terminal blending and on-site blending (Table 1).

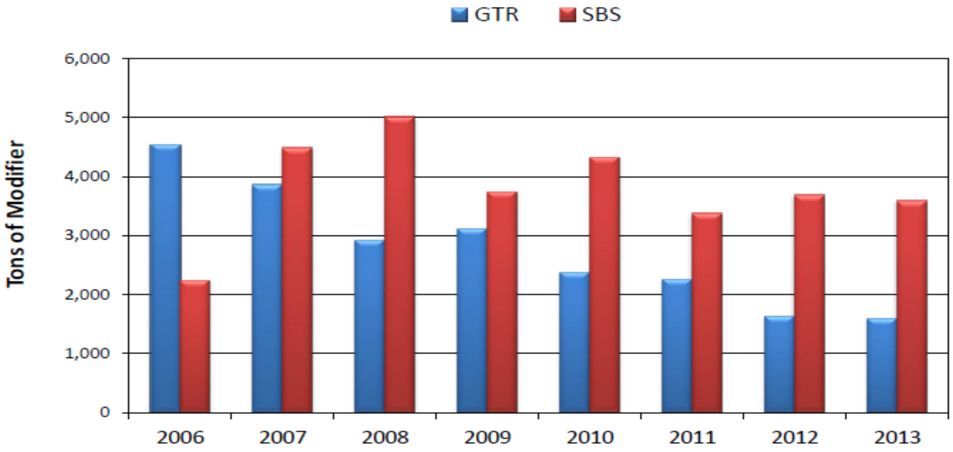
Table 5. Wet process, on-site vs. terminal blending

Method	***GTR Size***	***Rubber Amount***	***Mix Gradation Type***
On-site Blending	1.4-2 mm	15 to 22%	Gap-graded or Open-graded
Terminal Blending	< 0.6 mm	5 to 10%	Dense-graded

Terminally blended crumb rubber-modified asphalt is typically produced at an asphalt terminal. Rubber is introduced into binder in a turbulent environment. The rubber is allowed to “cook” for hours to days under continuous agitation, and terminals routinely add chemicals to the rubberized binder in order to meet their own performance and quality specifications. The finished product is pumped onto trucks (with or without agitation capabilities on-board). Like polymer-modified asphalts, the suspended rubber/asphalt solution is transported by truck or rail to the end-user, where the modified binder is stored in a dedicated tank before use. Separation of rubber and binder during transportation in un-agitated trucks is common and can lead to quality issues in the finished mix product. In addition, asphalt tankers do not always pump all of the settled rubber out of the tanker, and rubber clean-outs are necessary before the tanker can be used again.

Xiao et al. (2015) investigated the rheological properties of terminally blended and laboratory-blended asphalt binders in terms of three aging states: unaged, short-term aged, and long-term aged. The results indicated that rheological properties of both of the binders are similar. A recent study conducted to evaluate the long-term field performance and life cycle costs of pavement sections constructed with terminally-blended GTR and Poly (styrene-butadiene-styrene) SBS polymer modifier showed that both pavement sections showed good performance after 10 years of service (Nazzal et al., 2016). Laboratory studies on field cores extracted from the sections indicated similar fatigue resistance for both sections but GTR field cores showed slightly higher resistance to low temperature cracking and moisture induced damage. Life cycle costs for the section constructed by using mixes containing GTR was slightly higher than the one constructed by using polymer-modified mixes. It was due to higher initial cost of GTR mixes. A life cycle cost analysis approach has been developed by FHWA that can be used to evaluate the life cycle costs of asphalt pavements. The results indicated that the use of asphalt rubber is cost effective in Arizona and California (Hicks, et al., 2000).

Mix designs with rubber require differing virgin binder amounts than their polymer-modified counterparts. Since the rubber does not add binder equivalence, 5 to 10% additions of rubber to a mix design actually require the addition of virgin binder to compensate for the presence of rubber in the modified binder as well as the limited amounts of binder absorption on the rubber surfaces. In general, 10% by weight of binder (two grade Performance Grade (PG) bump equivalent) rubber additions require the addition of 0.2 to 0.4% binder addition in order to coat the increased amounts of fine particulate in the mix and to offset the absorption of binder light ends into the crumb rubber matrix. Therefore, produced rubberized asphalt mixes can be significantly stickier than standard hot and warm mix asphalts depending on the amounts of rubber used, and this makes wet process crumb rubber-modified asphalt mixes more difficult to produce, transport and place/compact. This is a key issue in the commercialization of rubberized asphalt. In Florida, the Florida Department of Transportation (FDOT) reports that when contractors are given the choice between rubber-modified asphalt and polymers, they choose polymers (Figure 9). There has been a steady erosion in the use of rubber asphalt in Florida over the last decade as a result.



FDOT Florida Department of Transportation

Figure 21. Loss of rubberized asphalt market share in Florida (FDOT)

Current Market for the Wet Process/Terminal Blend Rubber

Once wet process crumb rubber-modified asphalt pavements were demonstrated to be an effective alternative to polymer modification, asphalt producers began to focus on the relative costs and benefits of rubber versus polymer modification. Users noted that higher levels of rubber addition required the use of special equipment and handling procedures because the rubber additions made the hot and warm-mix asphalt stickier during material movement and handling. This required the development of special equipment and workability additives that would allow effective and efficient addition of rubber to asphalt. As wet process adoption began to expand, and the technology was written into various state specifications (AZ, FL, CA). Most of the polymer modification of binders already occurred at various oil terminals, and when rubber was introduced, DOTs were effectively asking many terminals to introduce a rubberized asphalt product. As a result, the terminals that provided blended rubber did so at prices that were equal to or greater than polymer modification. Therefore, states that mandated or otherwise specified rubber use in asphalt did not find it economically as attractive as polymer-modified binders.

With a pricing model that did not offer any performance or competitive advantage, wet process or terminal blend rubber-modified asphalt has been somewhat successful, but primarily where its use has been mandated or strongly encouraged by state DOTs. In spite of state mandates, the total amounts of rubber going into asphalt have plateaued in the past decade, with primary use focused in a handful of states located in warmer climates (southern and southwestern states) where significant attention has been paid to rutting resistance. However, there are industry concerns over the use of rubber in colder climates based on assertions that rubberized asphalt will prematurely fail in those environments. The FHWA notes that some earlier cold climate failures have been tied to construction issues, but rubberized pavement designs should be effective in colder climates (FHWA, 2014). Rhode Island, Missouri DOT, the City of Chicago and The Illinois Tollway Authority all report significant success in using wet process and/or terminal blend rubber-modified asphalt in large quantities over the last decade in colder climates (Success reported on I-29, I-88, I-294, I-290, I-355 and I-90) (Gillen, 2015). The Illinois Tollway notes the FHWA requirement to use recycled materials whenever possible to do so (FHWA, 2014), but the Tollway also notes that there is little or no economic incentive to use wet process rubber in place of polymers in modified asphalt applications (Gillen, 2015).

Current national growth in demand for wet process and terminal blend rubberized asphalt appears to be driven by state-level mandates for rubber use. Experimentation in other state markets continues, but demand growth for the product appears to be flat. Applications across a range of pavement designs and use environments appears to be successful, but absent state mandates/market incentives and/or assignment of some sort of premium for the reuse of rubber in pavements, significant production growth seems unlikely.

Dry Process

Crumb rubber-modified asphalt began to take root in the U.S. asphalt market in the early 2000s. Testing and commercialization of the “dry mix” process – the introduction of engineered crumb rubber at the producer’s site during the production of hot and warm-mix asphalt - was one of those efforts. In the dry process, crumb rubber is added to the hot aggregates similar to reclaimed asphalt pavement (RAP) at the plant and then mixed with binder. Typically, larger rubber size particles between 0.85 to 6.4 mm are used to substitute for fine aggregates, at a 1-3% replacement rate (Huang, 2007).

Dry process rubber introduction included use of engineered crumb rubber designed to reduce mix stickiness, improve workability and ease the introduction of rubber into the asphalt production process while producing a high quality, reliable modified asphalt mix. One of the most successful of the dry process efforts uses a metered, loss in weight pneumatic feeding system to inject fine, engineered crumb rubber into the mill during asphalt production, creating an asphalt rubber composite that performs as well as wet mix and polymer-modified asphalt. Depending on the performance criteria for the modified asphalt, these processes typically cost 15 to 50% less than wet process rubber and polymer-modified asphalt binders.

The Georgia DOT was the first state to specify both wet process and dry process rubberized asphalt as an alternative to polymer-modified asphalt. In the past ten years, the dry process has been effective in deeply penetrating the Georgia asphalt marketplace. The wet process has made no headway in Georgia, and polymer modification has lost market share (Figure 10). In Florida where a minimum level of rubber use is mandated in asphalt, the state allows contractors to choose between polymer modification and terminally-blended rubber in modified asphalt projects. In that market, rubber has consistently lost market share while polymer modification has gained steadily, and that evolution is driven by the fact that wet process/terminal blend rubberized asphalt offers a negative economic incentive when used. As a result, rubber has an important place to fill in the asphalt pavement industry, but rubber use in asphalt pavements is not likely to grow unless either states mandate rubber use or unless there is an economic incentive to use rubber in asphalt.

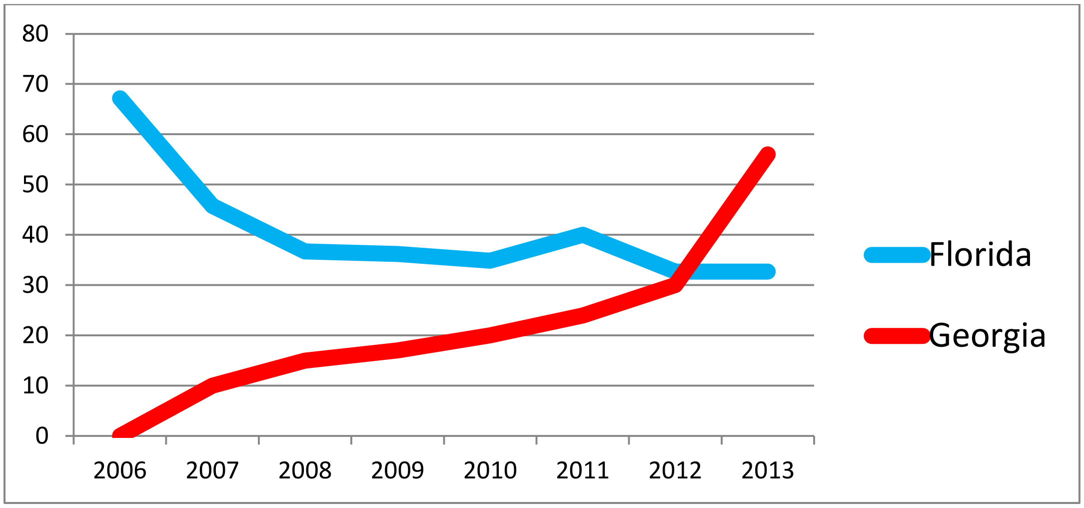


Figure 22. CR-Modified Asphalt Market Trends, FL and GA (after Romagosa and Kelly, 2006)

In addition to economic benefits, improvement in pavement performance is also reported as a result of using dry process CRM in asphalt mixes. Cao (2007) indicated that addition of scrap tire to the asphalt mixes using dry process can improve asphalt mix performance. It was concluded that the

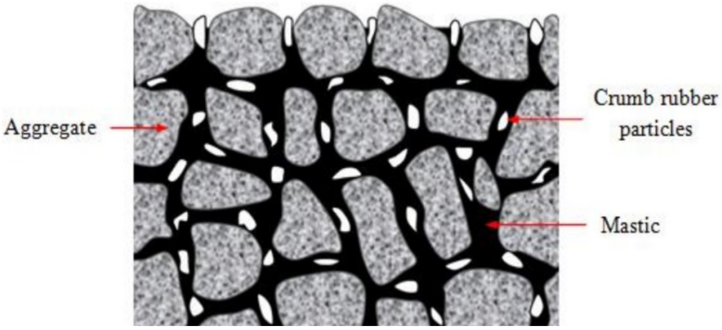


Figure 23. Rubber particles distribution within a gap graded rubberised (Takallou et al., 1988)

amount of rubber added to the mix significantly affects the high temperature resistance of the mix to permanent deformation and low temperature cracking (Cao, 2007). Cryogenic rubber is generally used in this process. As the rubber particles are relatively large, this process is suggested for gap-graded mixes that provide space for large rubber particles (Figure 11). The rubber modification's potential to improve fatigue resistance and ice control in pavements is shown in different studies (Fontes et al., 2010; Wang et al., 2012). These benefits are due to elastic behavior of rubber that results in more flexibility of asphalt mix. In addition, a research conducted in Italy, indicated that fatigue performance of dry processed CRM mixes, containing up to 3.5% crumb rubber by weight of the aggregates, is broadly comparable to conventional mixes (Di Mino et al., 2015). Visual inspection of rubberized porous European mix (PEM) indicated that rubberized PEM performs similar to polymer-modified asphalt pavement section in terms of rutting and cracking (Xie et al., 2015). Field measurements confirmed that rubberized asphalt paving reduces the traffic noise from light-duty vehicles (Sacramento County, 1999). Although there might be interaction between CRM and asphalt binder during mixing, storage, hauling, placement, and compaction the asphalt binder is not assumed as a modified binder in the dry process (Caltrans, 2005). This process is generally used for hot mix asphalt.

In a recent study, Hassan et al. (2014) indicated that critical design factors for designing dry processed CRM mixes are aggregate gradation, rubber gradation, binder content, and air voids content (Hassan et al., 2014). The following general guidelines for dry process CRM mixes were therefore suggested:

- Gap-graded or coarse densely-graded aggregates are preferred.
- Same binder grade or higher penetration binder must be used compared to HMA.
- Higher binder content should be used compared to HMA (1-2%).
- Combination of coarse and fine rubber is desirable.
- Low design air voids content is critical (approximately 3%).
- A higher mixing temperature compared to HMA must be used.
- Rubber must be added to hot aggregate prior to adding the binder.
- 1 to 2 hours curing time is needed after mixing.

Laboratory and Field Data Supporting the Effectiveness of Dry Process

Despite mixed performance data reported for the asphalt mixes containing dry process CRM, the dry process is known to show promising outcomes. After more than a decade of lab and field work, it is more widely accepted that dry process works as good as wet process. The following sections will try to present blocks of lab and field testing that represent the progressive research that led to the development of this process.

Published and Assembled Lab Work

There has been a steady stream of work that focused on rubber additions to asphalt, and some of that work has directly or indirectly focused on dry mix processes. A summary of the more substantive efforts that helped shape the field use of dry process along with a discussion of the salient points from each effort, are presented in this section.

➢ Federal Highway Administration SuperPave Binder Modification Research: (D'Angelo, 2004)

Under the direction of Terry Arnold and John D'Angelo, the U.S. Federal Highway Administration performed evaluations of rubber additions to various asphalt binders. The testing evaluations also included an industrial wax additive used to reduce stickiness in the rubber-modified binders. Rubber was added in crumb form (ASTM-compliant 14 to 30 mesh material) at a 5% by weight of binder rate, both with and without the workability additive. The crumb rubber was mechanically blended with a shearing mixer and was not "cooked" or otherwise digested at high temperatures for extended periods like terminally-blended materials. All binder testing was performed by FHWA, and the source binders were provided by Citgo Oil. The true grade of the test binder (B6225 binder, TFHRC Lab ID) was measured at 67 -25.3ºC. With or without the addition of the workability additive, the rubber-modified binder was graded as PG 70-22 with a true grade that ranged from 70.3-26.1 ºC to 74.4 -27.1 ºC (with the workability additive). In general, the testing revealed that the addition of approximately 5% rubber by weight of the binder would "bump" the PG by one grade, and this effort suggested that the addition of rubber could marginally decrease the lower boundary temperatures as well. The viscosity of the binders also increased with the addition of crumb rubber.

Key Findings

- Addition of 5% crumb rubber will increase binder viscosity and bump the performance grade one level (approximately), depending on the base binder used.
- Crumb rubber not subjected to extended cooking still had a beneficial effect on the modified binder

- <u>Heiden Labor Vest Binder Tests of Crumb Rubber-modified Bitumen (Heiden Labor Vest, 2005)</u>

A German asphalt consultant was retained to study the effects of rubber and workability agents on asphalt binders. Two binders were used in the evaluations: 50/70 and 70/100 Bitumen. These are rough equivalents of SuperPave PG 64-22 and PG 76-22. The 50/70 Bitumen was evaluated with 5, 10 and 15% rubber additions, and the 70/100 Bitumen was evaluated with 10 and 15% rubber additions. In these analyses, a 5% mix equates to 95% binder and 5% crumb rubber.

The modified binders were subjected to the following traditional binder analyses:

- Needle penetration
- Ring and ball softening point
- Ductility
- Elastic recovery
- Deformation behavior (thermal stability) with a dynamic shear rheometer (DSR)
- Low-temperature behavior with the bending beam rheometer (BBR) and
- Deformation work

The binder samples were mixed with crumb rubber of undisclosed particle size, and the binder, rubber and additive were combined in a paddle mixer (low shear) for 120 minutes before testing. The 50/70 binder mixes (5, 10 and 15% rubber additions) showed expected increases in viscosity with more rubber additions. All samples passed needle penetration and elastic recovery tests. Complex shear modulus, phase angle, m-value and stiffness results were all good to excellent, but m-values decreased as the ratio of rubber to binder increased. The 70/100 10 and 15% crumb rubber blends were also evaluated, and showed similar results.

Key Findings

- Rubber additions enhance rutting resistance in direct relationship to the amounts of rubber added.
- The addition of increasing amounts of rubber appears to have a small negative effect on m-values and associated cracking resistance (as more rubber is added, it will bring the critical low (PG) temperatures slightly higher).

- <u>Penn State NECEPT Study – Binder and Mix Studies</u>

This study looked at the addition of crumb rubber to asphalt with an industrial wax product, and attention was paid to both binder and mix performance changes with the addition of rubber. The study used a PG 58-28 binder from Koch in Wichita, KS along with variable addition rates of minus 14 crumb rubber. The crumb rubber and modified crumb rubber were added to the binder and subjected to shear mixing for 30 minutes, which is a fair simulation of the violent mixing and hold time associated with dry process CRM asphalt hot-mix designs. Their work continued to build on the growing body of research associated with rubber additions to asphalt. Their findings included:

Key Findings

- Binder viscosity increased by 75 to 80% with the addition of 10% minus 14 mesh crumb rubber as a fraction of binder in the mix design.
- For the selected binder, one grade bumps were seen with a 5% addition of rubber, and three grade bumps were seen with an addition of 10% rubber.
- When compared to the control binder (58, -28), rutting resistance increased exponentially with increased rubber additions up to 10% of binder content (Figure 12).
- Similar rutting resistance results were seen in Rolling Thin Film Oven (RTFO)-aged binders.
- Fatigue testing of modified binders showed improvements in performance with the addition of 10% rubber with minimal cooking times and high shear mixing for both short-term and long-term aged binders (Figure 13 and Figure 14).
- Rubber additions to un-aged binders produced higher-viscosity liquids at 135ºC, but they still easily met ASHTO standards (M320-2) for pump-ability.
- Bending Beam Rheometer testing showed some marginal improvements in low temperature performance with the addition of minus 14 crumb rubber (See Figure 7). The m-values showed little or no change with the addition of rubber.
- Preliminary testing of mix designs suggests that rubber additions will be effective in rutting prevention.

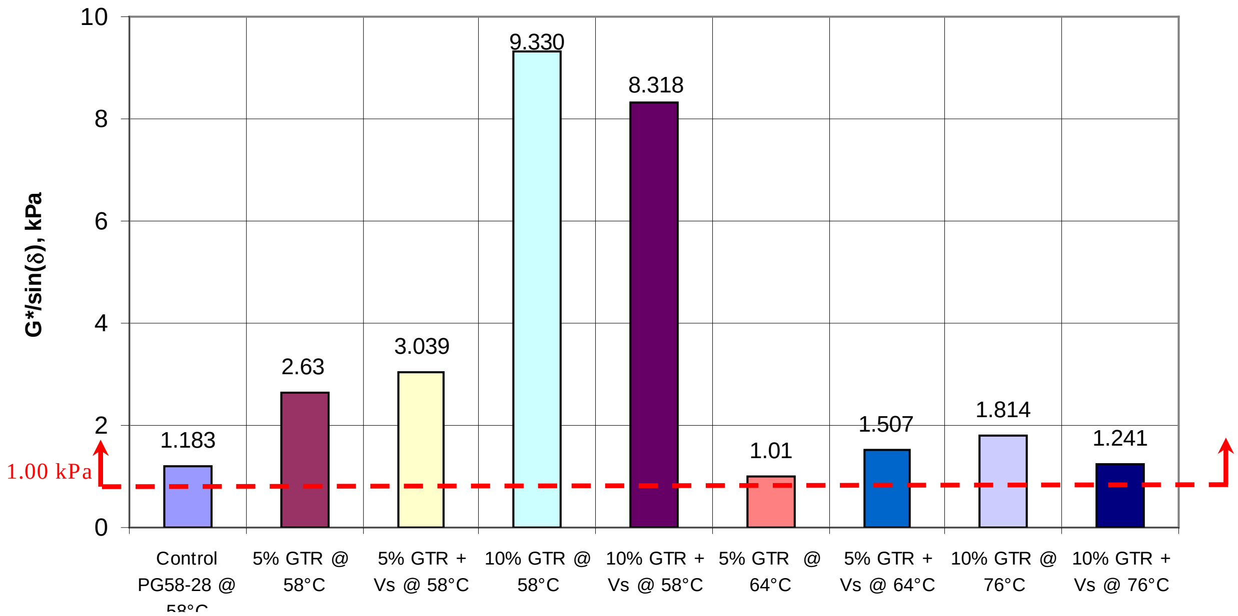


Figure 24. Improved rutting resistance caused by crumb rubber additions with short-term heating and high-shear mixing

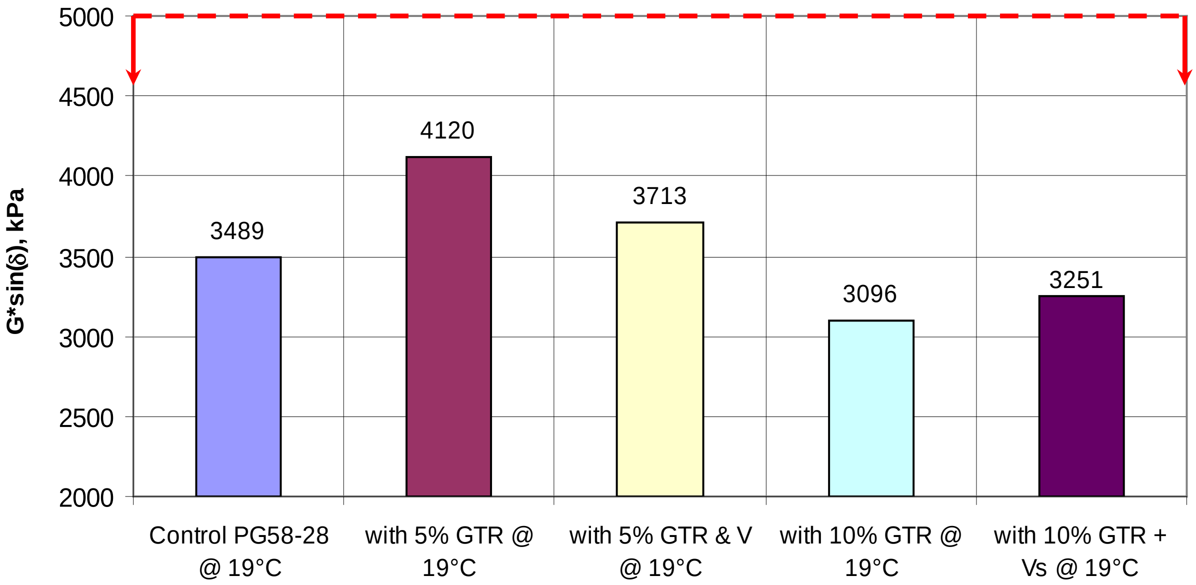


Figure 25. Improved fatigue performance caused by 14 mesh crumb rubber additions with short-term heating and high-shear mixing (Dynamic Shear Rheometer (DSR) results, short term aging Pressure Aging Vessel (PAV) binders)

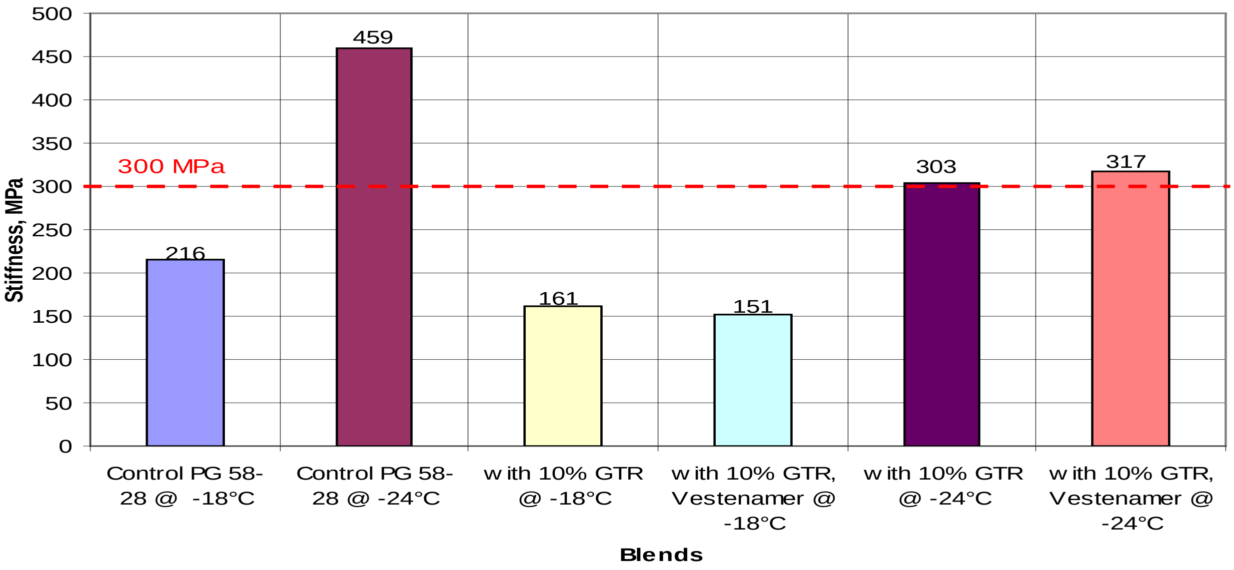


Figure 26. S values for different binder/rubber mix designs: PAV binder, 14-mesh rubber, long term aged binder: improved fatigue performance caused by crumb rubber additions with short-term heating and high-shear mixing

This study supports the positive effects of rubber-modified binder systems, and it demonstrates that significantly shorter cooking or digestion times with shearing mixing do not negatively impact CR–modified asphalt pavement performance

➢ Rutgers University: Dry Process Evaluation (Bennert et al., 2004)

The study compared the performance of unmodified PG 64-22 binder with polymer-modified (PG 76-22) binder, wet process modified binder with 20% rubber, and dry process modified binder with 20% rubber. Dynamic Shear Modulus (DSM) testing indicated that polymer-modified asphalt was significantly more rut-resistant than unmodified asphalt, but all of the rubber-modified asphalt samples were marginally more rut-resistant than polymer-modified asphalt (Figure 15). Permanent shear strain testing on the range of samples demonstrates that all of the modified asphalts performed significantly better than a standard PG 64,-22 binder, and the wet and dry mix rubbers performed marginally better than Polymer Modified Asphalt (PMA) (Figure 16).

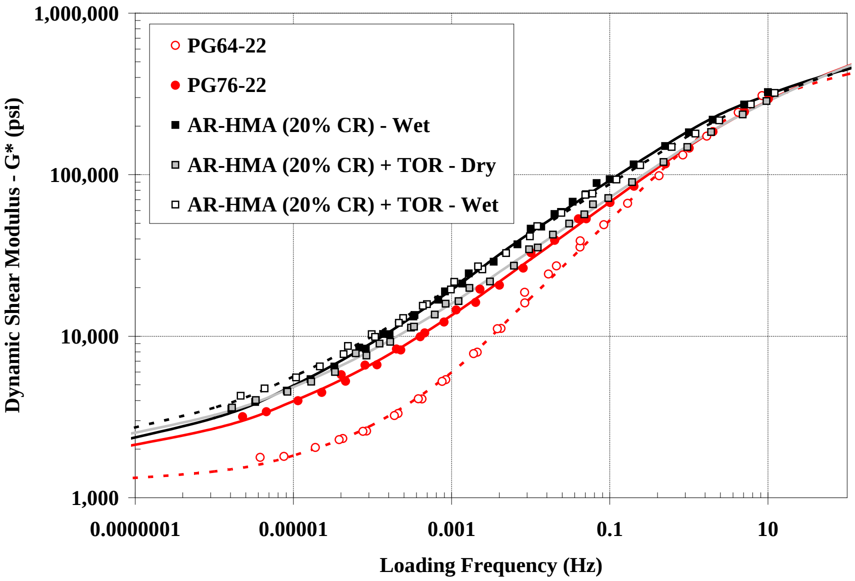


Figure 27. DSM testing comparison: PMA and dry/wet rubber asphalts (after Bennert et al., 2004)

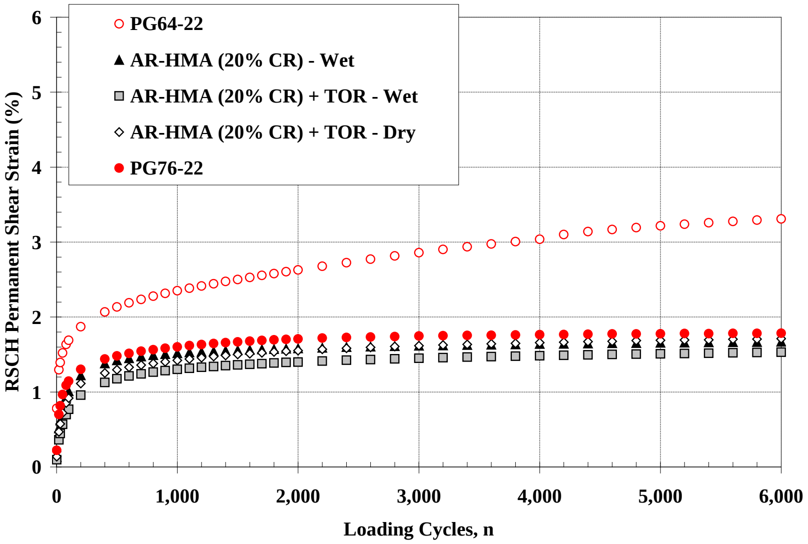


Figure 28. Permanent shear strain for various mix designs (after Bennert et al., 2004)

Key Findings

- Both wet and dry process Crumb Rubber Modified (CRM) mixes performed at least as well as PMA, if not better.
- Dry process CRM mix performance was competitive with wet process mix and better than PMR in all key test categories.
- The CRM pavements were more moisture and fatigue-resistant than PMA.

- Wet and dry CRM mixes accumulated approximately 18% less permanent shear strain at 5000 cycles compared to PMA.

➢ NCAT Report (Willis et al., 2012)

Follow-on research by NCAT focused on three outstanding questions: (i) Does the process of recycling rubber – cryogenic versus ambient – impact the performance of crumb rubber in asphalt? (ii) Does the grain size distribution of the crumb rubber impact the performance of rubber-modified asphalt? (iii) Do lab methods simulating dry process CRM asphalt show any loss in pavement performance compared to wet process asphalt modification?

Samples of rubber were taken from two large recyclers that produced cryogenic and ambient recycled crumb rubber. Eleven different samples of rubber (different production processes, different particle size distribution) were collected and used a single binder in order to create 13 different modified binders. Eleven of the samples included 10% crumb rubber modification, and two of the eleven were further modified to evaluate the CRM level to 15%. The rubber-modified binder samples were prepared using short-term, high-shear mixing. Each sample was evaluated through PG analysis, Multiple Stress Creep Recovery (MSCR) and Separation Tube/Softening Point settling evaluation. Also the source of the recycled rubber (auto versus truck tires) was tracked.

Crumb rubber particle sizes ranged from minus 14 to minus 140 meshes from both cryo and ambient sources. Mean particle sizes ranged from 50 to 600 microns. The particles were substantively the same in chemical makeup, but surface areas exhibited significantly different values, ranging from 0.044 to 0.75 square meters per gram of crumb.

In the mix designs, a PG 70-24 binder was used as the base binder. Modification with 10% rubber produced a PG bump of one to two grades, and almost all of the samples were close to or over PG 82-22 grade. This was consistent with earlier observations that a 10% of binder rubber addition produced a two-grade bump. The high temperature mean was 81.5 ºC with a 10% addition rate for crumb rubber. Low temperature tests showed that an addition of 10% rubber to the binder followed by shear mixing produced rubber-modified binders that averaged a low PG temperature of -23.4 ºC. This was approximately 0.6 degrees higher than the rating of the startup binder (-24 ºC) and was consistent with the observation that greater un-engineered crumb rubber additions will move both the high and low PG rating temperatures higher. This observation is supported by the fact that both of the 15% crumb rubber-modified binders failed to meet a -22 ºC specification. In general, the grinding method, temperature and particle sizes appear to have no impact on PG ratings (both high and low).

MSCR testing of the various mix designs demonstrated that almost all mixes qualified for traffic volumes in excess of 30 Million Equivalent Single Axle Loads (ESALs)-E-rated pavements. Separation tube/DSR analysis demonstrated evidence of significant separation or settling in all samples. Samples from the top and bottom of settling tube samples were subjected to a critical high temperature evaluation and found the mean variation between top and bottom critical high temperatures to be approximately 21 ºC, with the higher critical temperatures found in the bottom samples. This suggests a mean separation of approximately 20% of the rubber additive in this analysis. Larger particles separated the fastest. Softening point analysis showed that all but one of the samples had a greater than 2 ºC variance between upper and lower level modified binder samples, thus reinforcing the risks of separation in CRM binders.

A final portion of the NCAT study focused on the effects of polymer and workability agents on the performance of CRM asphalt binders. Three materials were evaluated: straight CR was added at 10%, Rubber-modified with a workability additive was added at 10% and a proprietary rubber/polymer hybrid was added at 10%. The true grades of the tested binders were all similar. MSCR testing indicated that the workability additive marginally improved elasticity, but softening point testing indicated that the same additive increased the rate and amounts of rubber separation in CRM binders.

Key Findings

- 10 and 15% addition rates of rubber produced close to a two-grade PG bump
- Short “cooking” of binder/rubber blends and shearing mixing had no apparent material impact on the quality of the binder compared to longer periods of digestion
- Neither the type of rubber (truck versus auto tires), the type of grinding process nor the particle size distribution had a significant impact on the performance of CR-modified binders
- Addition of more CR to binders increased the critical low PG temperatures of the modified binders
- Without properly engineered agitation systems, settling is an issue for wet-blended CR-modified binders

- Use of workability agents or polymer/rubber hybrids did not appear to materially improve binder performance (PG, MSCR, Settling)

Published and Assembled Field Work

➢ Georgia Department of Transportation (GDOT) Evaluation of Dry Process Rubber Pavements Following Extended Field Service (Shen et al., 2015)

An extensive investigation of multiple Interstate Highway projects using dry process rubberized asphalt in PEM and Stone Mastic Asphalt (SMA) mix designs was conducted in this study. These designs were evaluated after three and five years of service, and each project had an adjacent control lane constructed with the same mix designs using polymer-modified asphalt in place of dry process rubberized asphalt. The authors used a combination of field performance evaluations and core analysis along with two extensive laboratory analyses of mix performance. In the field and coring evaluations, the authors found no material evidence of any significant difference between PMA and dry process rubber performance. The authors also evaluated performance of wet process and dry process CRM asphalt and rubber and polymer-modified pavements placed side-by-side. No material differences were found in field performance between the different modification processes. Although the authors did not update their findings in the most recent report, the very first interstate section using dry process rubberized asphalt with PMA as a control is showing similar life-cycle performance as the project moves into its eleventh service year.

GDOT Study on CRM-HMA

In the field and coring evaluations, no material evidence of any significant difference was found between PMA and dry process CRM asphalt (Shen et al., 2015).

The laboratory analyses were also far-reaching, but several key conclusions were noted as follows.

Key Findings

- Both dry process rubber and polymer-modified binders were similarly rut-resistant.
- Within 30-60 minutes of mix production, dry process asphalt mimicked the performance of wet process asphalt across a wide range of binder and mix tests.
- Dry process rubber-modified binders exhibited strong similarities to wet process and polymer-modified asphalt binders in their respective master curves.
- The mixing associated with the turbulence and abrasion found during asphalt production acts to accelerate rates of light end segregation with the dry process.

- The authors conclude by observing that dry process rubberized asphalt mix designs can be used effectively in the field.

➢ Illinois Tollway Lab and Field Evaluation

The Illinois Tollway (Tollway) is a large, quasi-public authority over many of the most heavily-traveled interstate highways in Northern Illinois. Tollway began working with rubberized asphalt over seven years ago, and has thousands of tons of rubberized asphalt in their system that is performing at or beyond their expectations. Tollway is using both wet and dry asphalt modifications and devised its own system of mix testing in labs that is used to predict the expected field performance of various asphalt mix designs. Based on Tollway suggestions, rubberized asphalt should be competitive with PMA in the field.

Key Finding

- Extensive field testing of CRM asphalt mix designs and similar mix designs with PMA was conducted. The data presented indicated that the field performance and expected life – as measured in the field using a pavement condition rating system – of rubberized pavements (GTR sections) have a total expected service life of 17 to 23 years, while polymer-modified sections have a total expected service life of 12 to 18 years. At a minimum, the field performance of the tested mix designs with rubber appear to be comparable to those sections with PMA.

Summary of Published and Assembled Lab and Field Work

A careful reading of the aforementioned laboratory and field research reports leads to a series of conclusions that suggest new directions in rubber asphalt paving technology. Those conclusions are presented in a sequence that makes an argument for a more efficient addition of rubber in asphalt production.

1. Crumb rubber additions of approximately 5 and 10% produce one and two PG grade bumps in asphalt binders, respectively.
2. Rubber size, type, and grinding process affect but don’t materially impact binder or mix modification.
3. CRM binders are great for improved rutting resistance. More rubber results in stiffer pavements, but more rubber alone also can elevate critical low temperatures and cracking resistance.

4. Cumb rubber cook time in binder beyond 30 to 60 minutes does not materially improve binder performance.
5. With proper mixing, low and no-cook CRM asphalt seems to perform as well as terminal blend CRM asphalt, both in the lab and in the field.
6. Wet and dry process CRM asphalt perform as well or better than PMA (better fatigue and moisture resistance, lower permanent strain accumulation with rubber).
7. Separation of rubber and binder in terminal blends is a real risk.

To summarize further, wet and dry process rubber additions and polymer additions all seem to beneficially modify asphalt binders to a similar degree; and all technologies appear to reduce the life cycle cost of road surfaces.

Implications for Dry Process CRM Asphalt

These conclusions open the door for a serious look at dry mix asphalt. Research supports the performance of rubber in asphalt, and it appears that there are limited performance differences between uncooked (dry process) crumb rubber, cooked or digested crumb rubber and polymer-modified asphalts. In view of the presented information – and both field experience, follow-up lab testing and mix performance analyses suggest that they are true – this technology offers economic benefits to road owners while stimulating new demand for rubber in road construction and the marketplace.

Field Verification of CRM Asphalt

Various forms of CRM asphalt pavements using dry process engineered rubber have been used in the field for more than a decade, with total pavement placements now exceeding two million tons. Projects have ranged from initial efforts in parking lots and on municipal streets to multiple projects on state and interstate highways. At present, Dry Process Asphalt is in use on more than 5,000 lane-miles of pavement in multiple states.

As noted above, G DOT engaged independent researchers to evaluate the last decade's worth of dry process pavements in the state, with particular attention to interstate highway projects on I-20 and I-75. Test sections of up to 17 miles in length were placed in the 2008 to 2012 timeframe, and each test section had a polymer-modified control section of similar mix design included in the project design. Through 2016, dry process and control test sections exhibited no significant difference in either rutting or cracking performance. As of the end of

2016, Georgia will have more than one million tons of dry process asphalt in service (See Table 2 for a partial project list)

Table 6. Dry process rubber projects in service in Georgia

Dense Graded Mixes						
Contractor	Project #	Plant#	Mix Type	Tonnage	Route	County
ER Snell	CSSTP-M00-00(821)	80	12.5mm SP	22,419	SR140	Gwinnett
ER Snell	CSSTP-M00-00(832)	80	12.5mm SP	26,220	SR9	Gwinnett
ER Snell	CSSTP-008-00(578)	80	12.5mm SP	18,629	SR124	Gwinnett
The Lions Group	CSSTP-M003-00(754)	53	12.5mm SP	17,293	SR8	DeKalb
Reeves/Tugalo	CSNHS-M003-00(900)	91	12.5mm SP	10,744	SR17	Habersham
Reeves	CSSTP-M003-00(936)	37	12.5mm SP	7,212	SR26	Laurens
Reeves	CSSTP-M003-00(494)	46	12.5mm SP	14,736	SR28	Richmond
Reeves	M004173	15	12.5mm SP	20,000	SR10	Richmond
Reeves	CSNHS-M003-00(932)		12.5mm SP	17,293	SR27	Sumter
Reeves	CSSTP-M003-00(765)	4	12.5mm SP	10,971	US441	Baldwin
Reeves	CSSTP-M003-00(765)	4	19mm SP	1,071	US441	Baldwin
Reeves			12.5mm SP	2,000	SR26	Houston
Reeves/Baker	CSSTP-M003-00(910)		12.5mm SP	8,000	SR307	Chatham
Reeves/Baker	MLP00-0307-00(008)		12.5mm SP	6,000		Chatham
Reeves/Baker			19mm SP	6,200		Chatham
Reeves	M004271/72		12.5mm SP	22,000	SR247	Bibb
Baldwin	Various			50,000		
Southern	Various			1,000		
Reeves/Baker	M004590		12.5mm SP	14,000	US341	Wayne
Reeves/Baker	M004590		19mm SP	16,750	US341	Wayne
Reeves	NH000-0520-01(017)		12.5mm SP	13,575	US1/I-520	Richmond
Open Graded Mixes						
Contractor	Project #	Plant#	Mix Type	Tonnage	Route	County
Scruggs	CSNHS-M003-00(998)		PEM	28,049	I-75	Lowndes
Reeves	NH-IM-520-1(15)01		PEM	19,000	I-20/I-520	Richmond
Reeves	M004271/72		OGFC	3,000	SR247	Bibb
Reeves	CSNHS-M003-00(890)		OGFC	10,000	SR319	Tift
Reeves	CSNHS-M003-00(560)		OGFC	562	I-75	Houston/Peach
Reeves	NHIMO-0075-02(211)		PEM	10,900	I-75	Bibb
Reeves	10868		PEM	22,415	I-75	Turner
Reeves	NH000-0520-01(017)		PEM	7592	I-520	Richmond
Reeves	M004317		PEM	15525	I-520	Richmond

Dry mix products have been used on more than fifty significant projects located all over the US; the largest of these projects involved the paving of multiple 15-20 mile sections of Interstate Highway in heavy-use transportation corridors. The process is specified in Georgia and permitted in Louisiana, and the process is under various stages of review in a number of other states.

The following observations were made in the field:

Dry Mix Quality Control

- Engineered rubber infeed rates appear to have a narrow range of variation (± 2% according to conveyancing machine manufacturers and field measurement). State specifications ±5%.
- There is no record of any project showing material areal variations in pavement performance.

Field Application

- All plant-produced dry mix materials meet applicable production specifications.
- There have been no problems with basic operation of metered feeding systems and tracking of inputs.
- All dry process CRM asphalts exhibit excellent workability, good to excellent compaction, good to excellent minimum compaction temperatures, low field emissions and minimal stickiness during handling, even for rubber asphalt applications. This is true for breakdown temperatures as low as 113 ºC.
- With proper workmanship, placed pavements using 7 to 10% rubber as a fraction of binder are performing comparably to (if not better than) polymer-modified PG 64-22 binders with a true grade of PG 76-22.

Comparative Field Performance

- Ongoing comparative evaluations between dry mix CRM asphalts and polymer-modified asphalts (3 lbs. of SBS per 100 lbs. of binder, as low as 6.4 lbs. of rubber per 100 lbs. of binder) and wet mix rubberized asphalt show no difference in performance on roads including heavily travelled interstate highways over periods as long as a decade.

Rubber Additions

- Within limits, the size, type, grain size distribution (within a modestly narrow range) and processing method for crumb rubber don’t seem to materially impact the quality and performance of the paved surfaces.
- The method for rubber introduction into asphalt (wet or dry) does not have a material impact on the quality or the performance of the paved surfaces.

- The amounts of rubber added, the ratio of binder to rubber additions and the engineering of the rubber appear to be the most important variables influencing pavement performance.

Performance Comparison between Wet and Dry Process CRM Mixes

Semi-circular Bend (SCB) tests conducted on gap-graded CRM asphalt mixes indicated that asphalt mixes produced by wet and dry processes resulted in mixes with better fatigue performance (Arabani, 2007; Liu, 2011) compared with unmodified mixes. Similar results were obtained by conducting flexural bending beam fatigue tests (Souliman et al., 2016). Losa et al (2012) investigated the permanent deformation and fatigue cracking resistance of wet and dry processed gap-graded CRM mixes. Similar results were obtained for both wet and dry processed mixes from Indirect Tensile Strength Test (IDT). However, the Resilient Modulus (M_r) test data indicated that wet processed mixes had higher M_r values compared to the dry processed mixes. The indirect tensile fatigue test results indicated that dry processed gap-graded mixes could be superior to wet processed mixes in terms of fatigue cracking resistance. In another study, Kim et al. (2014) conducted research on CRM asphalt mixes in Korea. In this study, asphalt mixes produced using dry and wet process with CR contents of 8%, 10%, and 12% were investigated. The laboratory results indicated that fatigue performance of the CRM mixes at 20℃ showed the most significant improvement. It was concluded that wet processed CRM mixes are stronger than dry mixes in terms of high temperature deformation resistance and tensile strength at ambient temperature. It was shown that the moisture resistance of both dry and wet processed mixes is low after freezing-and-thawing cycles. Addition of hydrated lime was found to improve the resistance of the CRM mixes to moisture damage. Moreno-Navarro et al. (2016) investigated the fatigue cracking potential of four different mixes with the same aggregate gradation but with different binder types. It was concluded that fatigue life of mixes containing CR were considerably higher than that of conventional HMA. It was also shown that cracks in dry processed mix are thinner and less ramified than those in the other mixes.

Although the dry process has potential to recycle more scrap tires compared to the wet process; inconsistency in the performance and lack of standards for this method resulted in limiting its use among the asphalt pavement community (Hassan et al., 2014). However there are many studies which have shown superior performance of dry process CRM mixes. Most of these types of inconsistencies were observed in laboratory studies, due to a significant difference between lab-produced and plant-produced mixes as a result of different mixing procedures, and compaction efforts. Therefore, following a widely-accepted mixing and compaction methods which can represent the asphalt plant and field conditions, respectively, are needed for laboratory testing of CRM mixes.

GTR Applications/Field Operations

The literature review indicated that there is variety of applications of CRM materials throughout the United States. In this section the experience of different DOTs with CRM asphalt is discussed, briefly.

Florida

The Florida Department of Transportation (FDOT) is known as one of the agencies which conducted extensive research and field experiments on CRM pavements. In a 1996 study, FDOT investigated the effect of different grinding processes on the asphalt rubber properties. They found that GTR with greater surface areas and more irregular shaped particles produces asphalt binders with higher viscosities. It was also concluded that asphalt binders with cryogenically GTR have the most settlement and least drain down resistance (West et al., 1996).Three demonstration projects conducted by FDOT in 1989 and 1990 evaluated the constructability and short term performance of asphalt rubber pavements with various amounts of GTR in a typical production project. The first two (2) projects tested stability and constructability of mix designs Each of these projects used different binder content ranging from 3% to as high as 17% depending on the project objectives. The third project explored senstivity of dense-graded and open-graded mix properties to changes in CR particle size and binder content.

Three test sections and a control section were included in the first project. Three (3) GTR-modified binders with 3, 5, and 10% CR by total weight of binder were used in this study. All of the mix designs were developed by using Florida DOT Marshall Mix Design procedure. The binder content of 7% was selected for the control section. While, the binder contents of the sections with 3, 5, and 10% CR were 7.22, 7.37, and 8.25%, respectively. During construction and placement of the mixes the problems such as occurrence of mix pickup with the rollers and tenderness of the section with 10% CRM were observed. The experimental tests on plant-produced materials indicated that all the sections except that containing 10% CRM had similar Marshall stabilities with the design values. The stability value of the section with 10% CRM was half of the design value. It was hypothesized that the reduced stability is due to high binder content and low fine particles (Page, 1992).

Four (4) test sections and a control section were included in the second project. Four (4) GTR-modified binders with 5, 10, 15, and 17% CR by total weight of binder were used in the study. The total binder content of 6.3% was selected for the control section and the binder contents of the sections with 5, 10, 15, and 17% CRM were 7.16, 8.11, 9.18, and 10%, respectively. The construction process indicated that the mixture with 10% CR has the best constructability (Page, 1992).

In the third project conducted by FDOT, four (4) different sections were included in the construction. The results of this study indicated that dense-graded mix properties are more sensitive to changes in CR particle size and binder content than those of open-graded mixes. This sensitivity was attributed to the lower amount of void space available in dense-graded mixes. Based on the results of this project, FDOT drafted specifications for using crumb rubber in asphalt pavement surface course, validated by other researchers (Choubane, et al., 1999), which are still in use. For the dense-graded and open-graded surface courses, the CR amount was limited to 5 and 12% by weight of asphalt cement, respectively. The maximum size of ground rubber was selected to be 300 mm (No. 50 sieve) for dense-graded mixes and 600 mm (No. 30 sieve) for open-graded mixes (Page et al., 1992).

In 1999, a study was conducted on the three above-mentioned projects to evaluate their performance. The major finding of this 10-year study was that the application of scrap tires in asphalt pavements using the wet process improves the crack resistance of surface mixtures. The test sections constructed using CRM mixes showed about 1 to 6% cracked areas, depending on the CR amount. However, the test sections constructed using mixes containing virgin binder or dry-mixed sections showed about 30% cracked areas. CR amounts ranging between 10 to 15% were suggested as effective optimum rubber content in this study (Choubane, et al., 1999). According to the Florida Department of Environmental Protection (FDEP), Florida is the only state that uses modified rubber asphalt in the surface course of all state-maintained roads (FDEP, 2011).

FDOT started the use of CR asphalt mixes in interlayers and seal coats about 45 years ago. FDOT allowed the use of CRM in surface treatments and interlayers based on the finding of a project conducted in 1980 (Murphy and Potts, 1980). SAMI binders in Florida include 20% CR by weight of asphalt in order to achieve a high viscosity material. In the most recent revision of FDOT asphalt mixture guidelines, the use of scrap tires in asphalt friction courses and membrane layers is approved (Ellis, et al., 2014).

Arizona

Arizona Department of Transportation (ADOT) has more than 45 years of experience in incorporating asphalt rubber materials in the construction and rehabilitation of pavements. Rather than use of crumb rubber in asphalt paving mixes, ADOT has used GTR-modified binders in chip seals as stress absorbing membranes (SAMs) and SAMIs. In a 1994 study, ADOT evaluated the service life of the various CRM treatment materials using the data available in the ADOT pavement management system data base concluding that the average service life of SAMs was 6.4, 10.3, and 8, 9 years while the SAMIs average service life was 10.7, 9.5, and 10.7 for Interstate highways, state routes, and U.S. routes (Flintsch, et al., 1994).

Although Arizona has a wide range of climate zones from hot (Yuma, Bullhead City) to cold (Flagstaff, Grand Canyon); there has been many successful pavement constructions using GTR-modified materials throughout the state (Charania, et al., 1992; Flintsch, et al., 1994; Miller 1996; Way, 2000; Morris et al., 2001; Kaloush, et al., 2002; Caltrans, 2005).

ADOT designed and constructed a large scale project in 1990 to evaluate the effect of asphalt rubber on reflective cracking occurrence in thin overlays. The project was located in Flagstaff, AZ on Interstate 40. The overlay project was constructed on a badly-cracked concrete pavement which was originally built in 1969 with a thickness of 8 inches and total width of 38 feet (Way, 1991). The asphalt rubber for the project was produced with 20% GTR using the wet process. No other additives or modifiers were used in this project. ADOT reported that the performance of the asphalt rubber overlay was beyond the original expectation (Way, 2000). It was indicated that after nine years of service the overlay is still virtually crack-free with no rutting. Results of this project have led to significant increase in asphalt rubber application throughout Arizona.

Over 2,000 miles of asphalt pavements containing GTR have been built in Arizona, between 1990 and 2000. ADOT tracked all the asphalt rubber overlay projects in the state and reported that the percent cracking in asphalt rubber overlays is significantly lower than that in conventional overlays without any rubber (Figure 17). There are many gap-graded CRM mixes placed in the State of Arizona. Kaloush et al. (2007) conducted flexural fatigue test on the field specimens extracted from the gap-graded Arizona pavements and showed that crumb rubber modification results in higher pavement fatigue life. In a more recent study, point bending tests were conducted on Arizona mixes indicating that CRM mixes have longer fatigue lives compared to traditional HMAs which are consistent with field observations over a 16-year period (Way et al., 2015).

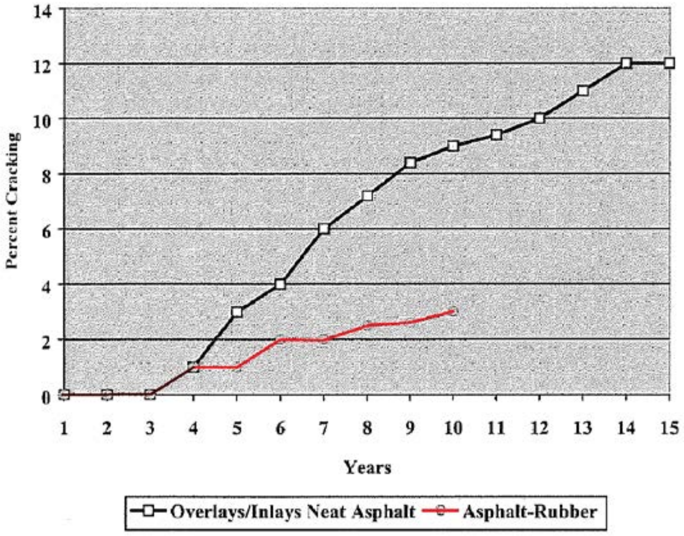


Figure 29. Percent cracking over a ten-year period with and without asphalt rubber (Way, 1999)

Arizona Transportation Research Center study also reported the noise reduction as an additional benefit as a result of using CRM asphalt in pavement construction (ARTR, 1996). It was indicated that an Asphalt Rubber Open Graded Friction Course (AR-ACFC) reduces the noise by 5.7 decibels (Figure 18).

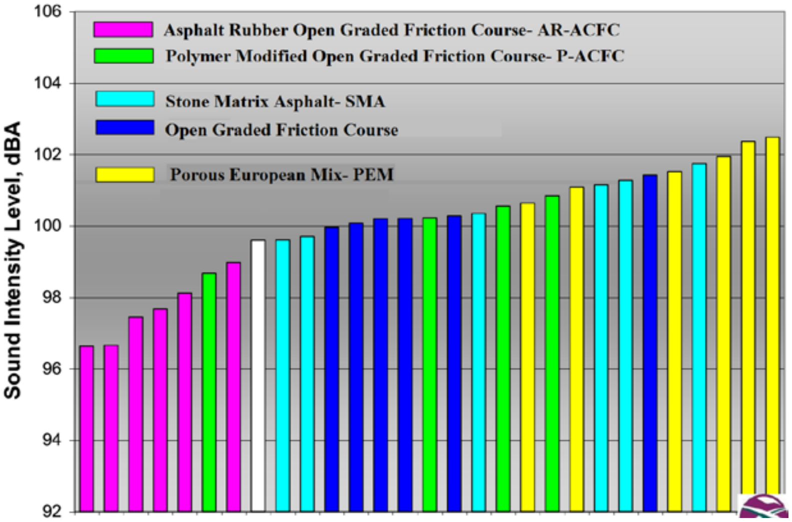


Figure 30. Comparison of tire-pavement noise of asphalt pavement courses (ATRC, 1996)

Studies of ADOT on use of scrap tire in pavements revealed that thickness of CRM pavements is half of that in conventional pavements. Furthermore, the percent cracking of CRM mixes is approximately one-fourth of a conventional mix in a similar period of time, making them an appropriate choice for the state (Way, 2000). In the state of Arizona, all high volume highways have been surfaced with asphalt rubber open-graded friction course (Shu, et al., 2014).

California

The California Department of Transportation (Caltrans) has been using scrap tires in chip seals since 1970s and has started using them in rubberized HMA since 1980s (Zhou et al., 2014). Approximately, 31% of all HMA mixes placed in California by the end of 2010, was rubberized HMA (Zhou et al., 2014). As mentioned earlier, the first Caltrans dry process CRM HMA pavement was constructed in 1978. The first Caltrans Rubber Asphalt Concrete (RAC) pavement by using wet process was constructed in 1980. The successful Caltrans experience with use of CRM asphalt changed Caltrans approach to the use of high viscosity CRM binders. The constructed pavements were monitored over time and the overall performance of the CRM mixes were rated excellent by Caltrans (DeLaubenfels 1985). Caltrans built more RAC projects and continued studying the RAC performance. It was clear in 1987 that thin RAC pavements perform better than thicker Conventional Dense-graded Asphalt Concrete (DGAC) (Caltrans, 2005).

Caltrans engineers reviewed the performance of over 100 RAC projects in California and 41 Arizona DOT projects (Hildebrand and Van Kirk, 1996). It was concluded that performance of RAC materials becomes excellent when properly designed and constructed. A very important finding of the study was that the progress of distresses in RAC pavements is much slower than that of a structurally equivalent DGAC pavement. Two hundred ten RAC projects were constructed by Caltrans by mid-2001 (Caltrans, 2005). Caltrans also included SAMIs in the pavement construction for a project in Ravendale, CA. The results of this study significantly changed Caltrans approach to the use of CRM materials (Doty, 1988).

New Jersey

The New Jersey Department of Transportation (NJDOT) conducted a study on seven experimental field projects, including a control section, constructed in 1991 through 1994, to evaluate the use of wet and dry processes. The results of this study indicated that the wet process DGAC mixes preform similar to DGAC mixes without GTR. The dry process CRM mixes performed inconsistency. In this study the emissions of six (6) CRM mixes were assessed. It was concluded that emissions levels of CRM mixes are generally higher than those of non-CRM mixes (Baker and Connolly, 1995).

New Mexico

The New Mexico Department of Transportation's (NMDOT) first experience with dry process CRM HMA was in 1984. The performance of the pavement was monitored for duration of nine (9) months and it was indicated that the pavement structure performed well during winter months. However, during the hot weather the pavement lost structural capacity and failed. As stated by the report the pavement "literally came apart". In 1985, NMDOT constructed the first wet process CRM pavement. Within the first year of service, the pavement surface showed excessive premature cracking. After these two unsuccessful projects NMDOT stopped using crumb rubber in asphalt pavements for ten years (Tenison, 2005). In 1994, six (6) Rubberized Open-graded Friction Course (ROGFC) projects were constructed by NMDOT. Monitoring the performance of the sections indicated that these mixes performed better than conventional Open-graded Friction Course (OGFC) pavements in New Mexico. It was also reported that cost of ROGFC was 33% higher than that of conventional OGFC (Tenison, 2005).

Texas

Texas Department of Transportation (TxDOT) has 40 years of experience in utilizing asphalt rubber in construction and rehabilitation of pavements. In Texas, CR has been used in four different types of pavement constructions: chip seal coat, underseal, HMA, and Porous Friction Course (PFC) (Estakhri et al., 1992). In a study conducted in 1982, researchers evaluated the performance of nearly 800 miles of Texas seal coat and underseal projects constructed from 1976 to 1981. The results indicated that using asphalt rubber binder in seal coat construction reduces alligator cracks and raveling compared to seal coat coats constructed by using conventional HMA (Shuler, et al., 1982). In a latter study conducted in 2002, it was concluded that asphalt rubber chip seals are good treatment option for Texas pavements (Freeman, et al., 2002). Pavement evaluation results indicated that CRM HMA projects have significantly better cracking resistance in comparison with conventional HMA. Good rutting resistance was also reported from CRM HMA projects (Tahmoressi, 2001). In a study conducted for TxDOT in 2001, it was stated that "All asphalt rubber Porous Friction Course (PFC) projects are exhibiting excellent performance properties. Resistance to cracking and raveling in asphalt rubber PFC is particularly impressive. From cost and benefits stand point, PFC represents the best application for asphalt rubber." (Tahmoressi, 2001).

Oregon

Seventeen test sections were constructed by Oregon Department of Transportation (ODOT) from 1985 to 1994 throughout the state. These sections were evaluated through visual condition ratings (based on ODOT's modified SHRP method) and ride values as measured by a South Dakota-type profilometer. The results indicated that performance of the dense-graded wet process and dry process CRM mixes was noticeably worse than the control sections. However, the open-graded mix with 12% CRM passing a 180-µm sieve (No. 80 sieve) performed slightly better than the control section. No construction issue was encountered with gap-graded dry process mixes, but raveling occurred shortly after construction. It was concluded that among the tested sections, the dry process mixes exhibited the worst performance. It was also indicated that higher temperatures are needed in field operations for mixes with high-viscosity CRM binders compared to unmodified control mixes (Hunt, 2002).

Alaska

Dry CRM process was used in several projects by Alaska Department of Transportation and Public Facilities (AKDOT&PF). Although good performance was reported for some sections in resisting low-temperature, fatigue cracking, and in improving ice control characteristics; in some cases there was no significant difference between the performance of dry process and control mixes (Raad and Saboundjian, 1998; Esch, 1984).

DOTs' Asphalt Rubber Usage Guide

Development of standard specifications is vital to control the design, production, and placement of CRM materials. A few state DOTs have developed and modified guidelines for use of CRM materials as their experience has grown. In the following sub-sections specification parameters for the four leading states in asphalt rubber utilization, i.e. Arizona, Texas, Florida, and California, are summarized.

Ground Tire Rubber Size and Gradation

Table 3 summarizes the gradation requirements for four leading states in use of GTR in HMA. The specified GTR gradation is for use in

GTR Size and Gradation…

Larger GTR sizes are allowed to be used in the inter layers and chip seals compared to asphalt mix layers.

GTR-modified binders of asphalt mixes, chip seals, and inter layers (for both terminal- and field-blending wet processes). The GTR shall be free of wire.

GTR Binder Properties

Table 4 summarizes the present specifications for terminal-blended CRM binders (with maximum viscosity of 1.5 pa.sec) in Arizona, Florida, and Texas. Texas DOT requires complete digestion of CRM.

Table 7. GTR gradation requirements

Sieve Number	Sieve Size	ADOT- Type A (Chip seals and SAMIs)	ADOT- Type B (Gap-graded and open-graded HMAs)	TxDOT-Grade A	TxDOT-Grade B (SAMIs)	TxDOT-Grade C (HMAs)	FDOT-Type A (HMAs)	FDOT-Type B (HMAs)	FDOT-Type C (SAMIs)	Caltrans
8	2.36 mm	100	-	100	-	-	-	-	-	100
10	2.00 mm	95-100	100	95-100	100	-	-	-	-	98-100
16	1.18 mm	0-10	75-95	-	70-100	100	-	-	100	45-75
30	600 µm	-	30-60	-	25-60	90-100	-	100	70-100	2-20
40	425 µm	-	-	-	-	45-100	-	-	-	-
50	300 µm	-	5-30	0-10	-	-	100	40-60	20-40	0-6
100	150 µm	-	-	-	-	-	50-80	-	-	0-2
200	75 µm	-	0-5	-	0-5	-	-	-	-	0

Table 8. Specifications for terminal-blended CRM binders

State DOT	ADOT- PG 76-22 TR+	TxDOT- AC-20-5TR	FDOT- ARB 5	FDOT- ARB 12
Tests on un-aged binder				
Base asphalt cement grade	PG 76-22	AC-20	PG 67-22	PG 67-22
Minimum CRM by total weight of binder, %	-	5	-	-
Minimum CRM by weight of asphalt cement, %	9	-	5	12
Minimum Rotational Viscosity- Pascal·seconds	-	-	0.4 at 150	1.0 at 150
Viscosity AASHTO 202, poise at 60ºC/ 135ºC	-	Min 2000/ Max 10.0	-	-
Minimum interaction temperature, Maximum interaction temperature	-	-	150 , 170	150 , 175
Minimum Interaction Time	-	-	10 minutes	15 minutes
G*/sin δ @ 76ºC @ 10 rad/sec	Min 1.0 kPa	-	-	-
G*/sin δ @ 64ºC @ 10 rad/sec	-	Min 1.0 kPa	-	-
Phase angle, δ	Max 75°	-	-	-
Needle Penetration @ 25 /77°F, 100g, 5 sec, 0.1 mm	-	75-115	-	-
Softening Point, ºC, min	60	49	-	-
Elastic Recovery, 10ºC, %, min	55%	55%	-	-
Tests on RTFO-aged binder				
Retained penetration ratio @25ºC, % of original	-	60-100	-	-
G*/sin δ @ 76ºC @ 10 rad/sec	Min 2.2 kPa	-	-	-
Tests on PAV-aged binder				
G*/sin δ @ 31ºC @ 10 rad/sec	Min 5000 kPa	-	-	-
Creep Stiffness, S @ -12ºC, 60 sec	Max 300 Mpa	-	-	-
Creep Stiffness, S @ -18ºC	-	Max 300 Mpa	-	-
m-value @ -12ºC, 60 sec	Min 0.300	-	-	-
m-value @ -18ºC	-	Min 0.300	-	-

Table 5 summarizes the existing specifications for on-site-blended CRM binders (with minimum viscosity of 1.5 pa.sec) in Arizona, Florida, California, and Texas.

Table 9. Specifications for on-site-blended CRM binders

State DOT	ADOT-Type 1 Binder	ADOT-Type 2 Binder	ADOT-Type 3 Binder	TxDOT- Type I Binder	TxDOT- Type II Binder	TxDOT- Type III Binder	FDOT-ARB 20	Caltrans
Base asphalt cement grade	PG 64-16	PG 58-22	PG 52-28	(PG 58-28/PG 64-22)	(PG 58-28/PG 64-22)	(PG 58-28/PG 64-22)	PG 64-22	AR-4000
Minimum CRM by total weight of binder, %	-	-	-	15	15	15	-	-
Minimum CRM by weight of asphalt cement, %	20	20	20	-	-	-	20	18
Modifier content by weight of asphalt cement, %	Not Allowed	Not Allowed	Not Allowed	Not Used	Not Used	Not Used	Not Used	-
Minimum interaction temperature, Maximum interaction temperature	163 ℃, 190	163 ℃, 190	163 ℃, 190	-	-	-	170 ℃, 190	190 ℃, 226
Minimum Interaction Time	60 minutes	60 minutes	60 minutes	-	-	-	30 minutes	45 minutes
Rotational Viscosity-Pascal·seconds	1.5-4.0 at 177	1.5-4.0 at 177	1.5-4.0 at 177	1.5-5.0 at 175	1.5-5.0 at 175	1.5-5.0 at 175	1.5 at 175	1.5-4.0 at 190
Penetration: 4 (39.2 °F), 200 g, 60 sec. (ASTM D 5); 0.1 mm, minimum	10	15	25	-	-	-	-	-
Cone Penetration @ 25 /77°F, 150g, 5 sec, 0.1 mm	-	-	-	-	-	-	-	25-70
Needle Penetration @ 25 /77°F, 100g, 5 sec, 0.1 mm	-	-	-	25-75	25-75	50-100	-	-
Softening Point: (AASHTOT 53); ℃, minimum	57	54	52	57	54	52	-	52
Softening Point: (AASHTOT 53); ℃, maximum	-	-	-	-	-	-	-	74
Resilience: 25 (77 °F)(ASTM D 5329); %, minimum	30	25	20	25	20	10	-	18
Tests on residue from Thin Film Oven Test: Retained penetration ratio@ 4 ℃/39.2°F, % of original	-	-	-	75	75	75	-	-
Flash point, C.O.C.	-	-	-	232	232	232	-	-

GTR-Modified Binder Characterization

The Superpave® PG grading system was designed to characterize the asphalt binder based on the pavement performance parameters, namely rutting, fatigue, and low-temperature cracking. This grading system's philosophy is to correlate pertinent properties of the asphalt binder with the pavement's service life under given climate and aging conditions. Accordingly, different test methods and devices were introduced to conduct the performance grading of asphalt binders, namely RTFO, PAV, Rotational Viscometer (RV), Dynamic Shear Rheometer (DSR), Bending

Beam Rheometer (BBR), and Direct Tension Tester (DTT). The performance grade specifications are presented in AASHTO M 320-10. Although, the PG system was mainly developed for unmodified binders; it was believed that the developed specifications are “blind to source” and thus are applicable to all the binders, regardless of the source and modification type (Tabatabaee, 2009).

In the current Superpave® PG grading specifications, the high temperature performance grade of asphalt binder is determined by utilizing a DSR test conducted on 1.0 mm-thick binder specimens. The current gap height may cause issues, such as interference of large rubber particles (larger than 0.25 mm) with the measurements. Bennert, et al. 2015, conducted the PG grading tests as well as the MSCR test at a gap height of 2.0 mm in addition to 1.0 mm. They showed that the binder test results obtained from the tests on 2.0 mm gap height correlates better with the asphalt mix performance.

STATE DOT SURVEY ON USE OF GTR IN ASPHALT MIXES

In order to promote successful use of GTR in Oklahoma, it is imperative to help ODOT develop specifications/special provisions for utilizing rubberized asphalt by collecting information, common practice and specifications followed by other state DOTs. Therefore, a survey of construction specifications used by different DOTs, which allows the use of GTR in asphalt, was conducted in this study. Since DOT practices are generally not available in the open literature, this survey was found to be an effective tool for gathering data on the current practices including the methods, special provisions, and specifications associated with the use of GTR in asphalt pavement by DOTs. The survey questionnaire was prepared in close collaboration with ODOT and ODEQ. The survey was conducted through an online data collection website, namely www.surveymonkey.com, to maximize the efficiency and productivity of the data collection process. The survey questionnaire was distributed among different DOTs with the help of ODOT Materials & Research Division.

Survey Questionnaire

The survey questions distributed among DOTs is provided below.

STATE DOT SURVEY 2016

USE OF GROUND TIRE RUBBER (GTR) IN ASPHALT PAVEMENTS

Question 1: Does your agency use Ground Tire Rubber (GTR) in any form such as Crumb Rubber (CR) in asphalt mixes?

a. Yes

b. No

Question 2: If the answer to Question 1 is YES skip Question 2 and continue to Question 3. If the answer to Question 1 is NO, please specify the reason(s) for not incorporating GTR in asphalt mixes (please mark all that apply and write in your answer if applicable) and then skip to Question 11.

a. Unsuccessful experience of using GTR in asphalt mixes in the past (please specify).

b. Concern over the performance of asphalt mixes containing GTR.

c. Lack of performance data of asphalt mixes containing GTR.

d. Using GTR in asphalt is not cost effective.

e. There is not sufficient incentive to recycling scrap tires in pavement applications.

f. There is not a crumb rubber producer in the state.

g. Other (Please specify): ______________________________.

Question 3: What are the main reasons for using GTR asphalt pavements by your agency? (Please mark all that apply and write in your answer if applicable).

a. It is cost effective.

b. Better performance compared to conventional materials (Please specify) ___________.

c. Significant incentives to recycling scrap tires.

d. Other (Please specify): ______________________________.

Question 4: Please specify in what type(s) of mixes the GTR is used by your agency (please mark all that apply and write in your answer if applicable)?

a. Hot Mix Asphalt (HMA)

b. Warm Mix Asphalt (WMA)

c. Non-Structural Thin-Lift Overlay (<1.5 in.)

d. Structural Overlays (> 1.5 in.)

e. Mill-and-Fill Operation

f. Chip Seal

Question 5. Where do you use asphalt mixes containing GTR (multiple answers may be selected, if applicable)?

a. Interstate
b. City road
c. State highway
d. Other (Please specify): ________________________________.
g. Fog Seal
e. Other (Please specify): ________________________________.

Question 6: Please specify the type of process used by your agency in order to incorporate GTR or CR in asphalt mixes (please mark all that apply and write in your answer if applicable)?

a. Dry Process
b. Wet Process (Terminal Blend)
c. Wet Process (Field blend)
d. Other (Please specify): ________________________________.

Question 7: Please specify if your agency follows a guideline, technical specifications, special provision, etc. for incorporating GTR in asphalt mixes?

a. Yes (Please provide the link to the guideline, technical specifications, special provision, etc.)
b. No.

Question 8: What considerations are recommended by your agency to be taken into account in design of asphalt mixes containing GTR/CR (please mark all that apply and write in your answer if applicable)?

a. Mix Temperature (Please specify): ________________________________.
b. Modification to Binder PG Grade (Please specify): ________________________________.
c. Compaction Effort (Please specify): ________________________________.
d. Other (Please specify): ________________________________.

Question 9: Please specify test(s) and criteria used to set the maximum GTR content (%) limit in surface course and base course.

a. Surface Course (Max GTR) ____ %.
Test(s) (e.g. fatigue, low temperature cracking, etc.)_______________________.
Criteria (e.g. number of cycles to fatigue failure; creep compliance; indirect tensile strength, etc.)
___________________________.

b. Intermediate/Base Course: (Max GTR) ____ %.

Test(s) (e.g. fatigue, low temperature cracking, etc.)______________________.

Criteria (e.g. number of cycles to fatigue failure; creep compliance; indirect tensile strength, etc.)___________________________.

Question 10: What laboratory performance tests are conducted on asphalt mixes containing GTR (please mark all that apply and write in your answer if applicable)?

a. Rutting (Asphalt Pavement Analyzer or Hamburg Wheel Tracking)
b. Fatigue (Four-Point Bending Beam)
c. Fatigue (Viscoelastic Continuum Damage)
d. Creep compliance
e. Moisture damage (Tensile Strength Ratio or Hamburg Wheel Tracking)
f. Dynamic modulus, Flow Number, Flow Time
g. Other, (Please specify): ________________________________.

Question 11: Provide any additional comments or information you wish to share.

Collected Responses

reflects state DOTs and transportation agencies that participated in this survey. Based on the responses received, 37 state DOTs and agencies from the United States and 1 Canadian transportation authority responded to this survey. 74% of state DOTs participated in this survey.

Table 10. Transportation Agencies Participated in Survey

No.	Agency	State
1	Alabama Department of Transportation (ALDOT)	AL
2	Alaska Department of Transportation & Public Facilities (ADOT &PF)	AK
3	Arizona Department of Transportation (AZDOT)	AZ
4	Arkansas State Highway and Transportation Department (AHTD)	AR
5	California Department of Transportation (CALTRANS)	CA
6	Colorado Department of Transportation (CDOT)	CO
7	Connecticut Advanced Pavement Lab. (CAP LAB)	CT
8	Delaware Department of Transportation (DelDOT)	DE
9	Department of Transportation (DOT)	NH
10	Florida Department of Transportation (FDOT)	FL
11	Georgia Department of Transportation (GDOT)	GA
12	Iowa Department of Transportation (IowaDot)	IA
13	Kansas Department of Transportation (KDOT)	KS
14	Kentucky Transportation Cabinet (KYTC)	KY

15	Louisiana Department of Transportation & Development (LaDOTD)	LA
16	Maine Department of Transportation (MaineDOT)	ME
17	Maryland State Highway Administration (SHA)	MD
18	Michigan Department of Transportation (MDOT)	MI
19	Minnesota Department of Transportation (MnDOT)	MN
20	Mississippi Department of Transportation (MDOT)	MS
21	Missouri Department of Transportation (MODOT)	MO
22	Montana Department of Transportation (MDT)	MT
23	Nebraska Department of Roads (NDOR)	NE
24	Nevada Department of Transportation (NDOT)	NV
25	New Jersey Department of Transportation (NJDOT)	NJ
26	New Hampshire Department of Transportation (NHDOT)	NH
27	Ohio Department of Transportation (ODOT)	OH
28	Pennsylvania Department of Transportation (PennDOT)	PA
29	Rhode Island Department of Transportation (RIDOT)	RI
30	South Carolina Department of Transportation (SCDOT)	SC
31	Tennessee Department of Transportation (TDOT)	TN
32	Texas Department of Transportation (TxDOT)	TX
33	Utah Department of Transportation (UDOT)	UT
34	West Virginia Division of Highways (WVDOT)	WV
35	Wisconsin Department of Transportation (WisDOT)	WI
36	Washington State Department of Transportation (WsDOT)	WA
37	Vermont Agency of Transportation (VTRANS)	VT
38	Ontario Ministry of Transportation (MTO)	Canada

Based on the responses received, more than half of the participating DOTs (54%) allow the use of GTR in asphalt mixes. States which do not allow the use of GTR in their mixes noted some technical reasons.

Table 7 reflects the reasons cited by DOTs for not using GTR in HMA. According to Table 7, from the state DOTs which do not allow the use of GTR in asphalt mixes, 61% expressed the higher cost of using GTR in asphalt mixes as the main reason for this ban. Forty four percent (44%) of the DOTs surveyed mentioned their concern over the performance of asphalt mixes containing GTR. The performance concerns consisted of premature reflective cracks, concerns over blending quality and settlement in the tanks. However, a number of states (AK, PA, and WI) expressed improved performance of asphalt pavement as a result of using GTR in HMA. Thirty nine percent (39%) of the states, which banned using GTR in HMA, expressed unsuccessful experience of using GTR in HMA in the past as the main reason for this ban. Lack of sufficient incentives to recycling scrap tires was identified as a reason for 33% of the states which do not use GTR in HMA. . Lack of performance data and crumb rubber producers were reasons for 28% and 22% of the states which do not use GTR in asphalt mixes, respectively.

Table 7. Reasons for Not Using GTR in HMA

Please specify the reason(s) for not incorporating GTR in asphalt mixes.	
Answer Options	Response Percent
Unsuccessful experience of using GTR in asphalt mixes in the past.	38.9%
Concern over the performance of asphalt mixes containing GTR.	44.4%
Lack of performance data of asphalt mixes containing GTR.	27.8%
Using GTR in asphalt is not cost effective.	61.1%
There is not sufficient incentive to recycling scrap tires in pavement applications.	33.3%
There is not a crumb rubber producer in the state.	22.2%

Table 8 reflects the reasons cited by DOTs for using GTR in HMA. Sixty seven (67%) of the DOTs which allow using GTR in asphalt pavement constructionmentioned improved performance of the CRM mixes compared to conventional HMA as the main reason for using GTR in HMA. The performance benefits mentioned by DOTs as a result of using GTR include better thermal cracking resistance, better durability when used in OGFC pavements, successful use in hot rubber chip seal, cost-effective alternative to polymer modification, satisfactory performance compared to PMA mixes, improved resistance to moisture-induced damage, considerable noise reduction, superior rut and crack resistance, and better overall durability. Also, 25% of the agencies allowing the use of GTR in asphalt mixes mentioned the cost-effectiveness of CRM mixes compared to other options such as polymer modification as a reason for using GTR in HMA. Moreover, 21% of the agencies using GTR in HMA, identified the incentives offered for using scrap tires in pavement as an important reason for using GTR by their agencies. Other reasons for the use of GTR in HMA mentioned by 50% of the agencies include environmental benefits and incentives offered by the local departments of health to offset the cost of GTR-modified binder.

Table 11. Reasons for Using GTR in HMA

What are the main reasons for using GTR asphalt pavements by your agency?	
Answer Options	Response Percent
It is cost effective.	25.0%
Better performance compared to conventional materials	66.7%
Significant incentives to recycling scrap tires.	20.8%
Other.	50.0%

Table 9 reflects different GTR applications by DOTs. It was found that 87% of the DOTs/agencies allowing the use of GTR in asphalt mixes do so in HMA and 57% in Warm Mix Asphalt (WMA) mixes. Also, it was observed that while 56% of DOTs use GTR in structural overlays, 52% of them use it in non-structural thin-lift overlays. Moreover, 48%, 30% and 22% of participating DOTs, use GTR in mill–and–fill operations, chip seals, and fog seal construction. Finally, 26% of the agencies which allow using GTR in pavement, use it for other applications such as dense and OGFC, crack sealant, and for modifying asphalt binders to bump their PG grade.

Table 12. Different Applications of GTR in Pavement

Please specify in what type(s) of mixes the GTR is used by your agency?	
Answer Options	Response Percent
Hot Mix Asphalt (HMA)	87.0%
Warm Mix Asphalt (WMA)	56.5%
Non-Structural Thin-Lift Overlay (<1.5 in.)	52.2%
Structural Overlays (> 1.5 in.)	56.5%
Mill-and-Fill Operation	47.8%
Chip Seal	30.4%
Fog Seal	21.7%
Other	26.1%

Table 10 presents the applications of GTR in asphalt mixes with respect to type of projects. It was observed that 78%, 74% and 39% of states allowing use of GTR in their mixes use it in state highways, inter-state highways, and city roads, respectively. Also, 30% of the participating DOTs noted other types of projects. These applications were projects with a traffic level less than 10 million ESALs, state highways if there is high rutting risk, major state routes with significant truck traffic (approx. 4000 ADTT or higher), and state routes with frequent stop and go traffic or significantly slow traffic on a steep grade.

Table 13. Application of GTR in Asphalt Mixes Based on the Project Type

Where do you use asphalt mixes containing GTR (multiple answers may be selected, if applicable)?	
Answer Options	Response Percent
Interstate Highways	73.9%
City road	39.1%
State Highway	78.3%
Other (please specify)	30.4%

Table 11 reflects types of processes used by state DOTs in order to incorporate GTR or CR in asphalt mixes. According to Table 11, only 14% of the states which allow the use of GTR in asphalt mixes have usedthe dry process. However, 77% and 55% of the states have used wet process blended terminally and in the field, respectively. Although a majority of the states have used wet process, some states have started investigating the benefits of using dry process in lieu of wet process and reported success (e.g., MO).

Table 14. Types of Processes Used by States to Incorporate GTR or CR in Asphalt Mixes

Please specify the type of process used by your agency in order to incorporate GTR or CR in asphalt mixes (please mark all that apply and write in your answer if applicable)?	
Answer Options	Response Percent
Dry Process	13.6%
Wet Process (Terminal Blend)	77.3%
Wet Process (Field Blend)	54.5%

Table 12 reflects the availability of guidelines, technical specifications, or special provisions to states which use GTR in asphalt mixes. From Table 12 it can be observed that 86% of the states which use GTR in asphalt mixes follow specific guidelines for this purpose.

Table 15. Availability of Guideline/Specification/Special Provision to States Incorporating GTR in HMA

Please specify if your agency follows a guideline, technical specifications, special provision, etc. for incorporating GTR in asphalt mixes?	
Answer Options	Response Percent
No.	13.6%
Yes (Please provide the link to the guideline, technical specifications, special provision, etc.)	86.4%

Table 13 shows technical considerations for asphalt mixes containing GTR recommended by DOTs participating in the survey. According to Table 13, 50% of DOTs allowing the use of GTR in asphalt mixes require changing the mixing temperature when GTR is used. While a number of states (e.g., AZ, CA, ME, and NE) required mixing temperatures to be above 149 ºC, some (e.g., NH, and NJ) required temperatures to be maintained below 149 ºC in order to control odors. Also, 50% of states require a modification made to binder grade, when GTR is used. While some states require the final product to meet PG 76-22 binder specifications, others recommend using a lower grade base binder to compensate for two (2) to three (3) PG grade bumps as a result of using GTR in HMA mixes. Furthermore, 15% of DOTs require a modification in compaction effort when GTR is used. Moreover, use of WMA additives, additional binder viscosity testing, and PG grading conducted by contractors are other requirements recommended by 30% of the DOTs which allow using GTR in asphalt mixes.

Table 16. Technical Considerationsfor Asphalt Mixes Containing GTR/CR

What considerations are recommended by your agency to be taken into account in design of asphalt mixes containing GTR/CR (please mark all that apply and write in your answer if applicable)?	
Answer Options	Response Percent
Mix Temperature (Please specify in the comment field).	50.0%
Modification to Binder PG Grade (Please specify in the comment field).	50.0%
Compaction Effort (Please specify in the comment field).	15.0%
Other (Please specify in the comment field).	30.0%

Table 14 and Table 15 reflect the criteria required by DOTs for using GTR in surface course and intermediate/base course mixes, respectively. Based on the responses received, while almost all of the DOTs using GTR in asphalt mixes try to maximize its use, most of them do not have maximum allowable GTR requirements. However, a number of agencies have more specific criteria in this regard. For example, Nebraska Department of Roads (NDOR) uses typically 10% GTR by the weight of binder and has 4 separate specifications for incorporating GTR in mixes, namely dry, wet terminal, wet plant, and one to meet AASHTO M320 requirements. New Hampshire Department of Transportation (NHDOT) recommends using typically 18% GTR by the weight of binder and suggests a viscosity test be conducted on blended binder. Arizona DOT does not specify a maximum allowed GTR in the mix but it requires a minimum of 20% GTR by weight of asphalt binder. Arizona DOT also runs rotational viscosity, softening point, penetration, and resilience on the crumb rubber asphalt. New Hampshire and South Carolina DOTs require a minimum GTR amount of 15% and 7% by the weight of asphalt binder, respectively. Georgia DOT did not specify a maximum amount for GTR but typically 8% to 10% GTR by the weight of binder is used. A workability additive is required when GTR is used in a mix. Other standard performance test requirements, namely APA-rutting susceptibility, moisture susceptibility, and permeability should be met by the GTR-modified mixes. Louisiana Department of Transportation & Development (LaDOTD) typically uses 10% GTR by weight of asphalt binder and requires testing the blended binder, wheel tracking test and semi-circular bend tests to be conducted on mixes. Although Wisconsin DOT does not have a limit for using GTR in mixes, it requires testing asphalt mixes for their susceptibility to low-temperature cracking. Caltrans has more specific requirements for using GTR in HMA. According to Caltrans, no more than 22% GTR by weight of asphalt binder is permitted in wet process. However, no upper limit for using GTR in HMA is specified in terminal blending process. In addition, PG tests are required in the terminal blending process. Viscosity, resilience and rebound, and softening point tests are other requirements for asphalt binders set by Caltrans when wet process is used. Maine DOT requires using a minimum of 15% GTR by weight of binder but does not specify a maximum amount.

Table 14. Criteria used for Surface Course Mixes Containing GTR

Please specify test(s) and criteria used to set the maximum GTR content (%) limit in surface course.	
Answer Options	Response Percent
Maximum GTR Allowed (%)	95.0%
Test(s) (e.g. fatigue, low temperature cracking, etc.)	70.0%
Criteria (e.g. number of cycles to fatigue failure; creep compliance; indirect tensile strength, etc.)	40.0%

Table 17. Criteria used for Base/Intermediate Course Mixes Containing GTR

Please specify test(s) and criteria used to set the maximum GTR content (%) limit in intermediate/base course.	
Answer Options	Response Percent
Maximum GTR Allowed (%)	100.0%
Test(s) (e.g. fatigue, low temperature cracking, etc.)	57.9%
Criteria (e.g. number of cycles to fatigue failure; creep compliance; indirect tensile strength, etc.)	36.8%

Table 16 shows the major tests conducted by DOTs on asphalt mixes containing GTR. From Table 16 it was observed that 71% of DOTs using GTR in their mixes conduct rut test (i.e., Hamburg wheel tracking and APA rut test) and moisture-induced damage test (Hamburg wheel tracking and tensile strength ratio test). Only 18% of the DOTs indicated that they conduct fatigue test on mixes containing GTR. Sixty five percent (65%) of DOTs conduct permeability, semi-circular bend (Louisiana method), and abrasion loss of mix tests (Cantabro test). Other tests conducted by 12% of DOTs include dynamic modulus, flow number and flow time.

Table 18. Laboratory Tests Conducted on Asphalt Mixes Containing GTR

What laboratory performance tests are conducted on asphalt mixes containing GTR (please mark all that apply and write in your answer if applicable)?	
Answer Options	Response Percent
Rutting (Asphalt Pavement Analyzer or Hamburg Wheel Tracking)	70.6%
Fatigue (Four-Point Bending Beam)	17.6%
Fatigue (Viscoelastic Continuum Damage)	0.0%
Creep Compliance	0.0%
Moisture-Induced Damage (Tensile Strength Ratio or Hamburg Wheel Tracking)	70.6%
Dynamic Modulus, Flow Number, Flow Time	11.8%
Other (please specify)	64.7%

SUMMARY

The major outcomes of the comprehensive literature review conducted in this study are listed as follows.

1. Researchers observed enhancement of mix performance resulting from utilization of scrap tire rubber in asphalt. The reported benefits include improved rutting resistance, thermal reflective crack resistance, resistance to fatigue cracking, reduction in maintenance costs, smooth ride, good skid resistance, and noise reduction (Heitzman,

1992; Hicks et al., 1995; Kaloush et al., 2002; Huang et al., 2002; Navarro et al., 2002; Bennert et al., 2004; Chiu et al, 2007; Willis et al., 2012; Shen et al., 2015).

2. Some studies showed that wet process CRM mixes resulted in better performance compared to dry process CRM mixes (Volle, 2000; Choubane, 1999; Bandini, 2011). However, a number of recent studies showed very successful experience with dry process CRM mixes (Bennert et al., 2004; Willis et al., 2012; Shen et al., 2015)
3. Among U.S. DOTs that use/have used CRM materials in pavement construction, 75% have never tried the dry-process (Bandini, 2011).
4. Overall, performance of gap-graded CRM mixes seems to be more desirable and consistent than dense-graded CRM mixes. Gap-gradation provides sufficient space to use higher CRM contents and larger CRM particles (up to 2 mm) in comparison with dense-graded mixes. Due to low void space in aggregate structure of dense-graded mixes, they can accommodate only limited CRM modification and fine CRM particles (passing 300 μm sieve size or finer). Properly designed dense-graded CRM mixes perform similar to conventional DGAC (Way, 2000; Huang, et al., 2002).
5. Evaluation and monitoring of the paved roads in Arizona and Florida indicated that application of CRM-modified SAMIsimprove the overall pavement performance. However, experience of other states including California has been mixed (Flintsch, et al., 1994).
6. Larger GTR sizes are allowed to be used in the interlayers and chip seals compared to asphalt mix layers.
7. Crumb rubber additions of approximately 5% and 10% produce one and two PG grade bumps in asphalt binders, respectively.
8. Rubber size, type, and grinding process affect but do not materially impact binder or mix modification.
9. CRM binders are great for improved rutting resistance. More rubber results in stiffer pavements, but more rubber alone also can elevate critical low temperatures and cracking resistance.
10. Crumb rubber cook time in binder beyond 30 to 60 minutes does not materially improve binder performance.

11. With proper mixing, low and no-cook CRM asphalt seems to perform as well as terminal blend CRM asphalt, both in the lab and in the field.
12. Wet and dry process CRM asphalt perform as well or better than PMA (better fatigue and moisture resistance, lower permanent strain accumulation with rubber).
13. Separation of rubber and binder in terminal blends is a real risk.

The major outcomes of the DOT survey conducted in this study are listed as follows.

1. Based on the responses received, more than half of the participating DOTs (54%) allow using GTR in their asphalt mixes.
2. The main reasons for not allowing the use of GTR in mixes were higher cost of using GTR in wet process (54%) and concerns over the performance of asphalt mixes containing GTR (44%). These concerns included premature reflective cracks, blending quality, and settlement in the tanks. Other reasons for not using GTR in mixes are unsuccessful experience of using GTR in HMA in the past (39%), lack of sufficient incentives to recycling scrap tires in the state (33%), lack of performance data (28%) and lack of crumb rubber producers in the state (22%).
3. The main reasons for allowing the use of GTR in mixes were improved performance of CRM mixes compared to conventional HMA (67%). The performance benefits mentioned by DOTs as a result of using GTR include better thermal cracking resistance, better durability when used in OGFC pavements, successful use in hot rubber chip seal, cost-effective alternative to polymer modification, satisfactory performance compared to polymer-modified asphalt mixes, improved resistance to moisture-induced damage, considerable noise reduction, superior rut and crack resistance, and better overall durability. The cost-effectiveness of CRM mixes compared to other options (25%) and incentives offered for using scrap tires in pavement (21%) were other reasons for using GTR in HMA. Other reasons for use of GTR in HMA mentioned by the agencies (50%) include environmental benefits and incentives offered by the local departments of health to offset cost of GTR-modified binder.
4. Dry process has been used by only 14% of states for incorporating GTR in the mixes.
5. Of the states allowing the use of GTR in their mixes, 86% follow specific guidelines for this purpose.

ACKNOWLEDGMENTS

The research team would like to thank the Oklahoma Department of Environmental Quality for funding this study. Also the assistance received from Mr. Ken Hobson from the Oklahoma Department of Transportation is highly appreciated. The research team would also like to express its sincere thanks to Dr. Redmond (Red) Clark, the president of Asphalt Plus, LLC, for sharing his knowledge, up-to-date technical content, documents, write-ups and providing the research team with permission to use them in this report.

REFERENCES

1. Abdeirahman, M. "Controlling the performance of Crumb Rubber Modifier (CRM) binders through the addition of polymer modifiers." In *Proc. 85th Annual Meeting of the Transportation Research Board*. 2006.
2. Airey, G. D., T. M. Singleton, and A. C. Collop. "Properties of polymer-modified bitumen after rubber-bitumen interaction." *journal of materials in civil engineering* 14, no. 4 (2002): 344-354.
3. Al-Khateeb, Ghazi G., and Khaled Z. Ramadan. "Investigation of the effect of rubber on rheological properties of asphalt binders using superpave DSR."*KSCE Journal of Civil Engineering* 19, no. 1 (2015): 127-135.
4. Amirkhanian, Serji N. "Utilization of scrap tires in flexible pavements—Review of existing technology." In *Use of Waste Materials in Hot-Mix Asphalt*. ASTM International, 1993.
5. Arabani, M., and B. Ferdowsi. "Laboratory evaluating and comparison of the SCB Test results with other common tests for HMA mixtures." *Advanced Characterisation of Pavement and Soil Engineering Materials* (2007): 20-22.
6. Artamendi, I., & Khalid, H. A. (2006). Diffusion Kinetics of Bitumen into Waste Tyre Rubber. *Journal of the Association of Asphalt Paving Technologists*, *75*, 133-164.
7. Asadi, S. S., T. NagaSeshu Babu, B. Harish Kumar, M. Sumanth, and G. Sumanth Kumar. "Crumb Rubber Utilization in Pavements to Improve the Durability: An Experimental Study." *International Journal of Applied Engineering Research* 11, no. 9 (2016): 6418-6423.
8. ATRC, Asphalt Rubber Friction Course Reduces Traffic Noise, ADOT Research Notes (1996).
9. Bahia, Hussain U., and Robert Davies. "Effect of crumb rubber modifiers (CRM) on performance related properties of asphalt binders." *Asphalt paving technology* 63 (1994): 414-414.
10. Bairgi, Biswajit, Zahid Hossain, and Robert D. Hendrix. "Investigation of Rheological Properties of Asphalt Rubber toward Sustainable Use of Scrap Tires." In *IFCEE 2015*. 2015.
11. Baker, Robert F., and Eileen Connolly. "Mix designs and air quality emissions tests of crumb rubber-modified asphalt concrete." *Transportation research record* 1515 (1995): 18-27.
12. Bandini, Paola. *Rubberized Asphalt Concrete Pavements in New Mexico: Market Feasibility and Performance Assessment*. Department of Civil Engineering, New Mexico State University, 2011.
13. Bennert, T., Maher, A., & Smith, J. (2004). Evaluation of crumb rubber in hot mix asphalt. *Final Report, Rutgers University, Center for Advanced Infrastructure & Transportation, and Rutgers Asphalt/Pavement Laboratory*, Piscataway, NJ.
14. Bennert, Thomas, Raj Dongre, Christopher Ericson, and Zoeb Zavery. "High-Temperature Characterization of Crumb-Rubber-Modified Asphalt Binders and Mixtures in New York State." In *Transportation Research Board 94th Annual Meeting*, no. 15-2964. 2015.
15. Billiter, T. C., R. R. Davison, C. J. Glover, and J. A. Bullin. "Physical properties of asphalt-rubber binder." *Petroleum Science and Technology* 15, no. 3-4 (1997): 205-236.

16. Blumenthal, M. " The Use of Scrap Tires in Rubber-modified Asphalt: A Sustainable Technology." *Rubber Manufacturers Association* (2013).
17. Cao, Weidong. "Study on properties of recycled tire rubber-modified asphalt mixtures using dry process." *Construction and Building Materials* 21, no. 5 (2007): 1011-1015.
18. Carlson, Douglas D., Han Zhu, and Can Xiao. "Analysis of traffic noise before and after paving with asphalt-rubber." In *Proceedings Asphalt Rubber 2003 Conference, Brasilia, Brazil, ISBN*, pp. 85-903997. 2003.
19. Charania, Equbalali, Joe O. Cano, and Russell H. Schnormeier. "A Twenty Year Study of Asphalt-Rubber Pavements in the City of Phoenix, Arizona." (1992).
20. Chesner, W. H., R. J. Collins, and M. H. MacKay. *User Guidelines for Waste and By-product Materials in Pavement Construction, US Department of Transportation, Federal Highway Administration, Publication No*. FHWA-RD-97-148, 1997.
21. Chiu, Chui-Te, and Li-Cheng Lu. "A laboratory study on stone matrix asphalt using ground tire rubber." *Construction and Building Materials* 21, no. 5 (2007): 1027-1033.
22. Chiu, Chui-Te. "Use of ground tire rubber in asphalt pavements: Field trial and evaluation in Taiwan." *Resources, Conservation and Recycling* 52, no. 3 (2008): 522-532.
23. Choubane, Bouzid, Gregory Sholar, James Musselman, and Gale Page. "Ten-year performance evaluation of asphalt-rubber surface mixes."*Transportation Research Record: Journal of the Transportation Research Board* 1681 (1999): 10-18.
24. D'Angelo, J. (2004). Characterization of Vestenamer polymer and ground tire rubber blends. *Federal Highway Administration Research Report*, 50 pgs.
25. Decker, Dale S. Critical Review of ADOT's Hot Mix Asphalt Specifications. No. FHWA-AZ-08-630. 2008.
26. DeLaubenfels, Larry. *Effectiveness of Rubberized Asphalt in Stopping Reflection Cracking of Asphalt Concrete*. State of California Department of Transportation, Division of Facilities Construction, Office of Transportation Laboratory, 1985.
27. Di Mino, Gaetano, Maurizio Di Liberto, Silvia Noto, Fernando Martinez Soto, and I. Palermo. "The resistance to fatigue of dry asphalt rubber concrete for sub-ballast layer." In *15th International Conference of Railway Engineering*. 2015.
28. Eaton, Robert A., Richard J. Roberts, and Robert R. Blackburn. *Use of scrap rubber in asphalt pavement surfaces*. No. CRREL-SR-91-27. COLD REGIONS RESEARCH AND ENGINEERING LAB HANOVER NH, 1991.
29. Ellis, Ralph, and Duzgun Agdas. "Developing improved opportunities for the recycling and reuse of materials in road, bridge, and construction projects." (2014).
30. Esch, David C. *Asphalt pavements modified with coarse rubber particles-Design, construction, and ice control observations*. No. FHWA-AK-RD-85-07 Final Rpt. 1984.
31. Estakhri, Cindy K., Joe W. Button, and Emmanuel G. Fernando. *Use, availability, and cost-effectiveness of asphalt rubber in Texas*. No. 1339. 1992.
32. Farina, Angela, M. C. Zanetti, Ezio Santagata, Giovanni Andrea Blengini, and Michele Lanotte. "Life Cycle Assessment of Road Pavements Containing Crumb Rubber from End-of-Life Tires." In *Proceedings, International Symposium on Pavement LCA 2014, Davis, California, USA, 14-16 October*. 2014.
33. Federal Highway Administration (2014). The Use of Recycled Tire Rubber to Modify Asphalt Binder and Mixtures. Report no. FHWA-HIF-14-015, FHWA, U.S. Department

of Transportation. http://www.fhwa.dot.gov/pavement/pubs/hif14015.pdf (Accessed on 07/28/2016)

34. Flintsch, Gerardo W., Larry A. Scofield, and John P. Zaniewski. *Network-level performance evaluation of asphalt-rubber pavement treatments in Arizona*. No. 1435. 1994.
35. Florida Department of Environmental Protection (FDEP). “Waste Tires in Florida: State of the State.” 2011.
36. Florida, D. O. T. "Standard specifications for road and bridge construction."Florida Department of Transportation, Tallahassee, FL (2010).
37. Fontes, Liseane PTL, Glicerio Triches, Jorge C. Pais, and Paulo AA Pereira. "Evaluating permanent deformation in asphalt rubber mixtures." *Construction and Building Materials* 24, no. 7 (2010): 1193-1200.
38. Fraser, Jessica M. "Rubber Roads for the Rubber City: Testing the Suitability of Rubberized Asphalt for Roads in Northeast Ohio." (2016).
39. Freeman, T., D. Pinchett, R. Haobo, and C. Spiegelman. "Analysis and treatment recommendations from the supplemental maintenance effectiveness research program (SMERP)." (2002).
40. Gillen, S., & Tollway, I. (2016). Lab evaluation of tollway SMA surface mixes with varied ABR levels. 2016 Illinois Asphalt Paving Association Annual Meeting. http://www.il-asphalt.org/files/3614/5814/2117/2016Gillen.pdf (Accessed on 07/28/2016)
41. Glover, Charles J., and Richard R. Davison. *High-cure crumb rubber-modified asphalt for dense-graded mixes*. Texas Transportation Institute, the Texas A & M University System, 2001.
42. Glover, Charles J., Richard R. Davison, Jerry A. Bullin, Cindy K. Estakhri, Shelly A. Williamson, Travis C. Billiter, Jason F. Chipps et al. *A comprehensive laboratory and field study of high-cure crumb-rubber-modified asphalt materials*. No. FHWA/TX-01/1460-1,. 2000.
43. Hansen, Kent R., and Gary Anderton. "A laboratory evaluation of recycled tire rubber in hot-mix asphalt paving systems." In *Use of Waste Materials in Hot-Mix Asphalt*. ASTM International, 1993.
44. Hassan, Norhidayah Abdul, Gordon D. Airey, Ramadhansyah Putra Jaya, Nordiana Mashros, and Md Maniruzzaman A. Aziz. "A review of crumb rubber modification in dry mixed rubberised asphalt mixtures." *Jurnal Teknologi* 70, no. 4 (2014).
45. Heiden Labor Vest (2005). Untersuchungsbericht Bitumen Nr. 48-2005: Binder Tests of Crumb Rubber-modified Bitumen. *Heiden Vest Technical Report 48-2005*, 18 pgs.
46. Heitzman, Michael. *Design and construction of asphalt paving materials with crumb rubber modifier*. No. 1339. 1992.
47. Henderson, Michael P., and Sylvester A. Kalevela. "A comparison of traffic noise from asphalt rubber asphalt concrete friction courses (ARACFC) and portland cement concrete pavements (PCCP)." (1996).
48. Hernández-Olivares, F., B. Witoszek-Schultz, M. Alonso-Fernández, and C. Benito-Moro. "Rubber-modified hot-mix asphalt pavement by dry process."*International Journal of Pavement Engineering* 10, no. 4 (2009): 277-288.
49. Hicks, R. G. "Asphalt rubber design and construction guidelines–vol. 1 design guidelines." *Prepared for Northern California Rubberized Asphalt Concrete Technology*

Center (NCRACTC) and the California Integrated Waste Management Board (CIWMB) (2002).

50. Hicks, R. G., and Jon A. Epps. "Life cycle cost analysis of asphalt-rubber paving materials." In *WORLD OF ASPHALT PAVEMENTS, INTERNATIONAL CONFERENCE, 1ST, 2000, SYDNEY, NEW SOUTH WALES, AUSTRALIA*. 2000.
51. Hicks, Russell G., James R. Lundy, Rita B. Leahy, Doug Hanson, and Jon Epps. "Crumb Rubber Modifier (CRM) in Asphalt Pavement: Summary of Practices in Arizona, California, and Florida." *NASA* 19980011594 (1995).
52. Hicks, Russell G., Tighe S., Tabib, S., and Cheng, D. "Rubber-modified Asphalt Technical Manual." *Ontario Tire Stewardship* (2013).
53. Hildebrand, G., and J. Van Kirk. "Asphalt Rubber Performance Evaluation. Internal Caltrans report." (1996).
54. Huang, Baoshan, Louay Mohammad, Philip Graves, and Chris Abadie. "Louisiana experience with crumb rubber-modified hot-mix asphalt pavement." *Transportation Research Record: Journal of the Transportation Research Board* 1789 (2002): 1-13.
55. Huang, Yue, Roger N. Bird, and Oliver Heidrich. "A review of the use of recycled solid waste materials in asphalt pavements." *Resources, Conservation and Recycling* 52, no. 1 (2007): 58-73.
56. Hung, S. S., Frank Farshidi, David Jones, Mohammad Zia Alavi, John T. Harvey, and H. Sadraie. *Investigation of Wet-Process Asphalt Rubber Binder Testing with Modified Dynamic Shear Rheometer: Interim Report on Screening Tests*. No. UCPRC-TM-2014-02. 2014.
57. Hunt, Liz. *Crumb rubber-modified asphalt concrete in Oregon*. No. FHWA-OR-RD-02-13,. Oregon Department of Transportation, Research Group, 2002.
58. Jung, Jong-Suk, Kamil E. Kaloush, and G. Way. "Life Cycle Cost Analysis: Conventional Versus Asphalt-Rubber Pavements." *Rubber Pavements Association* (2002).
59. Kaloush, K. E., A. Zborowski, K. P. Biligiri, M. C. Rodezno, and L. De Mello. "Performance evaluation of asphalt rubber mixtures in Arizona–silver springs and badger springs projects." *Final Report. Arizona State University. Report prepared for the Arizona DOT* (2007).
60. Kaloush, K. E., M. W. Witczak, G. B. Way, A. Zborowski, M. Abojaradeh, and A. Sotil. "Performance evaluation of Arizona asphalt rubber mixtures using advanced dynamic material characterization tests." *Final Report submitted to FNF Construction, Inc. and the Arizona Department of Transportation. Arizona State University, Tempe, Arizona* (2002).
61. Kaloush, Kamil E. "Asphalt rubber: Performance tests and pavement design issues." *Construction and Building Materials* 67 (2014): 258-264.
62. Kandhal, Prithvi S., E. Ray Brown, and Robert L. Dunning. *Investigation and evaluation of ground tire rubber in hot mix asphalt*. No. NCAT Rept No. 89-3. National Center for Asphalt Technology, 1989.
63. Kim, Sungun, Sung-Jin Lee, Yeo-Bin Yun, and Kwang W. Kim. "The use of CRM-modified asphalt mixtures in Korea: Evaluation of high and ambient temperature performance." *Construction and Building Materials* 67 (2014): 244-248.

64. Kirk, Van, and L. JACK. "CalTrans experience with rubberized asphalt concrete." *Technology transfer session of an introduction to rubberized asphalt concrete. US: Topeka* (1991).
65. Krutz, Neil C., and Mary Stroup-Gardiner. "Permanent deformation characteristics of recycled tire rubber-modified and unmodified asphalt concrete mixtures." *Transportation Research Record* 1339 (1992).
66. Lee, Soon-Jae. "Characterization of recycled aged CRM binders." (2007).
67. Leite, L. F. M., and B. G. Soares. "Interaction of asphalt with ground tire rubber." *Petroleum Science and Technology* 17, no. 9-10 (1999): 1071-1088.
68. Leite, Leni Figueiredo Mathias, Romulo Santos Constantino, and Alexander Vivoni. "Rheological studies of asphalt with ground tire rubber." *Road Materials and Pavement Design* 2, no. 2 (2001): 125-139.
69. Liu, Jing Hui. "Fatigue life evaluation of asphalt rubber mixtures using semi-circular bending test." In *Advanced Materials Research*, vol. 255, pp. 3444-3449. Trans Tech Publications, 2011.
70. Losa, Massimo, Pietro Leandri, and M. Cerchiai. "Improvement of pavement sustainability by the use of crumb rubber-modified asphalt concrete for wearing courses." *International Journal of Pavement Research and Technology* 5, no. 6 (2012): 395-404.
71. Lundy, James R., R. G. Hicks, and H. Zhou. "Ground rubber tires in asphalt-concrete mixtures—three case histories." In *Use of Waste Materials in Hot-Mix Asphalt*. ASTM International, 1993.
72. Mashaan, Nuha S., Asim Hassan Ali, Mohamed Rehan Karim, and Mahrez Abdelaziz. "An overview of crumb rubber-modified asphalt." *International Journal of Physical Sciences* 7, no. 2 (2012): 166-170.
73. Miller, A. K., and G. A. Burr. "Health Hazard Evaluation Report HETA 96-0072-2603, Staker Construction Company, Casa Grande, Arizona. Cincinnati, Ohio: US Department of Health and Human Services." *Public Health Service, Center for Disease Control and Prevention, National Institute for Occupational Safety and Health* (1996).
74. Moreno-Navarro, Fernando, Maria Carmen Rubio-Gámez, and Ana Jiménez Del Barco-Carrión. "Tire crumb rubber effect on hot bituminous mixtures fatigue-cracking behaviour." *Journal of Civil Engineering and Management*22, no. 1 (2016): 65-72.
75. Morris, Gene R., and Douglas D. Carlson. "The apparent unique behavior of thin asphalt rubber hot-mix overlays in Arizona." In *Beneficial use of recycled materials in transportation applications*. 2001.
76. Murphy, K.H. and C.F. Potts. “Evaluation of Asphalt-Rubber as a Stress-Absorbing Membrane
Interlayer and as a Binder for Seal Coat Construction (SR-60 Hillsborough County).” Demonstration
Project 37, FHWA-DP-27-14. 1980.
77. Navarro, F. J., P. Partal, F. Martınez-Boza, and C. Gallegos. "Thermo-rheological behaviour and storage stability of ground tire rubber-modified bitumens." *Fuel* 83, no. 14 (2004): 2041-2049.
78. Navarro, F. J., P. Partal, F. Martınez-Boza, C. Valencia, and C. Gallegos. "Rheological characteristics of ground tire rubber-modified bitumens."*Chemical Engineering Journal* 89, no. 1 (2002): 53-61.

79. Nazzal, Munir D., Md Tanvir Iqbal, Sang Soo Kim, Ala R. Abbas, Moses Akentuna, and Tanvir Quasem. "Evaluation of the long-term performance and life cycle costs of GTR asphalt pavements." *Construction and Building Materials* 114 (2016): 261-268.
80. Nunez, W. P., J. A. P. Ceratti, V. Wickbouldt, L. A. T. Brito, and J. A. Oliveira. "Delaying crack reflection in overlays: an apt study comparing the efficiency of conventional asphalt concrete and asphalt rubber." *Belfast, UK: MAIREPAV4* (2005).
81. Page, Gale C. "Florida's initial experience utilizing ground tire rubber in asphalt concrete mixes." *Journal of the Association of Asphalt Paving Technologists* 61 (1992).
82. Page, Gale C., Byron E. Ruth, and Randy C. West. "Florida's approach using ground tire rubber in asphalt concrete mixtures." *Transportation Research Record* 1339 (1992).
83. Paje, S. E., Jeanne Luong, V. F. Vázquez, M. Bueno, and Rodrigo Miro. "Road pavement rehabilitation using a binder with a high content of crumb rubber: Influence on noise reduction." *Construction and building materials* 47 (2013): 789-798.
84. Palit, S. K., K. Sudhakar Reddy, and B. B. Pandey. "Laboratory evaluation of crumb rubber-modified asphalt mixes." *Journal of materials in civil engineering* 16, no. 1 (2004): 45-53.
85. Peralta, J., Silva, H. M., Hilliou, L., Machado, A. V., Pais, J., & Williams, R. C. (2012). Mutual changes in bitumen and rubber related to the production of asphalt rubber binders. *Construction and Building Materials*, *36*, 557-565.
86. *Presti, Davide Lo. "Recycled tyre rubber-modified bitumens for road asphalt mixtures: a literature review." Construction and Building Materials 49 (2013): 863-881.*
87. Raad, Lutfi, and Stephan Saboundjian. "Fatigue behavior of rubber-modified pavements." *Transportation research record: journal of the transportation research board* 1639 (1998): 73-82.
88. Sacramento County. "Report on the status of rubberized asphalt traffic noise reduction in Sacramento County." *Sacramento County Department of Environmental Review and Assessment and Bollard and Brennan, Inc. Consultants in Acoustics and Noise Control Engineering* 11 (1999).
89. Scofield, Larry. *The History, Development, and Performance of Asphalt Rubber at ADOT: Special Report*. Arizona Department of Transportation, 1989.
90. Shatanawi, Khaldoun, and Carl Thodesen. "GPEC Student Poster Abstract# 4 Title: Review of Utilization of Waste Tires in Asphalt." 2008.
91. Shen, J., & Xie, Z. (2012). Comprehensive evaluation of the long-term performance of rubberized pavement: Phase I: Laboratory study of rubberized asphalt mix performance. *Report No. FHWA-GA-12-1119, Georgia Department of Transportation, GA*.
92. Shen, J., Xie, Z., & Li, B. (2014). Comprehensive Evaluation of the Long-Term Performance of Rubberized Pavement: Phase II: The Influence of Rubber and Asphalt Interaction on Mixture Durability. *Report No. FHWA-GA-12-1229, Georgia Department of Transportation, GA.*
93. Shirini, Bahram, and Reza Imaninasab. "Performance evaluation of rubberized and SBS modified porous asphalt mixtures." *Construction and Building Materials* 107 (2016): 165-171.
94. Shu, Xiang, and Baoshan Huang. "Recycling of waste tire rubber in asphalt and Portland cement concrete: an overview." *Construction and Building Materials* 67 (2014): 217-224.

95. Shuler, Scott, Bob M. Gallaway, and Jon A. Epps. "Evaluation of asphalt-rubber membrane field performance." *Interim Research Report, Sep. 1979-May 1982 Texas A&M Univ., College Station.* 1 (1982).
96. Souliman, Mena I., Michael Mamlouk, and Annie Eifert. "Cost-effectiveness of Rubber and Polymer-modified Asphalt Mixtures as Related to Sustainable Fatigue Performance." *Procedia Engineering* 145 (2016): 404-411.
97. State of California Department of Transportation. "USE OF SCRAP TIRE RUBBER-STATE OF THE TECHNOLOGY AND BEST PRACTICES." 2005.
98. Tabatabaee, N., H. A. Tabatabaee, M. R. Sabouri, and P. Teymourpour. "Evaluation of performance grading parameters for crumb rubber-modified asphalt binders and mixtures." In *Proceedings of 7th international RILEM symposium on advanced testing and characterization of bituminous materials*, vol. 1. 2009.
99. Tahmoressi, Maghsoud. "Evaluation of asphalt rubber pavements in Texas."*PaveTex Engineering and Testing, Inc. Report prepared for Rubber Pavements Association* (2001).
100. Takallou, H. B., and Russell G. Hicks. *Development of improved mix and construction guidelines for rubber-modified asphalt pavements*. No. 1171. 1988.
101. Takallou, H. Barry, and Alain Sainton. "Advances in technology of asphalt paving materials containing used tire rubber." *Transportation Research Record* 1339 (1992).
102. Tenison, J. H. "NMDOT's Asphalt Rubber Experience. Executive Summary." *Internal document, State Materials Bureau, New Mexico Department of Transportation, Santa Fe, NM*, 2005.
103. Thodesen, Carl, Khaldoun Shatanawi, and Serji Amirkhanian. "Effect of crumb rubber characteristics on crumb rubber-modified (CRM) binder viscosity." *Construction and Building Materials* 23, no. 1 (2009): 295-303.
104. Vahidi, Siavash, Walaa S. Mogawer, and Abbas Booshehrian. "Effects of GTR and treated GTR on Asphalt binder and high-RAP mixtures." *Journal of Materials in Civil Engineering* 26, no. 4 (2013): 721-727.
105. Vázquez, Victor F., Fernando Terán, Urbano Viñuela, and Santiago E. Paje. "Study of a road test track with and without crumb rubber. Solutions for noise pollution." *Environ. Eng. Manag. J* 13, no. 10 (2014): 2487-2495.
106. Volle, Tessa H. *Performance of Rubberized Asphalt Pavements in Illinois*. No. FHWA/IL/PRR-136,. 2000.
107. Wang, Hainian, Zhengxia Dang, Zhanping You, and Dongwei Cao. "Effect of warm mixture asphalt (WMA) additives on high failure temperature properties for crumb rubber-modified (CRM) binders." *Construction and Building Materials* 35 (2012): 281-288.
108. Way, G. B., K. E. Kaloush, and J. M. B. Sousa. "Four point bending beam tests in Arizona and relationship to asphalt binder properties." *Semiconductor Laser Theory* (2015): 85.
109. Way, George B. "Asphalt Rubber–The Arizona Experience." *Arizona Department of Transportation-Materials Group, Asphalt Rubber* (1999).
110. Way, George B. "OGFC meets CRM where the rubber meets the rubber 12 years of durable success." *Anais do Asphalt Rubber 2000* (2000): 15-32.

111. Way, George. "Flagstaff I-40 Asphalt Rubber Overlay Project: Nine Years of Success." *Transportation Research Record: Journal of the Transportation Research Board* 1723 (2000): 45-52.
112. Way, George. "Flagstaff I-40 Overlay Project." *Conference and Road Show, Cincinnati, Ohio* (1991).
113. West, Randy, Gale Page, John Veilleux, and Bouzid Choubane. "Effect of tire rubber grinding method on asphalt-rubber binder characteristics."*Transportation Research Record: Journal of the Transportation Research Board* 1638 (1998): 134-140.
114. West, Randy, Gale Page, John Veilleux, and Bouzid Choubane. "Effect of tire rubber grinding method on asphalt-rubber binder characteristics."*Transportation Research Record: Journal of the Transportation Research Board* 1638 (1998): 134-140.
115. Willis, J. R., Plemons, C., Turner, P., Rodezno, C., & Mitchell, T. (2012). Effect of ground tire rubber particle size and grinding method on asphalt binder properties. *National Center for Asphalt Technology. NCAT Report 12-09*.
116. Willis, J. Richard, Clayton Plemons, Pamela Turner, Carolina Rodezno, and Tyler Mitchell. "Effect of ground tire rubber particle size and grinding method on asphalt binder properties." *National Center for Asphalt Technology. NCAT Report* (2012): 12-09.
117. Xiang, Li, Jian Cheng, and Guohe Que. "Microstructure and performance of crumb rubber-modified asphalt." *Construction and Building Materials* 23, no. 12 (2009): 3586-3590.
118. Xiao, F., Putman, B. J., & Amirkhanian, S. N. (2006). Laboratory investigation of dimensional changes of crumb rubber reacting with asphalt binder. *Road Materials and Pavement Design*, *10*, 1-21.
119. Xiao, Feipeng, Xiangdao Hou, Ouming Xu, Serji N. Amirkhanian, and Yongyue Wen. "Rheological Comparisons of Terminally-blended and Laboratory Blended Ground Tire Rubbers." *New Frontiers* (2015): 86.
120. Xie, Zhaoxing, and Junan Shen. "Performance of porous European mix (PEM) pavements added with crumb rubbers in dry process." *International Journal of Pavement Engineering* 17, no. 7 (2016): 637-646.
121. Zhang, Dong, Xiaoming Huang, Yongli Zhao, and Sulong Zhang. "Rubberized asphalt mixture design using a theoretical model." *Construction and Building Materials* 67 (2014): 265-269.
122. Zhou, Haiping, Sri Holikatti, and Peter Vacura. "Caltrans use of scrap tires in asphalt rubber products: a comprehensive review." *Journal of Traffic and Transportation Engineering (English Edition)* 1, no. 1 (2014): 39-48.