STATE OF KNOWLEDGE REPORT ON RUBBER MODIFIED ASPHALT

ON BEHALF OF

BY

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EXECUTIVE SUMMARY

Every year almost 300 million scrap tires are generated in the United States. Recycled rubber obtained from scrap tires can be used in a number of beneficial ways. One of the most beneficial uses involves producing Ground Tire Rubber (GTR) from scrap tires and using the GTR to create Rubber-Modified Asphalt (RMA). RMA has been used in the U.S. since the 1960s, but extensive market adoption is yet to occur. Thus, a central question regarding RMA that still remains unanswered is, **can RMA help eliminate scrap tire stockpiles in the U.S., boost pavement sustainability and longevity, and allow more miles of roads to be repaired**? Researchers at the University of Missouri-Columbia tested this hypothesis in collaboration with the U.S. Tire Manufacturers Association (USTMA) and The Ray, a philanthropic organization dedicated to the discovery and implementation of sustainable transportation technologies. The resulting **State of Knowledge (SOK) report** provides an up-to-date review of RMA, including its historical development and use, production methods, field performance, economics, safety, driver comfort, environmental impact, and sustainability benefits. Knowledge gaps and recommendations for future research and investment are also assessed in the SOK report.

The SOK study reviewed 312 scholarly articles and reports dating back to the early 1960's, and involved a **survey of 26 U.S. state highway agencies to better ascertain the gaps in knowledge and barriers to more widespread adoption of RMA nationwide**. The key findings of the SOK are summarized below and address the effect of RMA on pavement performance, economics, and sustainability:

PERFORMANCE BENEFITS:

The overarching research shows that rubber modified asphalt extends pavement life; resisting early pavement failures modes such as rutting and cracking. Additionally, RMA was also found to significantly mitigate noise from traffic, and enhance ride quality and safety.

- **Longevity** - The past two decades of research indicate that all three primary RMA approaches, i.e., traditional wet process, terminal-blend wet process, and the modern dry process (engineered crumb rubber) lead to **extended pavement life** as compared to pavements made with unmodified binders. Moreover, RMA can provide similar performance as pavements constructed with costly polymer-modified binders (West et al., 2012; Willis, 2013). RMA is particularly **resistant against early pavement rutting failures**, owing to the stability provided to the liquid binder system imparted by the swollen, elastic rubber particles (Choubane, Sholar, Musselman, & Page, 1999; G. B. Way, 2012). RMA is also **very resistant to fatigue cracking in high traffic volume applications and to low temperature cracking** (W. Buttlar et al., 2021; Raad, Saboundjian, & Minassian, 2001; Souliman, Mamlouk, & Eifert, 2016; Tao Wang, Xiao, Amirkhanian, Huang, & Zheng, 2017).
- **Pavement noise reduction** - or more precisely, the mitigation of road noise emanating from vehicles, has been quantified in several studies in recent years. **Noise reduction arising from RMA use has been measured to range from 1-10 decibels**, depending on a mix type, traffic level, vehicle speeds, and other environmental variables. Due to the exponential nature of the dB scale, **a reduction of just 2-3 dB creates a similar environmental benefit as a 50% reduction in traffic noise intensity**. In addition, long-

term field observations have indicated that noise reduction due to RMA decreases over the years but at a substantially lower rate as compared to other surfacing alternatives (Carlson, Zhu, & Xiao, 2003; P. Donavan & Janello, 2018; Sacramento County Public Works Agency, 1999).

- **Ride Quality and Safety** - RMA has been shown to **create smoother pavements and therefore better ride quality for motorists** (Vázquez, Luong, Bueno, Terán, & Paje, 2016). In addition, the use of RMA provides **better pavement skid resistance**, **which can reduce traffic accidents during wet weather** (Texas Department of Transportation, 2003b).

ECONOMIC BENEFITS:

RMA has been shown to be a cost-effective option as it increases the service life of a pavement and reduces and/or delays the occurrence of maintenance activities. This leads to significant cost savings when evaluated using life cycle cost analysis techniques.

- **Initial costs** – Based on initial, per-ton costs only, RMA is generally more expensive than unmodified asphalt, but less expensive than polymer modified asphalt (Howard, Baumgardner, Jordan, Hemsley, & Hopkins, 2021). However, in the case of asphalt overlay rehabilitation projects on a cost-per-square-yard basis, it has been shown that **thin RMA overlays can be built at a lower cost as compared to unmodified asphalt overlays - approximately 43% less cost with a 10% boost in pavement life** (William G. Buttlar & Rath, 2019). Similarly, an earlier study (Harvey, Bejarano, Fantoni, Heath, & Shin, 2000) demonstrated that **a 50% reduction in pavement layer thickness can be achieved by using RMA in lieu of unmodified mixtures while achieving better performance.**
- **Life cycle cost savings** – Life cycle cost analysis (LCCA) studies have reported life cycle cost savings for RMA spanning widely, from a range of 4% to 40% savings in a study compiled for Caltrans (Dingxin Cheng, Hicks, & Rodriguez, 2012) to more than 400% savings (Souliman et al., 2016) when basing the results on laboratory-based fatigue performance. More work is needed to develop a more comprehensive national database of pavement costs, including both initial costs and subsequent maintenance costs, and pavement service life, which can be used to more accurately assess the life cycle cost benefits of RMA.
- **Implications** – The current economic outlook for RMA has significant implications for the renewal of our nation's transportation infrastructure considering that most pavement expenditures are devoted to restoring the surface characteristics (smoothness, skid resistance) of existing roadway and airfield pavements. **By using RMA to upgrade significantly more miles of pavement each year for each dollar spent**, cities and states can begin to **address the** current **backlog of deferred pavement maintenance** that exists in their network. **Motorists will** also **benefit by saving on vehicle repair and fuel costs** by spending more time **driving on smoother pavements**.

ENVIRONMENTAL BENEFITS:

The use of RMA results in the reduction of CO2 emissions and lower energy consumption over the lifetime of a pavement. Additionally, since RMA pavements are stiffer and smoother, they reduce the generation of tire wear particles and improve water quality in roadway runoff.

- **Reduction in tire wear** - Generation of micro-particles from on-road vehicle traffic has generated significant research interest in recent times. Studies have shown that the use of **RMA pavement surfaces can significantly reduce tire wear** as compared to concrete pavements, **by providing a much smoother ride** as characterized by lower measured values of the International Roughness Index (IRI) (Allen, Kaloush, & Alexandrova, 2006; Cooper, Mohammad, & Abadie, 2007; J.Richard Willis, Carolina Rodezno, Adam Taylor, 2014). In addition, converting scrap tires to ground tire rubber and '**entombing**' **the rubber into very low permeability asphalt binder films in RMA**, has been shown to significantly reduce the chances of leaching of any potentially toxic chemicals from the scrap tire rubber to aquatic eco-systems (Gheni, Liu, ElGawady, Shi, & Wang, 2018; Nelson et al., 2001).

- **Reduction in rolling resistance and fuel consumption** – Studies have shown that substantial savings can be achieved by constructing stiffer pavements, leading to reductions in vehicular fuel consumption due to lower, localized pavement deflection and subsequently lower rolling resistance (Harvey et al., 2016). Compared to standard asphalt pavements, **RMA surfaces are usually stiffer and smoother**, and should therefore **lead to lower rolling resistance**. The existing literature on the impact of rubber modification on fuel consumption is sparse, but the limited studies available indicate a minor-yet-positive effect in RMA surfaced pavements as compared to polymer modified in terms of vehicle fuel consumption (Coleri & Harvey, 2017).
- **Environmental impact of RMA as estimated through LCA** –
  - Life cycle assessment/analysis (LCA) studies that have focused exclusively on the production process of RMA, without focusing on the whole life cycle and wider boundary conditions, unsurprisingly reported negative impacts of RMA. This is mostly due to higher production temperatures and the energy-intensive process needed to produce high-quality crumb rubber from scrap tires. On the other hand, **studies that considered the whole life cycle of RMA pavements in comparison to conventional or traditional polymer-modified pavements**, **with proper assumptions of service life and lift thicknesses**, **have shown RMA pavements to have a net positive environmental impact**. **These benefits include a reduction in CO2 emissions and lower energy consumption**, **driven in large part by extended service life and lower maintenance requirements** (Bartolozzi, Mavridou, Rizzi, & Frey, 2015; Chiu, Hsu, & Yang, 2008).
  - The majority of LCA studies in the literature are **attributional**, meaning that these studies present a comparison between two or more products of the same kind; for instance, comparing roads comprised of unmodified, rubber-modified, and polymer-modified asphalt mixtures. However, **given the need to leverage the growing circular economy paradigm shift**, **there is a need to develop up-to-date**, **consequential LCA studies to drive policy-based decisions that optimize the utilization of ground tire rubber** (**GTR**) **in various engineering applications**, **such as in sports turfs**, **embankments**, **roads**, **etc**.

KNOWLEDGE GAPS:

Based upon the comprehensive State-of-Knowledge (SOK) assessment of rubber-modified asphalt carried out in this study, the following general knowledge gaps were identified:

- **Most state highway agencies and asphalt contractors have limited-to-no experience with modern RMA products**, and limited knowledge of the new performance trends, economics, and sustainability of RMA. Rather than the current piece-meal approach, comprehensive, **national efforts to provide highway agencies and contractors with up-to-date technical data**, **best practice summaries and sample specifications are**

critically needed. Incentives for the deployment of RMA in demonstration projects as a sustainable and economical solution to address deferred pavement maintenance backlogs may also be needed to overcome current inertial barriers in the paving industry.

- **Almost none of the modern**, **advanced asphalt binder and mixture performance tests and associated specifications were developed with RMA in mind**. This must be addressed in new, purpose-built specifications for modern RMA materials and construction methods.
- **The ability to accurately design pavement layer types and thickness with RMA is currently difficult at best**. Additional research is needed to better reflect RMA properties and characteristics as inputs in modern pavement design software programs for new pavements and rehabilitation activities, such as resurfacing with asphalt overlays.
- **Life expectancy assumptions for rubberized pavements during the use phase in LCA studies are currently based on outdated studies**, particularly in the case of dry process RMA and impact categories for LCA studies involving RMA need to be expanded. Along with addressing these gaps, the LCA impacts of rubber-modified RAP should be more accurately quantified. **A comprehensive study is needed to facilitate more accurate consequential LCA calculations to be made for RMA materials**, **which will allow decision makers to properly assess where to best utilize RMA in their pavement networks**.
- LCA models for impact categories related to quantifying eco-toxicity are, at the current time, underdeveloped. This creates an undesirable level of uncertainty for those impact categories. **With the recent increase in attention to the question of generation of microparticles by RMA and its effects on aquatic life**, **it is a good time for the industry to come forward and establish an Environmental Product Declaration** (**EPD**) **for using rubber modification in asphalt mixtures**. An EPD standardizes the process of quantifying and communicating the environmental impacts of a product to the end user.
- **A more rigorous quantification of improvement in functional characteristics** (noise reduction, skid resistance) of pavements **resulting from the use of RMA is needed**. National-level collaborations to quantify and standardize these social elements of LCA, categorized as functional performance of pavements, is important.

In addition to the identified research gaps, **a comprehensive set of recommendations for future research and strategic investments** to enable the expanded use of sustainable, durable, and economical RMA pavements in the US **are provided at the end of the SOK report**.

In conclusion, RMA is a well-studied material that delivers significant, proven benefits in terms of pavement durability, economics, and environmental sustainability. It is hoped that the findings and recommendations of this report will help to facilitate the rapid growth in RMA usage in the United States and beyond. RMA is a proven and mature technology that is poised to play a key role in increasing the sustainability and resilience of America's highway and airfield pavement infrastructure as it is rebuilt and modernized in the coming years.

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
AC	Asphalt Concrete
APA	Asphalt Pavement Analyzer
AR	Asphalt-Rubber
ARFC	Asphalt-Rubber Friction Course
ASTM	American Society for Testing Materials
BBR	Bending Beam Rheometer
CRM	Crumb Rubber Modifier
DC(T)	Disc-Shaped Compact Tension Test
DOT	Department of Transportation
ELT	End of Life Tires
FDOT	Florida Department of Transportation
FI	Flexibility Index
GDOT	Georgia Department of Transportation
GTR	Ground Tire Rubber
FHWA	Federal Highway Administration
HMA	Hot Mix Asphalt
HWTT	Hamburg Wheel Tracking Test
LWT	Loaded Wheel Tester
MEPDG	Mechanistic-Empirical Pavement Design Guide
NAPA	National Asphalt Pavement Association
NCHRP	National Cooperative Highway Research Program
NMAS	Nominal Maximum Aggregate Size
OGFC	Open Graded Friction Course
PCC	Portland Cement Concrete
QA	Quality Assurance
QC	Quality Control
RAP	Recycled Asphalt Pavement
RAS	Recycled Asphalt Shingles
RMA	Rubber Modified Asphalt
SBS	Styrene Butadiene Styrene (polymer)
SCB	Semi-Circular Bending Test
SHRP	Strategic Highway Research Program
SMA	Stone Matrix/Mastic Asphalt
TRB	Transportation Research Board
TSRST	Thermal Stress Restrained Specimen Test
WMA	Warm Mix Asphalt

TERMINOLOGY

TERM	DEFINITION
ARFC	Asphalt Rubber Friction Course
Asphalt Rubber	Blend of rubber (minimum 15% by weight of binder) and asphalt via wet process. It is often used in gap- and open-graded asphalt mixtures.
Conventional Mixture	Asphalt mixture without any modification
DGAC	Dense-Graded Asphalt Concrete
ECR	Engineered Crumb Rubber refers to chemically-engineered rubber used in dry process modification of asphalt mixtures
ELTs	End of Life Tires or scrap tires
EPD	Environmental Product Declaration is a transparent, objective report that communicates the environmental impacts of a product.
GTR	Ground Tire Rubber obtained by mechanical grinding of scrap tires
RMA	Rubber-Modified Asphalt is a generalized terms used for any asphalt mixture with rubber incorporated in it via any process.
SAMI	Stress Absorbing Membrane Interlayers used underneath an asphalt overlay to prevent refective cracking

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INTRODUCTION

1. INTRODUCTION

Pavements represent one of the most critical elements of our nation's vast infrastructure. In a crude sense, pavements are made up of layers of aggregates on a soil base, called subgrade, with the topmost layer, also known as surface course, which contains the most premium materials as it bears the brunt of traffic and environmentally-induced forces. For the majority of pavements around the world, the surface course is either made up of cement concrete or asphalt concrete. In the US, asphalt roads make up more than 90% of the highway system and are the preferred option for local roads due to economic feasibility and easier maintenance (NAPA, 2009).

"Diminishing availability of natural resources along with the need to recycle the growing mass of waste materials has pushed the asphalt industry to find novel ways to use recycled materials in paving."

Pavement infrastructure is a huge undertaking and requires considerable amounts of resources. In recent times, diminishing availability of natural resources along with the need to recycle the growing mass of waste materials has pushed the asphalt industry to find novel ways to use recycled materials in paving. Most of the asphalt pavements are reused in form of aggregates, called recycled asphalt pavement (RAP), in new construction of pavements (Sondag, Bruce A. Chadbourn, & Drescher, 2002; Stroup-Gardiner, 2016). Various other waste products, such as waste roofing shingles (Hansen & Copeland, 2015; Haopeng Wang, Liu, Apostolidis, Erkens, & Skarpas, 2020), slag (Abukhettala, 2016; P. Kandhal, 1993; Rath & Mondal, 2014), waste plastic (Karmakar & Roy, 2016; Pouranian & Shishehbor, 2019), and ground tire rubber obtained from end-of-life tires (scrap tires) (W. G. Buttlar, Meister, Jahangiri, Majidifard, & Rath, 2019; D. L. Presti, 2013), are also used in pavement construction regularly. Among those waste materials, Ground Tire Rubber, or GTR, has received substantial attention globally due to its performance benefits and the need to divert the scrap from landfills.

This report intends to summarize the current state of knowledge for the use of GTR-modified asphalt mixtures, also known and referred to as Rubber Modified Asphalt (RMA), in pavements. It is meant to be a resource for paving agencies, institutes, researchers, and other readers who wish to attain a deeper understanding of RMA. The report is divided into eight sections, where each section is focused around a central theme, as follows:

- Section 1 provides background information, results of a national survey for RMA usage in the US, and states the motivation for this report
- Section 2 delves into various aspects of end-of-life tires (also known as scrap tires)
- Section 3 elaborates on production and paving applications of RMA
- Section 4 discusses the structural and functional performance of RMA
- Section 5 covers the environmental effects of RMA usage
- Section 6 includes discussions on economics associated with RMA
- Section 7 outlines the knowledge gaps pertinent to the use of RMA
- Section 8 presents the summary and recommendations of the SOK study

1.1. BACKGROUND

Life cycle analysis of rubber-modified asphalt has shown that even though the production process includes higher energy consumption...a net energy savings can be realized over the lifetime..."

Early research indicated that blending Ground Tire Rubber (GTR) obtained from scrap tires into asphalt binder improved its elasticity and physical properties and characteristics that promoted asphalt pavement performance (G. B. Way, Kaloush, & Biligiri, 2011). The obvious, initial appeal to pursue Rubber-Modified Asphalt, or RMA, was its potential ability to address two technical challenges at once, i.e., to: (a) increase pavement durability and longevity, and (b) create a substantial market for the billions of ELTs that overwhelmed landfills and sometimes led to dangerous, uncontrolled fires (D. L. Presti, 2013; Svoboda, Vaclavik, Dvorsky, Klus, & Zajac, 2018). Additionally, life cycle analysis of rubber-modified asphalt has shown that even though the production process includes higher energy consumption (higher mixing and compaction temperatures), a net energy savings can be realized over the lifetime of a rubber-modified asphalt pavement (Farina, Zanetti, Santagata, & Blengini, 2017a; Tao Wang et al., 2018). Usage of GTR in pavements, thus, has the potential to produce sustainability benefits on a very large scale.

RMA has existed for more than five decades; however, the lack of proven technologies and proper construction techniques led to mixed results in early field trials (Caltrans, 2005c; Lundy, Hicks, & Zhou, 1993; Rebala & Estakhri, 1995). Reasons for low and highly varied use of RMA can be attributed to both economic and non-economic reasons. Early RMA pavements were often expensive and therefore not cost competitive without introducing financial incentives. Early technical issues were encountered, including pavement failures for certain applications such as when large, shredded rubber particles were used in a dry mixing process (Estakhri, Fernando, Button, & Teetes, 1992). In general, wide usage of RMA was limited to mainly Arizona and California in early years. However, with advancements in technology, design and construction practices, the RMA marketplace has significantly evolved over the past two decades. Before reviewing these recent developments, it is instructive to first review the background and history of RMA in more detail.

1.1.1. The ELT Ecosystem

A global ELT management study commissioned by the World Business Council for Sustainable Development (WBCSD) found that ELT production in 13 major countries and Europe was close to 29 million metric tons annually (see Figure 1). The WBSCD reported that the US generates around 3,700 metric kilotons of ELTs annually (WBCSD & The Tire Industry Project, 2019). Additionally, the US Tire Manufacturer's Association (USTMA) projected a need to consume an additional 20.3 million scrap tires per year by 2022 just to maintain the current rate of use of ELTs (U.S. Tire Manufacturing Association, 2018). Figure 1 presents data extracted from the WBCSD report describing ELTs in the world and percentages of recovered and unrecovered ELTs classified by region/country. The data indicates a high potential market for ELTs continues to be asphalt pavements. The data clearly indicates that GTR is available in abundance for potential use in asphalt pavements, both in the US and Europe, and especially in China. India is another marketplace with high expected future availability of GTR.

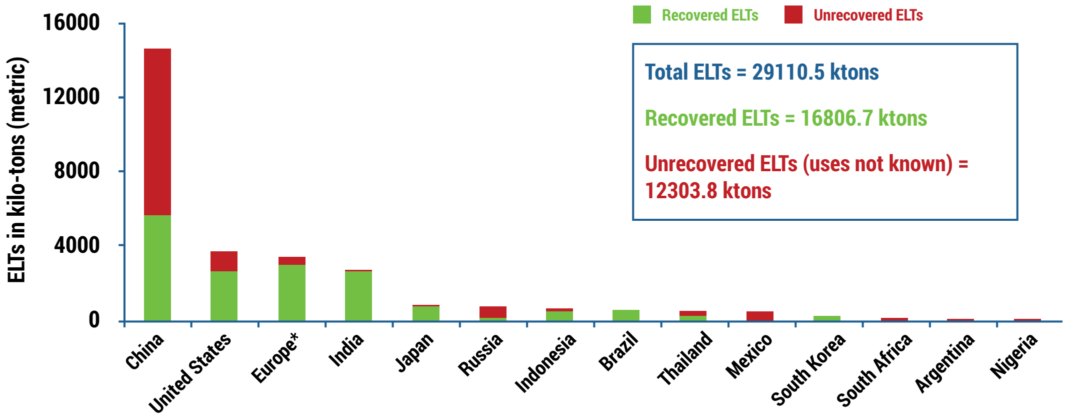


Figure 1. ELT generation by country/region (stats from (WBCSD & The Tire Industry Project, 2019))
**Europe = EU, Norway, Serbia, Switzerland, Turkey*

1.1.2. Economics

The economics associated with modifiers such as GTR when used in asphalt paving mixtures can be evaluated in two distinct ways; 1) in terms of initial bid price or capital cost, and 2) in terms of economic impact on costs over a selected life cycle. The incorporation of GTR in asphalt mixtures typically results in higher initial bid prices compared to conventional, unmodified, and non-premium mixtures, but often lower compared to premium mixtures. In addition, its ability to produce pavements that last longer, and thus delay maintenance, repair, and/or rehabilitation activities, as shown in Figure 2, may reduce costs for the owner agency in the long run. To account for these factors, a life-cycle cost analysis (LCCA) may be utilized. Authors of one of the earliest LCCA studies for RMA was reported by McQuillen et al. (1988). In this study, while referring to the possibility of delayed maintenance actions on RMA pavements, the authors noted that “Any costs (such as those for typical maintenance) that can be deferred to a later date will make pavements with higher capital cost appear much more economically attractive as future dollars are returned to the present” (McQuillen Jr., Takallou, & Hicks, 1988). Over time, a great deal has changed in terms of the economics of RMA, due to a variety of factors. This includes developments in manufacturing and asphalt technology, government interventions to drive wider adoption of recycled materials, greater awareness of LCCA benefits, etc. RMA pavement economics has generally been overlooked in previous literature summaries and is therefore reviewed in this SOK summary.

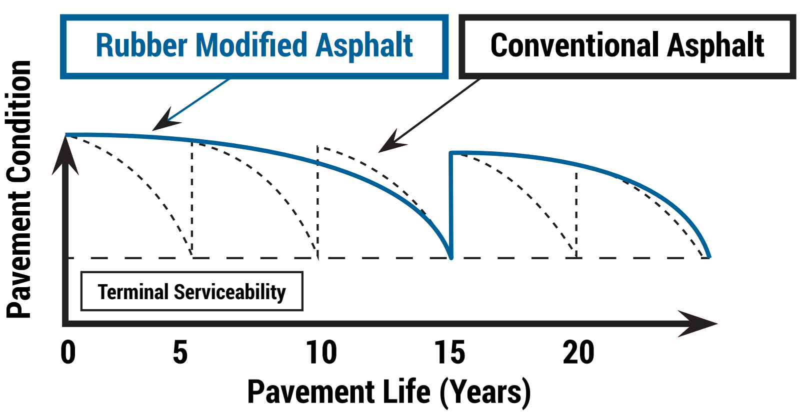


Figure 2. Schematic on maintenance phase for rubber-modified pavement compared to conventional pavement (adapted from (R. Hicks, Lundy, & Epps, 1999))

1.1.3. Structural and Functional Benefits

The quality of a given pavement is typically assessed by two broad metrics - structural and functional performance. First and foremost, a pavement needs to be designed with a sound structure that can carry traffic loads while holding up to prevailing environmental conditions over a specified design life. The incorporation of rubber into asphalt mixtures is generally acknowledged to produce stiffer, more elastic pavements with enhanced rutting and cracking resistance. Upon mixing GTR with asphalt, the rubber particles tend to absorb 'lighter ends' within the binder (oils, resin fractions). This in turn leads to softening and swelling of the rubber particles and an increase in the binder viscosity (Bairgi, Hossain, & Hendrix, 2015; Daly et al., 2019; Roberts, Kandhal, Brown, & Dunning, 1989; Singleton, Airey, I., & C.P., 2000). As a result of this interaction, the binder becomes stiffer overall and thus more resistant to permanent deformation or rutting the pavement. In addition, research has shown that rubber-binder interactions in typical RMA production processes remain primarily physical in nature, i.e., rubber particles retain their particulate structure rather than completely dissolving in the binder like other polymers. Being hyper-elastic in nature and possessing a low glass transition temperature, rubber particles in a mixture can inhibit crack propagation through mechanisms like crack pinning and bridging (Chekunaev & Kaplan, 2014; Ding, Rath, & Buttlar, 2021; Rath, Gettu, Chen, & Buttlar, 2021; Segre, Ostertag, & Monteiro, 2006; Smith & Hesp, 2007).

Functional properties of asphalt paving mixtures generally include surface characteristics such as smoothness, skid resistance, and roadway noise. RMA mixtures have been shown to improve certain functional characteristics of the pavement such as noise reduction, splash and spray reduction, and skid resistance over other kinds of pavements, an example of which is shown in Figure 3 (note- the asphalt rubber overlay was a porous friction course). They have also proven to reduce the rate of tire tread wear. These benefits vary depending on a number of factors, as reviewed and discussed later in this SOK summary. These benefits are likely to play an ever-increasing role as environmental and human health benefits are more holistically considered in the design of roadway infrastructure, for instance, using life cycle assessment (LCA) approaches.

Figure 3. Overlaying existing concrete pavement in San Antonio, Texas with RMA (porous friction course) resulted in better skid resistance, and less spray in wet conditions after (G. B. Way et al., 2011)

1.2. HISTORICAL PERSPECTIVE

The process of using ground scrap tire rubber has existed since 1870 in the United Kingdom (United States Environmental Protection Agency, 1971), but the first experiment of using natural rubber in bitumen was conducted almost 30 years earlier, i.e., in 1840 (Allison, 1967). Notably, around the same time, in 1839, Charles Goodyear introduced the vulcanization process for natural rubber (Takallou, 1987). With an exponential increase in use of automobiles through the latter half of the 20th century, the mountains of scrap tires piling up in landfills soon became a serious environmental issue, such as a source of difficult-to-contain fires (Figure 4), and a harbor for disease-carrying mosquitoes and vermin. Although 95% of peak stockpile quantities of scrap tires from the early 1990s had been cleaned up by 2019 via state programs, recently some end uses for scrap tires have declined. This is especially prevalent in Europe, due to strict environmental regulations for the reuse of scrap tires, for instance, Directive 2007/76/EC prohibited combustion of ELTs in cement kilns (Symeonides, Loizia, & Zorpas, 2019). Thus, there is a critical need to continue the search for the most environmentally friendly destination for scrap tires. Done correctly, RMA offers a potential win-win solution.

Figure 4. Tires in landfill (Image: Shutterstock). Uncontrolled scrap tire fire (Image: Shutterstock)

The commercial usage of scrap tire rubber in asphalt mixtures was developed in Europe and the US at approximately the same time. In the US, Charles McDonald, a material engineer from the city of Phoenix, Arizona, formulated a pavement surface patching material that combined asphalt binder and scrap tire rubber in the 1960s. Later in 1968, Arizona DOT placed its first Stress Absorbing Membrane (SAM), a hot asphalt-rubber chip seal applied to a deteriorated pavement surface. The durability of RMA was readily apparent in these early applications.

1.2.1. RMA Mandate in the 1990s

The first major national push for RMA came in the form of a mandate introduced as a part of the Intermodal Surface Transportation Efficiency Act, or ISTEA, in 1991. The mandate intended to steadily increase the use of RMA in all states, starting from 5% of all asphalt mixtures used in federal projects in 1994 to 20% in 1997. However, opposition by a number of states led to the repeal of the mandate in 1995, prior to its full implementation. The opposition was based on the fact that, prior to the mandate, many states had invested significant capital in demonstration projects for RMA. In a number of these early trials, RMA was found to perform poorly even compared to unmodified asphalt mixtures. In cases where the field performance was reported to be good, its cost-effectiveness was questioned in comparison to using conventional mixtures (Anderson & Jackson, 1992; Caltrans, 2003; Carlson, 1999; Epps, 1994; Fager, 2001; FHWA, 1993; Harmelink, 1999; M. A. Heitzman, 1992a; R. G. Hicks, Lundy, Leahy, Hanson, & Epps, 1995; Pennsylvania Joint State Government Commission, 2007; R. W. Beck, 2005; S. Shuler, 2014; Volle, 2000).

“With modern manufacturing methods, RMA can be very cost-effective.”

1.2.2. Early RMA Failures

The reasons for the early RMA failures were, in hindsight, quite understandable: a) a lack of technology prevented contractors from producing high-quality mixtures on a consistent basis, b) a lack of proper training of personnel compounded by a lack of understanding of the function of rubber in asphalt led to poor or inconsistent quality (for instance, it was not understood at the time that interaction time and temperature are crucial in the production of quality RMA), and c) many technologies that were used in the pilot projects were still patented at that time, leading to high initial costs for RMA and a perceived need for a national mandate to increase its usage. This, combined with the inability of the national mandate to spur RMA development or usage led to even lower usage and negative perceptions of RMA. These perceptions are still prevalent in many states, as evidenced by the new survey results presented later in this report and as detailed in the appendix.

1.2.3. RMA Second Wave

The troubled beginning for RMA notwithstanding, the market for rubber modification has undergone significant expansion in the latter half of the 2010s, partly due to new technologies available for modification and partly due to a better understanding of the mechanics behind rubber modification of asphalt mixtures. For example, in FHWA’s recent document entitled “Resource Responsible Use of Recycled Tire Rubber in Asphalt Pavements,” the authors point out that it is important to compensate for the lighter ends of the asphalt binder absorbed by GTR particles by incorporating supplemental binder or rejuvenating oils into GTR-modified mixtures (G. Baumgardner, Hand, & Aschenbrener, 2020). Failure to do so could lead to ‘dry’ mixtures, making them more susceptible to cracking. The authors explain that the composition of GTR particles is about 40-55% polymer, which reacts with binder, while the remainder consists of inert material functioning as filler which does not contribute to the effective binder content of the mixture, but which increases the non-asphaltic surface area in the binder.

A number of studies have shown that with modern manufacturing methods, RMA can be very cost-effective (Picado-Santos, Capitão, & Neves, 2020; D. L. Presti, 2013)(see section 6.1) and can serve as an environmentally effective way to dispose of scrap tires. A general upwards trend in GTR usage in pavements has been noted, as summarized in Figure 5.

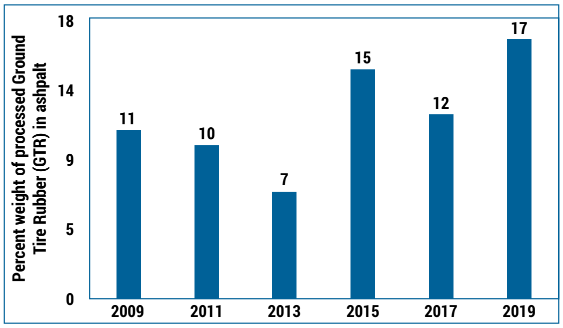


Figure 5. Percent weight of ground tire rubber from scrap tires used in asphalt. Stats obtained from (U.S. Tire Manufacturers Association, 2013, 2014, 2016, 2018, 2020)

Table 1 summarizes a timeline of all the major developments in RMA.

Table 1. Timeline of development in rubber modification of asphalt

Year	Description/Major Development	Reference
1839	Charles Goodyear developed vulcanization process for natural rubber.	(United States Environmental Protection Agency, 1971)
1840	The earliest experiments incorporating natural rubber into asphalt to increase its engineering performance properties.	(Allison, 1967)
1843	The process of asphalt modification involving natural and synthetic rubber reported.	(Thompson & Hoiberg, 1979)
1930s	Development of asphalt rubber materials for use in joint sealers, patches, membranes.	(Caltrans, 2003)
1954	Publication of results from two studies: 1) Lewis and Welborn for Bureau of Public Roads (BPR), California, conducted a study intending to evaluate "The effects of various rubbers on properties of petroleum asphalts", and 2) Rex and Beck at BPR, California, published "Laboratory study of rubber-asphalt paving mixtures."	(Caltrans, 2003)
1960	1st symposium on rubber in asphalt held by Asphalt Institute in Chicago, IL.	(Caltrans, 2003)
1960s	Charles McDonald fabricated surface patches for application on localized distresses on asphalt pavements. The surface patches had asphalt binder modified with high percentage of crumb rubber grains. This was further developed into spreading of stress absorbing membranes that included rubber-modified asphalt embedded with 3/8in. (9.5 mm) aggregate chips. Development of McDonald Process (traditional wet process). Minimum 15% rubber used by weight of binder. Arizona DOT places the first stress absorbing membrane in 1968.	(M. Heitzman, 1992; G. B. Way et al., 2011)
1960s	Development of dry process modification technology in Sweden under trade names "Skega Asphalt" or "Rubit".	(M. A. Heitzman, 1992b)
1970s	Modifications and developments of wet process method. Development of Arizona Refinery Method wherein 18-22% rubber is used, which is a blend of vulcanized and de-vulcanized rubber along with an extender oil (like kerosene, or tall oil) to facilitate the ease of application. Use of extender oils to help with ease of application was also common.	(M. A. Heitzman, 1992b; Schnormeier, 1986)

1970s	Dry process technology introduced in United Sattes under trade name "PlusRide" in 1978 by a company called EnviroTire. 1-3% of crumb rubber by weight of mixture is added to mix. Rubber sizes ranging from 4.2-2.0 mm (1/4 in. to #10 sieve size). Sections placed by Alaska DOT (1976), Minnesota (1979), Washington State DOT (1977), Caltrans (1983), New York (1989).	FHWA website
1980s	Development of Florida wet process which is a continuous blending technology instead of the batch wet processes (McDonald and Arizona Refinery processes). Lower percentage of rubber used (8-10% by weight of binder), finer size of particles, lower mixing temperature and shorter interaction time.	(M. A. Heitzman, 1992b; Schnormeier, 1986)
1980s	PlusRide technology specified gap-gradation which hindered its adoption. This led to development of Generic Dry Process wherein conventional mixtures (dense-graded) could be used. Rubber did not exceed 2% by weight of the mix. Florida, New York, Oregon, Ontario had field sections. Dry Process Chunk Rubber modification process, wherein rubber particles larger than 4.75 mm (#4 sieve) to 9.5 mm (3/8 in.), was investigated by the U.S. Army Corps of Engineers Cold Regions Research Engineering Laboratory (CRREL) to evaluate disbonding ice on pavements. Development of TAK process wherein a blend of coarse and fine rubber particles were used in conjunction with a catalyst to improve binder-rubber interaction.	(Eaton, Roberts, & Blackburn, 1991; Takallou & Sainton, 1992)
1991	Section 1038 of the Intermodal Surface Transportation Efficiency Act 1991 mandated increasing percentages of rubberized asphalt in federally funded highway projects as a requirement to continue receiving federal funds. The states were to increase usage of rubber from 5% in 1994 to 20% in 1997, with 5% increment every year to continue to receive federal funds. In response to the mandate, several states invested in paving trial section with different rubber technologies.	(Carlson, 1999)
1995	Most paving agencies were opposed to adopting the mandate due to following reasons: a) at this point most technologies were patented with talks about extending the patents, leading to high initial capital investment, b) initial trials by many states had not shown encouraging results, especially considering the additional capital investment, 3) there was a lack of understanding and awareness on mixture production/laying processes associated with rubber modified asphalt mixtures. Ultimately, the NHS Designation Act of 1995 amended Section 1038 of the ISTEA Legislation to effectively repeal the mandate.	(Harmelink, 1999)
1995-2005	Reports from various DOTs summarizing performance of the trial sections with rubber. Most reports reached a conclusion that using rubber was not cost-effective as it did not perform well enough to justify the high initial capital investment. Development of the Wright process (a sophisticated wet process technology), where approximately 10% rubber by weight of binder was added at elevated temperatures (approximately 190C) to obtain a product with better storage stability than traditional wet process methods. This process was the precursor to Terminal Blending - a popular wet process technology used today.	(G. Baumgardner et al., 2020)

1995	Most paving agencies were opposed to adopting the mandate due to following reasons: a) at this point most technologies were patented with talks about extending the patents, leading to high initial capital investment, b) initial trials by many states had not shown encouraging results, especially considering the additional capital investment, 3) there was a lack of understanding and awareness on mixture production/laying processes associated with rubber modified asphalt mixtures. Ultimately, the NHS Designation Act of 1995 amended Section 1038 of the ISTEA Legislation to effectively repeal the mandate.	(Harmelink, 1999)
2000-2010	**Innovation in rubber modification technologies**	
	In wet process, terminal blends start getting popular among users of wet process. Terminal blends are rubber-modified bitumen produced and stored at asphalt terminals, and transported to job sites when required. Caltrans preferred "wet process no agitation" as these blends used finer size rubber particles (less than # 50 sieve (0.3 mm)) put in binder at high temperatures (>200C) such that the rubber particles can be kept dispersed by normal circulation within the storage tank rather than by agitation by special augers or paddles. Polymers and other additives could be included to satisfy the viscosity and storage stability requirements.	(Caltrans, 2003)
	In dry process, use of finer particle size (30 to 40 mesh (0.600 to 0.420 mm)) and pre-treatment of rubber particles became common. Modern dry processes also did not require "replacement" of fine aggregates in mixtures, instead the rubber particles were added directly to the aggregates via the RAP(recycled asphalt pavement) collar. Parallel developments in US and Europe. Examples of such products commercially available- RARx (Reacted and Activated Rubber), SmartMix by Liberty Tire, and Elastiko by Asphalt Plus. Among these products, Elastiko has the most tonnage of asphalt mixtures (more than 8 million US tons till date) in Georgia, Illinois, Indiana, Louisiana, Missouri, and many other states in the US. Liberty Tire and RARx demonstrate new technology in recent projects in Michigan and Ohio.	(G. Baumgardner et al., 2020)
2010 and beyond	Significant increase in market for use of rubber modified asphalt with the new processes proving to be largely cost-effective and sustainable. Projections of increased usage in future years. USTMA hosts 7th Rubber Modified Asphalt Conference in Ann Arbor, Michigan in 2016. Research and Development continue.	(G. Baumgardner et al., 2020)

Figure 6 provides a summary of the evolution of RMA over time in terms of technologies and applications.

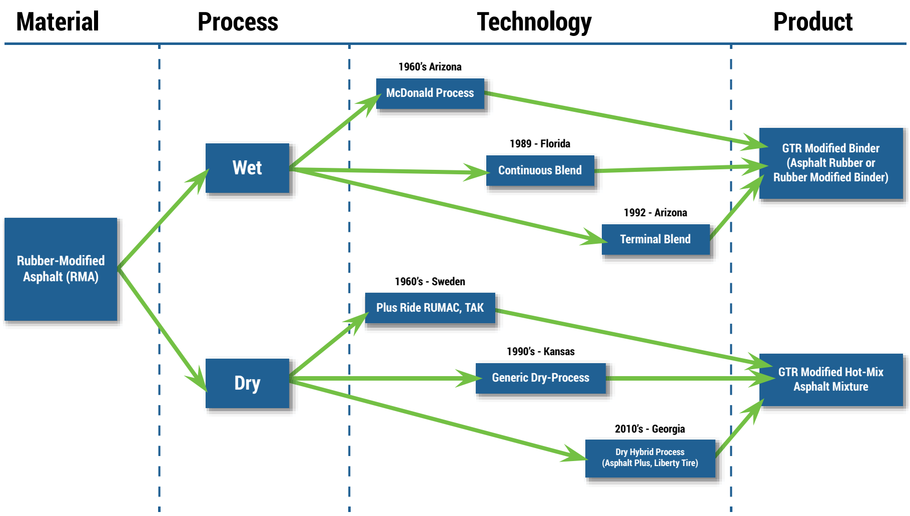


Figure 6. Development of processes for rubber modification of asphalt (after (G. Baumgardner et al., 2020))

1.3. STATE DEPARTMENT OF TRANSPORTATION SURVEY

As part of the SOK study, a survey was conducted to assess state highway agencies (SHAs) in the US in terms of their current usage and perceptions of RMA. Detailed results, including bar charts and written comments provided by respondents, are presented in the Appendix. The survey consisted of 12 questions, where the full script of the survey instrument developed is provided in the Appendix. A list of 26 respondent states is also included in the Appendix.

Based on the survey results, it is clear that most state highway agencies (SHAs) are still hesitant to develop modern specifications for RMA. Among the key findings, the survey revealed that:

- 54% of the responding SHAs reported no current usage of RMA in their states.
- 73% of the respondents consider lack of contractor/agency experience in RMA as the chief barrier in adoption of RMA in their states/geographical areas.
- The complexity and variability introduced in materials storage, handling, and stability was cited as the second-most important barrier (65%).
- Only 28% of respondents cited the past field experiences of RMA to be a barrier in its adoption.
- 50% of the respondents reported that RMA performs the same as or better than the traditional polymer (SBS) modified asphalt mixtures. Only 8% responded that RMA is inferior to SBS modified mixtures.
- In terms of pavement sustainability, 58% of the respondents were unsure of the effects of RMA, while about 37% reported a net positive effect of RMA on pavement sustainability.
- In terms of life cycle cost savings, more than half (65%) were unsure of any cost benefits due to RMA as compared to standard HMA. There was an even split (17% each) between respondents who believed that RMA results in costs savings versus those SHAs who did not. As previously mentioned, multiple studies have reported net life cycle savings when using RMA over standard HMA.

The survey results from SHAs seem to indicate that a number of state highway agencies are making current decisions regarding RMA usage, including delaying the development of RMA specifications for new approaches, based on results from initial RMA demonstration projects conducted decades ago. In fact, many states have not attempted RMA at all. For many states, the initial experiences with RMA occurred during the federal mandate period in the mid-1990s, as evident from published reports. During this time, RMA costs were still quite high in comparison to unmodified asphalt, and field performance results were still fairly inconsistent or not well documented. States that have yet to experiment with RMA often cite the lack of contractor interest in RMA. This is paradoxical, since contractor interest in RMA is likely driven by agency interest in RMA as evidenced by the existence of use of updated, or perhaps, permissive specifications. This has resulted in an apparent stalemate with respect to the prospect of increased RMA usage in those states.

> "50% of the respondents reported that RMA performs the same as or better than the traditional polymer (SBS) modified asphalt mixtures."

Agencies becoming more active in RMA specification development and research in recent years have generally done so by hosting demonstration projects utilizing new RMA materials. This allows contractors to experiment with new production methods and to utilize new research and mix design methodologies. This in turn has led to adoption or local development of new construction specifications for RMA. This includes new specification architypes based on 'balanced mix design concepts,' i.e., specifications built on new asphalt mixture performance tests. Because RMA mixtures represent a novel, composite paving material (built with a recycled material), testing of the full mixture of binder, aggregate, and rubber is more realistic than testing of the liquid asphalt binder plus rubber (as seen in earlier RMA specifications). Binder-centric specifications have generally limited the use of RMA over the years, as explained in this SOK.

1.4. PURPOSE, MOTIVATION, AND INTENDED AUDIENCE

GTR mixes have produced favorable results in certain, modern laboratory tests, leading to successful field trials and new specifications in the Midwest and East Coast US, and has become more economically competitive (Cao, 2007; Presti, 2013; Bressi, Fiorentini, et al., 2019; Buttlar et al., 2021). The processes used in the modification of asphalt mixtures with rubber have improved over time to produce more consistent, better-performing asphalt mixtures. The heightened emphasis on sustainability has led to tools that aim to objectively assess life cycle impacts of major civil infrastructure systems such as roads. The steady stream of developments over the past two decades has created the need for a single, holistic review of the State of Knowledge (SOK) in RMA. This report was designed to address the need for a comprehensive SOK and to summarize knowledge gaps and recommendations for addressing the identified gaps.

The SOK summary is intended for state highway agencies, other road and airport pavement facility owners, contractors, designers, researchers and investors working towards more sustainable, resilient infrastructure systems. It is also intended for those involved in environmental remediation and recycling, including those in the end-of-life tire community, environmental scientists and engineers, and policy makers. Researchers may also find the information contained in this SOK to be useful, particularly the up-to-date referenced literature, the review of new RMA processes, and the summary of knowledge gaps and critically needed research.

END-OF-LIFE TIRES (ELTS) 2

2. END-OF-LIFE TIRES (ELTS)

RMA represents a sustainable pavement solution, where the toughness of asphalt can be enhanced by the inclusion of material obtained from recycled scrap tires, otherwise known as End-of-Life tires or ELTs. The following sections briefly discuss the various aspects of ELTs, such as their availability, environmental impacts, and conversion processes to GTR.

2.1. AVAILABILITY AND USE

An estimated 1 billion end of life tires are produced globally each year (WBCSD & The Tire Industry Project, 2019). The composition of a typical tire is shown in Figure 7. As shown in the figure, tires are comprised of a combination of natural and synthetic rubber, carbon black, steel, and other fibers/fillers. The natural rubber is a form of isoprene polymer while the synthetic rubber is made from the combination of styrene and butadiene monomers. Passenger car tires have higher amount of synthetic rubber while truck tires have more natural rubber. The synthetic additives make the tires stiff and impermeable, thereby increasing their service life. During the lifetime of a tire, about 8-10% of the tire by weight is lost to abrasion. The rest, if not recycled, takes anywhere between 80-100 years to decompose (Torretta et al., 2015).

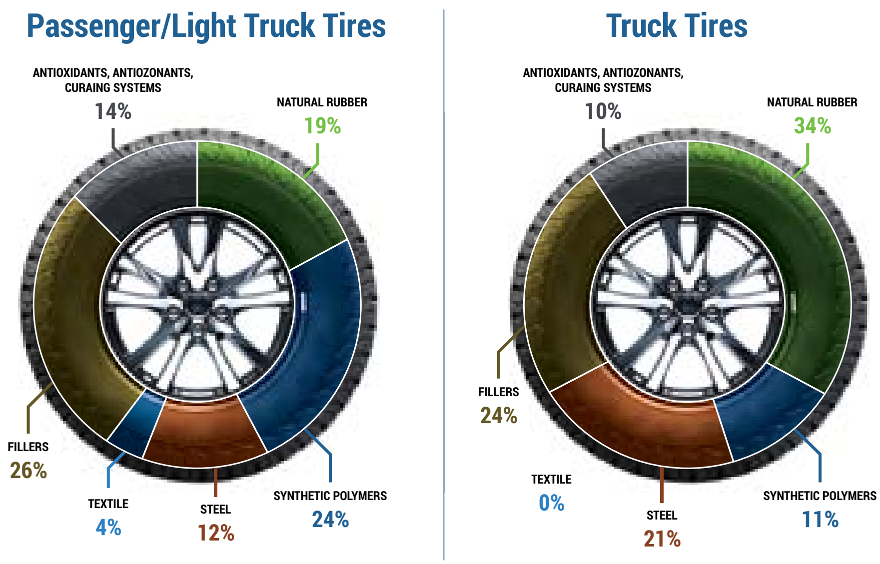


Figure 7. Composition of a tire (from (USTMA, n.d.))

The main markets for end-of-life tires, or ELTs, exist in two primary forms- a) energy generation, and b) material recycling (Bockstal, Berchem, Schmetz, & Richel, 2019; WBCSD, 2010). The relative prevalence of the two forms of reuse depends on the regulations of the geographical area (Grammelis, Margaritis, Dallas, Rakopoulos, & Mavrias, 2021; Torretta et al., 2015). In the United States, about half of the scrap tires end up being used in the form of energy generation as tire derived fuel (U.S. Tire Manufacturers Association, 2020). Lower requirements in processing contribute to the high usage of scrap tires for energy derivation. The energy recovered from ELTs often displaces the demand of non-renewable resources, such as coal, and the natural rubber content of tires is greenhouse gas neutral, making them the greener alternative. Moreover, the calorific value of scrap tires (i.e. the heat generated from whole tires or in the form of tire chips) is higher than coal (Hoang, Nguyen, & Nguyen, 2020). It is often used in industrial furnaces, for instance in cement kilns, or in paper manufacturing. There is substantial research on heating ELTs in absence of oxygen, or pyrolysis, which could result in lower emissions and material capture(Mastral, Callén, Murillo, & García, 1999; Myhre, Saiwari, Dierkes, & Noordermeer, 2012; Tire Business, n.d.). However, the long-term economics of pyrolysis from a circular economy perspective is still being evaluated.

> **"Asphalt pavements constitute 94% of all surfaced roads in the US and are clearly one of the market segments that offers the potential to utilize virtually all annually generated GTR in a given state."**

Material recycling from ELTs is realized mainly through reduction of whole tires into tire rubber granulates for various applications. Whole tires also have applications such as forming a coastal embankment, stabilizing slopes, etc., but comparatively, the use of shredded tire particles as a source of secondary raw materials is more prevalent. Manufacturing of tires is a complex process with various constituents, as shown in Figure 7, involving various chemical interactions (Grammelis et al., 2021; Naik & Singh, 1991; Pehlken & Essadiqi, 2005). The resultant tire is meant to be highly resistant to physical abrasion or chemical breakdown. Consequently, the mechanical reduction of ELTs for secondary use is an energy-intensive process. Thus, identifying proper market segments where the benefits obtained from the tire material derivatives outweigh the energy used in the recycling process is critical.

Asphalt pavements constitute 94% of all surfaced roads in the US and are clearly one of the market segments that offers the potential to utilize virtually all annually generated GTR in a given state. Substantial research has existed since the 1960s regarding the benefits and remaining challenges in incorporating GTR in asphalt mixtures. Studies have shown the various performance and sustainable benefits of paving asphalt roads modified with ground tire rubber recycled from ELTs. In United States, due to legislative actions in the 1990s, many states have attempted to use GTR in asphalt pavements (Bandini, 2011; Ghabchi, Zaman, & Arshadi, 2016), but only a handful of states have a broad understanding and strong track record in using GTR in asphalt mixtures. Nevertheless, asphalt pavements represent potentially the largest consumer segment for recycled tire rubber.

2.2. ENVIRONMENTAL CONSEQUENCES

Scrap tires not only occupy large volumes in landfills but also pose several environmental risks. The idle scrap tires in a landfill could ignite, leach into nearby soil and ground water, and provide a breeding grounds for insects and vermin (Tire and Rubber Recycling Advisory Council, 2003). In addition, modern tires take about 80-100 years to degrade, which is a long time to be idle in landfills (Torretta et al., 2015). Reducing scrap tire stockpile has long been recognized as an important environmental and legislative issue. Consequently, most states and countries have set up regulations to effectively reduce scrap tires stockpiles (Arizona Department of Environmental Quality, 2001; CalRecycle, 2019; Texas Commission on Environmental Quality, 2019).

As discussed in the previous section, there are two major ways of recycling scrap tires, a) energy recycling, which includes kilns and boilers using ELTs for energy instead of fossil fuels, and b) material recycling, which predominantly consists of applications such as pavement construction, sports turfs, roofs, etc. Energy recycling could potentially produce harmful particles, whereas material recycling often includes reduction of scrap tires into smaller particles, which is an energy-intensive process. Choosing a better alternative would require careful analysis of environmental impacts and a realistic market study. Researchers often rely on Life Cycle Analysis (LCA) as a tool to evaluate the environmental impacts of a product.

LCA studies can be classified into two major categories - attributional and consequential (Ekvall, 2019). According to Evkall, “An attributional life cycle assessment (ALCA) estimates what share of the global environmental burdens belongs to a product…a consequential LCA (CLCA) gives an estimate of how the global environmental burdens are affected by the production and use of the product.” In the case of RMA, for example, ALCA can be used to assess the amount by which the inclusion of rubber in asphalt concrete creates net positive or negative impacts in various environmental impact categories such as CO2 emissions, freshwater eutrophication, ozone depletion, etc. CLCA could be used to assess the net environmental impact of increasing RMA usage as an alternative to burning scrap tires for energy (pyrolysis). Thus, consequential LCA studies are well suited to inform high-level policy decisions with regards to minimizing the environmental impact of ELTs.

Feraldi et al. (2013) conducted a consequential LCA on treatment methods for ELTs, specifically focused on energy and material recycling (Feraldi, Cashman, Huff, & Raahauge, 2013). The findings suggested that shifting the ELTs used in energy recycling to material recycling would result in environmental benefits, i.e., provides a greener option (Feraldi et al., 2013). An LCA study from Germany found that using 400,000 tons of scrap tires in artificial turfs versus using them for energy recovery could result in reduction of 280,000 tons of CO2 from the environment (Schmidt & Kløverpris, 2009). Fiksel et al. (2011) and Clauzade et al. (2010) investigated the energy and material recycling of scrap tires and concluded that using waste tires as raw material for synthetic turfs/grass was the most promising alternative (Clauzade et al., 2010; Fiksel, Bakshi, Baral, Guerra, & Dequervain, 2011). However, Fiksel et al. (2011) reasoned that the market for synthetic grass in US is saturated, and hence energy recovery in cement kilns is the most environmentally profitable and feasible option. Other studies have reached similar conclusion that energy recycling of scrap tires in cement is a greener option as it saves natural resources (coal) and has higher calorific value than coal (Corti & Lombardi, 2004; W. Li, Wang, Jin, & Li, 2014; Ortíz-Rodríguez, Ocampo-Duque, & Duque-Salazar, 2017). It is noteworthy that rubber modified asphalt, which is an enormous, unsaturated market in the US, was not considered in the studies referenced above.

The environmental benefits of material recycling over energy recycling have made it an attractive option. In Europe, for example, material recycling is slowly inching ahead of the energy recycling route for scrap tires, as seen in Figure 8. Reports suggest that as much as 75% of all scrap tires are destined for material recycling (Global Recycling, n.d.). In the United States, the energy recovery from scrap tires has gone down from 53.1% in 2013 to 36.8% in 2019, and at the same time, material recovery market has jumped from 38.7% in 2013 to 48.9% in 2019 (U.S. Tire Manufacturers Association, 2014, 2020).

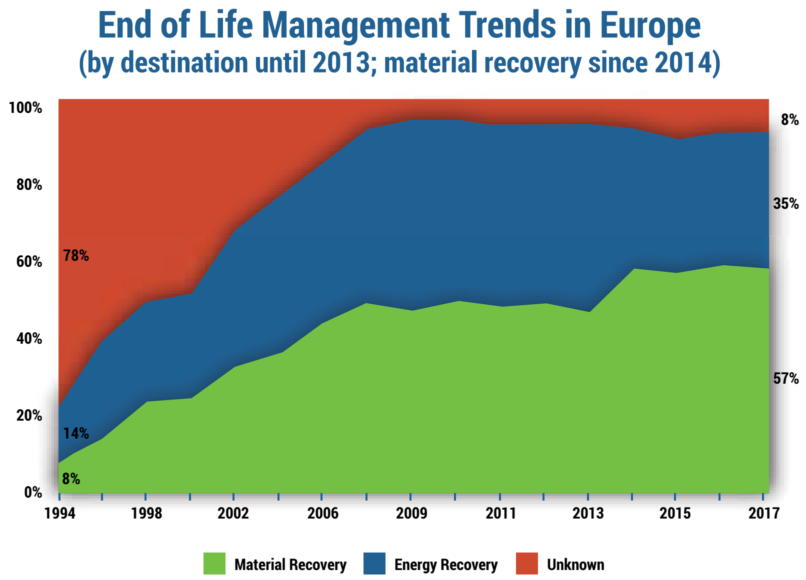


Figure 8. Use of scrap tires for energy and material recovery in European Union (from (Tire Business, n.d.))

2.3. ELTS TO CRUMB RUBBER

The reduction process of scrap tires starts with mechanical shredding. The shredded tires are then typically ground using one of two common methods: ambient and cryogenic grinding. In the ambient method, successive reduction of rubber tires take place at ambient temperatures using granulators, shredders, and other equipment. Due to the grinding method, the ground rubber produced has a rough surface and is partially oxidized from the generated heat. In the cryogenic method, the rubber tires are cooled down below -80C (-112F) using liquid nitrogen and then hammered into smaller sizes. At such low temperatures, rubber behaves like glass (very brittle) and readily fractures. While the cryogenic process requires less machinery than the ambient process, the addition of liquid nitrogen adds an extra expense. The cryogenic process produces particles that are more cubical in shape, or have sharp edges, and less surface area. There are other methods of reducing scrap tire rubber, such as waterjet size reduction. However, ambient and cryogenic grinding are most prevalent in terms of GTR production for asphalt paving applications. A high-resolution image of rubber obtained from both the processes in shown in Figure 9.

(a)

(b)

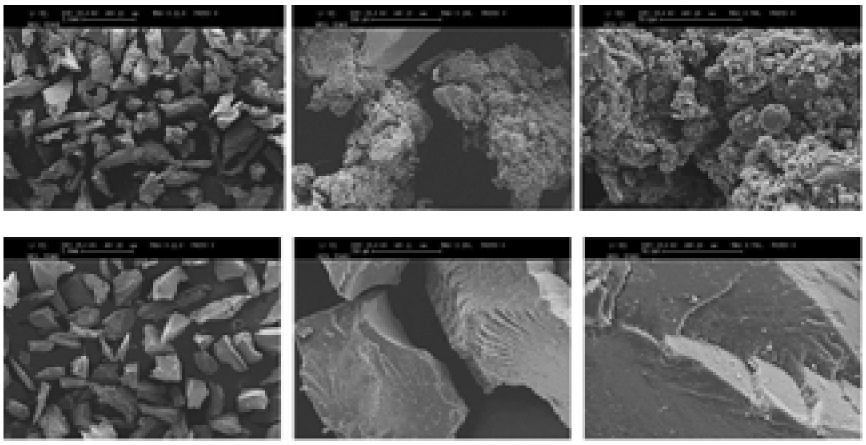


Figure 9. (a) Ambient 5-10 mesh ground tire rubber, (b) cryogenically produced 30 mesh ground tire rubber (from (Pais, Lo Presti, Santos, Thives, & Pereira, 2019))

3

RUBBER-MODIFIED ASPHALT (RMA)

3. RUBBER-MODIFIED ASPHALT (RMA)

Once GTR is produced from ELTs, there are various methods available to incorporate them into asphalt mixtures. The modification methods are grouped based on introduction of GTR via binder and via aggregate. The following sections discuss each method in detail and further delves into the interactions between rubber and asphalt binder.

“The rubber-asphalt interaction takes place for about 30-60 minutes at elevated temperatures ranging from 175-190C (350-375 F).”

3.1. WET PROCESS

The development of wet process in the US started in the mid-1960’s with Charles McDonald’s experiments on producing small patches that were made by embedding 3/8 in. chips in rubber-modified asphalt binder. Eventually, wet process rubber modification was defined to encompass the various processes in which ground tire rubber is used to modify the liquid asphalt binder, stored in tanks, possibly transported, and later used to produce an asphalt paving mixture. Wet process modification of an asphalt binder can be carried out either on-site at the asphalt mixture production plant or at an asphalt blending terminal. While a breadth of nomenclature has been reported in the literature with respect to wet process modification, the following classifications and terminology are the most broadly used:

Asphalt Rubber: By definition (ASTM D8, later defined in ASTM D6114), asphalt rubber is a blend of asphalt cement, reclaimed tire rubber, and certain additives, with at least 15% of rubber by weight of binder being used for modification. Typically, coarser size rubber particles (about 1.5 mm in size) are used for production of asphalt rubber. The rubber-asphalt interaction takes place for about 30-60 minutes at elevated temperatures ranging from 175-190C (350-375 F). There is a need for continuous agitation during production and storage of asphalt rubber. This process is carried out entirely at the asphalt plant where specialized equipment such as blending and storage tanks equipped with agitation are integrated with a ground rubber feeder.

Terminal Blends: The production of terminal blends resembles that of the asphalt rubber production process, except that the production takes place at a supplier terminal and usually, finer sizes of rubber particles (0.600 mm – 0.200 mm (#30-#80 mesh)) are used. Ground tire rubber and asphalt are mixed in blending tanks at elevated temperatures (175-190C (350-375 F)) and for at least 60 minutes. The blends are then stored at elevated temperatures until they are delivered to the work site. Terminal blends generally contain about 5-12% rubber and could also include specialized chemicals or polymers such as styrene-butadiene-styrene, or SBS (Han, Zheng, & Wang, 2016). Currently, the most popular terminal blend is called the “Wright Process”, which is prevalent mainly in Arizona, Texas, and surrounding states. The Wright process uses a longer rubber-binder interaction time and chemical additives to produce a blend that has good storage stability. Notably, rubber settlement, or lack of adequate storage stability, has been one of the main production and quality control (QC) issues with the wet process for RMA production.

3.2. DRY PROCESS

> Today's modern dry process technologies use even finer rubber particles (0.600-0.300 mm (#30-#50 mesh)) and may incorporate chemical surfactants..."

The Dry Process for RMA asphalt mixture production was developed initially in Sweden in 1960s under trade names "Skega Asphalt" or "Rubit" before making its way to the US under the name of PlusRide (D. Esch, 1982). This RMA production process involved replacing a small portion of the fine fraction of the blended aggregate structure of the asphalt mixture - in the range of 1-3% by weight- with rubber particles ranging from 4.2 mm to 2.0 mm. This size of rubber particles is quite large as compared to those used in modern dry process RMA mixtures. The motivation behind the early dry process approach with larger rubber particles was to increase the skid resistance and durability of the resulting rubber-modified asphalt pavement (D. Esch, 1982; McQuillen Jr. & Hicks, 1987; United States Department of Transportation, 2016).

The PlusRide technology specified gap-graded mixtures to be used with rubber modification. Gap-gradations, in contrast to 'well-graded' or 'dense-graded' blended aggregate structures, contain a shortage or gap in particles across a range of aggregate sizes (or sieves) somewhere in the middle of the particle size distribution curve. This can produce 'room' for rubber particles, including the facilitation of rubber particle swelling during uptake of light ends from the asphalt binder. However, many road agencies only use gap-graded mixtures in limited application categories. Dense gradations are preferred over gap and open graded mixtures in cold climates where pavement density and impermeability is preferred (to limit freeze-thaw effects throughout the pavement structure). A notable exception is stone mastic asphalt, or SMA, which is gaining favor as a high performance, gap-graded surfacing mixture regardless of prevailing climatic conditions. That notwithstanding, early reliance on gap-graded mixture applications hindered dry process RMA widespread adoption.

These limitations led to the development of the so-called "Generic Dry Technology," aimed at using any existing local mixture gradation for use in RMA, made possible through the use of finer rubber particles in the dry process (Takallou & Sainton, 1992). Specification of a range of rubber particles to be used in conventional mixture gradations allowed the dry generic technology to be assessed in field trials in many states. However, the flexibility in terms of particle size also led to an increase in cost of projects, as crumb rubber particles manufacturers had limited capabilities (M. A. Heitzman, 1992a; United States Department of Transportation, 2016).

Today's modern dry process technologies use even finer rubber particles (0.600-0.300 mm (#30-#50 mesh)) and may incorporate chemical surfactants, which facilitate the rate of rubber swelling and deliver other production, construction, and/or performance benefits to the resulting RMA mixture. In modern, dry process RMA production, rubber is injected into the mixing plant in the bottom portion of the mixing drum (typically through the RAP collar). Generally, an existing mix design is used, with only minor adjustment to the blended aggregate gradation needed, if at all. Trademarked products such as Asphalt Plus' Elastiko™, and Liberty Tire's SmartMix are examples of 'modern dry process' or 'dry-hybrid' approaches. Reports in the literature suggest that in the past decade more than five million tons of engineered crumb rubber (ECR) has been placed in multiple US states, the majority of them involving the ElastikoTM system (G. Baumgardner et al., 2020).

3.3. INTERACTION OF RUBBER WITH ASPHALT BINDERS AND MIXTURES

Extensive research has been devoted to better understand the precise nature of the interaction between rubber and asphalt binder in RMA. Findings suggest that the interaction is of a physical nature, whereby the rubber particles absorb the lighter ends (lower molecular weight) of the asphalt binder and swell up to 3-5 times their original volume (Dong, Huang, Li, & Zhang, 2012; Gawel, Stepkowski, & Czechowski, 2006). The migration of the lighter ends (saturates and aromatics) and subsequent swelling results in the disintegration of the outer periphery of rubber particles, as shown in Figure 10. However, the rubber particles maintain their physical integrity to a large extent, if produced and stored with normal temperature ranges (160-180C) and when using typical shear mixing ranges (Gawel et al., 2006; Ghavibazoo, Abdelrahman, & Ragab, 2013; Stroup-Gardiner, Newcomb, & Tanquist, 1993). Excessive temperatures (> 200C) and high mixing rates could result in depolymerization of rubber particles (Ghavibazoo et al., 2013; D. L. Presti, 2013), reducing their efficacy in physical property enhancement of the binder. The absorption of the lighter ends from asphalt binder and the consequent swelling results in an increase in the viscosity of the modified binder. Needless to say, the source of asphalt, time of interaction, mixing temperature, and rubber particle properties (source, grinding process, etc.) are all important factors that determine the degree to which the asphalt-rubber interaction will occur. For example, Frantzis (2004) reported that binder sourced from Venezuela had a higher reaction rate with GTR as compared to binders from the Kuwait region (Frantzis, 2004), Lougheed et al. (1996) found that softer binders grades reacted more readily with GTR (Lougheed & Papagiannakis, 1996). Lee et al. (2008) reported that GTR produced via the ambient grinding method resulted in a more viscous binder that is less susceptible to rutting and cracking (Soon J. Lee, Akisetty, & Amirkhanian, 2008).

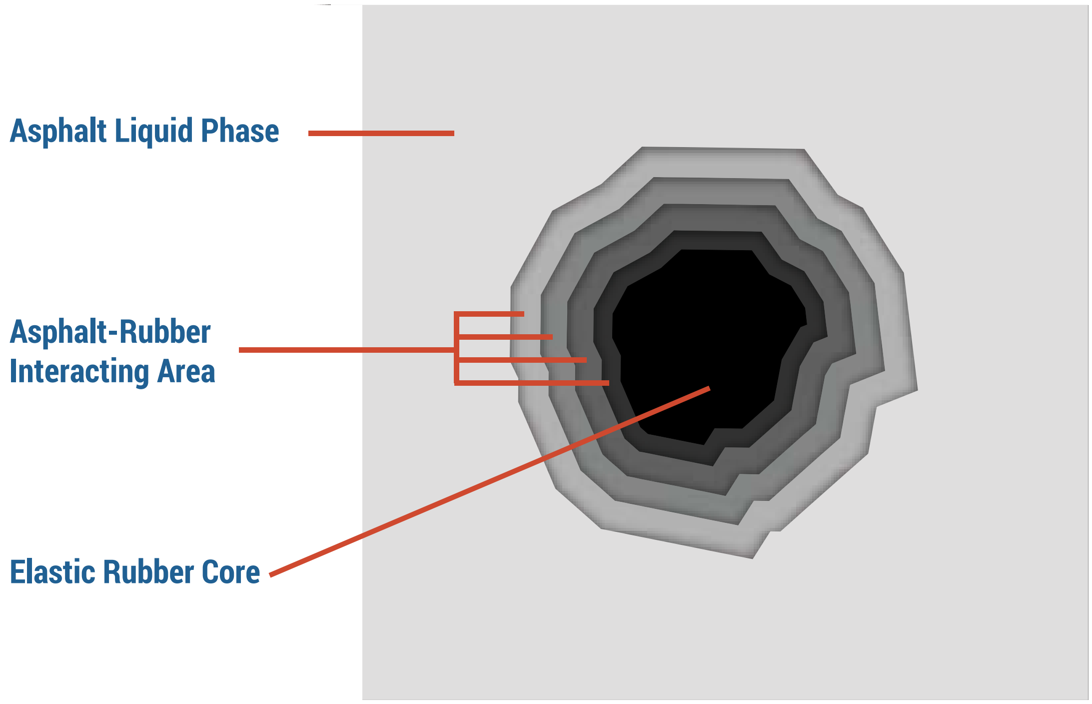
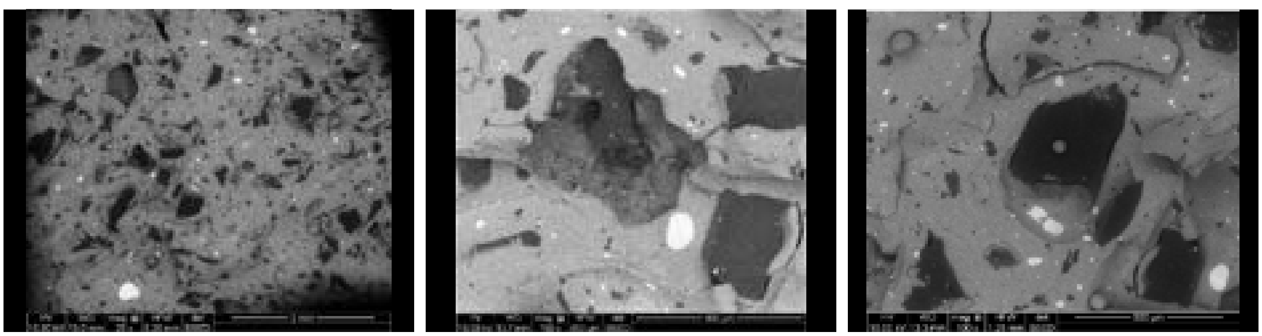


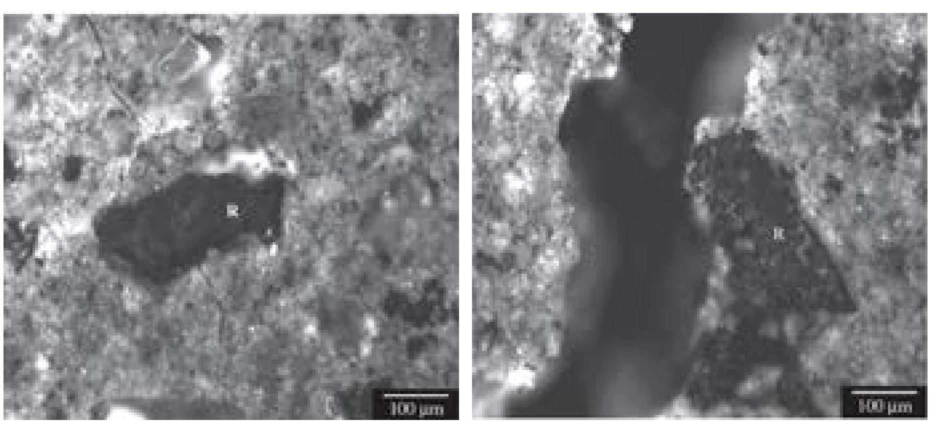
Figure 10. Rubber-binder interaction by selective absorption of binder fractions (from (Yu, Leng, Zhang, Li, & Zhang, 2020))

The fact that rubber particles retain their physical structure during the interaction with asphalt binder provides an important insight into to the crack inhibiting mechanisms introduced in asphalt mixtures due to incorporation of rubber. Research has shown that rubber particles in an asphalt binder behave as hyperelastic inclusions that provide crack pinning, thus impeding crack propagation until a significantly higher energy is imparted to the crack front, as shown in Figure 11 (a, b & c) (Ding et al., 2021; Rath, Gettu, et al., 2021). Alternatively, the crack is forced to take a path around the particle inclusion, thereby increasing the crack resistance of the asphalt matrix. Similar results have been shown with cement paste by Segre et al. (2006) (Segre et al., 2006), as shown in Figure 11 (d & e).

This is an important distinction between rubber and other common asphalt modification approaches, such as chemical and/or traditional polymer modification. GTR, which pre-dominantly contains styrene-butadiene rubber (SBR), is often compared with styrene-butadiene-styrene (SBS) polymer modification in terms of performance due to the perceived similarity in polymeric building blocks. However, unlike GTR particles that have bulk SBR produced by grinding solid tire rubber that behave as inclusions in asphalt binder/mixtures, SBS polymers create a crosslinked elastomer network once mixed with asphalt binder. While both provide performance benefits to the asphalt binder/mixture, the mode of failures for GTR - and SBS - modified binders in different temperature regimes can be fundamentally different. SBS resists crack propagation through stretching of the crosslinked network under stress while GTR introduces crack impeding mechanisms such as crack pinning or crack bridging (Rath, Gettu, et al., 2021; Segre et al., 2006). However, these systems have drastically different performance upon cooling to low temperatures, as discussed in section 4.



(a) (b) (c)



(d) (e)

Figure 11. a, b & c) Rubber particles embedded on the surface of asphalt binder (from (Rath, Gettu, et al., 2021)); (e & f) rubber particles embedded in cement paste (R represents rubber particle) (from (Segre et al., 2006))

3.4. PAVING APPLICATIONS

Asphalt pavement structures and asphalt paving surfaces have evolved considerably since their inception in the late 1800's, resulting in a number of fundamentally different structural systems and materials systems involving pavements comprised with asphalt. A brief listing of these asphaltic paving systems is now provided, with a focus on describing applications where GTR is either prevalent or potentially useful.

"GTR is now commonly used in Illinois Tollway SMA mixtures to arrive at economical surfacing materials..."

3.4.1. Full Structural Pavement Systems

RMA is appropriate and commonly used in traditional **hot-mix** and **warm-mix** asphalt paving layers. This includes use in traditional, or **conventional flexible pavement systems**, which are placed over unbound, granular subbase and base layers of aggregate, and **full-depth asphalt pavements**, where the total combined thickness of the asphalt layers is increased and subbase and base layers are generally eliminated. In both systems, base (or binder) course and surface course asphalt mixtures are used. Both mixture types provide an excellent opportunity for RMA use. The base asphalt courses can benefit from the fatigue resistance of RMA, while the surface course can benefit from both the rutting and cracking resistance imparted by RMA. Another possible use of RMA in new pavement construction is in **composite pavement** systems. These involve the use of a Portland cement concrete pavement section topped with asphalt concrete in new pavement construction. Although involving high initial capital costs, these systems are gaining popularity in high traffic areas where 40+ year design lives are desired. For instance, the Illinois Tollway now frequently constructs new composite pavement systems, with durable SMA mixes placed on the new concrete pavement to promote favorable surface characteristics such as skid resistance, smooth ride quality, and reduced noise. GTR is now commonly used in Illinois Tollway SMA mixtures to arrive at economical surfacing materials that meet modern balanced mix design requirements (W. Buttlar et al., 2021).

3.4.2. Pavement Overlay Systems

From the perspective of lane-miles of highway treated per year, the restoration or enhancement of pavement structural integrity and/or surface characteristics via the placement of asphalt overlays far exceed new pavement construction. **Asphalt overlays** are also prime targets for the use of RMA. In some cases, **stress absorbing membrane interlayers** (**SAMIs**) are used as the first course of a multi-layer overlay system. These are generally thin layers of high-performance, ductile/crack resistant asphalt pavement designed to mitigate the reflection of cracking from existing, aged pavement (asphalt or concrete) into the new overlay surface. From the results of the survey presented earlier, it is clear that some states are using GTR to achieve the high-performance requirements of SAMI's. In fact, one of the first uses of RMA was in the form of SAMIs in Arizona to prevent reflective cracking, as shown in Figure 12 (G. Way, 2012).

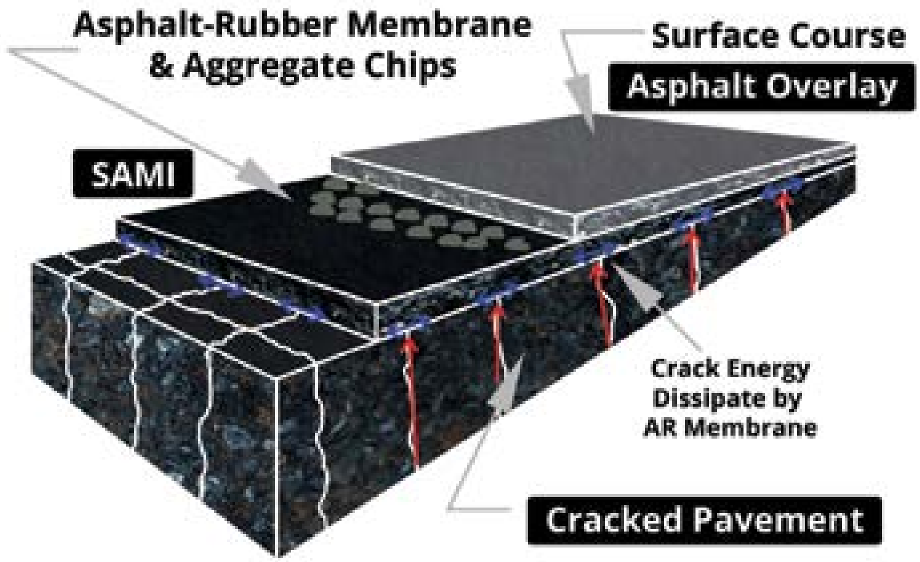


Figure 12. Schematic of Stress Absorbing Membrane Interlayer (SAMI) from Way (2012)

Data from the survey conduction in this study as well as published results show that RMA is used substantially in form of thin overlays. Depending on the sophistication of the pavement design system used, reduced layer thickness(es) may result from the use of RMA, increasing sustainability and leading to more attractive life cycle costs. In the late 1980s, California constructed various thicknesses of conventional DGACs and rubber-modified overlays over Rt. 395 in northeastern California. After a few years of monitoring, the authorities concluded that the performance of substantially thinner rubber sections was similar to the more traditional DGAC sections (J. Van Kirk & Holleran, 2000; J. L. Van Kirk, 1997). In 1990s, Caltrans set out to validate the work and conducted accelerated pavement testing on unmodified and rubber modified sections. The performance results showed that a reduction ratio of 3:1 was possible for rubber versus DGAC overlay lifts, enabling similar performance along with substantial cost savings. Later, Harvey et al. (2000) reported rubber-modified overlays in California to have similar performance as DGAC asphalt mixtures that were 2.1 times thicker (Harvey et al., 2000). Buttlar et al. (2019) reported a cost savings of up to 43% could be achieved by using lesser lift thickness of RMA in place of thicker unmodified pavement without compromising on pavement performance (William G. Buttlar & Rath, 2019).

In terms of routine design, it appears that no current pavement or overlay design software adequately incorporates RMA in sufficient detail with regards to its precise physical properties and resistance to distress formation ('transfer functions') in the design formulas and/or software. **Thus, it is no surprise that for states outside of Arizona and California have yet to experiment with thin overlay systems comprised of GTR in the pursuit of economical, sustainable and durable resurfacing systems. This represents another critical research gap**.

The ability to design SAMIs and other paving layers with GTR for high strain applications appears to suggest that it may be possible to use RMA on bridge decks. Bridge decks are subject to high strains in the roadway surface, due to bridge flexure and higher thermal cycling, resulting in the use of exotic and expensive surfacing materials, such as highly modified asphalt systems. More research is needed to see if RMA can be used to meet these extreme performance requirements with a more sustainable and cost-effective solution.

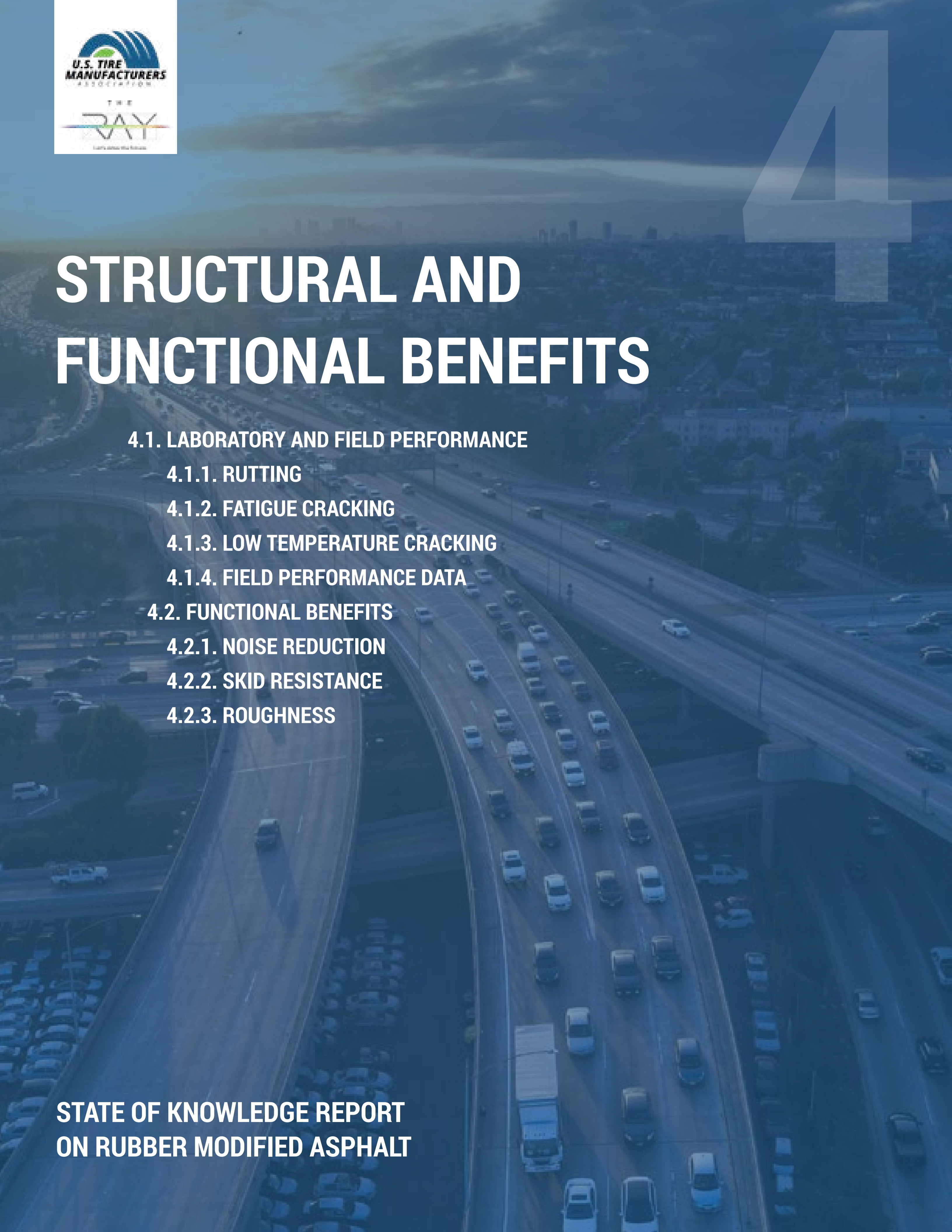
“Pavement life can be extended through the proper timing of maintenance treatments, and without them, poor life cycle economics result. GTR can be effectively used in these systems to further extend pavement life.”

3.4.3. Preventive and Restorative Maintenance Treatments

After a pavement is built, traffic and environmentally-induced deterioration forces immediately begin working on pavement integrity. Pavement life can be extended through the proper timing of maintenance treatments, and without them, poor life cycle economics result. GTR can be effectively used in these systems to further extend pavement life. Historically, gap-graded, **RMA-based thin overlay systems** have been used with great success in Arizona and California for the restoration of surface characteristics of Portland Cement Concrete (PCC) and asphalt pavements. These systems have an extensive track record in terms of their longevity and their resistance to reflective cracking (J. L. Van Kirk, 1997; F. Zhou & Scullion, 2008). Promising field data exists that supports the use of GTR in thin, maintenance overlays as summarized in the flowing studies: Walubita and Scullion 2008 (L. F. Walubita & Scullion, 2008); Scullion et al. 2009 (Scullion, Zhou, Walubita, & Sebesta, 2009); Zhou et al. 2009 (F. Zhou, Hu, Hu, & Scullion, 2009); Hu, Zhou, and Scullion 2014 (Hu, Zhou, & Scullion, 2014); Chou, Datta, and Pulugurta 2008 (Chou, Datta, & Pulugurta, 2008).

In other climates, and in more recent times, thin overlay systems, or **thin-lay** overlays, are gaining popularity for their ability to restore desirable pavement surface characteristics at a relatively low cost. Because of the high shear stress in these thin systems, particularly when poor bonding to the underlying pavement is present, tough overlay materials such as those containing GTR would be expected to yield the best field performance. Another subset of this category is spray-paver applied, **thin-bonded wearing courses**, including ultra-thin varieties (Chen, Gong, Ge, You, & Sousa, 2019). The advantage of these systems is their ability to achieve a high degree of bonding through the use of a heavily applied tack coat, often polymer modified, which is spray-applied just centimeters in front of the deposited paving mixture and paver screed using a sophisticated, multi-function ‘spray paver.’

Rubberized **chip seals** and **thin slurry seal** systems have also utilized GTR with success (J. Van Kirk, 2003; H. Zhou, Holikatti, & Vacura, 2014). The one preventive maintenance category that has yet to involve GTR use is the fog seal category, where a diluted asphalt/water emulsion is directly applied to a pavement surface as a sealant and/or rejuvenator. Because of the thin film used in these systems and the need to apply them through a distributor with spray nozzles, it is not clear if a GTR-modified binder system would be appropriate for use in fog seal applications. The retention of surface rubber particles would also pose an environmental concern for those systems.



4

STRUCTURAL AND FUNCTIONAL BENEFITS

4. STRUCTURAL AND FUNCTIONAL BENEFITS

A good pavement is characterized by a sound structure and superior functional properties. Structural performance is characterized by measurement of different distresses such as rutting and cracking, while the functional benefits encompass metrics that measure skid resistance, noise generation, and ride quality. The following sections will touch upon the effects of rubber-modification of asphalt on structural and functional performance of a pavement.

> "Permanent deformation or rutting is the formation of channels in wheel paths, typically due to either plastic flow of asphalt paving layers under traffic during high temperature events, or due to poor subgrade conditions."

4.1. LABORATORY AND FIELD PERFORMANCE

An important aspect of widespread adoption of a product is its impact on real-world performance. In the case of asphalt mixtures, a well-performing mixture would not only result in a more durable pavement but would also offset the cost of rehabilitation and repair by lowering the frequency of required maintenance activities. Rubber modification is known to improve asphalt mixtures in terms of field performance. In the following sections, the effects of rubber modification on major deterioration modes (or 'distresses') will be reviewed based on existing literature, followed by a review of field demonstration projects.

4.1.1. Rutting

Permanent deformation or rutting is the formation of channels in wheel paths, typically due to either plastic flow of asphalt paving layers under traffic during high temperature events, or due to poor subgrade conditions (P. S. Kandhal & Cooley, 2003; Rushing, Little, & Garg, 2014; L. Walubita et al., 2012). Modification of asphalt with GTR results in uptake of lighter ends, swelling of the rubber particles, and increased binder viscosity (Daly et al., 2019; Gawel et al., 2006; Ghavibazoo & Abdelrahman, 2013). This, in turn, makes the mixture stiffer, and as a result increases its resistance to rutting (Abdelrahman & Carpenter, 1999; Behnood & Olek, 2017).

Krutz et al. (1992) compared RMA and unmodified mixtures using a static and a repeated-loading test. The authors reported that in both methods, RMA had significantly less deformation at higher temperatures as compared to unmodified mixtures even with higher binder contents (Krutz & Stroup-Gardiner, 1992). Rebala et al. (1995) tested asphalt mixtures modified with wet and dry process rubber (Rebala & Estakhri, 1995). The authors reported that, if properly designed, both methods of modification would result in mixtures that are more resistant to permanent deformation as compared to conventional mixtures.

Lee et al. (2007) compared different asphalt mixtures including RMA with 10% and 15% dosage rates (wet process- by weight of binder) and 3% SBS (by weight of binder). The authors used an Asphalt Pavement Analyzer (APA) to determine the rut resistance of the mixtures. The findings suggested that even though RMA mixtures had higher optimal binder content as compared to the SBS mixture, the rutting resistance was similar. Higher binder content typically leads to enhanced cracking resistance (S. J. Lee, Amirkhanian, Putman, & Kim, 2007). Fontes et al. (2010) conducted repeated simple shear tests at constant height and wheel tracking tests on both gap- and dense-graded mixtures modified with rubber via different wet process techniques- continuous blend and terminal blend (Fontes, Trichês, Pais, & Pereira, 2010). The authors found that irrespective of the method of modification, rubber modification improved resistance to permanent deformation in comparison to a conventional dense graded mixture. Further, the authors reported that the gap graded mixture with continuous blend asphalt rubber performed better than other investigated mixtures.

Cao (2007) investigated the effects of dry process modification of rubber by varying crumb rubber contents from 1-3% by mixture weight. The author used gap-graded mixtures and on the basis of wheel tracking tests at 60C, the authors found that higher percentages of rubber led to higher resistance to permanent deformation (Cao, 2007). Subhy et al. (2017) showed improvement in rutting properties of an SMA with addition of rubber via dry and wet processes in comparison to an unmodified SMA mixture (Subhy, Airey, & Lo Presti, 2017). Shirini et al. (2016) conducted flow number and wheel tracking tests on porous asphalt mixtures modified with crumb rubber via wet process (at 10, 15, and 20% by weight of binder), and SBS polymer (5% by weight of binder) (Shirini & Imaninasab, 2016). The authors reported that asphalt mixtures with 10% crumb rubber performed comparably to SBS-modified mixtures, and an increase of rubber dosage from 10 to 20% resulted in a more than 50% boost in 'mixture performance.'

> **"The authors reported that asphalt mixtures with 10% crumb rubber performed comparably to SBS-modified mixtures."**

Significant research has also been devoted to RMA asphalt mixtures containing recycled/reclaimed asphalt pavement (RAP), which have generally showed a very high degree of rutting resistance. Xiao et al. (2009) investigated the effects of incorporating crumb rubber in asphalt mixtures with 25% RAP and reported an increase in rutting resistance with the addition of crumb rubber (Xiao, Amirkhanian, Shen, & Putman, 2009). In a prior study, Xiao et al (2007) had reported similar findings along with noting that the aged binder from RAP mixed with GTR-modified binder showed good workability during the mixing process (Xiao, Amirkhanian, & Juang, 2007). Vahidi et al. (2014) reported similar results for mixtures with 40% RAP, wherein addition of 10% GTR by weight of binder decreased the mixture rut depth from 6.3 mm to 0.74 mm, recorded at 20,000 wheel passes in an Hamburg wheel tracking device (Vahidi, Mogawer, & Booshehrian, 2014). Rath et al. (2019) evaluated the performance of mixtures containing GTR along with RAP and RAS, incorporated in SMA mixtures placed on I-88, Illinois (Rath, Love, Buttlar, & Reis, 2019). The findings suggested that incorporating GTR with RAP and RAS resulted in significantly higher rutting resistance of the mixture due to stiffness provided by the recycled content. In addition, the authors reported that higher recycled content (RAP/RAS/GTR) could be used if softer base binder is utilized in asphalt mixtures.

A number of other studies have shown the ability of rubber modification to significantly enhance permanent deformation resistance in asphalt pavements (Bahia & Davies, 1994; W. G. Buttlar et al., 2019; Harvey, Bejarano, & Popescu, 2001; Khalili, Amirkhanian, Karakouzian, Xiao, & Jadidi, 2016; S. Liu, Cao, Fang, & Shang, 2009; López-Moro, Moro, Hernández-Olivares, Witoszek-Schultz, & Alonso-Fernández, 2013; Lyacia, Ratiba, & Djaffar, 2019; Mohammad, Cooper, & Elseifi, 2011; Shafabakhsh, Sadeghnejad, & Sajed, 2014; Souliman et al., 2020; Haopeng Wang et al., 2018; He Wang & Buttlar, 2018; Zhang, Xing, Gao, Li, & Tan, 2016).

4.1.2. Fatigue Cracking

Fatigue cracking manifests itself as a series of interconnected surface cracks in the pavement wheel paths that resemble the skin of an alligator, and thus, is commonly referred to as alligator cracking. Fatigue cracking can develop as a result of repeated traffic load cycling, especially for thin pavements, pavements with debonding between layers, or wherever high pavement deflections or strains occur (Das, Jelagin, Birgisson, & Kringos, 2012; Mbarki, Kutay, Gibson, & Abbas, 2012). Rubber modification has been shown to increase the fatigue life of asphalt pavement irrespective of the method of addition (Schnormeier, 1986; Takallou & Sainton, 1992). The swelling of rubber particles as part of their interaction with asphalt binder increases the viscosity of the binder and results in thicker asphalt films surrounding aggregates leading to enhanced fatigue resistance and extended pavement structural integrity (Oliver, 2011; D. Wang, Yi, & Feng, 2014).

Full scale testing of terminal blend asphalt rubber sections in California and Arizona showed better fatigue results in terms of number of cycles to failure as compared to unmodified and traditional wet process mixtures (R. G. Hicks, Cheng, & Duffy, 2010; Qi et al., 2006). Kaloush (2014) showed through mixture testing that rubber modified mixtures accumulate lesser damage in the four-point bending beam test as compared to unmodified and polymer-modified mixtures, indicating high potential to withstand the onset of fatigue cracking (Kaloush, 2014).

> "The authors investigated various dosage rates ranging from 15% to 25% and found 20% dosage rate to have the best fatigue cracking resistance."

Raad et al. (2001) conducted bending beam fatigue tests on two mixtures, including a dense-graded conventional asphalt mixture and a gap-graded asphalt-rubber mixture. Both the sections were examined after 10 years of service life in southern California (Raad et al., 2001). Results showed lower fatigue damage on the rubber mixture as compared to the unmodified mixture. In addition, fatigue life predictions for new pavement sections constructed using the same mixture were predicted to have better fatigue life in the case of the rubber mixtures, based on test results obtained for both aged and unaged specimens.

Chekunaev and Kaplan (2014) showed that using ultra-fine rubber particles could slow down the rate of coalescence of microcracks to form macro-cracks (Chekunaev & Kaplan, 2014). The authors noted that rubber-modified mixtures are characterized by slower damage accumulation by external road traffic cycles and requirement of high energy for new surface generation. Similar work was done by Rath et al. (2021) wherein the authors conducted fracture tests on rubber-modified mastics tested in compact-tension at a low loading rate (0.2 mm/min) at a very cold temperature (-22C). A dramatic increase in fracture energy with an increase in rubber content was observed, and further analysis under a scanning electron microscope (SEM) showed densely populated micro-cracks in the vicinity of embedded rubber particles on the fractured face. Conversely, conventional and SBS-modified mixture specimens both showed very low fracture energy and glassy fracture surfaces when tested under identical conditions. This demonstrated the physical nature of crack pinning imparted by the meso-sized, swollen rubber particles in the mastic.

Mello et al. (2010) suggested that the extended fatigue life typically associated with asphalt-rubber mixtures was due to a combination of positive effects resulting from the presence of rubber inclusions and higher binder content, despite the higher volume of air voids exhibited by gap- and open-graded mixtures(Mello, Kaloush, & Farias, 2010). Losa et al. (2012) examined gap-graded wet and dry process rubber modified mixtures (Losa, Leandri, & Cerchiai, 2012). The authors showed that dry process mixtures had marginally higher fatigue life for the mixtures tested in this study. Wang et al. (2013) conducted notched semicircular bend (SCB) test at 5, 15, and 25C on rubber modified stone mastic asphalt (SMA-R) and dense-graded unmodified asphalt mixtures (Hainian Wang, Dang, Li, & You, 2013). The authors investigated various dosage rates ranging from 15% to 25% and found 20% dosage rate to have the best fatigue cracking resistance. Other studies have also shown similar results, i.e., an increase of fatigue life with the addition of rubber (Alfayez, Suleiman, & Nehdi, 2020; Mashaan et al., 2014; Saha & Biligiri, 2015; Souliman et al., 2016; Subhy et al., 2017; Xie & Shen, 2016; Zeiada, Underwood, Pourshams, Stempihar, & Kaloush, 2014).

4.1.3. Low Temperature Cracking

Thermal cracking, or low temperature cracking, occurs when the thermally induced stresses in a pavement section exceed the tensile strength of the asphalt mixture (William G. Buttlar, Rath, Majidifard, Dave, & Wang, 2019; Marasteanu, Buttlar, Bahia, Williams, & et al., 2012). It manifests itself as intermittent, transversely-oriented cracks across the pavement. Thermal cracking is one of the main forms of cracking in cold climates or wherever aging and rapid temperature changes occur, such as desert regions. Modification of asphalt with rubber is reported to improve the fracture toughness, increase tensile strength, and decrease the creep stiffness of the asphalt pavement, thereby increasing its resistance to thermal cracking (N. Lee & Hesp, 1994; Sebaaly, Gopal, & Epps, 2003).

> “Modification of asphalt with rubber is reported to improve the fracture toughness, increase tensile strength, and decrease the creep stiffness of the asphalt pavement, thereby increasing its resistance to thermal cracking...”

Wang et al. (2017) compiled bending beam rheometer data for rubber-modified binder from many researchers, showing that rubber modification decreased the creep stiffness while marginally diminishing the m-value (Tao Wang et al., 2017). Rath et al. (2021) presented results from Disk-shaped Compact Tension (DC(T)) test of rubber versus non-rubber mixtures, which showed that the addition of rubber increased the fracture energy of dense-grade mixtures in comparison to unmodified mixtures indicating higher thermal cracking resistance with rubber modification (Rath, Majidifard, Jahangiri, Chen, & Buttlar, 2021). Zeinali et al. (2014) also showed similar results with RMA showing higher DC(T) fracture energy in comparison to polymer-modified mixtures (Zeinali, Blankenship, & Mahboub, 2014). It is noteworthy to mention that the DC(T) test is the only low-temperature cracking test that has been shown to correlate well with field transverse (thermal) cracking on a national-level (William G. Buttlar et al., 2019). Wang et al. (2016) computed the fracture tensile strength and energy density for dense graded rubberized and non-rubberized mixtures by testing them in Semi-Circular Bend (SCB) test at 0, -10, and -20C (H. Wang, Zhang, Li, You, & Diab, 2016). The authors looked at five dosage rates (15, 18, 20, 22, 25% by weight of binder) and found that the tensile strength and energy density were the maximum for 20% dosage rate. Sybilski et al. (2011) conducted the thermal stress restrained specimen test (TSRST) to evaluate the low temperature cracking resistance of dense- and gap-graded rubber-modified mixtures in comparison with a conventional mixture (Sybilski, Bankowski, Mirski, Horodecka, & Andrzej Wrobel, 2011). The authors observed colder fracture temperatures with rubber modification for both gradations, indicating enhancement in thermal cracking resistance.

To better understand the mechanisms behind increased thermal cracking resistance of rubber-modified mixtures, **it is important to understand that in most cases**, **rubber particles retain their particulate nature rather than completely dissolve into the asphalt binder as was previously believed** (Bradley J Putman & Amirkhanian, 2006). The rubber particles are embedded on the interface of binder and aggregate. Due to their low stiffness at cold temperatures, the resultant mixture is more resistant to propagation of cracks. Additionally, the glass transition temperature of asphalt binder is reached at a much warmer temperature than rubber, which allows rubber to retain its toughness as colder temperatures are reached. Studies on rubber modified binder and mastics have shown the presence of cracking pinning and cracking bridging mechanisms (Ding et al., 2021; Hakimzadeh, Behnia, Buttlar, & Reis, 2017; Hoare & Hesp, 2000, 2007; Morrison, Van Der Stel, & Hesp, 1995; Rath, Gettu, et al., 2021; Segre et al., 2006; Smith & Hesp, 2007).

The performance of RMA in cold climates is well-supported by field performance data in the Midwest. The Illinois Tollway placed three test sections on I-88 that had rubber modifiers (terminal blend and dry process) in 2016 (William G. Buttlar & Rath, 2017). Field surveys conducted in the summer of 2019 revealed excellent performance in all of the 2016 sections. It should be noted that these sections went through a 50-year cooling event due to the polar vortex experienced in late January, 2019, where air temperatures in the vicinity of Chicago dropped below -32F (-34C) (Rath, Majidifard, et al., 2021). Buttlar et al. (2021) published information about other GTR sections placed on the Illinois Tollway that incorporated both wet- and dry-process GTR, dating back to 2009. All mixtures were shown to perform well under the heavy traffic and cold weather of northern Illinois (W. Buttlar et al., 2021).

> "The authors cited previous projects by Washington state in the 1990s wherein the rubber modified mixtures performed exceptionally well, with most of the sections lasting more than 10 years in service."

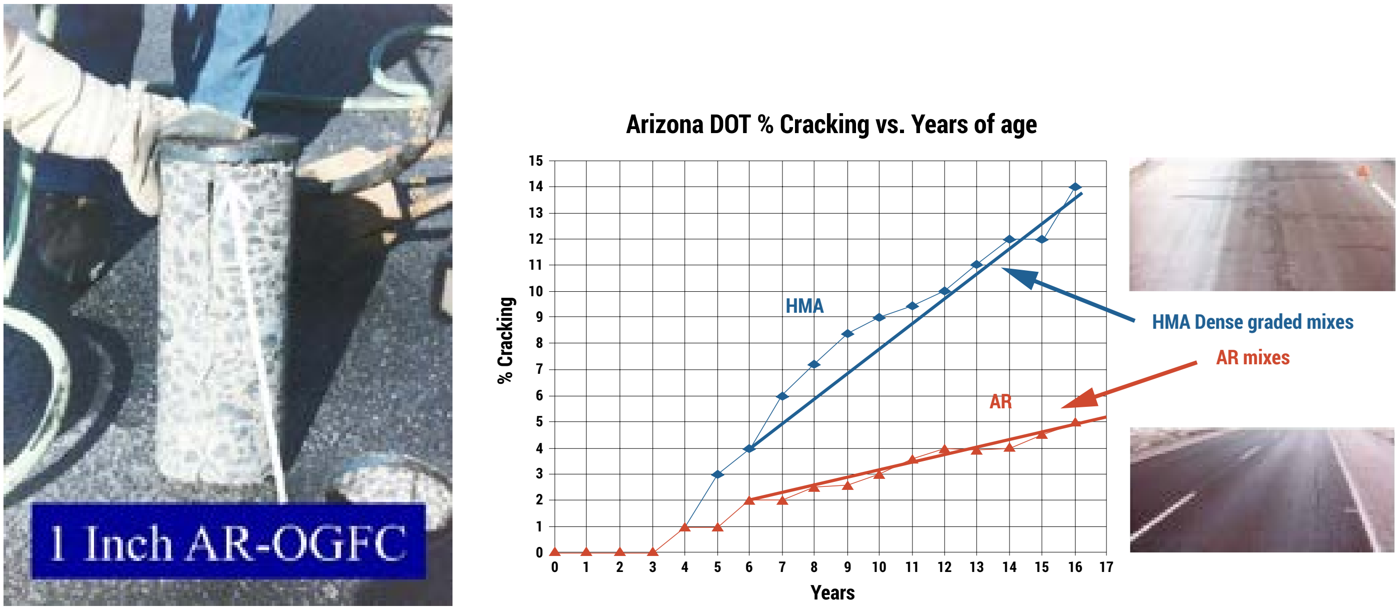
Hegazi (2014) evaluated eight field sections in Ontario, Canada, which used rubberized asphalt and were placed in 2011. Laboratory evaluation of the placed mixtures showed that RMA was able to withstand much colder temperatures (10C colder than conventional mixture) before the onset of cracking (Hegazi, 2014). Similar results were shown by Nordgren et al. (2012) for pavement sections in northern Sweden (Nordgren & Tykesson, 2012). A report by Wen et al. (2015) evaluated prevalent mixture types used in the harsh climates of Eastern Washington and recommended use of rubberized mixtures for better cracking and rutting resistance. The authors cited previous projects by Washington state in the 1990s wherein the rubber modified mixtures performed exceptionally well, with most of the sections lasting more than 10 years in service (Wen, Muench, & Littleton, 2015). In addition, RMA is routinely used in wet-freeze climates in other states such as New Jersey, Maine, Massachusetts, Pennsylvania, Michigan, etc. (Chen, You, Sharifi, Yao, & Gong, 2019; Hansen & Copeland, 2015).

4.1.4. Field Performance Data

In terms of the field performance track record for RMA mixtures, several decades of field experience and subsequently obtained data is available. As discussed in prior sections, Charles McDonald first popularized the use of rubber modification in asphalt binder in the 1960s. The first wave of reports and papers from that time period were concerned mainly with use of rubber modified asphalt as chip seals, seal coats, or stress absorbing membranes. Reports from that time period were quite positive regarding the field performance of rubber modification, especially in terms of alleviation of fatigue cracking (Esser, 1964; Huff & Vallerga, 1979; Huffman, 1980; Olsen, 1973).

A detailed evaluation of pavement seal coats made with rubber modified asphalt on three naval air stations was presented by Brownie in 1976 (Brownie, 1976). After detailed investigation of field cracking, the author reported that rubber-asphalt seal was at least as effective as 2-inch-thick overlay of conventional asphalt mixture with regards to prevention of reflective and fatigue-type cracking. In addition, the rubber modified seal coats provided excellent skid resistance, and cost approximately 20% less as compared to a 2-inch-thick asphalt mixture overlay.

Schnormeier (1975, 1983, 1986) published multiple detailed papers on the evaluation of asphalt-rubber in Arizona from projects with up to 15 years of service life and performance data (Schnormeier, 1975, 1983, 1986). Upon evaluation, the authors reported that RMA was able to significantly delay reflective and fatigue cracking, spalling, and raveling, as shown in Figure 13. In addition, the author noted that the popular method of application during that time period was seal coats, which waterproofed the pavement structure and improved pavement performance. This increase of pavement service life allowed RMA to be an economically viable option.



(a) (b)

Figure 13. (a) Showing arrest of reflective cracking due to asphalt-rubber overlay, b) Performance of asphalt-rubber mixtures in terms of cracking in Arizona (after (G. Way, 2012))

The second wave of field data were from early trials of, at the time, the new imported PlusRide™ technology, which represented an early dry process attempt involving GTR. The Alaska DOT was among the first DOTs to put down a trial section with PlusRide™ technology. To briefly recap, PlusRide™ technology used 2.0-4.2 mm size rubber particles to replace 1-3% of the fine aggregates in gap-graded mixtures. As a result of the large crumb rubber particles, shorter interaction time (and depth of penetration) with asphalt binder, and the use of an unusual aggregate gradation, the PlusRide™ technology resulted in a number of poor performing field sections. Takallou and co-workers published two papers regarding laboratory and field evaluation of the PlusRide™ technology (Takallou & Hicks, 1988; Takallou, Hicks, & Esch, 1986). The authors reported an increase in fatigue life of rubber modified mixtures and showed the need to establish protocols for manufacturing dry process rubber modified mixtures, especially in terms of achieving proper air voids. Field evaluations revealed that the rubber-modified mixtures did not fail in fatigue but rather in raveling or bleeding. Both issues were attributed to excessive voids or poor density achieved during compaction, most likely driven by the difficulty in compacting and retaining compaction in paving lifts when large rubber particles were used. Time-delayed absorption of light ends from the binder could have also led to poor mixture cohesion and durability.

The Alaska DOT conducted extensive tests on the wintertime ice control properties of the PlusRide™ technology. Esch (1980, 1984) tracked the skid resistance of field sections over three winters in Alaska, and reported higher skid resistance in RMA pavements (D. Esch, 1982; D. C. Esch, 1984). In addition, the stopping distances of vehicles in winter on rubber modified pavements improved by 25%.

Washington DOT (WSDOT) built two stress absorbing membrane sections in 1978, which immediately showed problems as a result of the aggregate chips becoming completely embedded in the asphalt-rubber matrix (Anderson & Jackson, 1992). The state laid two more sections in 1980 which performed satisfactorily but were reported to be expensive for the given field performance observed. WSDOT constructed six stress absorbing membrane interlayer projects between 1977-78 and reported mixed performance of the sections. WSDOT also placed dry process RMA (PlusRide™) in 1982-84 with mixed results and reported issues with construction.

In the lead up to 1990s, the forthcoming ISTEA mandate led many states to invest capital in building trial sections with rubber modification (Hughes, 1985; Khosla & Trogdon III, 1990). For instance, the state of Pennsylvania documented a trial RMA section with the traditional wet process in 1991 and reported significant cracking and raveling after three years of placement (Pennsylvania Joint State Government Commission, 2007). The cost of the RMA mixture was reported to be 60% higher than the standard mixture. The state also placed more rubber modified sections and reported production problems such as storage stability issues with wet process rubber modification, issues with determination of actual percentage of rubber in binder, clogging of asphalt pumps, poor compaction in dry process mixtures, and so on (Pennsylvania DOT, 2005; Pennsylvania Joint State Government Commission, 2007).

> **"By 2010, 31% of all hot mix asphalt placed by Caltrans was rubberized HMA..."**

Florida constructed three demonstration projects with different rubber percentages by the traditional wet process and one dry process test strip between 1989-1990 (Page, Ruth, & West, 1992). Evaluation after 10 years showed that addition of rubber improved rutting resistance of asphalt pavement. In terms of cracking, the wet process sections showed 1-6% cracked areas while virgin and dry process sections showed about 30% cracked areas (Choubane et al., 1999).

Colorado initiated a rubberized test section project in 1994 that included one conventional and three dry process rubber modified sections with varying dosage rates (Harmelink, 1999; S. Shuler, 2014). Evaluation after five years in service indicated good performance of rubber sections in comparison to standard asphalt mixture. However, the initial cost the rubberized mixture was 21% higher and the final recommendation was against using rubber in future projects until better LCCA outcomes could be achieved with RMA.

Kansas initiated thirteen projects from 1990 to 1995 that used crumb rubber modification. Laboratory tests and field surveys showed mixed performance, as the authors noted "For every successful attempt, there was an unsuccessful disaster." In addition, high initial cost of rubber mixtures led to the recommendation that use of rubber modification was not economically feasible for the state at that time (Fager, 2001). While other states have recorded similar field performance (Hunt & Peters, 1995; R. W. Beck, 2005; Sebaaly, Bazi, & Vivekanathan, 2003; Volle, 2000), states like California, Arizona, Florida, and Texas had fewer issues during construction and more successful projects due to their significant previous experiences (Caltrans, 2005b; R. G. Hicks et al., 1995; G. B. Way et al., 2011).

Two common themes emerge from the reports about field performance of rubberized asphalt during this time period (1960-early 2000s), a) lack of proper construction procedures for rubber modified asphalt mixtures; for instance, early on, wet process technology that was largely used as seal coats or chip seals, suffered from issues with aggregate adhesion (T. S. Shuler, Pavlovich, & Epps, 1985), while the dry process technologies suffered from compaction issues (Hughes, 1985; Takallou & Sainton, 1992), and b) high initial costs not being offset by exhibition of longer life (Estakhri et al., 1992; Fager, 2001; Harmelink, 1999).

Through the turn of the 21st century, there was an extensive growth in the use of wet process technologies in states like California, Arizona, Texas, and Florida, due to positive field results (DingXin Cheng, Hicks, Fraser, & Garcia, 2014; Venudharan, Biligiri, Sousa, & Way, 2017; G. B. Way, 2012; H. Zhou et al., 2014). For instance, by 2010, 31% of all hot mix asphalt placed by

Caltrans was rubberized HMA and most of it was wet process rubber modification (H. Zhou et al., 2014). This led to development of terminal blend technology which performed well and exhibited better storage stability by addition of proprietary polymer or by promoting rubber-binder interaction at elevated temperatures (> 200C) than the field blends or the traditional wet process (McDonald process) (Han et al., 2016; D. Lo Presti, Airey, & Partal, 2012).

Similarly, dry process technologies made large strides in terms of development in the past 20 years and the use of chemically enhanced or engineered crumb rubber products became mainstream. The modern dry process technologies use fine GTR particles in the size range of 600 to 40 microns (30 – 40 mesh size) and are added directly to the mixtures without any change in aggregate gradation. The logistical ease of mixture manufacturing along with attractive economics makes the modern dry process an attractive option. According to a recent report by FHWA (G. Baumgardner et al., 2020), more than five million tons of chemically engineered dry process asphalt has been placed in Georgia (J. Shen, Xie, & Li, 2014; Junan Shen & Xie, 2012), Illinois (W. Buttlar et al., 2021; William G. Buttlar & Rath, 2017; Rath, Love, et al., 2019), Missouri (W. G. Buttlar et al., 2019; Rath, Majidifard, Jahangiri, & Buttlar, 2019), Michigan (Chen, Gong, et al., 2019), Oklahoma, Texas (Scullion et al., 2009; F. Zhou & Scullion, 2008), Virginia, Indiana, Wisconsin (EnviroTx, n.d.) and other states.

"It is less expensive to an agency to build a quiet rubber-modified asphalt pavement with no sound barriers as compared to a Portland Cement Concrete (PCC) pavement with a noise barrier."

The results presented in this section appear to be consistent with the results of the agency survey provided in the appendix. **The states that experimented with RMA in the early years**, **but not subsequently**, **generally have a poorer opinion of the durability and economics of RMA**, **while states with experience with more modern wet**- *and dry-process RMA systems* (**past 20 years**), **generally have a positive viewpoint of RMA durability and cost vs. benefit**. This highlights the importance of sharing new data on RMA durability, economics, and sustainability, as summarized in this SOK.

4.2. FUNCTIONAL BENEFITS

The functional characteristics of a road refer to properties that affect the serviceability of the road but are not related to the pavement's structural performance, such as pavement smoothness (ride quality), pavement noise, skid resistance, etc. Traditionally, pavement evaluation has focused on structural performance, but the value of constructing roads with better functional characteristics is receiving greater attention in recent years (FHWA, 2017).

4.2.1. Noise Reduction

With increased urbanization worldwide, the harmful effects of unmitigated traffic noise on long-term human health has elevated noise pollution to a major public health issue (European Environment Agency, 2014). While various noise mitigation techniques are used worldwide, such as employing noise reducing sound barriers, the idea of reducing the noise at the point of acoustic generation, i.e., where rubber hits the road, represents an elegant and efficient engineering solution. Donavan et al. (2000) reported in NCHRP 10-76 that it is less expensive to an agency to build a quiet rubber-modified asphalt pavement with no sound barriers as compared to a Portland Cement Concrete (PCC) pavement with a noise barrier (P. R. Donavan, Pierce, Lodico, Rochat, & Knauer, 2013). Carlson et al. (2003) noted that every two feet of noise barrier/wall was expected to reduce noise by 1 dB, and thus argued that for an acoustically improved pavement surface, for every 1 dB reduction in noise, a 2-ft reduction in sound barrier height could be realized, thereby significantly reducing agency costs (Carlson et al., 2003). One of the first notable studies to investigate the noise reduction properties of RMA pavements was conducted in Brussels, Belgium, in 1981. The study showed a sizeable reduction in sound intensity of about 8-10 decibels (dB) (Sacramento County Public Works Agency, 1999). Following this, a series of projects at different locations all over the world corroborated the findings albeit reporting various ranges of noise reduction depending on the mixture type, vehicle speeds, and other variables.

Carlson et al. (2003) investigated three sites in Arizona before and after surfacing them with RMA (Carlson et al., 2003). The existing sites had aged Portland cement concrete pavements and were overlaid with a thin (2.5 cm or less) AR-OGFC (Asphalt-Rubber Open Graded Friction Course) with 20% rubber incorporated by the wet process. The authors measured the noise reduction at a distance of 50-400 feet from the highway and noted a decrease of 6 to 9 dB (A) after paving.

A very comprehensive study was conducted in Arizona as a part of its 'Quiet Pavement Pilot Program', or QPPP with an intention to evaluate the noise reduction that could be achieved by overlaying existing PCC pavements with ARFC (Asphalt Rubber Friction Course) (P. Donavan & Janello, 2018). The ARFC overlays resulted in a noise reduction of 9.6 dB on an average initially and 5.1 dB on an average at the end of about 10 years of service life, showing a reduction of 0.40 dB/year on average. The project also compared 27 sections built with different mixture types: ARFC, non-rubber asphalt concrete friction course (ACFC), stone mastic asphalt (SMA), porous ACFC, and porous European mix (PEM). Figure 15Figure 14 shows results from the report, showing that ARFC showed the least measured sound intensity. Notably, all the measurements were taken after two years of construction, which means that all the pavements had some traffic wear when the sound intensity data was measured.

Table 2. Results from Arizona's 'Quiet Pavement Pilot Program' (P. Donavan & Janello, 2018) showing that paving with rubber-modified asphalt reduces noise generation as compared to other mixtures.

Mixture Type	On-Board Sound Intensity Level, dBA
Asphalt Rubber Friction Course (ARFC)	97.6
Asphalt Concrete Friction Course (ACFC)	100.2
Stone Mastic Asphalt (SMA)	100.6
Porous Asphalt Concrete Friction Course (P-ACFC)	100.9
Porous Eurpean Mixture (PEM)	101.7

Way (2012) presented combined data of Arizona and California pavements to show the efficiency of asphalt-rubber in reducing noise levels (G. Way, 2012). Figure 14 shows data from a wide variety of pavements with varied ages and current conditions. As clearly highlighted on the figure, the asphalt-rubber friction course produced the lowest noise level, while one of the concrete pavements investigated produced the highest noise level in the data set.

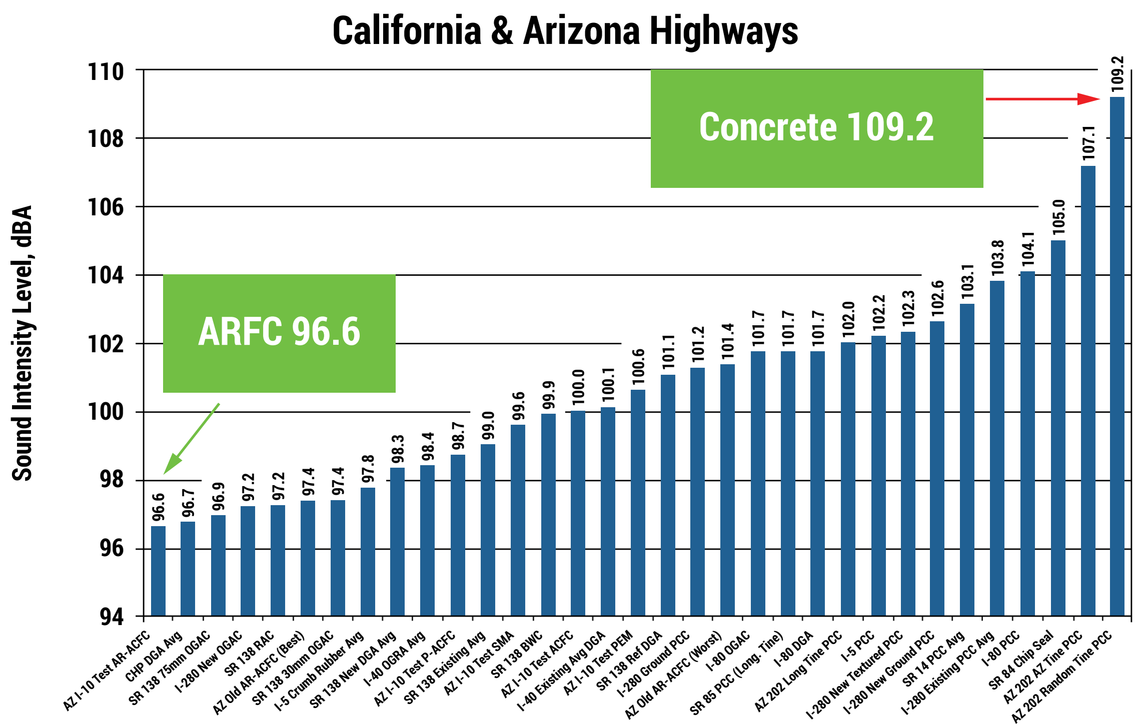


Figure 14. Noise data from highways in Arizona and California (from (G. Way, 2012))

In San Antonio, Texas, an existing CRCP (continuous reinforced concrete pavement) on IH35 was overlaid with rubber modified Porous Friction Course (AR-PFC)) (B. J. Putman & Amirkhanian, 2005; Texas Department of Transportation, 2003b). The Area Engineer of this project had noted that the CRCP, constructed in early 1980s, had low skid resistance and consequently a history of roadway accidents in wet weather. In addition, it was loud, rough, and considered a "worst-case-scenario" in term of functional performance of a pavement. The pavement was overlaid with a mixture that had 18% rubber incorporated by wet process in 8.3% binder and compacted to 18% air voids. The study reported an average decrease of international roughness index from 209 inches/mile to 81 inches/mile. The sound intensity decreased from 85 to 71 dB on average (average of north- and south- bound lane) after paving.

Lu et al. (2010) conducted an extensive field study in California in two phases (Lu, Harvey, Kohler, Rymer, & Motumah, 2010). The first phase compared a group of 72 field sections with standard and rubber-modified open graded mixture (OGAC, and RAC-O), rubber modified gap-graded mixture (RAC-G), and finally the standard DGAC. The initial noise measurements taken a year after construction showed that the RAC-G noise levels were lower than the DGAC and the RAC-O noise levels were lower than DGAC, highlighting the efficiency of rubber modification. The subsequent measurements after four years in service life, however, showed that all the mixtures approached the noise levels of the standard DGAC conventional mixture. This was attributed to lower levels of distresses observed in the DGAC mixtures. The second phase included investigation of nine trial sections with five different mixtures: wet process RAC-G, terminal blend dense-graded and gap-graded mixture (Type-D MB, and Type-G MB), dry process gap-graded mixture (RUMAC-GG) and standard dense graded asphalt mixture (DGAC). The results showed, once again, that the rubberized mixtures showed initial noise reduction benefits but the effects waned over the pavement service life. Notably, in comparing the open graded mixtures, the rubberized option provided noise reduction benefits for two additional years as compared to the non-rubberized option.

On the other hand, a report from Sacramento County on noise reduction values measured for over six years from three field sections, two built with rubberized asphalt and one with conventional asphalt mixture found that, a) rubberized pavements reduced noise by 4-6 dB, while conventional DGAC reduced noise by 2 dB when used as a rehabilitative surface over an existing PCC pavement, and b) conventional pavement had lost its noise reduction capability when values were measured after 4 years, but rubberized mixtures had only dropped 1 dB over a course of 5-6 years, as shown in Figure 16 (Sacramento County Public Works Agency, 1999).

Table 3. Study from Sacramento County, California, showing the effect of asphalt-rubber on noise reduction (from (Sacramento County Public Works Agency, 1999))

Route	Mixture Type	Time of measurement (post-construction)	Change in noise (dB Leq)
Alta Arden Expressway	Rubberized	1 month	-6 dB
		16 months (1 year, 4 months)	-5 dB
		72 months (6 years)	-5 dB
Antelope Road	Rubberized	6 months	-4 dB
		60 months (5 years)	-3 dB
Bond Road	Conventional	1 month	-2 dB
		48 months (4 years)	0 dB

*Leq is the preferred method to describe sound levels that vary over time, resulting in a single decibel value which takes into account the total sound energy over the period of time of interest

Losa et al. (2012) compared wet and dry process gap graded rubber modified mixtures with standard dense graded sections in Italy with regards to acoustic performance of the pavements. Findings indicated that the wet process reduced noise by 5.5 dB and the dry process reduced noise by 6.5 dB (Losa et al., 2012). Kehagaia et al. (2014) compared field sections in Greece with a wet process rubber modified dense graded mixture side-by-side with a conventional DGAC surface. Measurements taken immediately after construction and after 8 months revealed that the rubberized road showed 1-3dB noise reduction as compared to the DGAC surface. Frolova et al. (2017) studied field sections in Slovakia and showed that a dense graded mixture with crumb rubber (1.2% aggregate weight, dry process) exhibited 2.3 dB less noise levels as compared to an SMA, both made with the same maximum aggregate size of 11 mm (Frolova & Salaiová, 2017).

Paje et al. (2013) and Vazquez et al. (2016) reported sound intensity (noise) results from a conventional and a rubber-modified gap graded asphalt section located in Spain over a period of 3 years. The authors reported an initial reduction (values measured after construction) of 1.8 dB at 50 kph and 2.5 dB at 80 kph. For the RMA section, after three years of service life the values decreased down to 1.3 dB at 50 kph and 2.0 dB at 80 kph (Paje, Luong, Vázquez, Bueno, & Miró, 2013; Vázquez et al., 2016). Many other studies looking at traffic-related noise reduction in RMA mixtures have been reported in the literature (Ballie & Gal, 2000; Moisés Bueno et al., 2014; Gardziejczyk, Plewa, & Pakholak, 2020; Guo, Yi, Xie, Chu, & Feng, 2018; Jiang, Easa, Hu, & Zheng, 2019; Lan, Yongming, & Chunqing, 2009; W. Li, Han, & Huang, 2020; M. Liu, Huang, & Xue, 2016; Luong, Bueno, Vázquez, & Paje, 2014; Han Zhu & Carlson, 1999)

Studies have attempted to tie noise abatement in RMA mixture to characteristics such as macrotexture, roughness, dynamic stiffness and other important variables such as quality of road installation, presence of distresses, noise level measurement techniques, etc. For instance, a recent study by Vasquez et al. (2020) attempted to correlate the acoustic performance of the pavement with surface characteristics such as roughness (IRI) and macrotexture of the pavement. The authors considered an SMA section with 8 mm maximum aggregate size with crumb rubber modification (dry process, 0.5% by weight of mixture). The study found that there was no universal relationship between the sound intensity measurements of pavement-tire interaction and the pavement's surface characteristics. The surface texture only affected the sound intensity at low (500-600 Hz) or high (above 1.6 kHz) frequencies.

> "The rubber content, gradation, macrotexture, and other factors also play an important role in noise reduction..."

However, in another study by Vasquez et al. (2016) which looked at gap graded mixture with crumb rubber, the findings suggested that medium frequencies (around 800 Hz) were strongly correlated to surface texture and roughness. Bueno et al. (2014) and Shatanawi (2008) further reported that addition of crumb rubber alone is not enough to reduce the noise levels, but the rubber content, gradation, macrotexture, and other factors also play an important role in noise reduction (M. Bueno, Luong, Terán, Viñuela, & Paje, 2014; Shatanawi, 2008). Licitra et al. (2017) reported noise reduction measurements varying between 1-6 dB for four different rubberized sections in Italy and attributed the variability to the quality of pavement installation (Licitra, Cerchiai, Teti, Ascari, & Fredianelli, 2015).

In summary, **while most field results suggest that there is a noise reduction benefit of RMA**, **there is a definite need or research gap to acquire a deeper understanding of the mechanisms behind noise levels and how rubber modification alters those in comparison to non-rubberized mixtures**. Currently, efforts are underway to understand the exact mechanics of pavement-tire interaction that produces noise and how rubber modification alters those properties in comparison to a non-rubberized asphalt mixture. Research is also being performed on assigning an economic and social value to the negative impact of higher pavement noise levels in urban areas. This would allow agencies to better capture the benefits of RMA in designs involving LCCA and/or LCA considerations.

4.2.2. Skid Resistance

Skid resistance of a pavement surface can be defined as its ability to prevent any loss of traction between vehicle tire and the surface (Asi, 2007). Skid resistance is a critical user safety factor, especially in wet conditions on the road. Among other factors that affect skid resistance of the pavement, surface texture is the predominant factor. Surface texture is defined in terms of megatexture, macrotexture, and microtexture, depending on the scale of observation (Fontes, Pereira, Pais, & Trichês, 2006). As seen in Figure 15, pavement megatexture is in the range of 50 mm-500 mm, macrotexture is in the range of 0.5-50 mm, and microtexture is in range of less than 0.5 mm (Ting Wang et al., 2012). In general the surface texture is evaluated by measuring the friction offered to a standard tire or a standard object, such as a pendulum (Kogbara, Masad, Kassem, Scarpas, & Anupam, 2016).

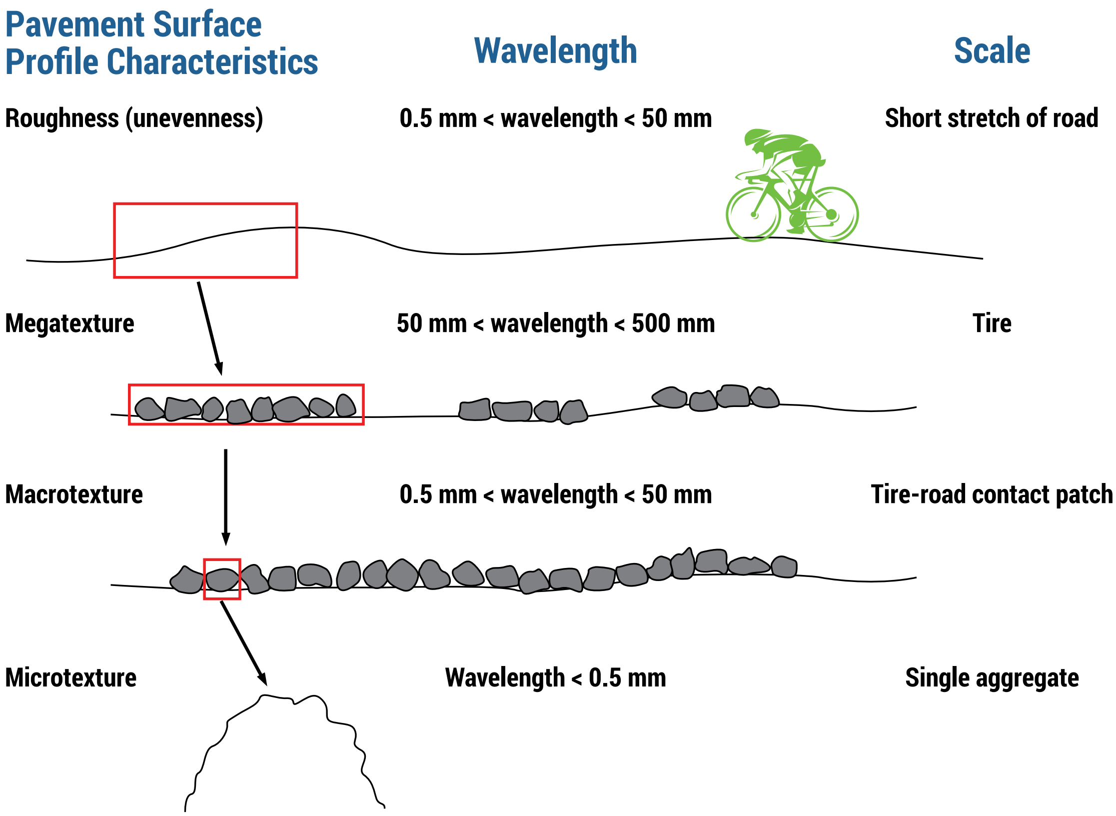


Figure 15. Pavement texture at different scales: megatexture, macrotexture, and microtexture (from (Thigpen, Li, Handy, & Harvey, 2015))

Fontes et al. (2006) compared the skid resistance for RMA prepared with terminal and continuous blends (wet process), to a conventional asphalt mixture (Fontes et al., 2006). The authors tested various gradations (dense and gap) and binder contents. Study findings indicated that with the addition of rubber, irrespective of the measurement method used, microtexture and macrotexture for mixtures increased (and thus, skid resistance increased). Gonzales et al. (2017) compared four modified mixtures, with polyethylene, polystyrene, polypropylene, and crumb rubber from scrap tires, added at 1% of the mixture weight (Lastra-González, Indacoechea-Pega, Calzada-pérez, Castro-Fresno, & Carpio-García, 2017). The authors found that except rubber, all other polymers decreased the skid resistance of the dense-graded mixture. The authors noted that in their study, rubber was the only polymer which maintained its particulate nature and had a melting point above the mixing temperature, while all other polymers had lower melting points and formed a polished surface.

Shirini et al. (2016) compared the skid resistance of RMA, SBS-modified, and conventional asphalt mixtures. The RMA mixtures were modified via wet process with 10, 15, and 20% by weight of binder and the SBS mixture included 5% SBS by weight of binder. All the mixtures investigated were gap graded. The authors found that RMA had the highest skid resistance followed by conventional and then the SBS-modified mixture, as shown in Table 4. An increase of crumb rubber percentage from 10 to 20 decreased the skid resistance. Bueno et al. (2014) also compared macrotexture of RMA and SBS sections to find higher values obtained from the RMA section, indicating better skid resistance (M. Bueno et al., 2014).

Table 4. Skid resistance results from Shirini et al. (2016)

Mixture Type	Skid Resistance (British Pendulum Number)
Control	65.6
SBS	62.8
Crumb Ruber (10%)	82.0
Crumb Rubber (15%)	76.4
Crumb Rubber (20%)	71.0

4.2.3. Roughness

Roughness is a term that quantifies the irregularities of a pavement surface (its deviation from the true planar surface) (FHWA, 2016). It is the most common measure of the riding comfort of a user. Used interchangeably with smoothness, it is measured through International Roughness Index (IRI) or by measuring the profile of the pavement. RMA pavements are known to provide smoother pavements. Irfan et al. (2017) measured IRI on field sections produced with and without rubber modification, which were placed as overlays on an existing asphalt pavement (Irfan, Ali, Ahmed, & Hafeez, 2018). The authors reported an improvement (drop) of 24% in the measured roughness in the case of the unmodified pavement sections and a 35% drop for the GTR overlay. Cooper et al. (2007) evaluated IRI for five field sections in Louisiana and reported that rubber modification with both dense and gap graded mixture produced equal or better smoothness level as compared to the conventional mixture sections (Cooper et al., 2007). Willis et al. (2014) also reported smoother pavements in Alabama resulting from rubberized mixtures, after being in service for five years (J.Richard Willis,Carolina Rodezno,Adam Taylor, 2014; NCAT, n.d.). Vazquez et al. (2016) compared two field sections with gap-graded asphalt mixtures (Vázquez et al., 2016). One of the sections was made with a 50/70 penetration grade binder, while the other had 8% crumb rubber modification via wet process. The authors measured the roughness in terms of mean profile depth (measurement of pavement texture) for both the sections, right after construction and after three years of construction. The findings, shown in Figure 16, suggested that rubber modification was able to produce much smoother pavement compared to the unmodified mixture.

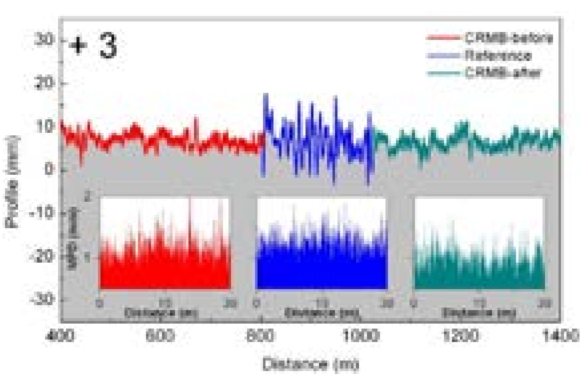


Figure 16. Showing the effect of rubber in producing smoother pavements (from (Vázquez et al., 2016))

A consequence of smoother pavements is lower production (emission) of tire wear particles, which could be beneficial to aquatic life and human health (Kreider, Doyle-Eisele, Russell, McDonald, & Panko, 2012; Simons, 2016; Wagner et al., 2018). A detailed study from Arizona compared the tire wear particle generation from surfaces of two types of pavements- asphalt-rubber friction course and PCC (Allen et al., 2006). The study also reported the roughness and friction characteristics of the pavements. **The findings suggested that PCC surfaces generate 1.4-2 times more tire wear particles per km as compared to RMA**. This finding was directly related to the lower roughness measured on the rubberized pavement as compared to the PCC pavement. **However**, **the lack of data regarding pavement roughness reduction with RMA**, **and subsequent effects on fuel savings and LCA benefits represent another important research gap**.

"A consequence of smoother pavements is lower production (emission) of tire wear particles, which could be beneficial to aquatic life and human health…"

U.S. TIRE MANUFACTURERS ASSOCIATION

THE RAY

5

ENVIRONMENTAL ASPECTS

STATE OF KNOWLEDGE REPORT
ON RUBBER MODIFIED ASPHALT

5. ENVIRONMENTAL ASPECTS

In the past few decades, there have been increased calls for the usage of sustainable technologies in infrastructure for increased environmental protection. Use of GTR sourced from scrap tires is environmentally friendly as it diverts ELTs from landfills towards beneficial use. However, it is important to have holistic, quantitative environmental assessments of recycled material systems such as RMA to assist decision makers in prioritizing their adoption and investing in the promotion of their widespread use. The following sections review the published literature reporting on the environmental impacts of RMA.

> "Depending on the impact categories investigated, use of rubberized pavement could reduce the environmental impact by about 30% over its lifetime compared to conventional asphalt pavement."

5.1. ENVIRONMENTAL LIFE CYCLE ANALYSIS

The environmental impacts of a product can be effectively evaluated by Life Cycle Analysis, or LCA. An LCA is divided into five main stages of evaluations: raw material extraction, manufacturing, transportation, use, and end of life (Horvath, 2003; Hoxha et al., 2021; Stripple, 2001; Treloar, Love, & Crawford, 2004). Each of these stages is broken down into unit processes with various inputs and outputs to ascertain their environmental impacts. While material and process costs are easier to quantify and important factors to consider in the evaluation of a product, an increasing number of agencies that are keen to adopt sustainable technologies have turned to using Life Cycle Analysis (LCA) in their decision-making process to show the long-term environment benefits of a product. LCA is not a new concept, but its application to modern road paving projects is a recent phenomenon. Significant efforts were put into harmonization and standardization of the LCA method globally during the 1990s (Y. Huang, Bird, & Heidrich, 2009; Klöpffer, 1997; Vigon et al., 1993). With some degree of process and terminology standardization, several studies featuring LCA of roads appeared in the literature in the early 2000s (Horvath, 2003; Hoxha et al., 2021; Stripple, 2001; Treloar et al., 2004).

To date, only a handful of studies have conducted environmental LCA analysis on rubberized pavements. Expectedly, most of the studies referenced in this section reported on attributional LCA, as their intention was to compare different additives in a pavement, such as rubber to SBS, or RMA to unmodified asphalt. Bartolozzi et al. (2012) conducted LCA for a rubberized pavement prepared by the wet method near Florence (Italy) to determine its environmental impacts in comparison to conventional pavement (I. Bartolozzi, I. Antunes, & F. Rizzi, 2012). The study did a cradle to grave analysis with the assumption that the rubberized pavement would need maintenance work done every eight years while the conventional pavement would need it every five years. Notably, it is one of the few studies that use a lower thickness of rubberized pavement in comparison with conventional pavement, meaning that the performance benefits of rubber modification are accounted for by the paving agency. The rubberized pavement outperformed the conventional pavement over its lifetime in all the ten environmental impact categories investigated in the study. On breaking down environmental impacts according to phases, the material production phase was dominated by rubberized pavements, mostly due to the additional energy-intensive activity of production of CRM modified binder. In the use and maintenance phase, however, the rubberized pavement outperformed the conventional pavement due to its lower thickness and lower maintenance requirements. **The authors summarized that depending on the impact categories investigated**, **use of rubberized pavement could reduce the environmental impact by about 30% over its lifetime compared to conventional asphalt pavement**.

Bartolozzi et al. (2015) performed another environmental LCA study on rubberized pavement located in Lamia, Greece (Bartolozzi et al., 2015). In this study, the authors assumed the service life of a rubberized pavement to be 40 years with maintenance required every 15 years, and for the conventional pavement that was used as a comparison, the service life was assumed to be 30 years with requirement of maintenance every 8 years. Both the pavement systems were assumed to have similar thicknesses; the top bituminous layer was 20 cm thick and in the case of RMA, the top 5 cm was made of wet process rubber modified asphalt mixture (10% by weight of binder). **The authors reported a benefit of 30-40% in various environmental impact categories by use of RMA, as shown in Table 5**. The authors also reported the contribution of different stages on the environmental impacts. Interestingly, it was noted that the majority of negative environmental impacts of rubberized pavements can be attributed to production phase which includes the extra energy consumed in production of rubber-modified binder (wet process, 2 hours mixing at 185C).

Table 5. Impact of rubberized and conventional pavements in various impact categories (from (Bartolozzi et al., 2015))

Impact category	Impact of Rubberized road with respect to Conventional road
Climate change (kg CO_2 eq)	-34%
Ozone depletion (kg CFC-11 eq)	-38%
Human toxicity (kg 1,4-DB eq)	-27%
Photochemical oxidant form. (kg NMVOC eq)	-34%
Terrestrial acidification (kg SO_2 eq)	-35%
Freshwater eutrophication (kg P eq)	-20%
Terrestrial ecotoxicity (kg 1,4-DB eq)	-37%
Freshwater ecotoxicity (kg 1,4-DB eq)	-26%
Water depletion (m^3)	-30%
Fossil depletion (kg oil eq)	-37%

Chiu et al. (2008) reported similar findings by using an indicator that took into account human health, resource consumption, and ecological quality with weighting factors of 40%, 20%, and 40%, respectively (Chiu et al., 2008). The indicator, known as Eco-indicator 99, showed that although over a 40-year life cycle the use of rubber modification decreases the eco-burden by 23% as compared to the conventional mixtures due to higher life expectancy, the material (production) phase of rubberized mixture (wet process) is more energy-intensive. Separate from the study, if one considers an alternate case of using dry process modification wherein rubber particles are added directly to the mixture at 165-170C, the environmental impacts during material production phase would be much lower compared to the case presented in the referenced study.

Zhu et al. (2012) examined wet and dry process rubber modification in comparison to conventional and SBS (polymer) modified mixtures (Haoran Zhu, Cai, Yan, & Lu, 2014). The wet process rubber modification was sub-divided into traditional (rubber-modified asphalt binder manufactured in asphalt plants before mixture production) and terminal blends (rubberized asphalt binder manufactured at asphalt terminals and transported to plants for mixture production). The dry process included extender oil additive called trans-polyoctenamer, or TOR. During raw material production/procurement stage, the SBS modified mixture showed much higher energy consumption due to production of SBS pellets as compared to the use of recycled rubber. However, the greenhouse gas emissions were slightly higher for rubber modified mixtures due to higher production temperatures. Inclusion of construction phase in the analysis showed similar results wherein the rubberized mixtures had lower energy consumption but higher greenhouse gas emissions. In this study, notably, the dry process modification was assigned similar burdens as terminal or field blends (wet process) during raw material production phase, despite the prolonged blending time required to produce field or terminal blend asphalt rubber. This burden was mostly attributed to production of the extender oil (TOR), and not to production of rubber-modified asphalt binders like in the wet process. In the past decade, the dry process techniques have evolved to move away from use of the extender oils (Fornai, Sangiorgi, Mazzotta, Bermejo, & Saiz, 2016; Rath, Love, et al., 2019).

> "The newer, modern dry process technologies have shown field performance superior to the traditional and equivalent to wet process and polymer modified asphalt mixtures, as presented previously."

Farina et al. (2017) also investigated wet- and dry-process rubber modified mixtures that had recycled asphalt pavement (RAP) (Farina, Zanetti, Santagata, & Blengini, 2017b). The findings suggested that although wet process technology did give an environmental advantage over standard mixtures, dry process technology made no difference in terms of global warming potential and energy consumption. However, this study assumed similar performance of dry process rubber modified mixtures as compared to standard mixtures, while assuming enhanced performance by the wet process rubber modified mixtures, evident from lesser maintenance requirements and lower construction thickness (3 cm vs. 5 cm for wet and dry process mixtures). Given that the use phase was dominant in emission quantities measured, the assumption of not obtaining superior service life from dry process technology seem to have resulted in the reported inferior environmental performance of the dry process.

Bressi et al. (2019) also conducted an environmental LCA on dry process rubber modified mixture with two different rubber dosages using vulcanized and devulcanized rubber (Bressi, Santos, Marko, & Losa, 2019). The system boundaries of this study included processes from cradle to gate. The results showed that overall, rubber modification led to negative impacts over the twelve environmental categories investigated in this study. Use of devulcanized rubber led to significant increase in the negative impacts, as devulcanization of rubber is an energy-intensive process. The authors opined that to be environmentally beneficial, rubber modified mixtures must deliver extended service life. This study did not consider the use phase as the authors assumed that the traditional and dry process rubber modified mixtures would perform equally. This assumption was based on reports from the early pilot projects of dry process technology. The newer, modern dry process technologies have shown field performance superior to the traditional and equivalent to wet process and polymer modified asphalt mixtures, as presented previously.

In another study by White et al. (2010), asphalt pavements with and without rubber (wet process) were compared to Portland concrete pavements with and without fly ash in terms of their global warming potential (White, Golden, Biligiri, & Kaloush, 2010). **The findings suggested that, considering the material production phase alone, use of asphalt rubber (wet process) resulted in 71% decrease in global warming potential in comparison to Portland cement concrete pavement.** Cement production was concluded to be the highest producer of carbon dioxide emissions.

5.2. EFFECTS ON AQUATIC LIFE

In its current state, environmental LCA of asphalt mixtures is largely focused of energy consumption and greenhouse gas emissions. However, recent studies have found that there is an imminent need to consider other environmental impact categories when using rubber or any other recycled waste as a secondary source of raw materials in pavement systems.

"Once rubber is encapsulated in a binding agent, the leaching of metals and other compounds is drastically reduced."

Several research studies have shown once rubber is encapsulated in a binding agent, the leaching of metals and other compounds is drastically reduced. Kayhaniyan et al. (2010) tested leachates obtained from laboratory-controlled rubberized sections and found that the sections did not show concentrations of any compound/metal that was measured above the EPA regulations (Kayhanian et al., 2010). The authors used carefully devised laboratory apparatus and obtained leachates at multiple temperatures (4,20,45 C). In addition, the study also showed that no change in concentrations of pollutants was observed with change in temperature or aging level.

Vashisth et al. (1998) had done similar prior work at a limited scope and had investigated the leaching of metals and other compounds from RMA mixtures in Rhode Island, US (Vashisth, Lee, & Wright, 1998). The findings suggested that although RMA mixtures did exhibit a higher zinc content, it was well within the permissible limits and did not pose any threat to aquatic or human life. Lwin et al. (2017) reported similar findings for open-graded wearing course with 1% crumb rubber modification via dry process (Lwin & Utomo, 2017). Reddy et al. (1997) had investigated the effects of leaching of benzothiazole and similar benzene derivatives from RMA roads in Rhode Island (Reddy & Quinn, 1997). The authors collected eleven samples of roadway runoff during storm periods and four liters of water from a highway-settling pond for testing. The authors concluded that RMA roads would likely leach out benzothiazole but, a) it will rapidly diminish over time, and b) these compounds can be microbially degraded and thus pose low risk to the aquatic life. Specifically, in terms of leaching of crumb rubber, the authors put 4 grams of crumb rubber in 100 mL of deionized water in a sealed centrifuge tube at 25C for 24 hours. The authors conducted chemical analysis on the leachate and returned the crumb rubber to another centrifuge tube and repeated the process five times. The authors reported a decrease in leaching of benzothiazole by 40% in the second leaching event itself, successfully decreasing by another 30-40% for every leaching event.

Liu et al. (2018) studied the effect of asphalt treatment of tire particles (size range – 2.00 mm to 4.75 mm) by investigating leaching of zinc from tire particles coated with asphalt in 50% of surface area and 100% of surface area, in comparison with uncoated tire particles (X. Liu, Wang, Gheni, & ElGawady, 2018). The authors found that under acidic conditions (pH<6) 50% coating of tire particles with zinc resulted in 67% reduction in zinc leaching under acidic pH conditions, and 100% coating led to 82% reduction in zinc leaching from tire particles. The findings are shown in Figure 17. Similar results were reported by Gheni et al. (2018) who performed leaching assessment of a rubberized chip seal where mineral aggregates were partially replaced by crumb rubber particles, under different pH conditions (Gheni et al., 2018). Findings from that study indicated that the amount of zinc leached from asphalt-treated crumb rubber decreased by 50% in comparison to virgin/untreated crumb rubber particles. The leaching also decreased with an increase in pH, similar to results shown by Liu et al. in Figure 17.

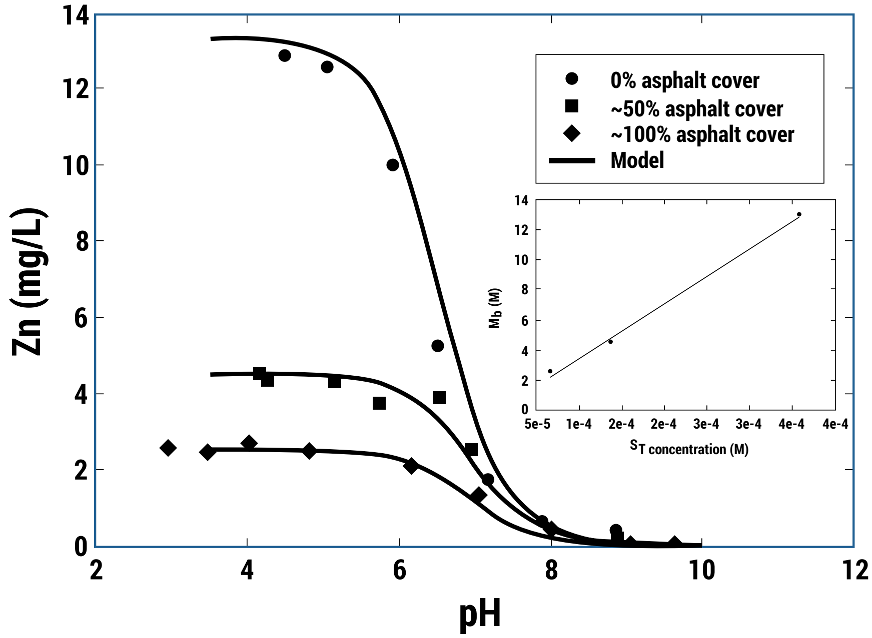


Figure 17. Zinc leaching of tire particles coated with different levels of asphalt cement (from (X. Liu et al., 2018))

Azizian et al. (2003) evaluated RMA mixtures for complex organic and metallic substances (Azizian, Nelson, Thayumanavan, & Williamson, 2003). The results showed that any contaminants from RMA surfaces are retarded and delayed in their transport to nearby groundwater or soils due to peripheral soil sorption. Similarly, findings from NCHRP Project 25-9 showed that although ground tire rubber might exhibit aquatic toxicity in their original form, toxicity was eliminated or greatly reduced in their as-built forms, e.g., after incorporation into paving (entombment by asphalt films) or fill due to entombment in asphalt binder and soil sorption (Azizian et al., 2003; Nelson et al., 2001).

Although the scope of this report is focused on rubber modified asphalt, it was deemed as important to review a recent study reporting on the effects of rubber particles on aquatic life, which has garnered significant media attention. A study by Tian et al. (2021) linked a specific chemical used in manufacture of tires, N-(1,3-dimethylbutyl)-N'-phenyl-p-phenylenediamine, or 6-PPD, to the mortality of adult Coho salmon that often migrate to urban creeks to reproduce (Tian et al., 2021). The chemical in question, 6-PPD, is an antioxidant (or anti-ozonant) that prevents tires from reacting with ozone present in the air which would otherwise lead to degradation of the tires. The study established sufficient concentration of 6PPD quinone in roadway runoff to cause juvenile Coho salmon mortality. The result was reached by comparing gas chromatography-mass spectrometry assessments of TWP leachates and synthetically produced 6PPD quinone, which is a derivative of 6-PPD upon reaction with ozone. **However, given the entombment of rubber particles in asphalt films and the much higher volumes of rubber tire surface emissions as compared to rubber volumes in RMA, it is not clear if RMA pavements would contribute in any significant manner to these levels of 6-PPD concentrations in roadway runoff. However, without further proof, this represents a current research gap.**

The survival rate of the species in control and spiked sediment had no significant statistical difference."

Studies by Stephensen et al. (2005) and Day et al. (1993) had previously shown toxic effects of water run through a newly-bought rubber hose and rubber tires respectively, on rainbow trout (Day, Holtze, J., Bishop, & Dukta, 1993; Stephensen, Adolfsson-Erici, Hulander, Parkkonen, & Förlin, 2005). Both authors noted a significant decrease in leaching of toxic compounds over time. Panko et al. (2013) reported that under typical chronic exposure conditions, TWP in sediments posed low risk to aquatic life (Panko, Kreider, McAtee, & Marwood, 2013). The authors collected TWP from a road simulator laboratory, and spiked a reference sediment from a local water reservoir at 10 g/kg, in an attempt to create representative aquatic ecosystem conditions. The survival rate of the species in control and spiked sediment had no significant statistical difference. Marwood et al. (2011) also reached at similar conclusions with a similar experimental design (Marwood et al., 2011). The authors found that the leaching of tire wear particles could be toxic to aquatic systems under high-temperature conditions, which are not representative of an aquatic ecosystem. Humphrey et al. (2006) presented a review that examined data from seven field studies concerned with water quality influenced by tire derived aggregates used above and below groundwater level. The authors noted that use of TDA, both below and above groundwater level, was unlikely to cause increase in levels of metals in drinking water that would exceed primary drinking water standard (D. Humphrey & Katz, 2001; D. N. Humphrey & Swett, 2006).

There are a plenty of studies concerned with other civil engineering applications of rubber sourced from scrap tires, such as use of tire derived aggregates (Sheehan, Warmerdam, Ogle, Humphrey, & Patenaude, 2006; Tatlisoz, Edil, Benson, Park, & Kim, 1996), use of whole tires as embankments (Brophy & Graney, 2004; Collins, Jensen, Mallinson, Roenelle, & Smith, 2002), sports turfs (X. Li, Berger, Musante, & Mattina, 2010; Llompart et al., 2013), and so on (Kayhanian & Harvey, 2020; Wik, Nilsson, Källqvist, Tobiesen, & Dave, 2009), but a detailed review of those studies was not considered to be within the scope of this report. Finally, Wagner et al. (2018) presented an extensive literature review on the effects of TWP on aquatic life and it is clear from the reported literature that this area of research is currently active and there is a need of more in-depth field studies to better understand the effect of rubber particles from tire wear on aquatic life (Kreider, Panko, McAtee, Sweet, & Finley, 2010; Thorpe & Harrison, 2008; Wagner et al., 2018). It should be noted that LCA models for impact categories related to quantifying eco-toxicity are, at the current time, unrefined. This gives rise to a high range of uncertainty in those impact categories. **With the recent increase in attention to the question of generation of microparticles by RMA and its effects on aquatic life, it is a good time for the tire industry to come forward and establish an Environmental Product Declaration (EPD) for using rubber modification in asphalt mixtures** (Rangelov, Dylla, Mukherjee, & Sivaneswaran, 2021). **An EPD will ensure standardized means of communication of environmental impacts of a product, which not only will allow more streamlined, standardized, and comparable LCA studies, but also enable better quantification of impact categories related to ecotoxicity**.

5.3. OCCUPATIONAL SAFETY

In a national-level study concerning the emissions from using rubber modified asphalt in plants (conducted in 1994-1997), Burr et al. (2001) reported that the exposure of RMA workers to total particulates (TP), benzene soluble particulates (BSP), polycyclic aromatic compounds (PAC) and volatile organic compounds (VOC) were higher as compared to conventional asphalt workers (Burr, Tepper, Feng, Olsen, & Miller, 2001). On the other hand, several other studies reported insignificant differences between emissions from a plant producing conventional and rubberized asphalt. Watts et al. (1998) conducted a personal exposure monitoring study that analyzed gaseous emissions of RMA and conventional asphalt mixture. The authors quantified fine respirable particles (< 2.5 microns) and particle-bound polycyclic aromatic hydrocarbons (PAHs). Although the raw results showed RMA workers to have higher exposure to PAH at a work site, a statistical analysis indicated that there were no significant differences with respect to standard mixtures.

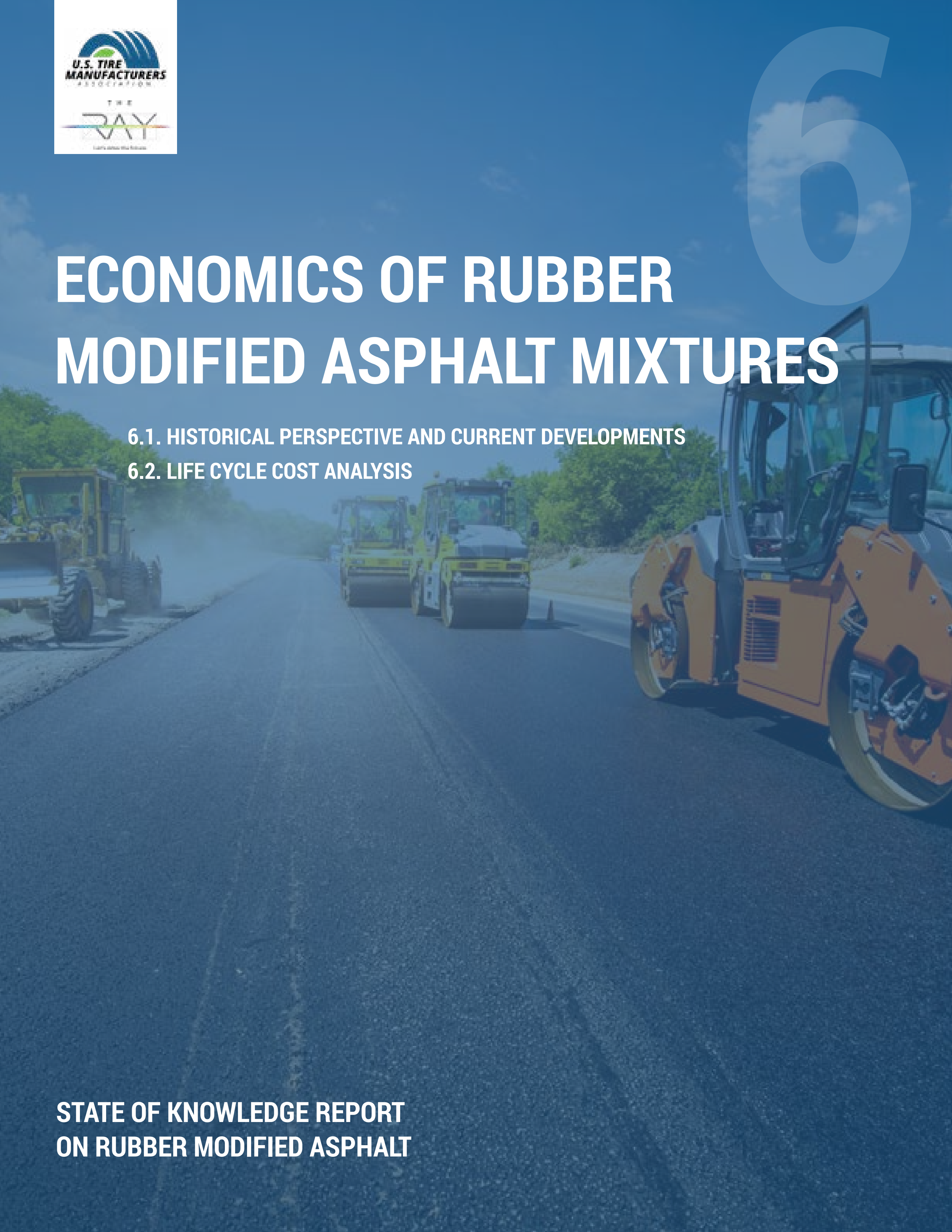
Figure 18. Asphalt plant are continuously evolving to capture emissions from being released to the atmosphere. Image from World Highways website.

Stout et al. (2003) produced a synthesis of studies done on the emissions from the production of rubberized mixtures (Stout & Carlson, 2003). The authors looked at data from Michigan, Texas, and California to conclude that the emissions from production of wet process asphalt rubber is not significantly different from conventional asphalt mixtures. Additionally, the authors commented that rubber remains as physical particles in the asphalt binder and thus does not contribute to emissions. Sousa et al. (2007) focused solely on the CO2 emissions for mixtures in California and Arizona, and found that compared to standard hot mix asphalt, use of rubberized asphalt mixture (terminal blend) will result in significant savings per lane mile (154 tons CO2 for gap graded, 343 tons CO2 for open graded) (Sousa, Way, & Carlson, 2007).

A few recent studies have measured carcinogenic emissions from asphalt plants when RMA was being produced. For instance, Yang et al. (2019) measured emissions from an asphalt plant that produced an unmodified asphalt mixture with a PG 58-28 binder, and a rubber-modified binder (12% by weight of binder (PG58-28), terminal blend) with and without warm mix additive. The mixing temperature for unmodified and rubber-modified mixture without warm mix additive was 160C and 158C, respectively. At similar mixing temperature, the authors found that except for xylene, all other compounds (such as benzene, toluene, etc.) were within the state of Michigan's specified limits. The authors pointed out that asphalt source has a major effect on emissions and any unknown additive in the terminal blend rubber modified binder to adjust/meet the required planned grade could potentially have caused higher emissions.

In another study, Zanetti et al. (2014) measured the volatile organic compounds (VOCs) and polycyclic aromatic hydrocarbons (PAHs) by conducting chemical analysis on fumes collected at different locations near the paver (at driver's seat, and near the screed) (Maria Chiara Zanetti, Fiore, Ruffino, Santagata, & Lanotte, 2014). The study included unmodified, polymer modified, and wet and dry process rubber modified binders/mixtures. The authors reported that most of the compounds released were from the bitumen/binder and not from crumb rubber where the process of vulcanization causes extensive cross-linking, preventing its degradation. The authors concluded that the workers at an asphalt plant are not exposed to any higher degree of risk due to working with crumb rubber modification.

It is noteworthy that newer processes and technologies, such as warm mix additives that reduce mixing temperatures by 50-75F (10-25C), are resulting in less energy-consuming mixtures. Modern rubber modification processes, especially the dry processes, have also aided in the manufacturing of more workable mixtures, which facilitates manual asphalt spreading operations such as raking and looting around utilities and manhole covers.



6

ECONOMICS OF RUBBER MODIFIED ASPHALT MIXTURES

6. ECONOMICS OF RUBBER MODIFIED ASPHALT MIXTURES

"It has been shown that thin RMA overlays can be built at a lower cost as compared to unmodified asphalt overlays - approximately 43% less cost with a 10% boost in pavement life..."

It has been shown that thin RMA overlays can be built at a lower cost as compared to unmodified asphalt overlays

The successful market adoption of a product is largely contingent upon its favorable economics. The existing literature on RMA indicates that it was not cost-effective in a lot of states that tried to adopt it in the 1990s. However, advancement in production technologies and availability of modern decision-making tools such as Life Cycle Cost Analysis (LCCA) have allowed RMA to be competitive in the market, as will be discussed in the following sections.

6.1. HISTORICAL PERSPECTIVE AND CURRENT DEVELOPMENTS

As noted in the earlier sections, the cost of RMA mixtures was a prohibitive aspect in adoption of rubber modification by many paving agencies or states. Maupin reported mixture costs from four projects in Virginia that used RMA and were constructed between 1990 to 1993 (Maupin, 1996). The cost of producing RMA mixtures ranged from 64% to 102% higher than the conventional mixtures. Huang et al (2002) reported a cost increase of at least 100% and up to 360% with use of RMA in comparison to unmodified mixtures (B. Huang, Mohammad, Graves, & Abadie, 2002). The state of Pennsylvania reported an increase of up to 60% in cost of rubber mixtures in comparison to conventional mixture sections placed 1991-1995 (Pennsylvania Joint State Government Commission, 2007). Volle (2000) reported eleven RMA projects from Illinois paved in the period of 1991-1995. Of the eleven projects that used RMA, nine were about within 25% higher than conventional mixture, one was 43% higher, and one was 101% higher (conventional mix cost = $39.90, RMA cost = $80.00) (Volle, 2000). In 1994, Colorado built three sections with dry process rubber which cost 21% more than the conventional HMA when rubber was added at 20 lbs./ton (Harmelink, 1999).

While rubber was deemed to be cost-ineffective for most states, several states that had extensive experience in using rubber were able to justify costs by citing the increase in pavement service life obtained by rubber modification. For instance, in 2003, Texas DOT conducted an LCCA and estimated that it cost $78.15 less on an average per lane mile to use a hot asphalt rubber seal compared to a traditional seal coat (Texas Department of Transportation, 2003a). In 2003, the average cost of producing RMA in California was $60.80 while conventional mixture cost 16% less at $52.43 per mix ton. But according to LCCA, the rubberized applications were cost-effective 70% of the time (Caltrans, 2005c). **In the case of asphalt overlay rehabilitation projects on a cost-per-square-yard basis, it has been shown that thin RMA overlays can be built at a lower cost as compared to unmodified asphalt overlays - approximately 43% less cost with a 10% boost in pavement life (Buttlar and Rath, 2019)**. Similarly, an earlier study (Harvey et al., 2000) demonstrated that a 50% reduction in lift thickness can be achieved by using RMA in lieu of unmodified mixtures while achieving better performance.

In recent years, with an increased awareness of performance enhancement of rubber modification, a proliferation of LCCA as a decision-making tool instead of comparing initial bids, and availability of less expensive manufacturing technologies, rubber modification has become economically competitive in the marketplace. This is evidenced by the increased use of RMA in recent years in a number of locations, including Georgia and the Illinois Tollway, where RMA has been used on large, competitively bid projects involving hundreds of thousands of tons of mainline, interstate paving.

It is important to mention here that the initial cost of producing a GTR-modified mixture is lower than the other premium mixture counterparts, such as polymer (SBS) modified asphalt mixtures. In general, unmodified asphalt binders are "bumped" to produce modified asphalt binders by addition of synthetic polymers, such as SBS. Baumgardner et al. (2018) compared costs of GTR and SBS per ton and reported that GTR costs about 1/6th of the price of SBS (G. L. Baumgardner, Hemsley, Jordan, D'Angelo, & Howard, 2018; Howard et al., 2021). In addition, the authors listed the annual average price of a common unmodified binder from the state of Mississippi, as shown in Figure 19 from Howard et al. (2021). It is noteworthy to observe that while asphalt cement prices have risen drastically since 2006, GTR prices have remained relatively stable at about $380/ton. The authors (Howard et al., 2021) also stated that while SBS prices could be assumed to be $2,280/ton, during the supply shortage of 2011, prices reached as high as $4000/ton. **Thus**, **many states and agencies**, **such as Illinois Tollway**, **Georgia DOT**, **Oklahoma DOT**, **etc.**, **have moved towards replacing SBS with GTR to obtain mixtures that satisfy similar performance criteria**, **but with increased mixture economy and sustainability**.

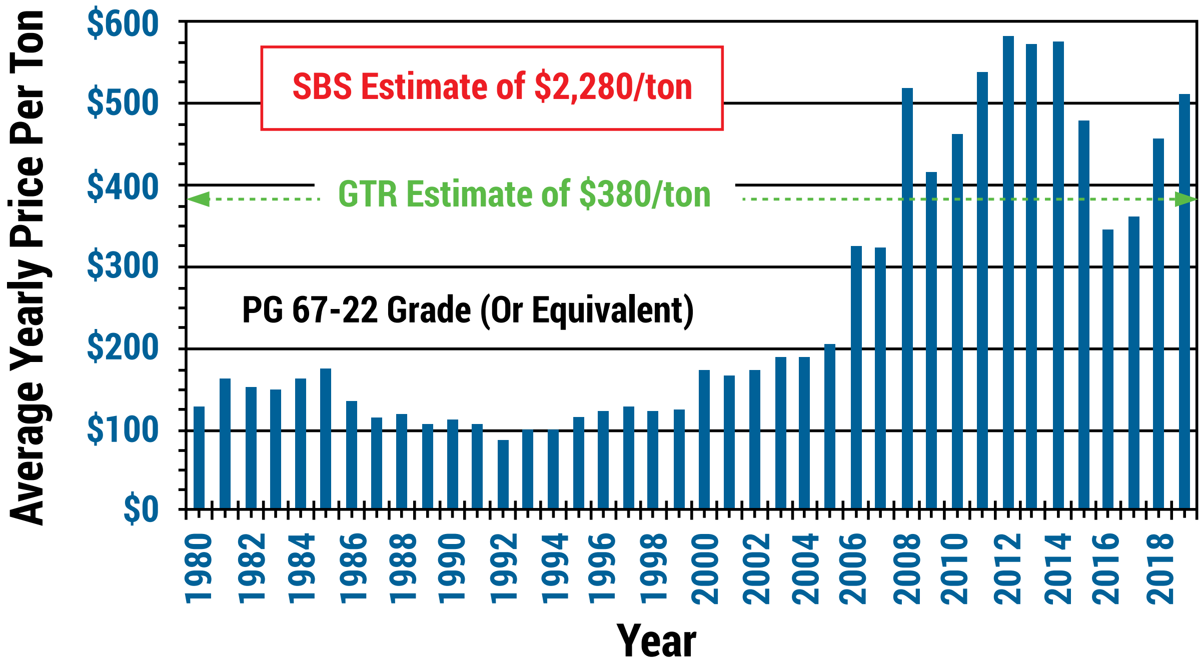


Figure 19. Asphalt Cement prices for the state of Mississippi (after (Howard et al., 2021))

A discussion of LCCA studies evaluating the cost-effectiveness of RMA is covered in next section.

6.2. LIFE CYCLE COST ANALYSIS

Life Cycle Cost Analysis (LCCA) has been used as a decision-making tool by paving agencies since the 1980s. The AASHTO Guide for Design of Pavement Structure, published in 1986, provided guidance and encouraged the paving agencies to utilize LCCA to evaluate the cost effectiveness of different paving alternatives available to an agency (R. Hicks et al., 1999). It is analogous to the normal LCA but is concerned with the economics of paving processes rather than the environment impacts. A report published by FHWA in 1998 defined LCCA as follows, "LCCA is an analysis technique that builds on the well-founded principles of economic analysis to evaluate the over-all-long-term economic efficiency between competing alternative investment options. It does not address equity issues. It incorporates initial and discounted future agency, user, and other relevant costs over the life of alternative investments. It attempts to identify the best value (the lowest long-term cost that satisfies the performance objective being sought) for investment expenditures." (Federal Highway Administration, 1998). This approach is an improvement over the practice of comparing initial project costs to choose the best available alternative. For example, a lot of reports about rubberized asphalt from the 1990s note that the adoption of rubber modification would be difficult in most places even if rubber modified mixtures showed potential benefits because the initial cost of using it were too high (Epps, 1994). But if the cost savings due to increased pavement life and the low maintenance activities that resulted from paving RMA were factored in, then perhaps the adoption could have been shown to be more economically feasible. Expectedly, the rise in the use of LCCA as a decision-making tool coincided with the rise in the use of innovative material modification technologies such as polymers, rubber, etc.

"RMA becomes capitally advantageous at a layer thickness equivalency ratio of 1.2:1 to 1.4:1, meaning that the structural thickness of an RMA pavement can be reduced by 20-40% to obtain the same performance as the conventional pavement, thereby reducing capital costs."

One of the first studies on LCCA of RMA was conducted by McQuillen et al. (1988) for the Alaska Department of Transportation, wherein the authors compared life cycle costs of a conventional dense graded mixture with an asphalt mixture modified according to PlusRide™ technology (dry process) (McQuillen Jr. et al., 1988). It should be noted the initial capital costs also included the patent royalties at that time (8% of the total mix cost per ton). The authors included three types of LCCA procedures that accounted for capital costs, different structural layer thicknesses, and different maintenance scenarios. Upon analysis of different maintenance scenarios, the authors found RMA to be cost effective if it could be in service for 20-23 years compared to 15 years of service life for conventional mixtures, assuming a maintenance cycle of five/six years for RMA and four years for conventional mix. In addition, the authors found that RMA becomes capitally advantageous at a layer thickness equivalency ratio of 1.2:1 to 1.4:1, meaning that the **structural thickness of an RMA pavement can be reduced by 20-40% to obtain the same performance as the conventional pavement**, **thereby reducing capital costs**.

Jung et al. (2002) compared two pavement systems located in Arizona, one conventional and one RMA (Jung, Kaloush, & Way, 2002). Both the pavements were located end to end on west-bound I-40. The conventional pavement system was a full depth pavement which included 4 inches of aggregate base, 6 inches of bituminous treated base, and 11 inches of asphalt concrete. It was built as a full depth replacement of a deteriorated concrete pavement. Adjacent to that section, an asphalt-rubber section including 8 inches of aggregate base with broken old concrete pavement, 3 inches of conventional asphalt concrete, 2 inches of asphalt-rubber gap graded mixtures, and half an inch of asphalt rubber open graded friction course. The authors used IRI and pavement serviceability rating to determine the performance over the service life of the pavement systems. Considering the initial cost of construction, the rubberized pavement system saved more than $640,000 for the agency due to the reduced total thickness of the pavement. In addition, serviceability and IRI measurements suggested that the use of asphalt-rubber would provide much higher service life and better serviceability than the conventional pavement. Finally, the authors concluded that asphalt-rubber pavement would be more cost-effective in terms of agency as well as user costs, as can be seen in Figure 20.

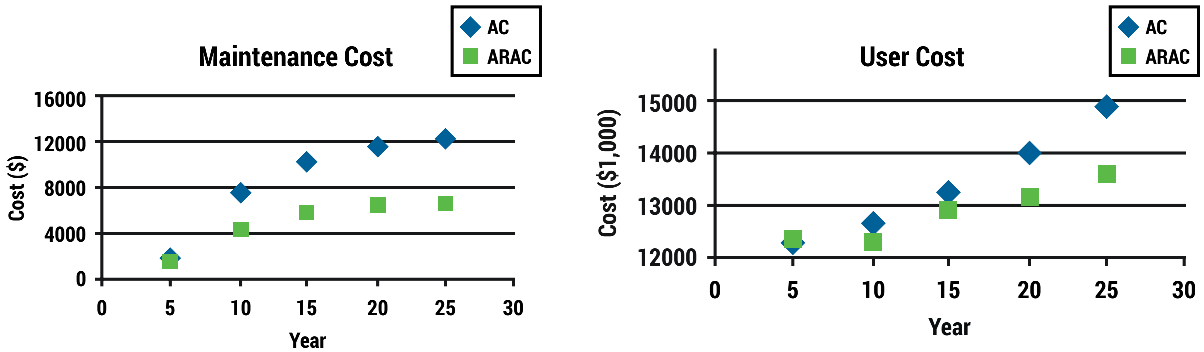


Figure 20. Maintenance cost comparison of conventional and RMA pavement (from (Jung et al., 2002))

"The analysis culminated in the conclusion that use of asphalt-rubber was cost-effective in the majority of medium to large paving projects."

Shatnawi (2014) presented a case for using rubber-modified stress absorbing membrane interlayers (SAMI-R) along with an HMA as a rehabilitative measure for a distressed pavement instead of using only conventional HMA (Shatnawi, 2014). As such, the author compared four scenarios- first, a 105 mm (~4 inches HMA overlay, second, SAMI-R with 60 mm (~2.4 inches) of HMA, third, 60 mm (~2.4 inches) of gap-graded RMA, and fourth, SAMI-R with 30 mm (~1.2 inches) of gap-graded RMA. Performance of the mixtures adopted in this study was informed by data from Caltrans' research. The author showed that on calculation of Net Present Value (NPV) for all the four scenarios considered in the study, the fourth scenario, which was using SAMI-R with 30 mm of RMA resulted in the least cost associated with the agency and the user. In comparison, the fourth scenario cost 40%, 35%, and 4% less than the first, second and the third scenarios in terms of total cost (agency cost + user cost). Similar findings were reported by Cheng et al. (2012) who analyzed 126 asphalt rubber projects in California's 12 districts for their cost-effectiveness in comparison to conventional mixtures (Dingxin Cheng et al., 2012). The analysis culminated in the conclusion that use of asphalt-rubber was cost-effective in the majority of medium to large paving projects.

Souliman et al. (2016) conducted an LCCA to investigate whether using modified asphalt mixtures represents a cost-effective solution to mitigate fatigue cracking in comparison to unmodified mixtures (Souliman et al., 2016). The authors compared the fatigue performance of unmodified, polymer-, and rubber-modified mixtures using the beam fatigue test and computed the average cost per mile (1.6 km) of pavement (in US dollars) per 1000 cycles offatigue life. Upon considering various lift thicknesses and vehicle velocities on roads, on average, RMA cost $25 while polymer-modified mixture cost $36, and finally the unmodified mixture cost $108, thus highlighting the effectiveness of RMA in resisting fatigue cracking.

7

KNOWLEDGE GAPS

STATE OF KNOWLEDGE REPORT
ON RUBBER MODIFIED ASPHALT

7. KNOWLEDGE GAPS

Rubber modification of asphalt mixtures has been used on roadways worldwide for more than half a century. However, its increased usage seems to be hampered by dated institutional knowledge tying back to early failures or high initial costs in early trials. The early failures could be attributed to poor compaction techniques and lack of experience with rubber modification, but these attributes are seldom reported in published papers, which results in a fairly broad consensus of the potential for poor field performance when RMA is used. However, in the past two decades, significant technological advances have pushed RMA to deliver high performance in a variety of asphalt mixture types placed in a variety of climates, but at a much lower cost.

> "There are numerous research reports that have shown that rubber modified mixture perform adequately, and are on par with the polymer modified mixtures."

Even as a relatively mature technology, the examination of literature conducted herein has uncovered several of clear research gaps, which are summarized in the sections below.

LACK OF EXPERIENCE AND PROPER DESIGN TOOLS

Most state highway agencies and asphalt contractors have limited-to-no experience with modern RMA products, and limited knowledge of the new performance trends, economics, and sustainability of RMA. In addition, the following specific gaps were noted:

- Almost none of the modern, advanced asphalt binder and mixture performance tests and associated specifications were developed with RMA in mind. For instance, the high stiffness and elasticity imparted by rubber particles lead to very high mixture strength, high stored elastic energy and limited deformation, all of which may lead to lower scores in simple asphalt mixture cracking tests such as the IDEAL CT index test. In the MSCR binder test, a work-around is needed (replace Jnr,diff with Jnr,slope) to properly assess RMA.
- The ability to accurately design pavement layer types and thickness with RMA is currently difficult at best. Additional research is needed to better reflect RMA properties and characteristics as inputs in modern pavement design software programs for new pavements and rehabilitation activities, such as resurfacing with asphalt overlays.

LIFE CYCLE ASSESSMENT (ENVIRONMENTAL IMPACTS AND COST ANALYSIS)

It is worth noting that even though efforts have been taken to standardize LCA processes at a global level, an LCA procedure specific for roads has not yet been universally agreed upon (Santero, Masanet, & Horvath, 2011). Conducting LCAs for recycled materials incorporated in asphalt mixtures is not straight-forward. There are some inherent hurdles in the LCA process, such as lack of reliable primary sources of data, use of different and appropriate allocation methods, etc. All these LCA-related gaps are discussed elsewhere (Hoxha et al., 2021), but key knowledge gaps specific to rubber modified asphalt mixtures can be summarized as follows:

- **Assumption of life expectancy of rubberized pavements in use phase**: Even though rubber modification of asphalt mixtures has been around for a few decades at this point, there have been rapid developments in modification technologies, both wet and dry. There are numerous research reports that have shown that rubber modified mixture perform adequately, and are on par with the polymer modified mixtures. It is important for LCA studies accounting for use phase of pavements that includes maintenance to base their assumptions on the current performance record of rubber modified mixtures, and not on outdated reports/findings.

- **Improvement of functional characteristics** (**noise reduction**, **skid resistance**): Research has shown that rubber modification improves the functional characteristics of the road such as noise reduction, skid resistance, ride quality (smoothness) , etc. compared to other pavement systems. Traditional LCA analysis often ignores a proper quantification of these social factors. Some recent work has been done towards quantifying the effect of noise reduction in urban areas by using rubber modified roads, but it is yet to be fully incorporated into LCA.
- **Focus on limited impact categories**: Most LCA studies for rubber modified asphalt are focused on energy consumption and emissions (greenhouse gas emissions). Recent studies on the environmental effects of tire wear rubber particles in water streams have proved that more emphasis needs to be given to eco-toxicity and other similar impact categories in the LCA procedure for pavements. Research has shown that rubberized pavements produce less tire wear rubber particles due to a smoother surface compared to other pavement/mixture types. A quantification of such impacts for different types of mixtures would allow the decision of choosing a pavement type to become multi-dimensional (instead of looking at a limited number of impact categories). Another broader aspect associated with this issue is that the current LCA models for quantifying ecotoxicity are not fully refined, which results is poor resolution of obtained results.
- **Life Cycle Cost Analysis** is primarily affected by assumptions on maintenance and rehabilitation of pavement sections. Much like the incorrect assumption of low life expectancy in the effect of use phase in environmental LCA, LCCA also suffers from similar assumptions which are based on outdated literature.
- **Avoided burden for recycled crumb rubber**: Ground tire rubber is an efficient way of converting a waste material into a stream of raw materials for asphalt mixtures. While this helps to reduce scrap tire stockpile issues, RMA does not appear to be allocated any avoided burden in current LCA studies. It is worth noting that allocating an avoided burden in attributional LCA studies would require an expansion of system boundaries to include end of life phase of tires, and such system expansion would be rather convoluted.
- **Lack of consequential LCA studies**: Policy-based decisions in the US on the use of ELTs by various means, material recycling or energy recycling, could be aided by rigorous consequential LCA studies, which are not widely available at this point.

“There is a lack of in-depth research on the quality of air emissions from rubber modified RAP which could be variable depending on the process of mixture manufac-turing (dry versus terminal or field blends).”

INFORMATION ON USE OF RUBBER-MODIFIED RAP

In the United States, and around the world, it is becoming commonplace to re-use the milled asphalt pavement as an aggregate stockpile, called recycled asphalt pavement (RAP). While it is known that rubber modification provides enhanced performance, limited data exists on its reuse from testing of crumb rubber modified RAP resulting in research gaps. For instance, there is a lack of in-depth research on the quality of air emissions from rubber modified RAP which could be variable depending on the process of mixture manufacturing (dry versus terminal or field blends) (Caltrans, 2005a; Rice & Halligan, 2020). In addition, the degree of binder availability from crumb rubber modified RAP would need to be thoroughly investigated. The work relating to this is still under debate for conventional RAP, but an additional dimension to this research gap for rubber modified RAP would be the quality of binder available since it is known that rubber particles absorb the lighter ends of the binder. Finally, research needs to be directed to determine if there needs to be any modifications to the existing mixture design process to incorporate rubber modified RAP. Notably it has been reported that milling of rubber-modified roads need extra energy (Bischoff & Toepel, 2004). Factoring this into an LCA analysis would give a clearer picture of the complete reusability of rubber modified pavements.

NOISE REDUCTION

While there is an overwhelming agreement on the positive effects of rubber modification in terms of noise reduction, there are a few instances where reports disagree on the longevity of the noise reduction effect of RMA. For instance, reports from Sacramento County (Sacramento County Public Works Agency, 1999) and Arizona (G. Way, 2012) indicated long-lasting effects (>6 years) of rubberized pavements for reducing noise levels, but a study by Lu et al. (2010) in California showed that the positive effects of RMA diminish within a few years (2-4 years) of paving in comparison to conventional mixtures (Lu et al., 2010). Although it is known that the ability to reduce noise levels would depend on mixture types, pavement quality, and other factors, there is a need to obtain a deeper understanding of the effects of rubber in noise attenuation. In addition, the choice of sound level measurements and the ensuing calculations also differ from study-to-study, and hence needs standardization.

ENVIRONMENTAL EFFECTS

The effect of RMA on aquatic and human toxicity is currently gaining a lot of media attention. While past research reports that once rubber particles are entombed or treated with asphalt binder, the rate of leaching reduces drastically, recent studies are identifying newer chemicals from tire rubber that could be harmful for aquatic life. There is a great opportunity for the industry to develop an Environmental Product Declaration (EPD) for the usage of rubber in asphalt mixtures. EPDs would also provide the building blocks for conducting standardized LCA analysis with due consideration of ecotoxicity.

OCCUPATIONAL SAFETY

Occupational safety is an important issue in any industry. Even though the current state of knowledge and field experience has shown that RMA is safe to work with in the long-term, there is a lack of quality primary data on plant emissions and its long-term effects on workers, especially in the United States. It is important to mention that measuring plant and field emissions are complex tasks and are affected by many factors, as pointed out in a study by Zanetti et al. (2014) (Maria Chiara Zanetti et al., 2014). Furthermore, studies conducted at different points of time have shown differing results, for instance Stout et al. (2003) and Yang et al. (2019) reported gaseous emissions from asphalt plants producing RMA in Michigan and found subjectively contradictory results (Stout & Carlson, 2003; Yang et al., 2019). There is a need to bring in standardization in the method of measurements that would account for site-specific factors, as pointed out by Zanetti et al. (2015) (M. C. Zanetti et al., 2015).

It is noteworthy that newer processes and technologies, such as warm mix additives that reduce mixing temperatures by 50-75F (10-25C), are resulting in less energy-consuming mixtures. Modern rubber modification processes, especially the dry processes, have also aided in the manufacturing of more workable mixtures, which facilitates manual asphalt spreading operations such as raking and looting around utilities and manhole covers .

7

SUMMARY AND RECOMMENDATIONS

STATE OF KNOWLEDGE REPORT
ON RUBBER MODIFIED ASPHALT

8. SUMMARY AND RECOMMENDATIONS

> "Realizing this potential can lead to tens-of-millions of annual savings for state highway agencies, and thus hundreds-of-millions nationwide in the reduction of paving costs, increased pavement life, and decreased maintenance activities."

The path leading to the current state of knowledge in rubber modified asphalt has been filled with technological innovations, many great success stories, and a few challenges along the road as best practices for RMA have developed over the past several decades. With the second wave of RMA innovations gaining a solid foothold across the US in recent years, the asphalt industry and end-of-life tire stakeholder communities have an opportunity to build on the current momentum, and to finally realize RMA's full potential as a mainstream, asphalt paving technology. Realizing this potential can lead to tens-of-millions of annual savings for state highway agencies, and thus hundreds-of-millions nationwide in the reduction of paving costs, increased pavement life, and decreased maintenance activities. These savings can then be reinvested to address the substantial deferred maintenance needs that have steadily accrued since the completion of various roadways comprising the national highway system, built 30-60 years ago, along with the vast network of other roads, airports, parking lots, and pavement facilities across the US. In addition, the increased use of RMA can effectively utilize scrap tires in the US and prevent stockpiles, while significantly contributing to overall pavement sustainability and citizen-centric benefits such as quieter and smoother pavements, lower vehicle operating costs, and lower vehicle maintenance costs.

To help fully realize these goals, the key knowledge gaps identified in this study should be rigorously addressed. It is recommended that the closure of these knowledge gaps be addressed without delay, in order to build on the current momentum in RMA usage across the US. The following steps are recommended to further the responsible and sustainable use of rubber in asphalt pavements:

1. Gaps in knowledge related to RMA sustainability and its role in transportation resiliency should be addressed in a comprehensive, integrated fashion. Not only will this serve to guide the responsible use of RMA in the asphalt paving industry, it will enable far more accurate LCA estimations and forward-looking pavement designs as the transportation community moves towards increased attention to sustainable and resilient infrastructure.
2. Gaps in knowledge with respect to RMA performance testing, modern performance specifications, and integrated pavement/materials design should be addressed with an eye towards national standardization, bolstered by a national clearinghouse of test results, field performance data, improved performance prediction models, and templates for new RMA construction and materials specifications. Advances in data science and, in particular, machine learning should be developed and fully exploited in an effort to reduce the time-to-adoption of new research results, reduce testing, design, and pavement evaluation costs, and to bolster the efficacy of RMA performance prediction.
3. The establishment of a National Center of Excellence for Rubber-Modified Asphalt would facilitate the timely conduct of the aforementioned critically needed research and could assist in the dissemination of research being carried out at other institutions nationwide and across the world. Partnership with a local department of transportation and existing center for transportation research and innovation would serve to expedite the timeline to reach full center operational capacity, by capitalizing on access to existing laboratory facilities with existing RMA research capabilities, experienced research personnel, and in the establishment of a national test road facility dedicated to RMA research.

4. Investment in regional demonstration projects, scrap tire recycling infrastructure, and hot-mix asphalt plant recycling infrastructure to facilitate RMA usage, particularly in areas with little-to-no current RMA usage should be given priority. The strategic investment of existing tire recycling fees or the establishment of other funding streams to support the expansion of rubber recycling into pavements should be considered in light of the opportunity to build on the current positive momentum in RMA usage and innovation in the US and abroad.
5. A national steering group (expert task force) should be established, which can help develop and coordinate national research priorities and studies for RMA, provide oversight to a national center of excellence for RMA research, and help prioritize and coordinate regional demonstration projects, strategic investments in recycling infrastructure, and provide overall industry leadership and advocacy towards increased pavement sustainability, resiliency and circular economy solutions involving RMA.

8

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APPENDIX – DETAILED SURVEY RESULTS

STATE OF KNOWLEDGE REPORT ON RUBBER MODIFIED ASPHALT

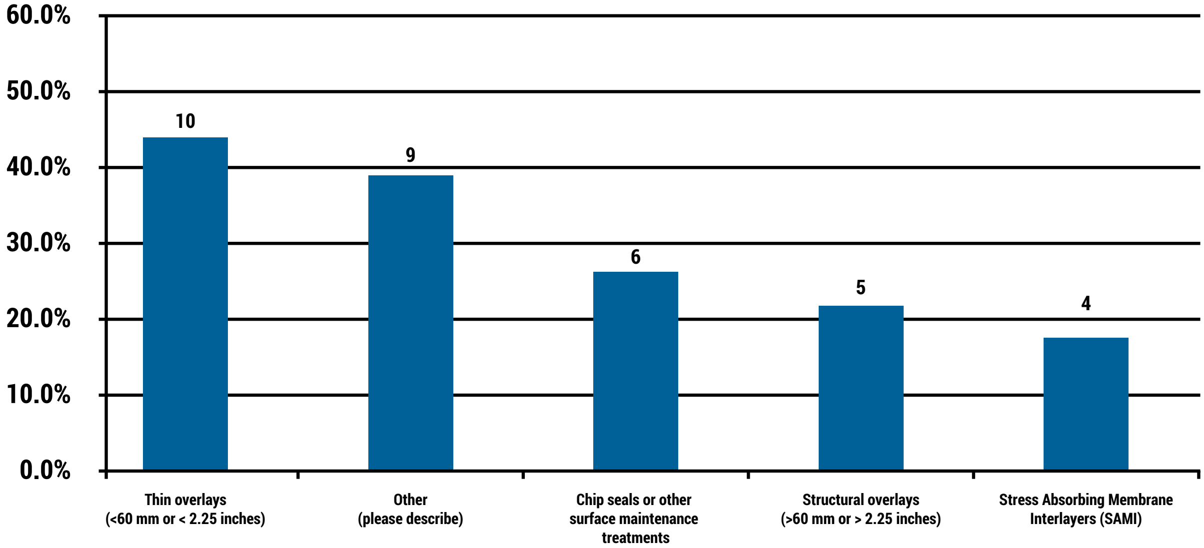
Q1. Which of the following most closely describes your agency?

Type	Count
State Department of Transportation	26
City of Municipal Transportation Authority	0
Tollway Authority	0
Airport Authority	0
Others	0

Q2. Your Location

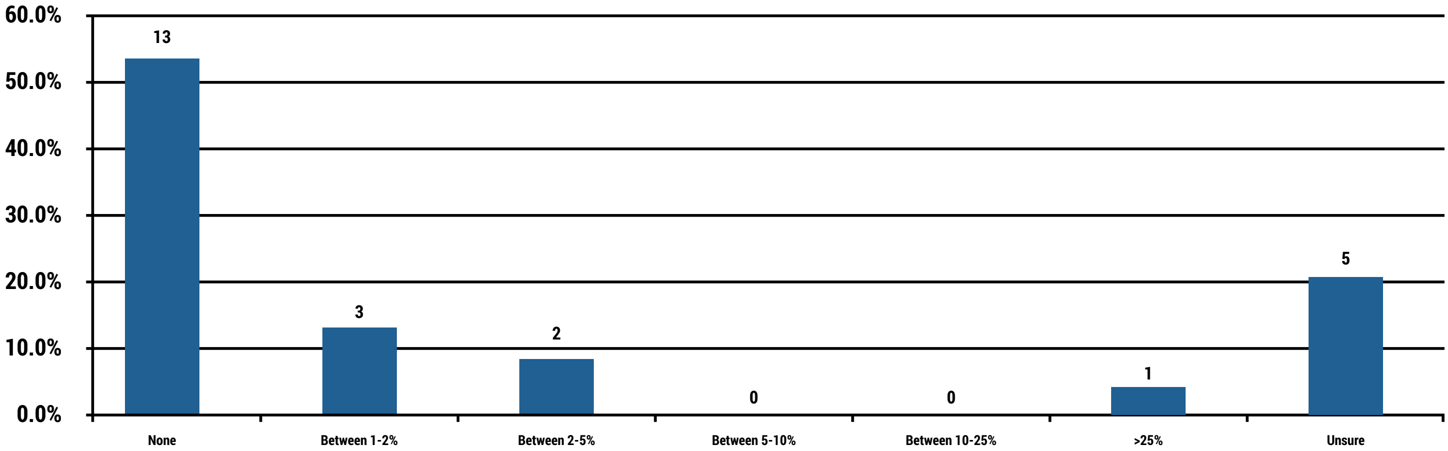
State	
Vermont	Michigan
Kansas	Indiana
Colorado	Tennessee
Georgia	Utah
South Carolina	New Hampshire
Ohio	NC
Connecticut	Montana
Louisiana	Arkansas
Oklahoma	Alaska
Florida	Wisconsin
North Dakota	Delaware
Maryland	Hawaii
California	Mississippi

Q3. Which Rubber-Modified Asphalt (RMA) applications has your agency used from the year 2000 to present?



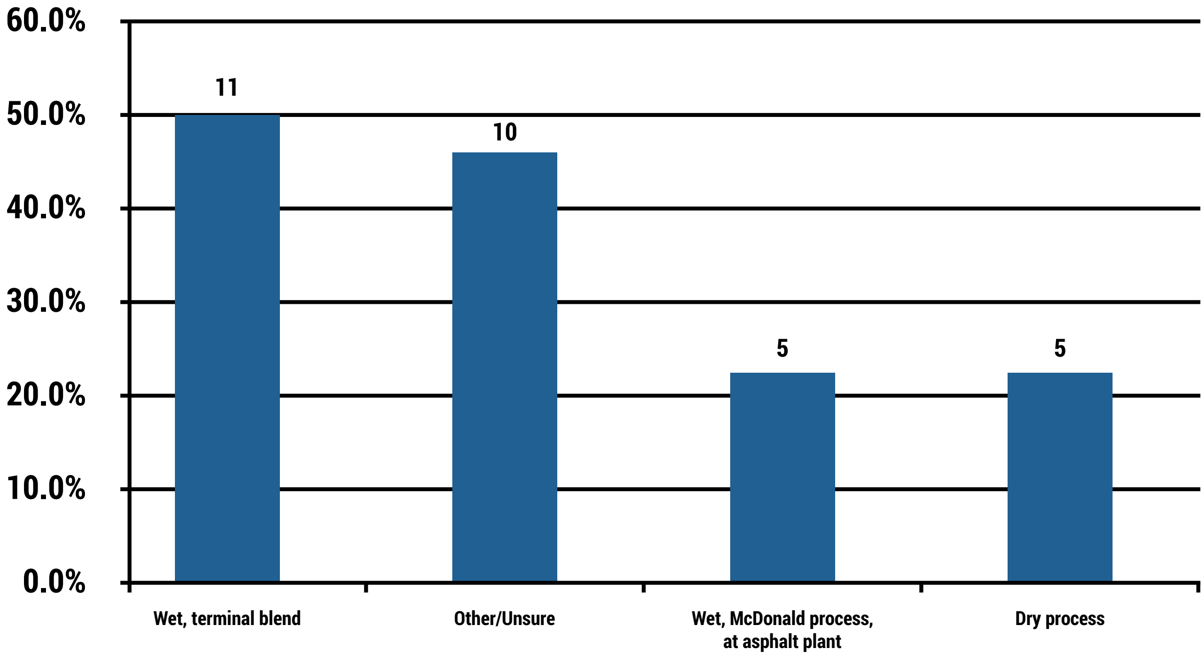
State	Response
Florida	Asphalt rubber binder in desnse-graded structural and friction courses.
North Dakota	None
Maryland	None
Indiana	None
Montana	None
Arkansas	None
Alaska	Mill-and-Fill/overlay
Wisconsin	one research project with RMA, WHRP 0092-19-05
Hawaii	Does not use RMAz

Q4. Please provide a rough estimate of the percentage of rubber-modified asphalt mixtures (percent of total asphalt mixture tonnage) that is currently being used in your road or airport pavement system(s) or network(s).



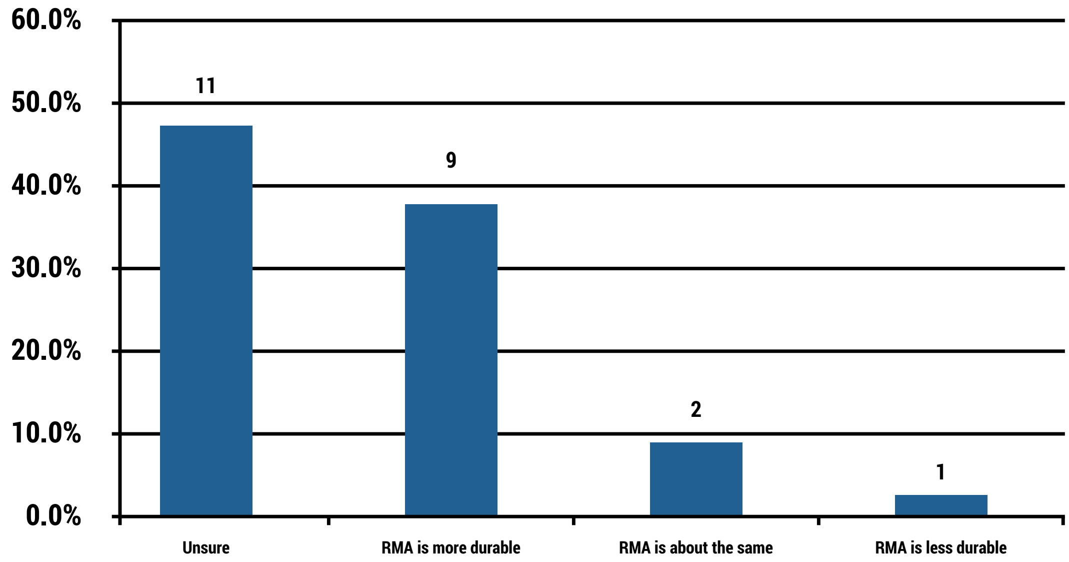
State	Response
Colorado	1% pilot project only, none recently.
Louisiana	Main contractor using it out of business
Florida	I am not aware on any current projects using asphalt rubber binder.
California	~40%
Michigan	We have a permissive spec but in recent years no one had chosen the option
NC	1-2 locally-let contracts with SAMI, only.

Q5: Which rubber-modified asphalt technologies are being used in the pavements managed by your agency (please check all that apply and estimate relative percentage used, where estimated proportions should sum to 100%)?



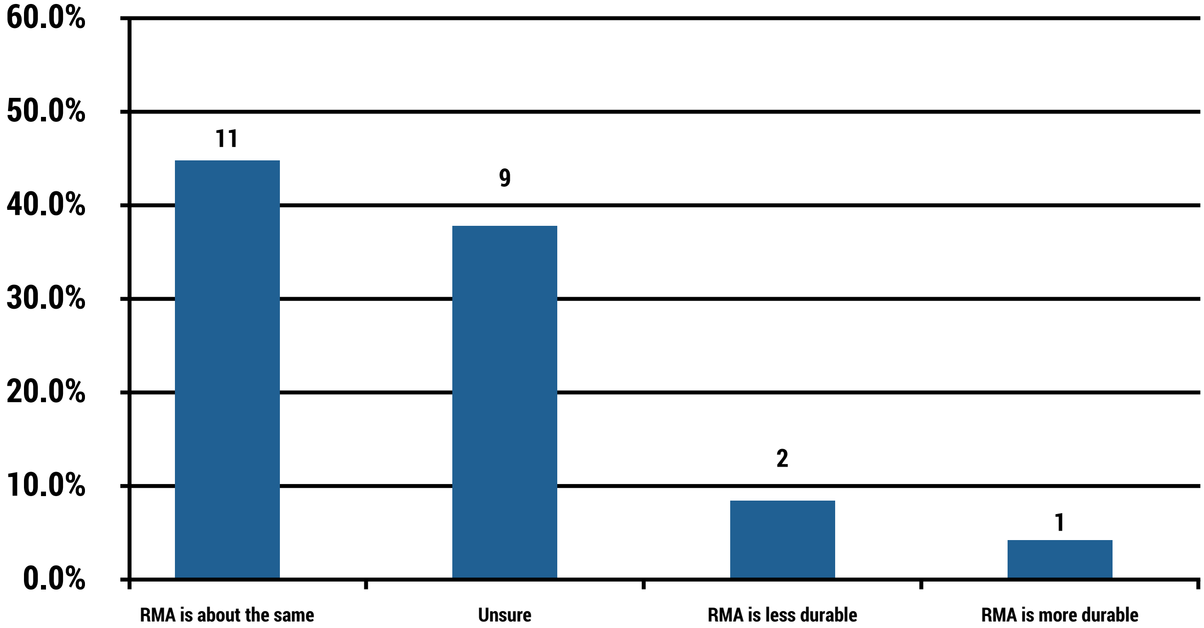
State	Relative portion of Wet, McDonald Process (%)	Relative portion of Dry Process (%)	Relative portion of Other (decribe process) (%)
Colorado	1% pilot project only	1% pilot project only	
Georgia			
South Carolina		1.5	
Ohio		100	
Louisiana	10	10	
Oklahoma		1%	
Florida	0%	When produced, rubber is blended at the terminal	0%
North Dakota			none
California	95	5	
Michigan		dependent on mix design	
Indiana			none
Tennessee		100	
Utah			while we use latex- and polymer modified asphalts extensively, we are not using GTR in our binders or pavements.
New Hampshire	100%		
NC			1% via SAMI's only.
Montana			none
Arkansas			RMA is not used
Alaska			Dry process has been used after 2000. Before that, both wet and dry processes were used (in the 80's).
Wisconsin			
Delaware		100%	

Q6. What is your experience or perception of Rubber Modified Asphalt (RMA) in terms of its durability relative to mixtures made with neat (unmodified) asphalt?



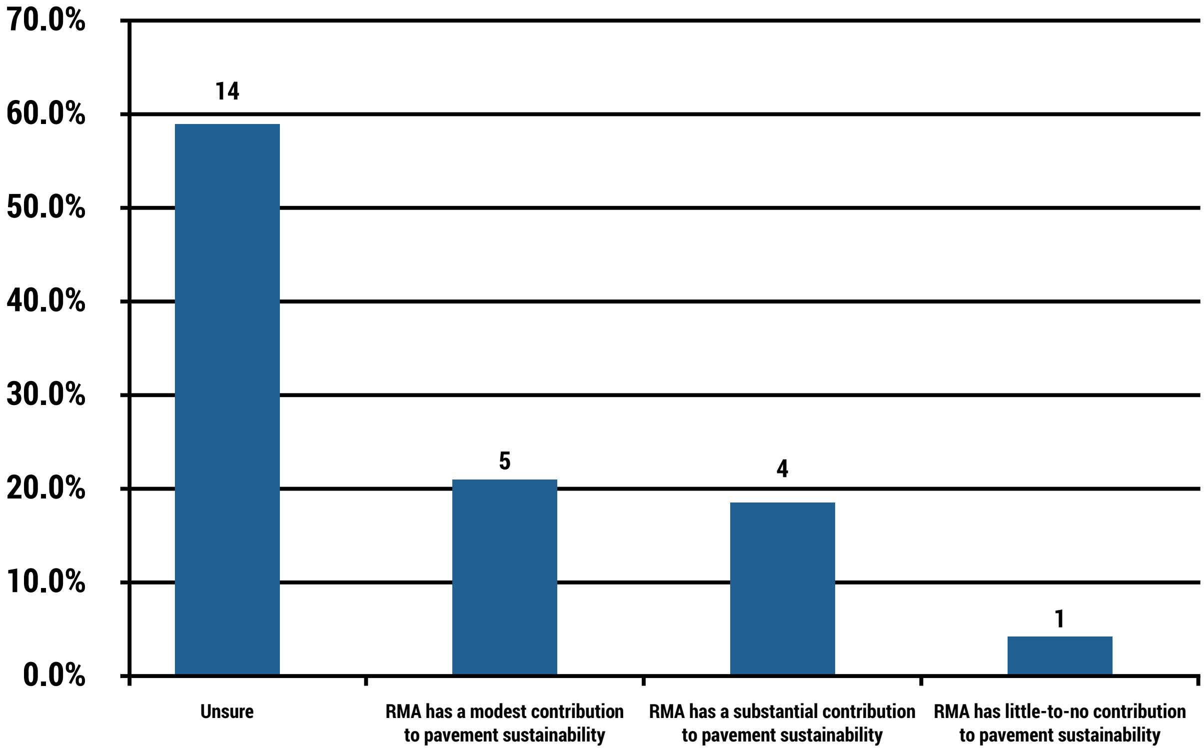
State	Response
Colorado	https://www.codot.gov/programs/research/pdfs/2014/use-of-waste-tires-crumb-rubber-on-colorado-highways
South Carolina	We typically compare to PMA; our PG 76-22 SBA modified
Ohio	RMA in Ohio is used where other modified (SBS) binders are used. Contractors also wouldn't use it when not specified in place of a neat binder due to the extra cost.
Louisiana	I don't have field performance data, but research indicated RMA was able to be used as an alternate to SBS-blended polymer. As SBS polymer mixes are considered more durable than unmodified mixes, it follows suit RMA is considered more durable.
Florida	Older specifications required asphalt rubber binder in dense-graded and open-graded friction courses. Current specifications require modified binders which can be either rubber or polymer modified.
California	University of California Pavement Research Center (UCPRC) and the Department has found that RHMA-G is more resistant to fatigue/reflective cracking compared to conventional dense graded HMA. I don't have the reports and refer you to UCPRC.
Michigan	We had a pilot project that exhibited early cracking.
Indiana	Our perception is that RMA, done right, can lead to improvements in performance. The difficulty has always been in specifications. What process do we use? How do we evaluate the material and the gains in performance?
Utah	As UDOT uses polymer-modified binders in the vast majority of applications, with some use of latex-modified asphalt in some chip seals and micro surface applications. We don't have a good basis for comparison of GTR modified asphalt or mixtures to those with neat asphalts.
NC	NCDOT has not placed a Rubber Modified Asphalt mixture. We do have a draft specification which is 5+ years old, but have never used it on NCDOT-let contract work.
Montana	I held the belief that rubber modification didn't perform well in colder climates but am learning that is probably an incorrect assumption, however our state has no experience with rubber modification of any kind in the past 20 years at least if not longer.
Arkansas	No experience with RMA
Alaska	Rubberized asphalt mixes were used in Alaskan projects in the 80's. In the mid-80's, PlusRide rubberized mixes were used in paving the A-C Couplet in Anchorage (close to downtown), and Airport Way in Fairbanks. The Anchorage mix lasted more than 30 years. Old timers report that the Fairbanks mix lasted two weeks and was replaced with conventional mix, after the occurrence of several accidents caused by the slick pavement surface. Workmanship and accurate proportion of ingredients that go into the mix are crucial for the longevity of the mix. More recently (2007-2017) a number of Anchorage projects used RMA. The aim was to minimize studded tire wear (lab testing of mixes showed acceptable wear resistance). However, field performance was less than desirable, and most of the RMA sections were replaced with PMA mixes containing hard aggregates.
Wisconsin	The research project lab tests were promising to improve mix performance over neat binder.

Q7: What is your experience or perception of Rubber Modified Asphalt (RMA) in terms of its durability relative to mixtures made with traditional polymer-modified asphalt, such as styrene-butadiene-styrene (SBS)?



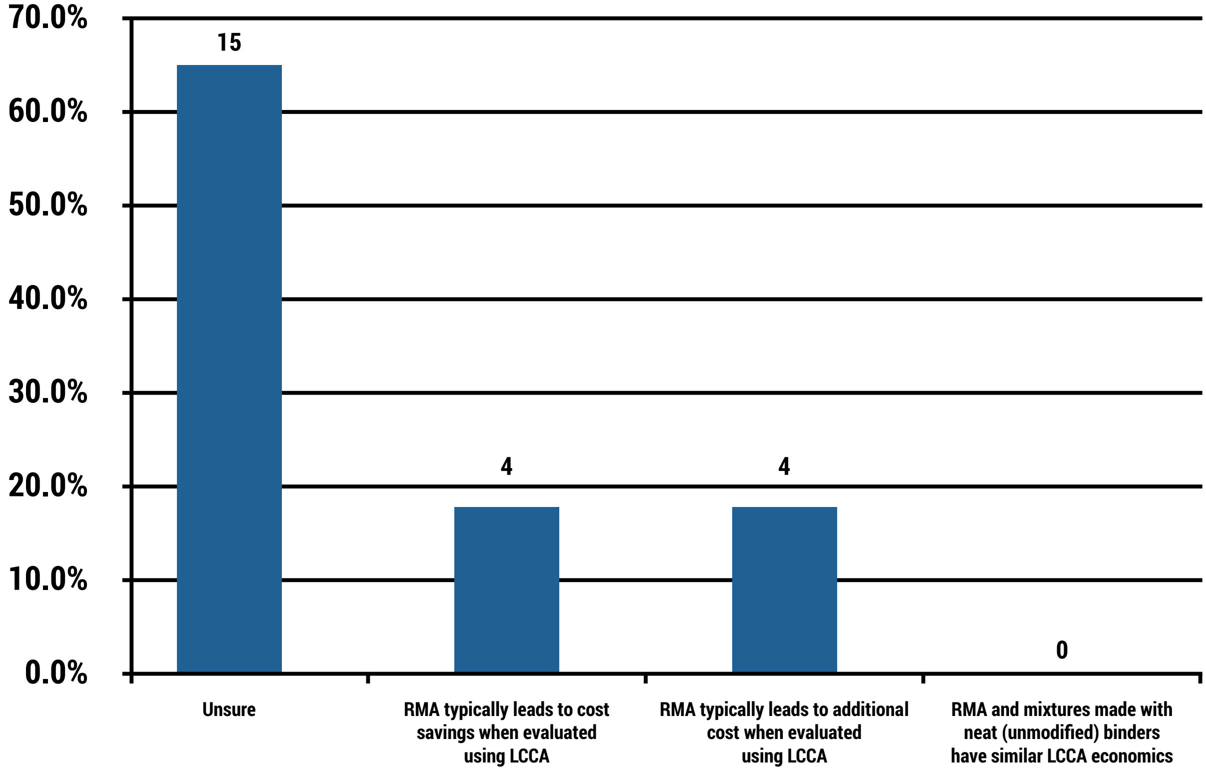
State	Response
Colorado	https://www.codot.gov/programs/research/pdfs/2014/use-of-waste-tires-crumb-rubber-on-colorado-highways
Georgia	GDOT's experience with RMA has predominately involved the use of GTR via the dry method meaning it is introduced much like a filler material and not a modified binder. The difference is seen in the mix design performance tests such as rutting measurements using the Hamburg Wheel Tracking Device where RMA (via dry method) mixtures display slightly higher rutting measurements than conventional polymer modified mixtures. Also, open-graded mixtures using RMA via the dry method are more sensitive to ambient temperature changes than PMA open-graded mixtures.
South Carolina	The road stays blacker longer gives improved contrast with pavement markings.
Louisiana	As in the previous comment, RMA is an alternate to SBS-polymer blends, so durability would be expected to be similar.
Florida	Polymer modified binder surface courses have all but replaced asphalt rubber modified binder surface courses in current production.
Michigan	We have found that it is difficult for RMA to pass PG binder tests and be cost competitive with traditional polymer modified asphalt.
Tennessee	We have only had a few experimental/demo projects that are only a few years old. We built side by side with a PMA so far so good, but rather short time frame of comparison at this point. We have opened the specification to be permissive of RMA but so far very little interest from industry.
Utah	Past work with RMA in structural asphalt mixtures was limited but proved problematic with initial rutting and long-term performance. Experiments with RMA in hot-applied chip seals were disappointing and discontinued.
NC	NCDOT has not placed a Rubber Modified Asphalt mixture.
Montana	Same comments as question 6.
Arkansas	RMA is not used
Alaska	In the high-traffic volume, high studded-tire use areas of Anchorage (largest city of the state), we started using HiMA (high-polymer modified asphalt mix) with ~7%SBS content, with hard aggregate. Preliminary field performance shows promise in minimizing wear.
Mississippi	We consider RMA as an acceptable alternative to traditional polymer modified asphalt.

Q8: What is your experience or perception of Rubber Modified Asphalt (RMA) in terms of its contribution to pavement sustainability?



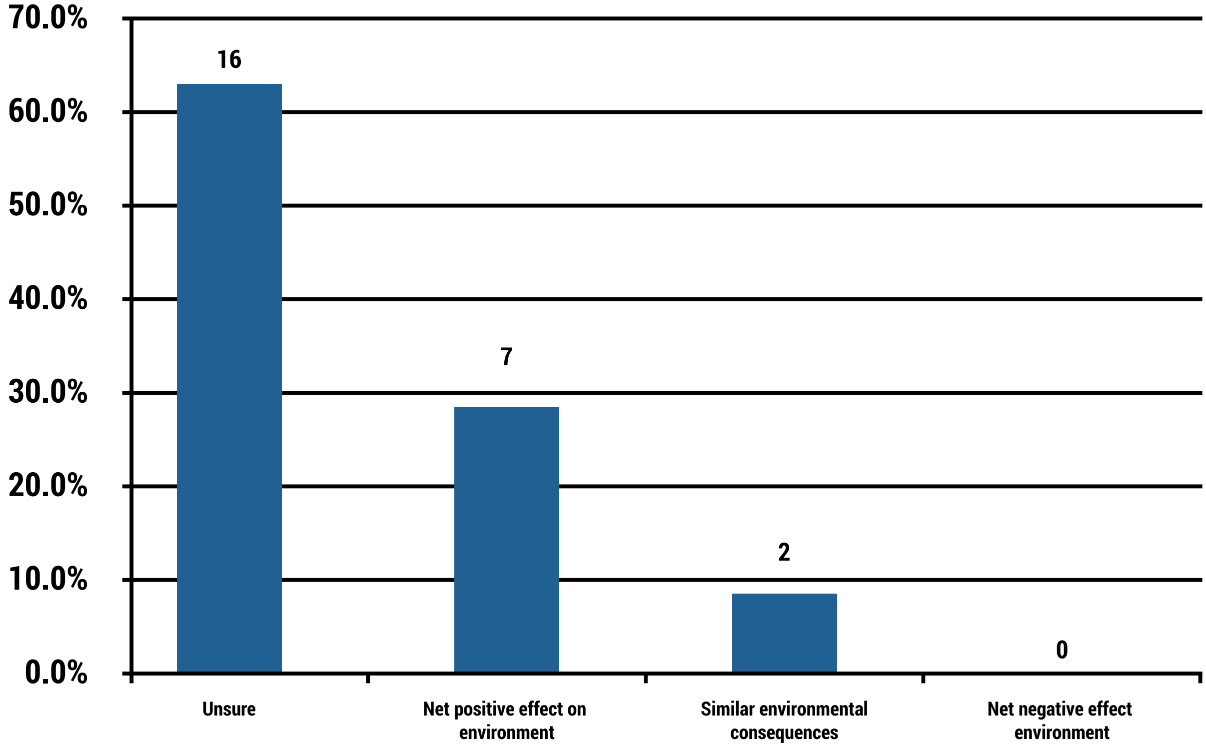
State	Response
South Carolina	We don't have any mixtures that have been down long enough to compare with conventional mixtures to accurately estimate LCA.
California	RMA consume scrap rubber tire and reduce landfills. I don't have the report but check with UCPRC for LCA on Asphalt Rubber Binder.
NC	NCDOT has not placed a Rubber Modified Asphalt mixture.
Arkansas	RMA is not used
Alaska	There is no production of GTR in the state. When rubber was/is used in our mixes, it is imported from out of state (BC, Canada; Seattle area). The aim of using RMA was to enhance mix performance, and not minimize landfill volume.

Q9: What is your experience or perception of Rubber Modified Asphalt (RMA) in terms of its contribution to pavement economics in terms of life-cycle cost analysis (LCCA) as compared to mixtures made with neat (unmodified) binders?



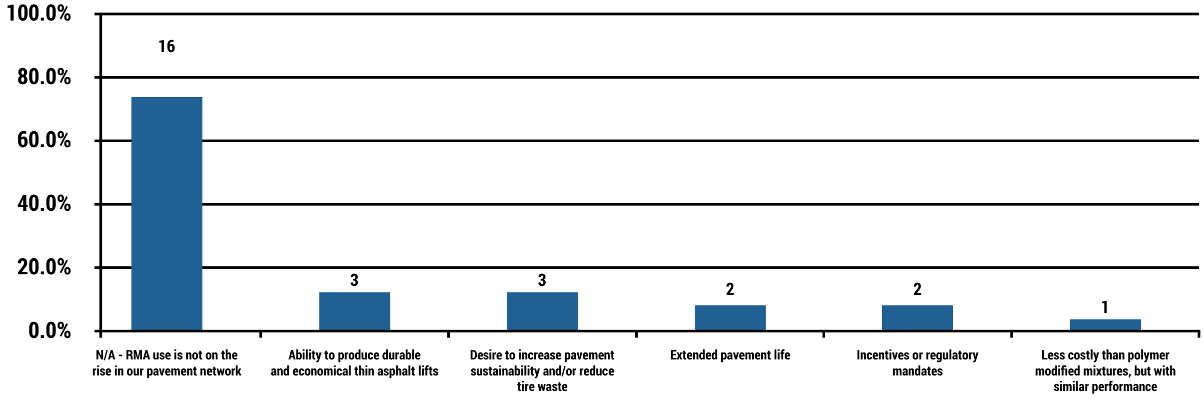
State	Response
Colorado	https://www.codot.gov/programs/research/pdfs/2014/use-of-waste-tires-crumb-rubber-on-colorado-highways
South Carolina	Same as above…certainly better than neat binder.
Louisiana	Initial costs are more due to the cost of the modifier and processing, but long-term costs should be similar to other modified blends. We typically use non-modified blends in non-wearing course applications, so comparing the two for LCCA may not be apples-to-apples.
Tennessee	While RMAs can work, there is a history of risk if the material is not managed at a higher level than is typical of other materials used in HMA EG: settling of the GTR out of the binder in a wet process, swelling after compaction for a dry process. These risks drive contractors in our experience to be hesitant to utilize RMA and if forced to do so to build the risk into their bid.
Utah	As UDOT uses polymer-modified binders in the vast majority of applications, with some use of latex-modified asphalt in some chip seals and micro surface applications. We don't have a good basis for comparison of GTR modified asphalt or mixtures to those with neat asphalt.
NC	NCDOT has not placed a Rubber Modified Asphalt mixture.
Arkansas	RMA is not used
Alaska	Initial project cost may be higher than conventional mix project, however RMA may outperform conventional mixes in certain climates (hot (AZ, CA, FL, TX) and very cold (wet process RMA is very flexible and resistant to low temp cracking). LCCA attempts have been made, refer to "LCCA of ASPHALT-RUBBER PAVING MATERIALS, by G.Hicks & J.Epps, 1999", probably found at the Rubber Pavement Assoc.

Q10: What is your experience or perception of Rubber Modified Asphalt (RMA) in terms of its overall effect on the environment as compared to mixture made with neat (unmodified) binders (including environmental impacts such as tire and road wear particle generation, carbon impacts, stormwater impacts, or the like)?



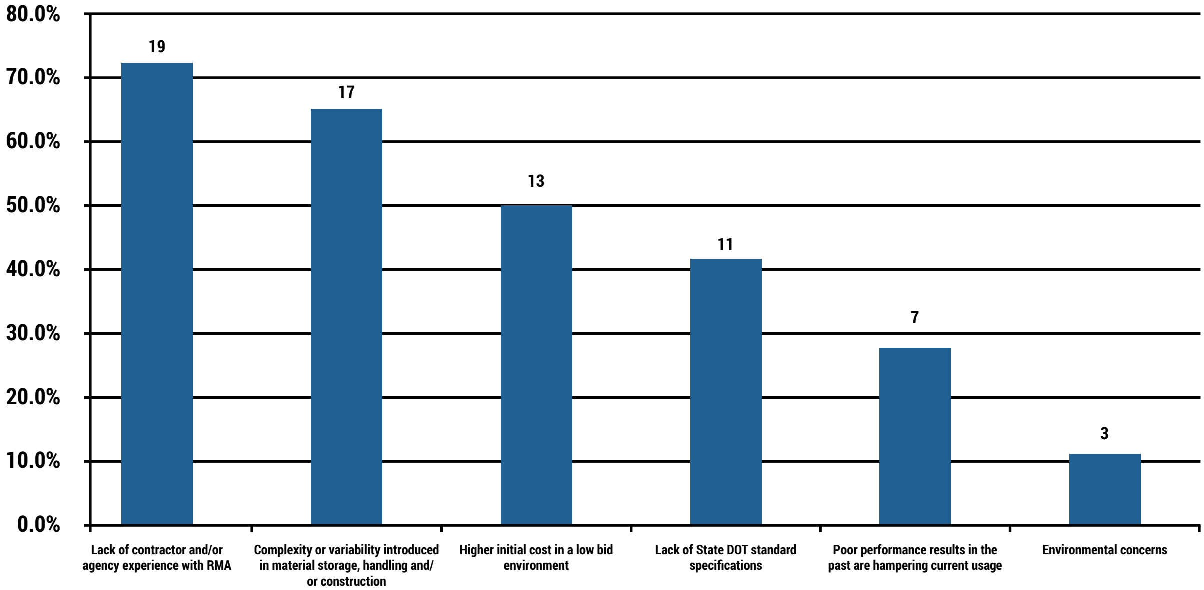
State	Response
Colorado	https://www.codot.gov/programs/research/pdfs/2014/use-of-waste-tires-crumb-rubber-on-colorado-highways
South Carolina	Having to heat the GTR higher than conventional binder and other SBS modifieds is a concern and a negative impact along with storage stability in the tanks. The availability of the material in the wet process is a major issue in finding a local supplier and being competitive with similar performing SBS 76-22 materials. I think the future is in the dry process as a mix modifier, however the process should not cost more if we are truly recycling and not trying to make a tremendous profit for being green. These are ground waste tires, finding other means of recycling like mulch in landscaping, should be more competitive with wood mulch. 10-12 dollars a bag is not a cost competitive product, same exact issue for plastic lumber, 3x4 times the price of wood for dimensional lumber.
Louisiana	RMA still requires a base asphalt, so the environmental effects of producing the neat asphalt will still be the same. The crumb-rubber reduces tire waste in landfills, which should be a positive. However, processing crumb-rubber requires additional investment which could reduce the positive impact. Crumb-rubber may not fit neatly into the "recycled" category anymore.
Utah	As UDOT uses polymer-modified binders in the vast majority of applications, with some use of latex-modified asphalt in some chip seals and micro surface applications. We don't have a good basis for comparison of GTR modified asphalt or mixtures to those with neat asphalts.
NC	NCDOT has not placed a Rubber Modified Asphalt mixture.

Q11: If RMA usage is increasing in your area, to what do you attribute the increased usage (check all that apply)?



State	Response
Georgia	Currently, use of RMA is fairly steady.
Connecticut	Asphalt Rubber chip seal is used frequently due to durability, ease of construction and low cost.
Louisiana	The main contractor using RMA was not in business in 2020, and usage was not increasing prior to 2020.
New Hampshire	We were ramping up the use of RMA but had a problem with one contractor so we have temporarily suspended production until we can revise our specifications
Arkansas	RMA is not used

Q12: What is your experience or perception of the barriers to the increased use of Rubber Modified Asphalt (RMA) usage by your agency (check all that apply)?



State	Response
Ohio	We allow RMA currently as a modification type for PG 70-22M and PG 76-22M, but those grades have been SBS modified unless we specifically spec out RMA.
Connecticut	Wide adoption of PMA over the last few years. Still evaluating a section of ARGG placed a few years back for performance.
Louisiana	Logistics of handling quality assurance for plant-blending, which was our main source of RMA, is difficult. The contractor must be experienced, and inspectors must know what to look for. Handling / storage requires additional measures to ensure rubber particles react properly and stay in suspension.
Florida	Contractors prefer polymer modified binders due storage and handling issues experienced with rubber modified binders.
North Dakota	Lack of processed recycled rubber tires in our area.
California	Caltrans encourages the used of Rubber Modified Binder.
Montana	Lack of availability. During the FHWA mandate for Crumb Rubber usage what rubber was used had to be shipped to us from Utah, thus defeating many of the supposed benefits.

STATE OF KNOWLEDGE REPORT ON RUBBER MODIFIED ASPHALT

ON BEHALF OF