INFLUENCE OF GROUND TIRE RUBBER ON STONE MASTIC ASPHALT MIXTURES AND PRELIMINARY SUSTAINABILITY STUDIES ON RUBBER-MODIFIED ASPHALT PAVEMENTS

A Thesis
presented to
the Faculty of the Graduate School
University of Missouri-Columbia

In Partial Fulfillment
of the Requirements for the Degree
Master of Science

By

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DECEMBER 2021

The undersigned, appointed by the Dean of the Graduate School, have examined the thesis entitled

INFLUENCE OF GROUND TIRE RUBBER ON STONE MASTIC ASPHALT MIXTURES AND PRELIMINARY SUSTAINABILITY STUDIES ON RUBBER-MODIFIED ASPHALT PAVEMENTS

presented by Nandita Gettu,

a candidate for the degree of Master of Science,

and hereby certify that, in their opinion, it is worthy of acceptance.

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To Amma and Nana – who have given me everything I have today.

And to every person that has taught me something.

ACKNOWLEDGEMENTS

I would like to thank Dr. Bill Buttlar for his mentorship and giving me the opportunity to be a part of this esteemed research group at MAPIL. Secondly, I express my sincere gratitude to Dr. Punyaslok Rath and Mr. Jim Meister for their guidance and help throughout my research journey. I would also like to thank my fellow researchers and colleagues at the University of Missouri for their companionship and support. I am grateful to the Civil and Environmental Engineering Department at MU for making my experience through this pandemic a smooth one. Most importantly, I would like to thank my friends, family, and teachers back home in India and the ones at Mizzou, for being the greatest source of encouragement. I express my heartfelt appreciation to Prof. V.S. Gopalaratnam, Dr. S.L. Orton, and Dr. G. Washer for helping me tremendously and presenting me with various opportunities as a new graduate student at the university that have brought me a long way. I am especially appreciative of Ashita, Christian, Nathan, Alex and Navin for believing in me and being my pillars of support through every obstacle. Last but certainly not the least, I am grateful to my parents, Padma and Ravindra for everything they have done for me.

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ABSTRACT

Over the last few decades, the use of Stone Mastic Asphalt (SMA) has been adopted by several states in the U.S. as a specialty mix for high-traffic volume purposes. Extensive research on these mixes has revealed its unique characteristics, along with significant performance benefits, such as enhanced cracking and rut resistance, that are essential to mitigate critical pavement distresses. However, certain economic issues pertaining to SMA mixtures resulting from the need for high-quality aggregates and elevated binder content make it less favored by state transportation and highway agencies. To offset these costs, numerous studies have been conducted that encourage the incorporation of recycled material, such as recycled asphalt pavement (RAP), recycled asphalt shingles (RAS) and recycled rubber into SMAs. Of these, the rubber modified SMA mixes have exhibited superior performance, and economic and sustainability benefits. The incorporation of recycled scrap tires, as ground tire rubber (GTR), into the asphalt mixtures helps reduce the accumulation of end-of-life vehicle tires in landfills, which is a growing environmental concern.

At present, the state of Missouri does not allow the use of recycled material in its SMA mixes. This thesis was proposed to assess GTR as viable means modification suitable for SMA pavements, with respect to the extreme climatic conditions of Missouri. To achieve this, two GTR-modified SMA mixes with 10% modification were compared against an unmodified SMA mix. A suite of performance tests was conducted to address prime pavement distresses, namely, Disk-Shaped Compact Tension test (DC(T)) to assess low-temperature cracking, Hamburg Wheel Tracking test (HWTT) for high-temperature deformations, and indirect tensile asphalt cracking test (IDEAL-CT) to determine intermediate-temperature fracture resistance. Further, a performance space diagram was also used to evaluate the overall performance or balance of these mixes. All experimental results concluded that the GTR-modified mixes performed better than the unmodified mix. Nevertheless, all three SMA mixes were within satisfactory performance threshold. The performance space plot clearly indicated that the GTR-modified SMA mixes were ideal for high-traffic volume pavements, in terms of thermal cracking and rutting distresses.

To understand the potential of recycled rubber modification in a holistic manner, apart from performance analyses, sustainability studies on rubber-modified asphalt (RMA) pavements were conducted on a preliminary level, as a part of this thesis work. Life Cycle Assessment (LCA) is an environmental impact evaluation tool that has played a significant role in the recent years, for promoting advances in the use of recycled material in asphalt pavements to reduce the overall environmental burden and energy consumption. A widespread and comprehensive literature review was performed with an intention to obtain significant findings and learn the varied approaches used in these pavement LCAs. The defining LCA aspects such as the goal, functional unit, system boundaries and impact categories were analyzed and compared. This study established the following key knowledge gaps and recommendations: the inclusion of the maintenance phase of pavements and end-of-life phase of scrap tires in the system boundaries are critical for RMA pavements, there is a need to assign standardized eco-credit for RMA, using up-to-date performance data including functional characteristics, and quantifying additional impact categories can significantly improve sustainability analysis outcomes for rubber-modified pavements. Addressing such issues could contribute to apprehend the full sustainability potential of rubber as a recycled material for pavement application.

CHAPTER 1 INTRODUCTION

In the United States, 94% of all paved roads are asphalt surfaced or asphalt pavements, i.e., 2.6 million miles of road, as reported by the national asphalt pavement association (NAPA). This indicates how significant and impactful research in asphalt materials and design is with respect to the pavement, environmental and transportation industry. In recent decades, the asphalt industry has focused on adopting more sustainable practices and solutions as environmental issues, such as climate change as a result of global warming, human toxicity, resource depletion, etc., continue to worsen. A major step forward towards this goal has been cutting-edge research reinforcing or modifying asphalt mixtures with various engineered recycled materials. Latest findings have shown that the use of recycled material in pavements has not only contributed to environmental sustainability but has also enhanced pavement performance and benefited the economy. Currently, the more widely known recycled components implemented in flexible pavements are recycled asphalt pavement (RAP), recycled asphalt shingles (RAS), and crumb rubber (CR), other materials such as waste plastic pellets (PE) are also being studied. Recently, the incorporation of ground tire rubber as a recycled material (GTR) in stone mastic asphalt mixes has been a topic of interest in the state of Missouri.

1.1 STONE MASTIC ASPHALT

Stone mastic asphalt (SMA), commonly referred to as stone matrix asphalt, is a specialty gap-graded mixture that is characterized by its stone-to-stone skeleton structure and a high asphalt content. SMA mixes were initially developed in Germany in the late

1960s *(1)*, with the original intention of creating asphalt mixes with a structural integrity that was better resistant to studded tires in high-traffic volume roads and drain-down of asphalt binder in the mix *(2),* and consequently designed with coarser high-quality aggregates. By the 1990s, the use of SMAs was adopted by many states in the U.S. as a premium mix, to enhance cracking and rut-resistance in the pavements, positively reflecting on the life expectancy of heavy duty and high-traffic volume pavements. Figure 1.1 highlights the current use of SMA mixes in the United States.

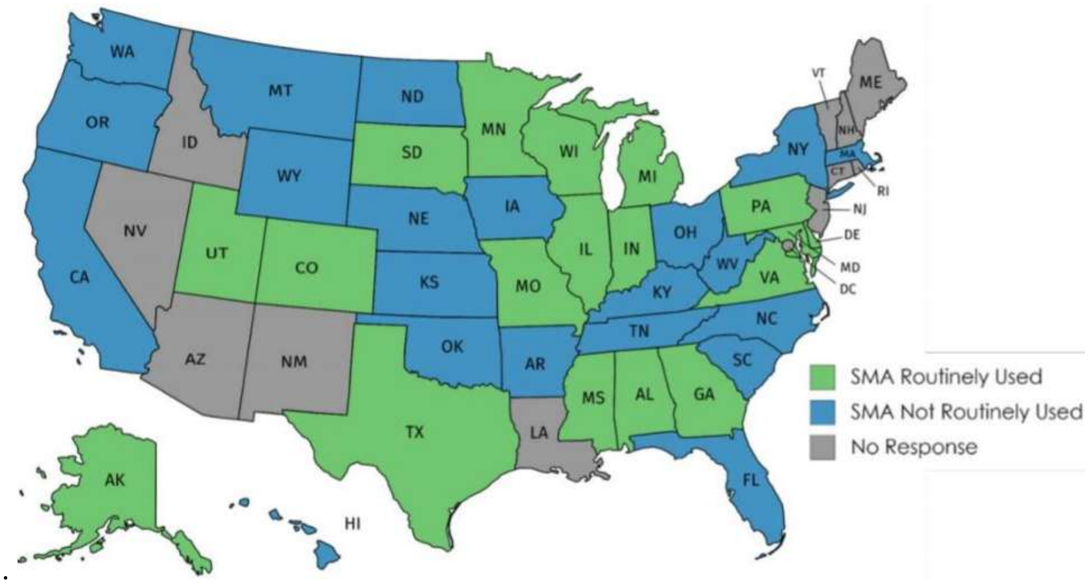

Figure 1.1 SMA usage in USA (1)

The stone-to-stone contact between the coarse aggregates enables better wheel-load dispersion and reduces the effect of high binder content *(3)*, resulting in the ability to resist surface deformation, making it suitable for high traffic conditions. The high-quality aggregates provide for more durable mixes, though the addition of modifiers and fibers, and the elevated binder content, tend to make SMA mixes more expensive. Due to this reason, many states in the Unites States are reluctant to implement it. To offset the high initial expense of laying SMA pavements, with respect to acquisition of raw materials and production costs, numerous studies and demonstration projects have been invested in exploring the utilization of recycled materials in stone mastic asphalt mixes. One such demonstration project was initiated to investigate the effect of a new crumb rubber product in SMA mixtures through the dry process in the vicinity of St. Clair, Missouri, on interstate highway I-44. This mix was evaluated against an unmodified, conventional SMA mix, and continues to be monitored for long-term performance effects. This project was led by Dr. Bill Buttlar at the Missouri Asphalt Pavement and Innovation Laboratory (MAPIL) at the University of Missouri–Columbia, in collaboration with the Missouri Department of Transportation (MoDOT) and the Missouri Center of Transportation (MCTI).

Apart from enhanced performance of stone mastic asphalt mixtures, in terms of rutting and fracture, there are several other significant advantages, such as reduction in tire noise, improved wet-weather friction and resistance to surface wear, impermeability, stability in high temperatures, etc., *(4)*. An important distinction between SMAs and conventional dense graded asphalt mixes is the difference in binder content. As a result of the high binder content in SMAs, the air voids tend to be lower than those in conventional dense graded asphalt mixture, i.e., 6% versus 7% for laboratory specimens.

Figure 1.2 Lab specimens of dense graded versus SMA mixes

1.2 SCRAP TIRES AS RECYCLED MATERIAL

A significant part of landfill wastes consists of end-of-life vehicle tires (ELTs), commonly known as scrap tires, posing as a major threat to the economy and environment as they are composed of non-degradable material. Scrap tires stockpiles are also susceptible to environmental hazards, such as leaching of toxic chemicals into waterbodies *(5,6),* uncontrolled fires (shown in Figure 1.3), disease risks, etc. 80% percent of used and discarded tires are recycled and as of 2017, 25% of these are converted into ground tire rubber for asphalt pavement purposes.

Figure 1.3 Scrap tire stockpile fire risk (Published by ABC News)

With over a billion scrap tires generated annually worldwide, using them in asphalt pavements not only allows diversion from the overflowing landfills but, if properly used, takes advantage of their potential to impart certain performance benefits to the asphalt roads.

Ground tire rubber (GTR) or engineered crumb rubber (ECR) are fine granules or crumbs of recycled rubber tires that are a blend of synthetic rubber, natural rubber, carbon black, antioxidants, fillers, and extender oils, which enable acceptable processability of the scrap tires. They are used as a binder or aggregate replacing modifier in asphalt mixtures to enhance specific performance properties, such as fatigue cracking, early onset rutting, thermal cracking, etc., as they yield high fracture energy and elastic behavior *(7),* when compared to conventional flexible pavements, influencing the durability and lifespan of the pavement. Other significant environmental benefits of GTR-modified asphalt include the significant reduction (40-88%) in tire to pavement noise *(8)*, skid resistance and resistance to moisture damage.

Another popular use for scrap tires is energy recovery through tire-derived fuel (TDR); 43% of recycled tires *(9)* are incinerated for this application resulting in environmentally harmful impacts, such as emission of toxic compounds (i.e., Greenhouse gases, smog), ore consumption, respiratory effects on humans, etc. *(10).* Recent studies suggest that TDR has a higher environmental burden or environmental impact factor than GTR.

1.3 GROUND TIRE RUBBER

Ground tire rubber (GTR) has gained popular use in the United States over the last three decades; Figure 1.4 shows the routinely use of GTR-modified asphalt in different states. GTR can be employed in asphalt mixtures through various techniques, of these the primary mixing approaches are traditional wet process, terminal blend process and modern dry process *(11)*. The traditional wet process, also known as Asphalt Rubber (AR) technology, refers to the mixing technique where rubber particles are added to the asphalt by weight of binder, acting as a binder modifier. The entire blending process is done on-site at the asphalt mixture production plant, prior to the addition of aggregates, at an elevated temperature range of 175-190°C. As per ASTM D6114, AR is defined as a blend of asphalt cement, reclaimed tire rubber and certain additives, where the rubber component is at least 15% of rubber by weight of the total blend and has reacted sufficiently to cause swelling of the rubber *(12)*. The modification process takes about 30-60 minutes and heavily relies on the swelling mechanism, during which the polymer chains absorb a portion of the oils from the base of the binder, resulting in high elasticity *(13)*. This technique typically entails the use of coarser rubber particles of about 1.5mm in size and requires special equipment to ensure constant agitation of the asphalt rubber to avoid phase segregation.

Figure 1.4 Routinely use of GTR-modified asphalt in USA (14)

While the traditional wet process served well in terms of performance for open and gap graded mixes, the technology suffered drawbacks, such as high-viscosity, poor workability and the need for continuous agitation of the modified binder *(15)*. In the pursuit of a solution to the former, the Terminal Blend wet process containing about 5-12% rubber was developed, where the production of the asphalt rubber is done at the supplier terminal, rather than on-site. This mixing technique uses finer rubber particles between the sizes of 0.2-0.6mm and the mix is stored at similar elevated temperatures as the traditional wet process, until they are delivered to the asphalt production plant. Through this process, the rubber is completely digested and dispersed, and a stable rubber-modified binder is produced having low viscosity and the ability to work well with dense graded mixtures. However, certain issues associated with the terminal blend wet process such as low fatigue resistance and reduced rubber elasticity still persist.

The early or generic Dry Process was an improved approach to rubber-modified asphalt (RMA), developed to blend the rubber as a portion of the aggregate, with 1-3% replacement by weight of the total blended aggregates in the asphalt mixture, after which the binder is added during the production process *(16)*. In this technique the rubber particles act essentially as elastic aggregates in the asphalt concrete matrix. The intention of this mixture modification method was to enhance the skid resistance and durability of the pavement *(17)*. The limitation of the dry process was that it had to be used specifically with gap-graded mixes, which was advantageous only to agencies implementing stone mastic asphalt mixes but not to others. The internal structure of gap-graded mixes allowed for the occupancy and swelling of rubber particles that were much bigger in size, i.e., in the range of 4.2-2.0 mm. For effective blending of the mix, the addition of rubber requires the incorporation of additives or modifiers to improve the mixing and compaction properties. The dry process also enables the possibility of larger quantities of rubber to be added to the asphalt mix at the plant, which turns out to be more cost effective for the contractors (*18*), alongside other advantages that improve the engineering properties of the mix such as reduction in temperature sensitivity and effects of aging in the mix *(19)*, increase in elastic performance of the binder, and improvement in the resistance to cracking and plastic deformations in the pavement. To tackle the issue of its unsuitability to conventional dense graded mixes, the modern dry process was developed, which incorporated finer GTR particles (0.6 to 0.3mm) through percentage addition of fine aggregates rather than replacement, making it appropriate for all types of aggregate blend structures. In this technique, the rubber is injected into the mixing plant through the bottom portion of the mixing drum at high production temperatures. This technology resulted in equal performance benefits as the other processes, facilitated the incorporation of chemical surfactants for prolonged rubber-binder interaction time, required less modification of the mix, and proved to be more economical. On these grounds, the modern dry process is logistically more accommodating and is now, therefore, the mixing technique preferred by contractors for rubber-modified asphalt mixtures.

1.4 SCOPE AND OBJECTIVE OF STUDY

At present, MoDOT does not allow any recycled materials in its stone mastic asphalt pavements. This thesis proposes to assess the use of recycled ground tire rubber introduced to asphalt mixtures via dry process as a viable recycling component in Missouri's SMA mixtures. A suite of performance tests was conducted to achieve this, deformation by high-temperature rutting and low-temperature fracture were the parameters used to evaluate the effect of rubber in SMA. The DC(T) fracture energy and Hamburg rut depth test results were plotted on a Performance-Space diagram to further analyze the ideality of the SMA mixes in terms of resistance to specific pavement distresses. Although the performance benefits of GTR-modified SMA can be realized by laboratory testing, it is equally important to understand the environmental impact of rubber-modified asphalt on pavement sustainability. The life cycle assessment tool was selected as a method of analysis for the sustainability studies, where the first step was taken to identify the knowledge gaps in existing literature.

CHAPTER 2 LITERATURE REVIEW

Early literature defined stone mastic asphalt as a hot mix asphalt mixture (HMA) prepared with a gap-graded aggregate gradation in order to maximize the asphalt binder content and coarse aggregate fraction *(20)*. By 1991, the first SMA mixes had been placed in the U.S., in the states of Wisconsin, Michigan, Georgia and Missouri, and by 1997, most of the other states had SMA projects of their own. A review of these projects had been conducted in 1997 by the National Center for Asphalt Technology (NCAT) and concluded that the SMA pavements showed satisfactory performance in high-traffic volume conditions, resulting in an extended pavement life and delayed road maintenance *(21).* To offset the economic effect of SMA pavements (due to higher quality aggregates and binder content), researchers began studying the possibility of incorporating waste products from different manufacturing industries. Further, the introduction of waste fibers from the tire processing industry and automotive carpet industry, into asphalt, was also motivated by the need to mitigate the disposal of large amounts of wastes into landfills *(22).*

The use of recycled materials, such as RAP, crumb rubber, waste fibers, etc., has realized performance benefits but most importantly, has aided in confronting important economic and environmental concerns. To put into perspective the gravity of some of these environmental issues, as reported by the Rubber Manufacturing Association (RMA), it can be noted that three tractor trailer loads of crumb rubber derived from scrap tires are discarded into landfills twice every month by a single company's tire processing plant, with a total of approximately 33,00,000 tires processed into crumb rubber per year. For this reason, the incorporation of crumb rubber or GTR in asphalt mixes has been highly encouraged.

The first attempts of blending rubber particles into asphalt mixtures were made in the mid-1960s by an engineer in the Federal Highway System named Charles McDonald, who is today considered the father of asphalt-rubber *(23),* with the intention of generating a solution to revive pavements that had failed on account of preliminary cracking. Later in 1978, he patented the wet process mixing technique, which was more suitable for chip seals, seal coats, surface treatments, etc. In the same year, the dry process technology was introduced in the United States by a company called EnviroTire, though its adoption was hindered through the years due to its exclusivity to gap-graded mixes *(16)*. By the 1980s, the generic dry process was developed, using larger rubber aggregates at less than 2% rubber content by weight of mix *(24)*. However, through the 1990s and early 2000s, the mandates implementing the use of rubber made in different states were not successful due to the lack of knowledge in mixture production, laying processes suitable for RMA pavements, high initial capital investment and initial trials showing discouraging results *(25).* In the past decade, advancements have been made in rubber-modified asphalt technologies, leading to the development of the modern dry process that resulted in good performance and extended pavement life, amongst other benefits. Through analytical results of the indirect tensile test and wheel-tracking test, Cao et al. *(18)* concluded that rubber-modified asphalt mixes using the dry process present improved mixture performance, in terms of high-temperature rut resistance and low-temperature cracking. The availability of pre-treated rubber products, such as SmartMix by Liberty Tire and Elastiko by Asphalt Plus, for the purpose of this mixing technique, have become popular during this time.

With respect to stone mastic asphalt mixes, crumb rubber has been a successful means of modification, as they have proved to work well with gap-graded mixes. SMA mixes modified with fibers or polymers have been largely beneficial in inhibiting drain-down in the asphalt, acting as a binder stabilizer. Several research studies have reported various benefits of using GTR in SMA mixes, including enhanced fatigue resistance leading to better cracking and rutting characteristics, improvement in overall mixture stability, and prevention of binder drain-down. Mashaan et al. evaluated the effect of crumb rubber as a modifier in SMA mixes, through the stiffness and fatigue properties at different modification levels. Experimental results from the same author's indirect tensile fatigue tests indicated that such mixes exhibited significantly higher fatigue life than conventional SMA mixes (*26*). An additional observation was made that the resilient modulus could be a more accurate indicator to estimate the fatigue life of asphalt mixes as it is a direct measure of stiffness for unbound materials in pavement systems *(27).* Another study by the same authors *(28)* concluded that the stiffness modulus of crumb rubber reinforced SMA mixtures were less severely impacted by high temperatures in comparison to unmodified SMA mixes.

Apart from all the performance and environmental advantages associated with the incorporation of ground tire rubber into stone mastic asphalt mixes, several noteworthy concerns still exist that require further investigation and solutions. GTR-modified mixes are not suitable for low-temperature paving, i.e., when the atmospheric and pavement surface temperature falls below 13°C *(29).* Rubber modification also poses difficulties during plant mixing, making its implementation less favored by contractors and therefore require chemical treatments to facilitate better workability *(30)*. Although the use of GTR is a more long-term cost-effective solution to counterbalance the high initial investment of SMA mixes, the manufacturing costs of rubber-modified asphalt is moderately higher than conventional HMA *(31)*. The most prominent concerns are the exceedingly high heat demand and toxic fumes emission in the mixing and compaction phase, which affect the immediate working environment, in addition to contributing to the global warming potential of rubberized mixes.

CHAPTER 3 DESCRIPTION OF THE EXPERIMENTAL WORK

As discussed in the previous chapter, there is significant motivation for the use of ground tire rubber (GTR) in SMA mixes. However, waste materials have hitherto not been used in the State of Missouri, with the exception of RAP and RAS being used in exceedingly limited quantities. Therefore, it is imperative to assess the potential of using recycled rubber in SMA mixes, as they are particularly advantageous in high-traffic highways in terms of cracking and rutting resistance. Further, there is an environmental motivation to reduce the disposal of scrap tires in landfills in this region.

Aided by MoDOT, this research work was established to assess the incorporation of waste rubber as a viable recycled material suitable for SMA mixes in Missouri. Two types of GTR with possibly different chemical compositions and/or treatments, denoted as GTR-I and GTR-II, were chosen for this performance testing suite. The suite consisted of the DC(T) – disk-shaped compact tension test (for assessing low-temperature crack performance), HWTT – Hamburg wheel tracking test (for determining the rut resistance), and IDEAL-CT – indirect tensile asphalt cracking test (for assessing crack performance at intermediate-temperatures). Based on the results, a performance-space diagram was used to evaluate the overall performance of the mix in terms of rut depth in HWTT and low-temperature fracture energy from DC(T).

The laboratory mix designs were replicated from job mix formulas (JMF) of the virgin SMA and GTR-modified plant-produced SMA mixes received from various contractors. Appropriate to the extreme climatic conditions of Missouri, Superpave asphalt binder PG 64-22 was selected for the SMA mix designs. The high temperature is in accordance with the 7-day average high pavement temperature, while the lower limit pertains to a single occurrence low temperature *(32)*. The volumetric properties and performance test results of the two 10% GTR-modified SMA mixes were compared against a virgin SMA mix, denoted as the control mix. The details of the materials used in the mixes are given in the following sections.

3.1 SMA AGGREGATE BLEND

A significant and evident difference between conventional asphalt and stone mastic mixes is their aggregate stockpile blends. SMA mixes consist of a high percentage of coarse aggregate stockpiles reflecting in their distinct stone-to-stone skeleton structure designed to aid rut resistance and other performance enhancing properties. The plot in Figure 3.1 represents the gap-graded aggregate stockpile blend of the SMA mixes tested, with respect to the passing percentage of particles and standard Superpave sieve sizes.

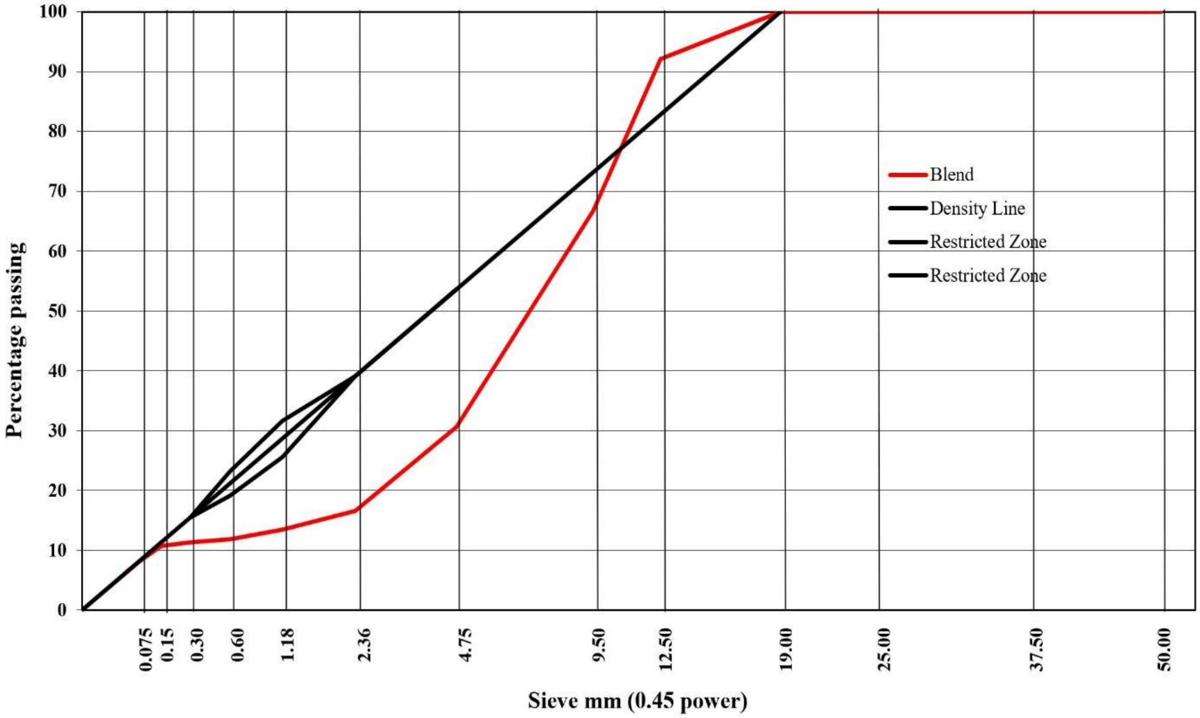

Figure 3.1 Aggregate stockpile blend

The nominal mix aggregate size (NMAS) is selected as per NCAT's SMA gradation specification bands, in this case is 12.5 mm; shown in the plot along with the restricted zones of the mix and maximum density line. The maximum aggregate size of the blend is 19.0 mm, defined by the smallest sieve size passing 100% of the particles. All blends consist of the limestone and granite stockpiles as described in Tables 3.1 and 3.2, along with details regarding the aggregate gradation, the source and location of procurement of the aggregate stockpiles. ASTM Class C fly ash was employed as mineral filler in the GTR-modified SMA mixes, whereas limestone filler was used for the virgin SMA mix.

Table 3.1 Aggregate gradation for virgin SMA mix

Agg. Material	Limestone	Granite	Limestone	Limestone	Lime Filler
Location	Eureka	Iron Mountain	Eureka	Eureka	Genevieve
Sieve size	**3/4"**	**3/4"**	**3/8"**	**Scrg**	**MF**
2" (50.8mm)	100.0	100.0	100.0	100.0	100.0
1 1/2" (38.1mm)	100.0	100.0	100.0	100.0	100.0
1" (25.0mm)	100.0	100.0	100.0	100.0	100.0
3/4"(19.0mm)	100.0	100.0	100.0	100.0	100.0
1/2" (12.5mm)	80.0	90.0	100.0	100.0	100.0
3/8" (9.5mm)	40.0	48.0	100.0	100.0	100.0
No.4 (4.75mm)	3.0	3.0	61.0	75.0	100.0
No.8 (2.36mm)	2.0	1.0	10.0	45.0	100.0
No.16 (1.18mm)	1.0	1.0	2.0	35.0	100.0
No.30 (600µm)	1.0	1.0	1.0	25.0	100.0
No.50 (300µm)	1.0	1.0	1.0	22.0	99.5
No.100 (150µm)	1.0	1.0	1.0	18.0	99.5
No.200(75µm)	1.0	0.2	1.0	15.0	75.0

Table 3.2 Aggregate gradation for GTR-modified SMA mix

Agg. Material	Limestone	Granite	Limestone	Limestone	Fly ash
Location	Eureka	Iron Mountain	Eureka	Eureka	Springfield
Sieve size	**3/4"**	**3/4"**	**3/8"**	**Scrg**	**MF**
2" (50.8mm)	100.0	100.0	100.0	100.0	100.0
1 1/2" (38.1mm)	100.0	100.0	100.0	100.0	100.0
1" (25.0mm)	100.0	100.0	100.0	100.0	100.0
3/4"(19.0mm)	100.0	100.0	100.0	100.0	100.0
1/2" (12.5mm)	80.0	90.0	100.0	100.0	100.0
3/8" (9.5mm)	40.0	48.0	100.0	100.0	100.0
No.4 (4.75mm)	3.0	3.0	61.0	75.0	100.0
No.8 (2.36mm)	2.0	1.0	10.0	45.0	100.0
No.16 (1.18mm)	1.0	1.0	2.0	35.0	100.0
No.30 (600µm)	1.0	1.0	1.0	25.0	100.0
No.50 (300µm)	1.0	1.0	1.0	22.0	100.0
No.100 (150µm)	1.0	1.0	1.0	18.0	97.0
No.200(75µm)	1.0	0.2	1.0	15.0	95.0

3.2 GTR MODIFIER

The performance of stone mastic asphalt mixes with 10% addition of GTR-I and GTR-II to the mix, by weight of binder, i.e., approximately 0.5% weight of the whole mix, were analyzed. The GTR crumbs (as shown in Figure 3.2) were manufactured through the cryogenic fracture method, where the mechanically shredded scrap tire bits are frozen with liquid nitrogen to a temperature of -80°C to embrittle them, and further reduced to crumbs by crushing, typically between the size of 4.75mm to 9.5mm *(33)*.

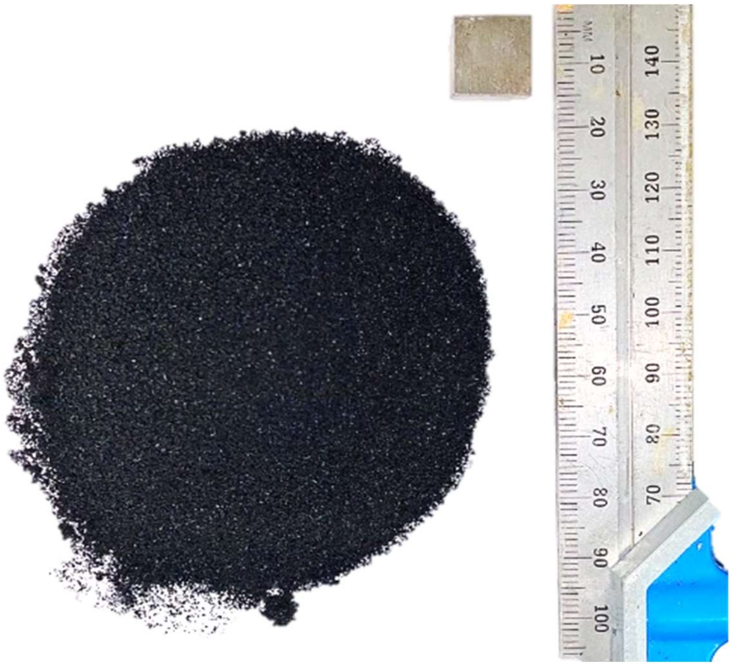

Figure 3.2 Ground tire rubber granules with scale

The incorporation of GTR into the SMA mixes is done through the dry process. The rubber particles are blended with the aggregates in the asphalt mixing plant, prior to the addition of asphalt binder to the mix (schematically shown in Figure 3.3), after which the manufacturing process begins. High production and mixing temperatures in the range of 149°C and 177°C are used, as recommended by FHWA *(34)*.

To simulate similar plant mixing conditions and results in the laboratory, with respect to the dry process, the rubber granules are blended into the binder in a high shear mixer at 170°C at a speed of 3500 rpm. During the mixing process, the rubber experiences a diffusion-infused volume expansion when exposed to the binder *(35),* and consequently swells to about twice their size. The GTR-modified binder is then mixed in with the aggregates, ensuring that drain-down of the binder does not occur and enforcing uniform coating of the aggregates, by frequently stirring the mix.

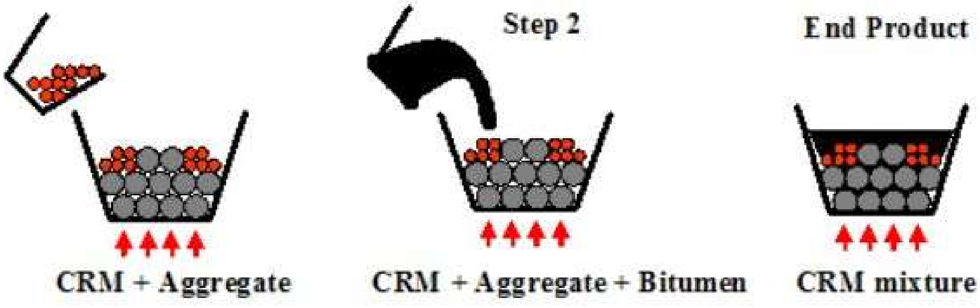

Figure 3.3 Dry mixing Process (36)

3.3 ADDITIVES

The integration of recycled material or any type of modifying material in asphalt mixes make the incorporation of additives such as waxes, chemicals, polymers, etc. necessary, as they have the tendency to improve the properties of the mixture, such as the viscosity of the asphalt. For GTR-modified SMA mixes using the dry process, the use of additives is required as the activated rubber particles tend to stiffen the asphalt binder. Subsequently, the additives provide the desired mixing and compacting characteristics in the mix, without necessarily influencing the performance or volumetric properties of the mix and preventing drain-down of the binder.

3.3.1 Warm Mix Additives

The high energy costs and elevated greenhouse gas emissions involved in the production of Hot Mix Asphalt (HMA) led to the necessity of a more fuel-conserving and carbon footprint conscious method of asphalt production. Consequently, Warm Mix Asphalt (WMA) technologies have the capacity to produce asphalt at temperatures 20°C to 40°C lower than HMA mixes that require high mixing and compaction temperatures of 150°C to 180°C *(37)*, significantly reducing the energy consumption and minimizing toxic emissions (shown in Figure 3.4). Accordingly, Yang et al. (*38*), and several other recent sustainability studies have strongly recommended the use of warm mix technology in order to significantly lower emission levels, as well as the exorbitant energy expended during the material production phase of rubber-modified asphalt mixtures.

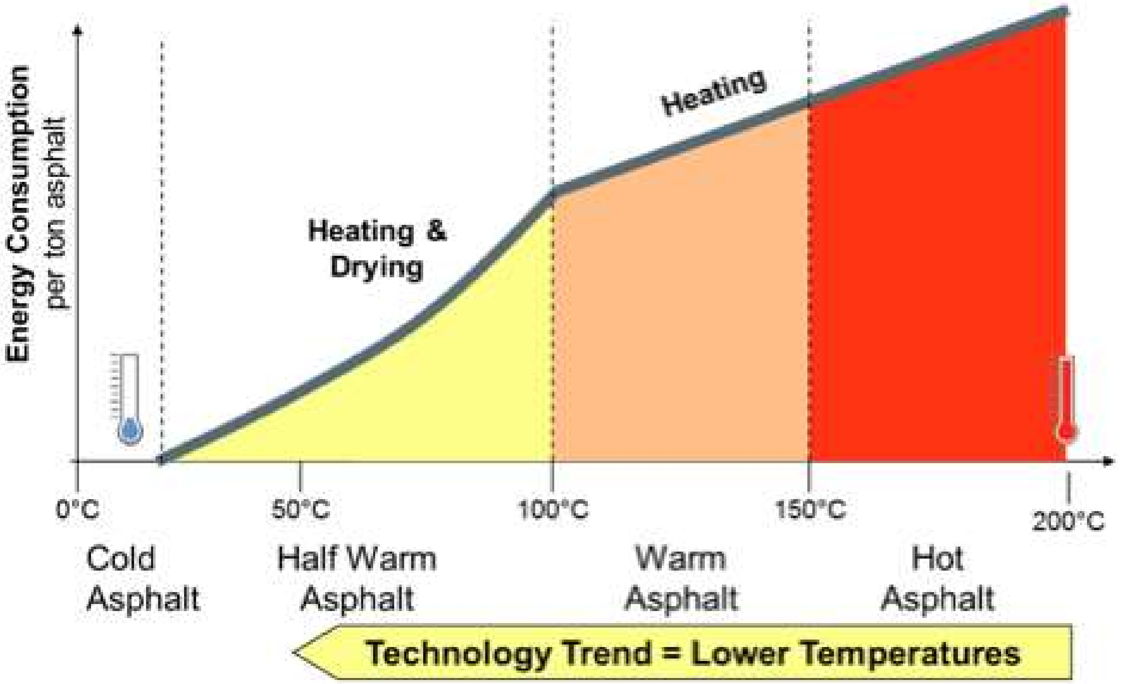

Figure 3.4 Temperature range of different asphalt mixes (39)

WMA additives increase the workability and compactability of the mix by reducing the viscosity of the binder at lower temperatures. Other benefits of WMA mixes include an extended time period for transportation and laying of asphalt, safer working environment due to less CO_2 emissions and cooler working conditions, and earlier setting time of the asphalt pavement. The most commonly used additives are classified into (i) foaming agents, (ii) chemical additives and (iii) organic additives. Chemical additives enable the reduction of surface energy within the aggregate-binder interface of the asphalt matrix, ensuring proper coating of the aggregates. This work used a proprietary chemical WMA additive called Evotherm-P14 in the SMA mixes, replacing the weight of the asphalt binder by 0.5%, in order to reduce the production temperature of the mix, attaining temperatures up to 32°C lower than the required temperatures for conventional HMA mixes. Further, this additive also imparts antistrip properties to the asphalt mix.

3.3.2 Cellulose fibers

Cellulose fibers are considered a mandatory additive in SMA mixtures in Missouri State as they have the ability to absorb and stabilize the binder. These long fibers are obtained through chemical treatment of natural wood, and they mainly consist of cellulose, hemicellulose and lignin, with some impurities. They are uniformly distributed within the asphalt mixture, creating a three-dimensional network structure due to their low specific gravity and large surface area *(40)*. Several other advantages of cellulose fibers include arresting the propagation of micro-cracks and improving self-healing ability and high-temperature performance (i.e., lower rutting in pavements). For the SMA mixes tested in this work, the cellulose fibers were added at 0.3% weight of the whole mix (see Appendix A). The texture of the fiber can be observed in Figure 3.5. For laboratory mixing, this supplementary additive is incorporated into the mixture after the aggregates and binder have been blended.

Figure 3.5 Cellulose fibers

CHAPTER 4 EXPERIMENTAL METHODOLOGY

This research focuses on the performance of ground tire rubber modified SMA mixes, in terms of fracture and rut resistance, with the materials and proportions described in the previous chapter. The ability for pavements to withstand distresses significantly depends on the fracture potential of the asphalt mixture, and therefore, the DC(T) test was conducted to mitigate thermal cracking, and the IDEAL-CT test was used to analyze fracture energy of the asphalt at intermediate temperature. The Hamburg wheel-tracking test was done to determine the rutting susceptibility of the asphalt mixtures. A schematic representation of the suite of tests conducted for the control, GTR-I SMA and GTR-II SMA mixes are given in Figure 4.1.

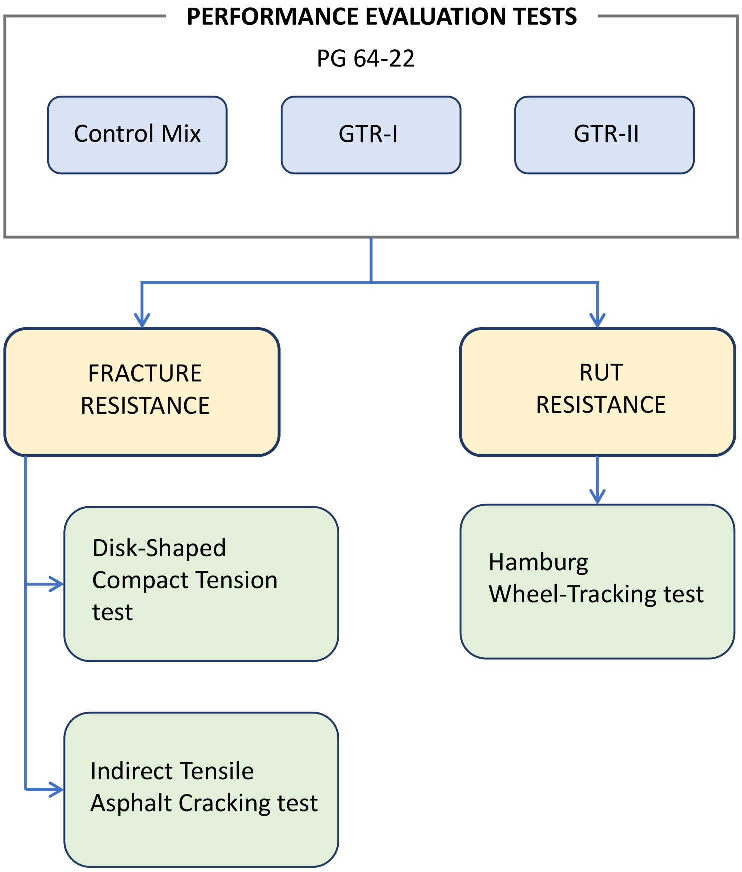

Figure 4.1 Flowchart of testing suite

This chapter presents a detailed description of each experimental procedure and its significance to the evaluation of the respective asphalt mixtures. Standardized tests for characterization of the material for a balanced mix design were also conducted and presented in the following section. All specimens for the respective tests were compacted in a Superpave Gyratory Compactor (SGC) that used a ram pressure of 600 kPa, suitable for cylindrical molds of 150 mm diameter with variable height.

4.1 VOLUMETRIC PROPERTIES

The volumetric properties of asphalt mixtures are an integral part of defining a balance Superpave mix design, with modifications to accommodate requirements of stone mastic asphalt mixes and the incorporation of recycled material. All asphalt mixes in the testing suite were designed for 4.0% targeted air voids, which is the standard specification for stone mastic asphalt mixes as per NAPA, with a binder content (AC) of 6.2% for the GTR-modified mixes and 6.0% for the control mix, which is relatively high compared to conventional asphalt mixes. The slight difference in binder content between the mixes is attributed to the fraction of AC absorbed by the crumb rubber. The final mix designs used are given in Appendix A. Due to the lower percentage of air voids, the SMA mixes have higher density compared to conventional dense-graded mixes. The air voids are calculated based on the theoretical maximum specific gravity of the loose asphalt mixture (Gmm) and the bulk specific gravity of the compacted mix, as per ASTM D2041 and ASTM D2726, respectively *(41,42)*. The binder content of these mixes is seen to be higher than the usual binder content of 4.5-6% in conventional HMA mixes. The void structure of the asphalt matrix is defined by the volumetric properties. The air void calculations for the lab specimens are given in Appendix B.

4.2 DISK-SHAPED COMPACT TENSION TEST

The Disk-shaped Compact Tension Test, with the acronym DC(T), was developed to measure the fracture energy of asphalt specimens at low temperatures, and is generally performed at 10°C warmer than the Performance Grading (PG) low temperature of the mixture, in accordance to ASTM D7313-13 *(43)*. The fracture energy obtained through this test is used to represent the fracture response of asphalt concrete in terms of the crack resistance and is part of performance-type specifications needed to control the various distresses that typically occur in during freeze-thaw cycles, presenting themselves as transverse cracks across the pavement when the thermal stresses exceed the tensile strength of the pavement. The DC(T) test specimen, with the dimensions shown in Figure 4.2, is compacted in a Superpave gyratory compactor (SGC).

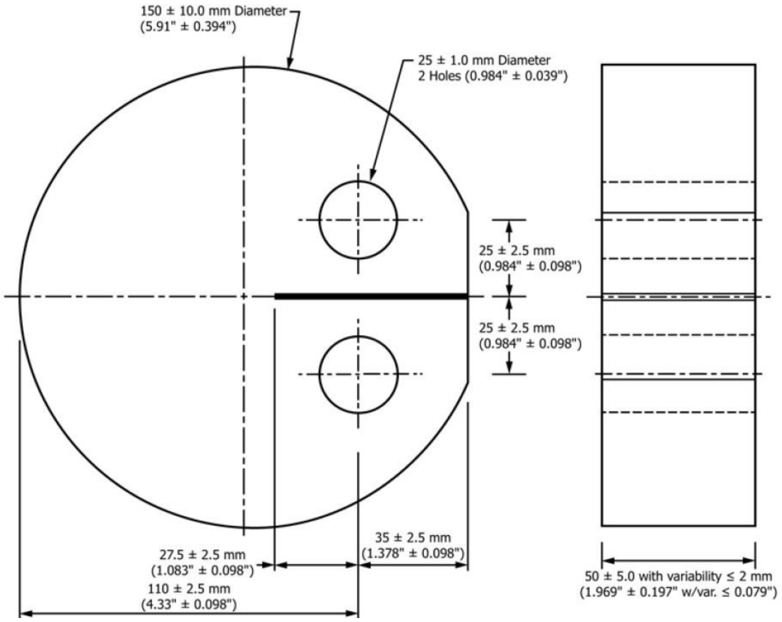

Figure 4.2 DC(T) specimen dimensions (43)

This test is performed under tensile loading to induce Mode I fracture in the specimen through crack-mouth opening displacement (CMOD) control. Two loading holes are drilled close to the center of the specimen to facilitate the tensile loading of the specimen. A notch is sawed through the specimen as shown in order to induce crack propagation diametrically along the specimen. The specimen is conditioned in a temperature-controlled chamber for 8-16 hours prior to testing. It is then mounted on the loading frame with a constant or seating load of 0.2 kN. A clip-on gage is affixed across the notch on the knife edges to measure the relative displacement of the crack mouth. The test setup is shown in Figure 4.3. The disk-shaped compact tension test is run under crack mouth opening (CMOD) control mode at a rate of 0.017 mm/sec. The two channels of data acquisition are load and CMOD. The specimen is loaded in tension at the required temperature, and after it reaches the cracking limit, the test cycle is complete when the post-peak load reduces to 0.1 kN.

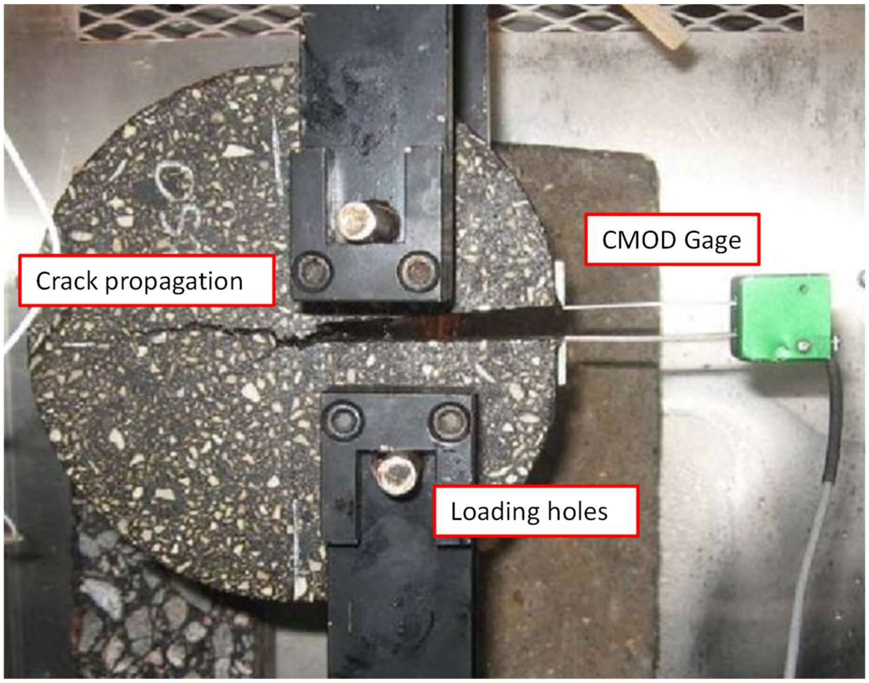

Figure 4.3 DC(T) test setup (44)

The fracture energy is the measure of energy required to extend a crack by a unit. This is computed from the area under the curve of the fitted load versus CMOD plot (Figure 4.4) and the dimensions of the specimen, using Equations (1) and (2):

$$A = \int_0^{\delta\mathrm{max}} \mathrm{P}(\delta)\mathrm{d}\delta \qquad \text{.....(1)}$$

$$G_f = \frac{A}{\mathrm{b}\times\mathrm{L}} \qquad \text{.....(2)}$$

where A is the area under the Load-CMOD$_{\mathrm{fit}}$ curve, $P(\delta)$ is the load CMOD value, δmax is the maximum CMOD value, Gf is the DC(T) fracture energy, b is the width of the DC(T) specimen and L is its ligament length that fractures.

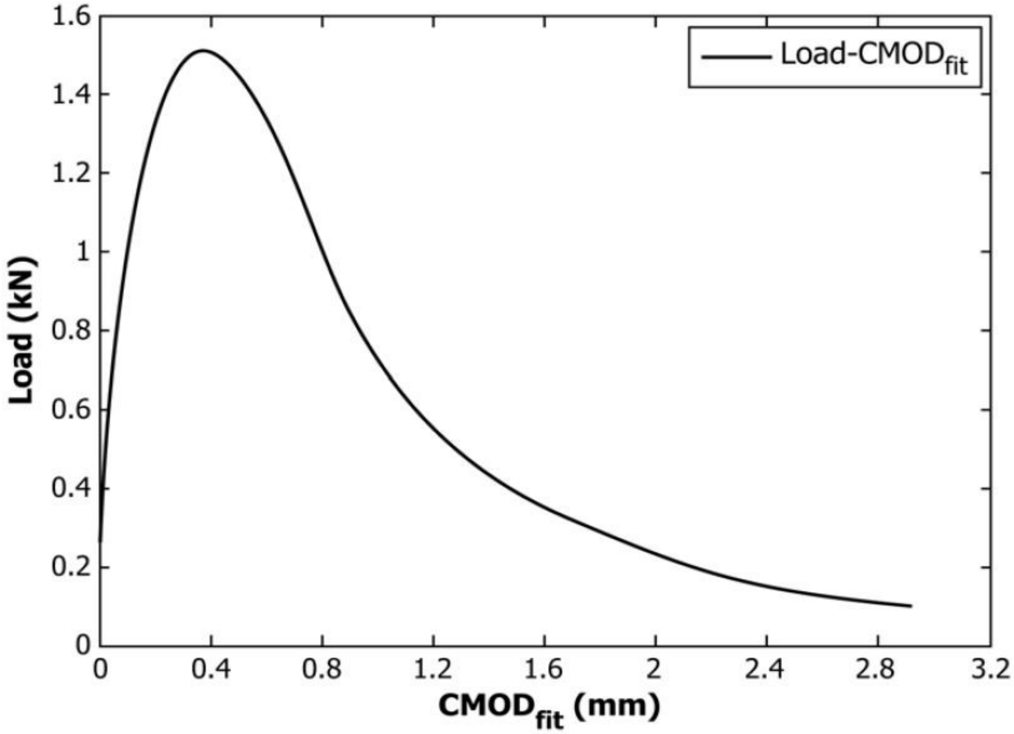

Figure 4.4 Load-fitted CMOD plot

4.3 HAMBURG WHEEL-TRACKING TEST

The Hamburg wheel-tracking test (HWTT) is performed as per AASHTO T324-19 Standard in order to determine the rutting resistance of an asphalt mixture *(45)*. The purpose is to simulate extreme shear strains by vehicular traffic loading conditions on asphalt pavements, in an accelerated manner, resulting in permanent deformation. The test is conducted in submerged condition, by immersing two pairs of specimens with equal air voids, in a water-bath maintained at 50°C, and then subjecting them to passes of steel wheel loads of 71.7 kg, as shown in Figure 4.5. The Hamburg specimens are compacted in a cylindrical SGC with a height of 62 mm and a diameter of 150 mm. The rut depth or deformation of the specimens is observed after 20,000 passes, which is in turn used for pavement evaluation of the mix in terms of rutting potential.

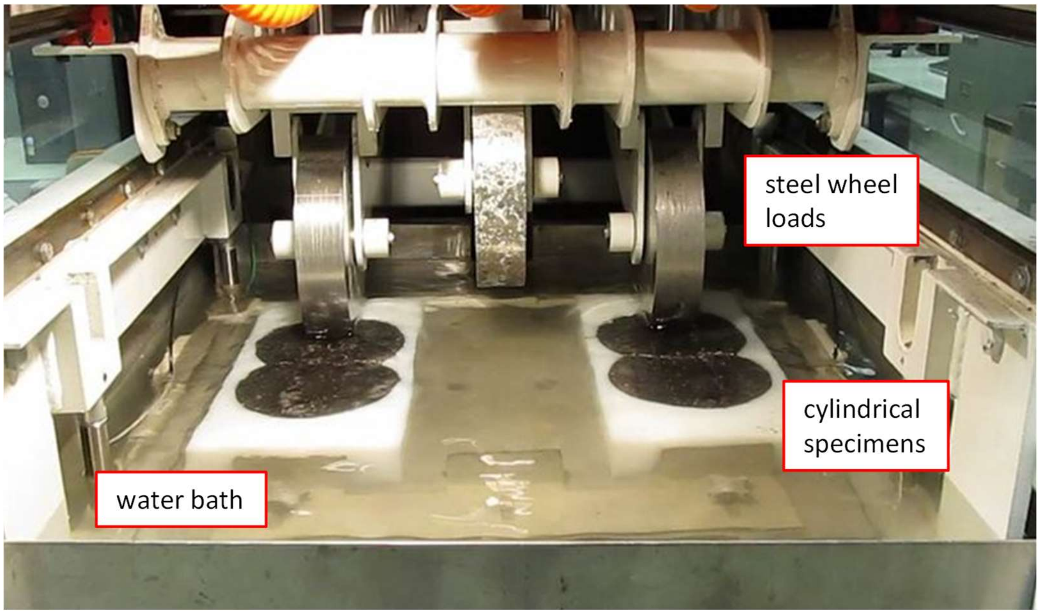

Figure 4.5 Hamburg wheel-tracking test setup (46)

The rut depth is plotted against the number of passes as shown in Figure 4.6, and the stripping inflection point and the stripping slope, which are parameters used to evaluate the moisture sensitivity of the asphalt mix, are obtained from this plot. The stripping inflection point is defined as the number of passes corresponding to the intersection of the creep and the stripping slopes. However, this was not relevant to the present work and was, therefore, not calculated.

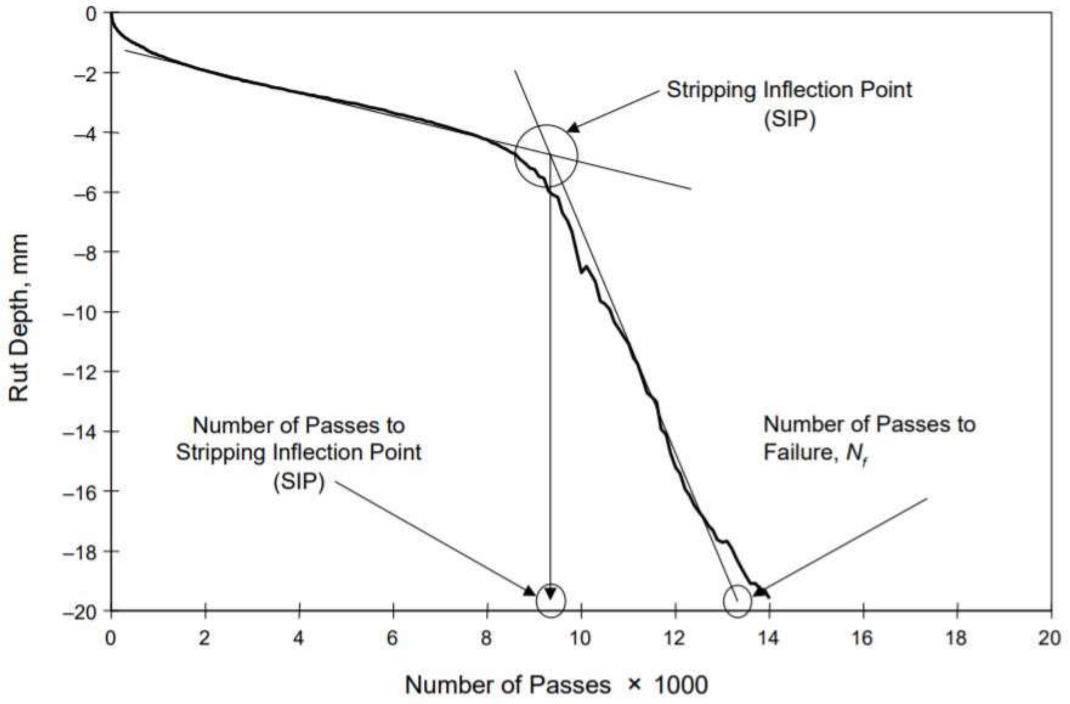

Figure 4.6 Hamburg curve with test parameters (45)

A significant feature of SMA mixes is their enhanced ability to withstand rutting deformations, which is a result of the robust contact between with the coarse aggregates of the mix. Therefore, the rutting parameter derived from the HWTT rutting test is an important factor for evaluating the performance of stone mastic asphalt mixes.

4.4 INDIRECT TENSILE ASPHALT CRACKING TEST

The indirect tensile asphalt cracking test (IDEAL-CT), developed more recently, is conducted to determine the fracture resistance of asphalt mixtures at intermediate temperatures, i.e., resistance to fatigue cracking. These distresses occur due to either cyclic loading or high strains in the pavement. The parameter obtained from this test is the cracking tolerance index, denoted as CT_{index}. As per ASTM D8225-19 Standard, the cylindrical IDEAL-CT specimens are prepared in a Superpave Gyratory Compactor with dimensions of 62 mm in thickness and a diameter of 150 mm *(47)*. The specimens are loaded in axial tension (see Figure 4.7) with the load-line displacement (LLD) increasing at a constant rate of 50 min/mm, at a testing temperature of 25°C.

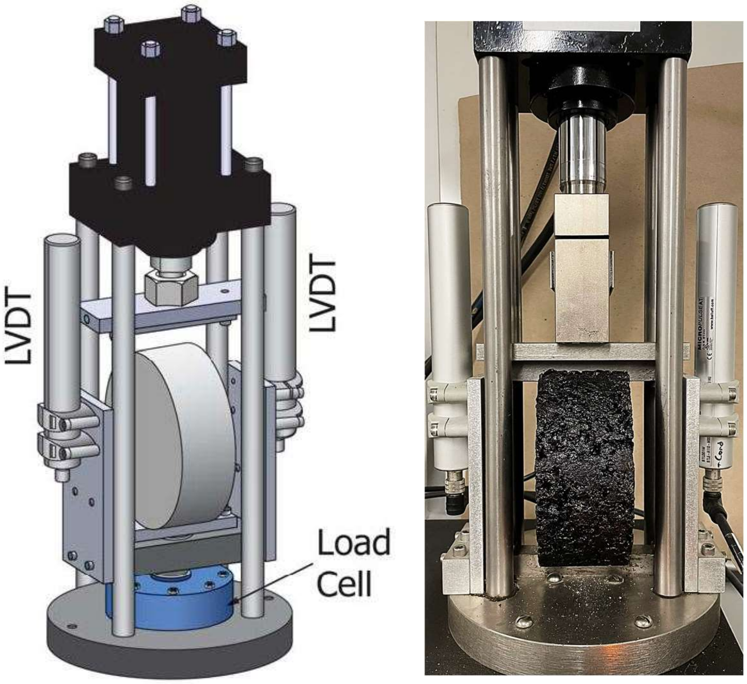

Figure 4.7 Specimen in Axial Loading Device (47)

The asphalt specimens are placed at 25°C in a temperature-controlled environmental chamber for 2 hours before testing. The conditioned specimens are then mounted into the IDEAL-CT fixture, as shown in Figure 4.7. The LLD is applied on the specimen until the load drops to 100 kN, upon which the test is terminated. The failure energy is terms of Joules/m^2, calculated by dividing the area under the load versus the average LLD curve by the failure area, as indicated in Equation (3). The failure energy along with other test parameters, such as displacement and the post-peak slope, are used to compute the CT$_{index}$, given in Equation (4).

$$G_f = \frac{Wf}{D \times t} \times 10^6 \qquad ...(3)$$

where G_f is the failure energy of the specimen, W_f is the area under the load versus average LLD curve, D is the diameter of the specimen and t is its thickness.

$$\mathrm{CT}_{Index} = \frac{t}{62} \times \frac{l75}{D} \times \frac{Gf}{|m75|} \times 10^6 \qquad ...(4)$$

where |m75| is the tangential post-peak slope of the zone at about 75% of the peak load and l75 is the post-peak displacement at 75% of the peak load. These parameters are depicted in Figure 4.8.

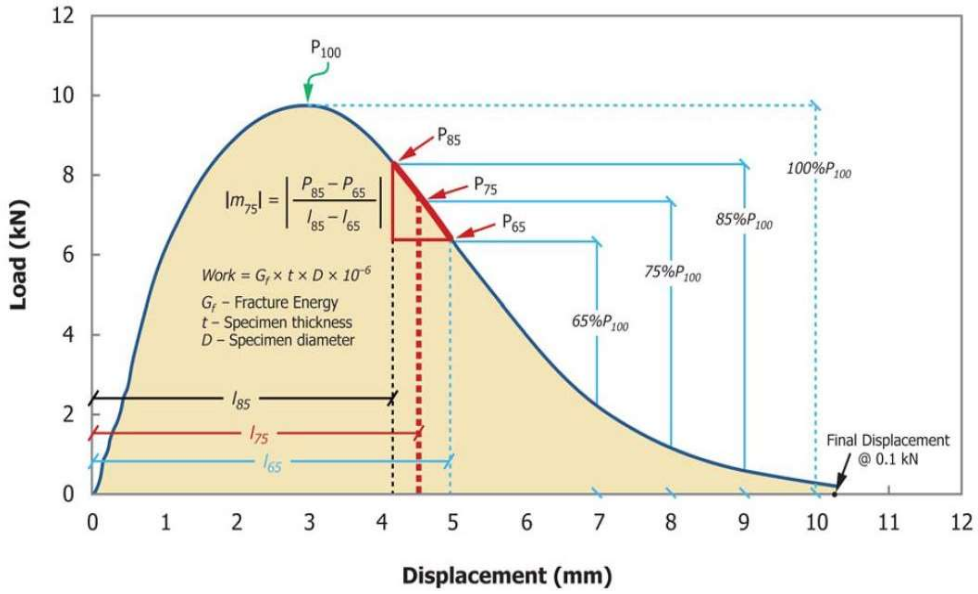

Figure 4.8 Recorded Load versus Load-Line Displacement Curve (47)

4.5 PERFORMANCE SPACE DIAGRAM

Buttlar et al. (2016) developed a performance-space diagram based on the Hamburg-DC(T) plot to simultaneously analyze the high and low-temperature performance of asphalt mixtures *(48)*. This diagram is generated by plotting the Hamburg rut depth on the Y-axis and the DC(T) fracture energy on the X-axis, with the axes in arithmetic scale. As stated in the previous sections, the Hamburg test assesses high-temperature deformations, i.e., rutting, and the DC(T) assesses low-temperature cracking in asphalt mixture. This method of analysis provides a more holistic outlook on the overall performance of a mixture, particularly beneficial for SMA mixes, than what could be obtained by analyzing the results of the different tests individually. Figure 4.9 demonstrates how the performance-space diagram characterizes asphalt mixes based on stiffness, traffic volume, etc. The plot enables a clear-cut perspective on the effects of implementing mixture variables.

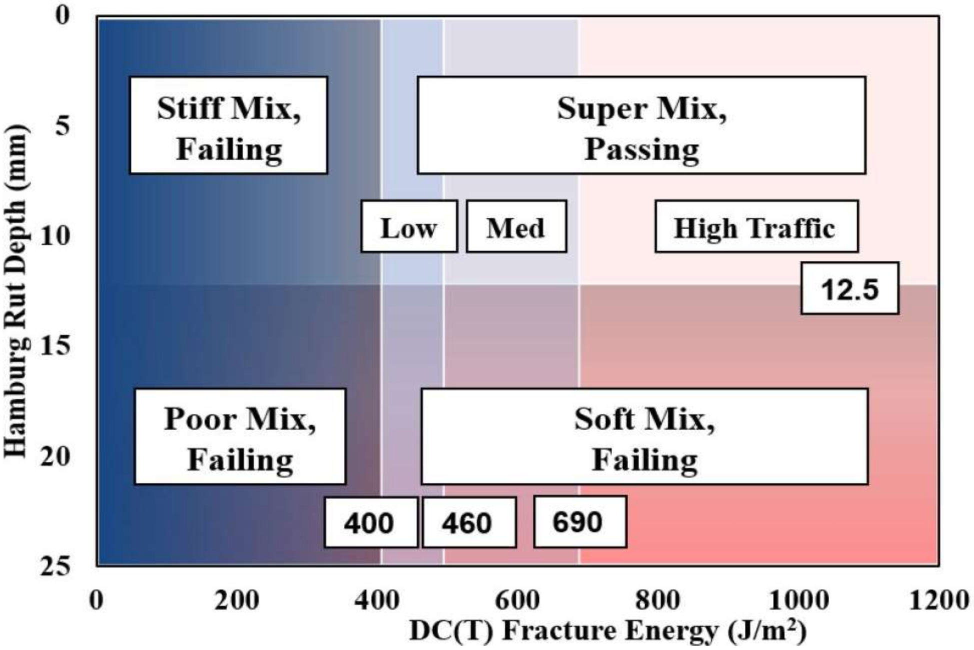

Figure 4.9 Performance-Space Diagram (49)

CHAPTER 5 RESULTS AND DISCUSSION

For the materials described in Chapter 3, the performance tests described in Chapter 4 were satisfactorily conducted as planned. The results obtained are summarized in Table 5.1. Three specimen replicates were tested for each mix respectively, and the data for the average, standard deviations and coefficients of variation (CoV) are provided. The following sections describe the significance of these values respective to each performance test.

Table 5.1 Summary of test results

Mix Name	Rep 1	Rep 2	Rep 3	Avg.	Std. Dev.	CoV
DC(T) Fracture Energy (J/m^2)						
Control	658	753	621	677	68.09	10.05
GTR-I	796	669	679	715	70.61	9.88
GTR-II	796	794	827	806	18.50	2.30
Hamburg Rut-Depth (mm)						
Control	5.85	5.81	6.41	6.02	0.34	5.57
GTR-I	5.17	3.7	6.63	5.17	1.47	28.35
GTR-II	5.73	5.03	4.73	5.16	0.51	9.94
IDEAL-CT index						
Control	166	228	280	225	57.07	25.40
GTR-I	300	245	242	262	32.65	12.45
GTR-II	264	334	223	274	56.13	20.51

5.1 ANALYSIS OF DC(T) FRACTURE TEST RESULTS

The three SMA mixtures in the performance suite were assessed for low-temperature cracking at -12°C (i.e., 10°C higher than the PG low temperature of the binder) using the Disk-Shaped Compact Tension test. Figure 5.1 presents a graph of the average DC(T) fracture energies (FE) for each mix, from 3 replicates in each case, with error bars indicating the standard deviations. Since the mixture performance requirements are currently under development for the State of Missouri *(50)*, engineers at the University of Missouri and MoDOT have established certain passing criteria for high-traffic volume roads. Accordingly, it has been recommended that the fracture energy for SMA specimens exceed 690 J/m^2 for resistance against thermal cracking.

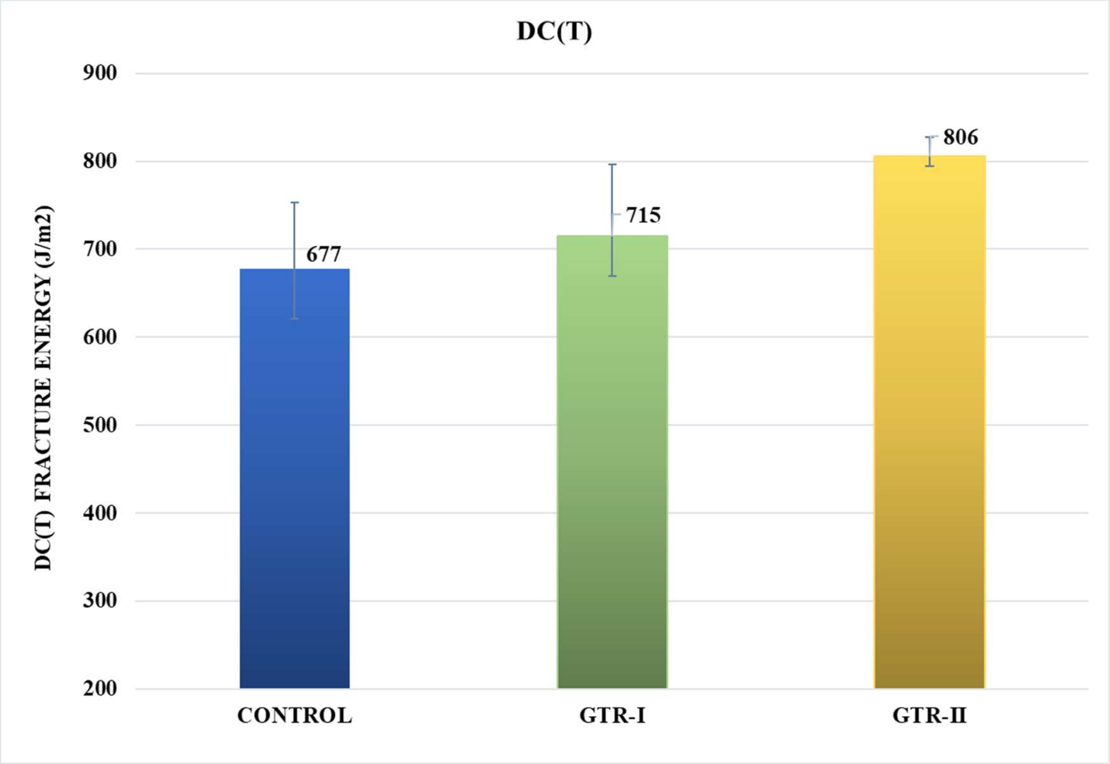

Figure 5.1 DC(T) fracture energy

From Figure 5.1, it is evident that GTR-modified SMA mixes yield fracture energies that clearly satisfy with the recommendation and are significantly higher than that of the unmodified (control) SMA mix at -12°C temperature, indicating better resistance to thermal stresses. Further, the average FE value of the control mix did not satisfy the passing requirements of SMA mixes and out of the three replicates, only one specimen passed the criterion. GTR-II specimens performed significantly better than other mixtures in the testing suite. Sebaaly et al. (*51*) inferred, from a study of low-temperature rheological properties of rubber-modified binder, that the thermal fracture resistance of the binder improved due to the creep stiffness reduction (i.e., redistribution of the thermal stresses) and increase in tensile strength caused by the addition of crumb rubber. The results of study by Sebaaly et al. (*51*) reinforce the results obtained in the present testing suite. Another study by Rath et al. (*52*) analyzed the cracking resistance of a dense-graded mixture with the same level of rubber modification (i.e., 10% addition) through the DC(T) test and obtained an average fracture energy of 641 J/m^2, which was higher than those of other polymer-modified and unmodified mixes in their study. Comparing the FE results from that study (*52*) with those of this testing suite, it is evident that the present SMA mixes have higher resistance to thermal cracking than the dense-graded mixes.

The coefficients of variation for the control, GTR-I and GTR-II mixes were 10%, 10% and 2%, respectively (shown in Table 5.1). The more consistent fracture energies of GTR-II mix resulted in a lower CoV value, which in turn suggests more certainty in the overall test results. All data points fell within the 95% confident intervals.

5.2 HWTT RUTTING TEST

The Hamburg Wheel-Tracking test determines the rutting susceptibility of asphalt mixtures to high-temperature distresses. For SMA mixes, the specimens were targeted to yield rut depths of less than 12.5 mm at 20,000-wheel passes, appropriate to the climatic conditions of the State of Missouri. The results from the HWTT are depicted in Figure 5.2, with a summary of replicates and statistical details in Table 5.1.

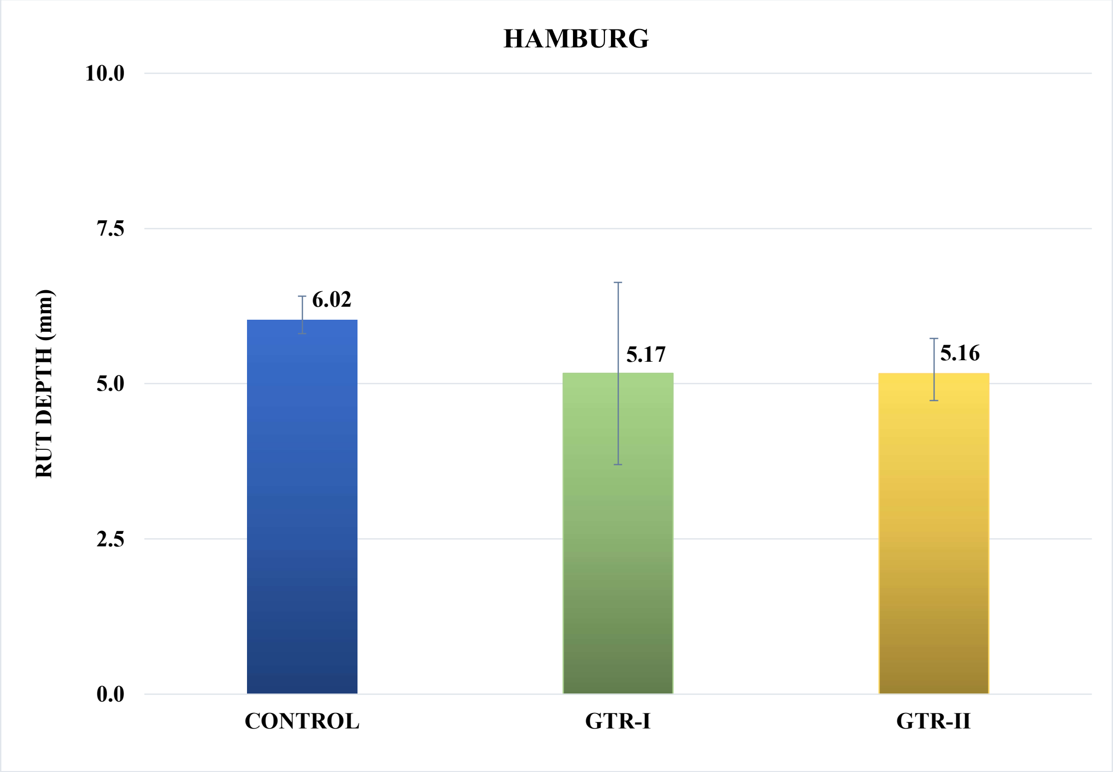

Figure 5.2 HWTT Rut depth

The trend of the average rut depths of each mix in Figure 5.2 was as expected, where the 10% GTR-modified mixes yielded higher rut resistance compared to the control mix. The specimen replicates of the GTR-II mix showed the least rut depths, suggesting that the mix has higher resistance to plastic deformation at high temperatures. This is due to the increase in the viscosity of the binder due to the binder-to-rubber interaction, causing a proportional increase in the stiffness of the mix and ultimately impacting the rut resistance positively *(53)*. Subhy et al. (*54*) reported similar results, where the 10% GTR replacement of asphalt binder of SMA mixes made by both dry and wet processes showed improved rutting properties when compared against unmodified SMA mixes.

Although Replicate 3 of the GTR-I mix showed the highest rut depth of 6.63 mm, the other two yielded satisfactory values of 3.17 and 5.17 mm. Nevertheless, there is a sizeable spread in the datapoints for this mix, i.e., coefficient of variation of 28%, which reduces the certainty of the results. On the other hand, the control mix and GTR-II showed more consistency in the data points with CoVs of 6% and 10%, respectively. However, all the mixes were well within the SMA passing criteria and displayed satisfactory performance in terms of permanent deformation, i.e., rutting. This confirms the well-known fact that SMA mixes resist wheel loads better than conventional mixes due to the uniform dispersion of stresses through the stone-to-stone aggregate structure *(3),* which also regulates the effect of the higher binder content.

5.3 IDEAL-CT FRACTURE TEST

The Indirect Tension Asphalt Cracking Test produces a CT-index for each specimen tested that reflects the fatigue cracking resistance. Figure 5.3 shows the average CT-indexes at intermediate temperatures for the control and GTR modified mixtures, respectively. Out of the three mixes in the testing suite, GTR-II mix exhibited the highest resistance to fracture. CT-indexes of 262 and 277 were obtained for the 10% GTR modified mixes, with no significant difference between them. A quality control and quality assurance (QC/QA) report generated by the Texas A&M Institute of Transportation based on the IDEAL-CT results from various asphalt mixtures established that for SMA mixes a minimum CT-index of 145 was acceptable *(55)*. Similar in trend to that of the fracture energy results generated from the DC(T) test, the GTR-modified SMA mixes performed significantly better than the reference SMA mix. This is in line with the observations of

Wang et al. (*56*), who obtained better anti-fatigue cracking properties in CR-modified SMA mixes when compared to unmodified dense-graded asphalt mixtures, while performing the notched semi-circular bending test. Based on their study, the authors recommended that gap-graded mixes (as in the SMA mixes used in the present work) are better suited for rubber modification, as opposed to dense-graded mixes *(56)*.

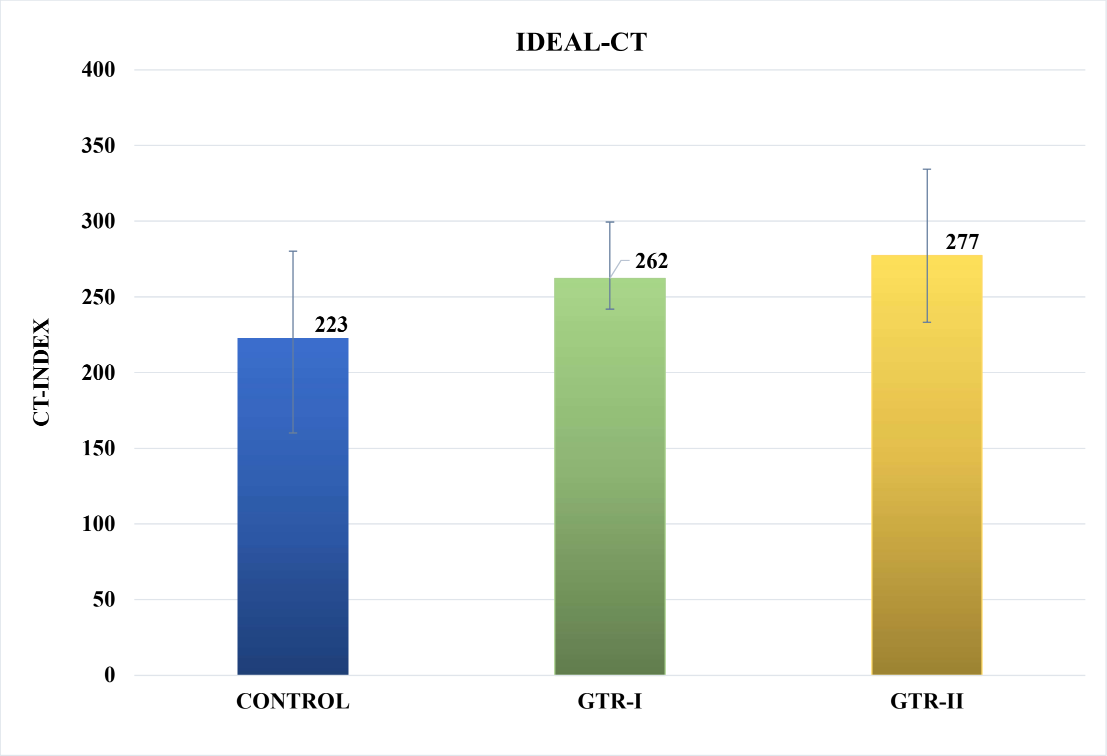

Figure 5.3 IDEAL-CT fracture index

The coefficients of variation for the results of all three asphalt mixtures were on the higher end of preferred values (i.e., between 15-20%); lower CoVs are generally preferred for better confidence in the experimental data. However, GTR-I had more consistent datapoints with an acceptable CoV of 12%, allowing conclusive test results, whereas the control and GTR-II mixes had CoVs of 25% and 20%, respectively. Consequently, a clear conclusion could not be drawn from results of the three test replicates for the control SMA mix. Nevertheless, all the results showed sufficiently high values of fatigue cracking resistance, i.e., fracture at intermediate temperature.

5.4 PERFORMANCE SPACE DIAGRAM

Figure 5.4 presents a performance space diagram comprised of the DC(T) fracture energy and the Hamburg rut depth results of the SMA mixtures tested. The mixes falling in the top right section of the plot (see Figure 4.9) satisfy the requirements for a super mix, i.e., stiff mixture failing mainly by fracture. On the other hand, mixes falling in other sections of the Hamburg-DC(T) plot are characterized as poor mixes. Mixes in the bottom-right section are expected to be soft and fail significantly by rutting, and those mixes that fall in the bottom-left section fail in overall performance.

All mixes tested in the present work are situated in the top-right section (Super Mix) of the plot, which is critical for SMA pavement mixes (see Figure 4.9). The GTR-modified SMA mixes were ideal in terms of overall performance for high-traffic volume pavements. However, the control mix did not meet the passing criteria for fracture energy as per MoDOT, i.e., needs to be higher than 690 J/m^2. However, all mixtures had rut depths under 12.5 mm, complying with the passing requirements for rutting. The GTR-II mix proved to be the most efficient with respect to resistance to permanent deformations at high-temperature and low-temperature endurance to thermal distresses.

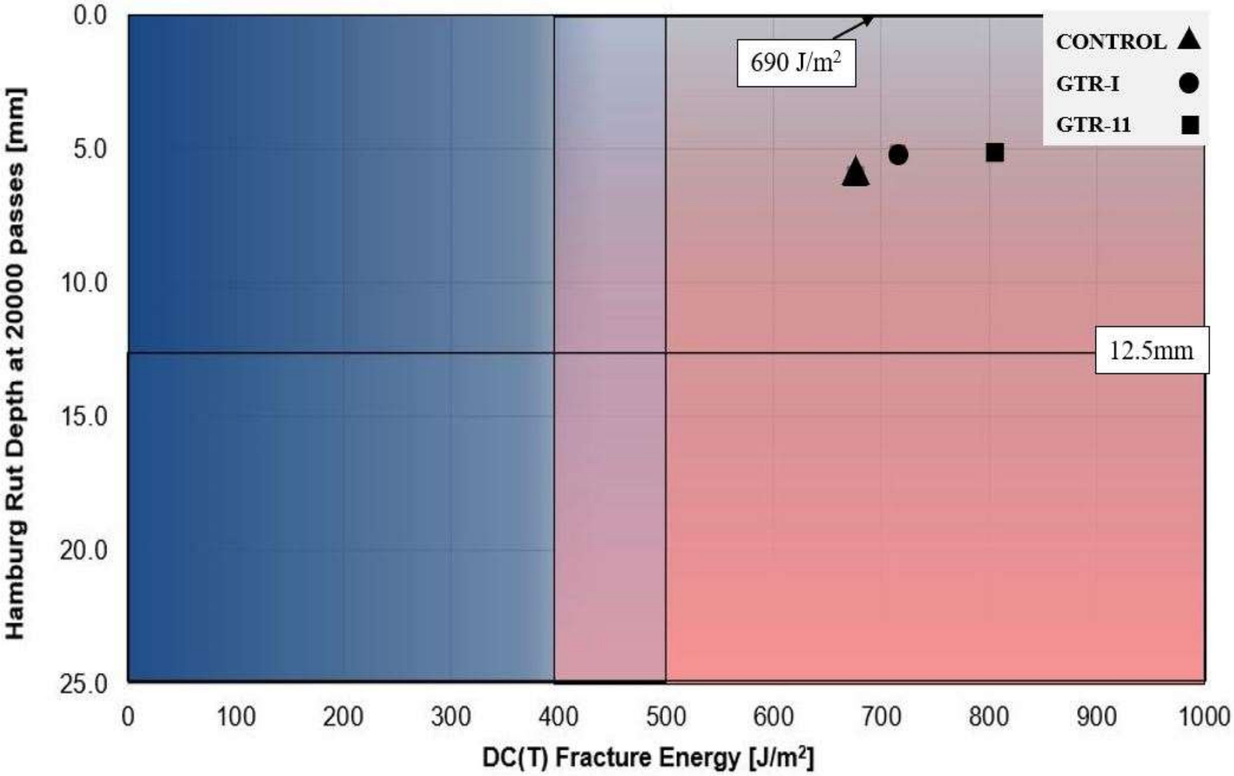

Figure 5.2 Performance Space Diagram

5.5 SUMMARY OF RESULTS AND INFERENCES

The stipulated performance tests were carried out to evaluate GTR as viable recycled materials (through 10% modification) suitable for SMA mixes for application in the State of Missouri. The DC(T) test was performed at -12°C, appropriate to the extreme cold climatic conditions. The GTR-modified SMA mixes satisfied the passing criteria of 690 J/m^2 provided by MoDOT. Considering that SMA mixes are predominantly designed to endure high-traffic conditions, the low-temperature cracking resistance is an important defining performance parameter for the climatic conditions. To this end, the DC(T) results support 10% addition of crumb rubber, by weight of binder, in SMA mixtures to enhance the resistance to thermal pavement distresses. The Hamburg test was conducted to determine the resilience of these mixes against high-temperature deformations. The results of all the mixes were found to be within the range of desirable performance, though the GTR mixtures did perform better than the control SMA mix, by a small margin. This shows that the SMA mixes have good durability to continually withstand plastic deformations caused by high-traffic wheel loads. To assess the performance of the asphalt mixes at intermediate temperature, the IDEAL-CT test was executed to obtain the fracture or cracking tolerance indexes. From the results, it is evident that GTR-modified SMA mixtures have better resistance to fatigue cracking, reflecting good resistance against pavement distresses at intermediate temperature. Comparing the CT-indexes of all the SMA mixes to the results of relating literature, it is evident that their performances are within the satisfactory threshold. The performance space diagram provides a clear picture of the overall performance of the SMA mixes with respect to both fracture energy and rut depth. The SMA mixes modified with GTR proved to be ideal mixes, with good resistance to high and low-temperature pavement distresses.

CHAPTER 6 SUSTAINABILITY STUDIES

The sustainability assessment in this research work began with an effort to identify the general gaps in research and knowledge with respect to the environmental assessments of rubber-modified asphalt (RMA). Motivated by the U.S. Tire Manufacturing Association (USTMA), an extensive literature review was performed, on various RMA-focused Life Cycle Assessment (LCA) reports, journals and conference papers, to grasp an understanding of the many environmental impacts that are taken into consideration with respect to the series of activities involved in the construction of a rubber-modified asphalt pavement. This comprehensive study also helps understand the full environmental potential of RMA technology, implement the responsible use of rubber-modification, and pave the way to establish standardized specifications for RMA pavements.

6.1 LCA OVERVIEW

Life cycle assessment, commonly referred to as LCA, is a systematic analytical tool developed to quantify the sustainability potential or environmental impact of the processes involved in a product or system, i.e., a whole life cycle. It was initially developed in the late 1960s to analyse air, water and land emissions from solid wastes, and was later extended to incorporate chemical emissions and the energy embodied in resources *(57)*. The current developments in LCA allow for a comprehensive approach, taking into consideration all the inputs and outputs in a flow, in terms of energy consumption, greenhouse gas emission, global warming potential, etc., over the life cycle of a product or system, from the extraction of the raw materials to the end-of-life phase (i.e., cradle-to-grave), for evaluating its environmental burden. LCA is conducted under the guidance of the ISO 14040 series of standards. Although LCA is a developing technique, it has earned a significant place in the industrial and academic world since sustainable consumption continues to be an important goal in today's society *(58)*.

As per ISO 14040-2006, analysis through LCA consists of four different stages: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment and life cycle interpretation *(59)*. The relationship between these stages is shown in Fig. 6.1. The goal definition gives a general description of the product or system under study, the reasons for the use of LCA in this work, and the motivation behind the LCA analysis. The scope definition gives more defining details of the product or system, such as the functional unit, system boundaries, data categories, impact assessment method, etc. The life cycle inventory stage involves data collection of all inputs and outputs of a unit process or product system, and the quantification of all the material resource and energy, i.e., environmental load associated with those inputs and outputs. Most LCA software come with a pre-existing LCI database consisting of inventory data of common materials and processes. However, the database may be insufficient for certain geographies, and new technologies and products. The steps involved in the LCI are implemented as per ISO 14041-1998 *(60)*. Life cycle impact assessment (LCIA) in LCA, in accordance ISO 14042-2000, is where the significance of potential environmental impact categories of a system is classified, characterized, weighted, and then analysed *(61)*. The most common impact categories considered in LCIA are global warming potential (GWP), greenhouse gas emission (GHG) ozone depletion, acidification, human toxicity, eutrophication, resource depletion, etc. Life cycle interpretation is the final stage of assessment in LCA, in which the final values of all significant emissions and environmental impacts are quantified and summarised for interpretation. Based on these results, the conclusions and recommendations can be drawn that allow us to make environmental improvements and long-term sustainability planning, provide key environmental information, identify knowledge gaps for future studies, sustainable decision-making purposes, etc.

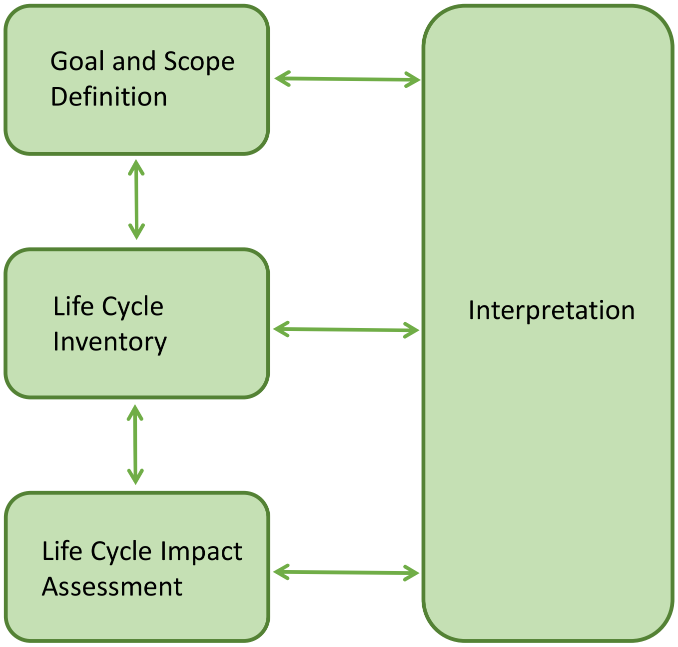

Figure 6.1 Stages of Life Cycle Assessment (LCA)

6.2 SIGNIFICANCE FOR RUBBER-MODIFIED ASPHALT PAVEMENTS

In recent years, life-cycle assessment (LCA) has played a significant role in promoting the advances in the use of recycled materials in asphalt pavements, in terms of the mitigation of the depletion of non-renewable resources, and reduction of the overall environmental burden, such as energy consumption, toxic emissions, global warming potential (GWP), etc. Extensive research has been dedicated to investigating the incorporation of waste products in asphalt pavements, with an emphasis on ground tire or engineered crumb rubber derived from scrap tires. The literature on rubber-modified asphalt is overwhelmingly dominated by the reports of its inadequacies; most LCA analyses have reported negative environmental impacts and high eco-burden. These conclusions were arrived at mainly due to the high energy consumption in the mixing process of asphalt paving, in addition to the high production temperatures demanded in the construction phase with RMA mixes *(62)*. The fabrication of high-quality crumb rubber from end-of-life tires is another energy-intensive process (*67*) that majorly contributes to the environmental burden of RMA pavements. Most of these assessments have been attributional, i.e., have focused exclusively on the production process of RMA (gate-to-gate), excluding important contributing factors outside of the system boundaries, such as appropriate assumptions on service life. Consequential LCA focusing on the whole life cycle (cradle-to-grave), or wider boundary conditions, could potentially show positive or more supporting overall environmental effects. Studies that did perform cradle-to-grave analysis of RMA pavements demonstrated benefits, such as the reduction in CO_2 emissions and lower energy consumption, which result from extended service life, better long-term performance and lower maintenance frequency, in comparison to traditional asphalt pavements *(63,64)*.

6.3 SUMMARY OF RELEVANT CONCLUSIONS FROM THE LCA STUDIES

To learn the extent and approaches of the life cycle assessments in the literature, a widespread and thorough review was conducted. The main findings are as follows:

Goals: The objectives of the LCA studies surveyed vary significantly from the analysis of the effect of incorporating materials such as RAP and CR in asphalt (*65,66,70*) to comparisons between different asphalt mixtures, i.e., cold mixtures, warm mixtures, RAP and RMA mixtures. One study did a consequential LCA between material recycling (i.e., crumb rubber) and energy recovery of scrap tires (i.e., tire-derived fuel) *(67).*

Functional unit considered: The functional units for the calculations were usually a unit length, say 1km, of roadway, though there are significant variations in traffic load, geography, number of lanes, type of base course etc. *(65,70)*. As a variant, certain studies used a square meter of road as the functional unit *(66)*. One significant limitation in some studies is the assumption made that all options considered had the same durability *(65)*, which is obviously not true. Also, a life of certain number of years has been considered, where durability can also be considered (*66,67,70,71*).

System boundaries: Mostly, the cradle-to-gate (also known as ground-to-gate or mine-to-gate) system has been used, which includes all processes involved in the extraction of material and fuel, production of asphalt, transportation, and construction phases *(62,65,72)*. Cradle-to-grave studies also included the end-of-life processes (*63,66,70,71*).

Metrics used for impact characterization: The common indicators quantified in the studies are CO_2 emissions, energy consumption or embodied energy *(65,72)*, and utilization of waste *(62).*

With specific reference to rubber-modified asphalt, it is understood the main impacts are due to the shredding and devulcanization of the crumb rubber, both of which could be energy-intensive; asphalt production and base course construction *(65)*. A large impact of the recycling of rubber is seen on water depletion, freshwater eutrophication, and climate change *(65,70,71)*. Under certain conditions, it was found *(62)* that the incorporation of 18-20% rubber gave 90% higher CO_2 emissions and needed about 14% higher energy than virgin asphalt. However, when the pavement is analyzed, the AR mixes required less energy (*62*). Some studies focused on assessing other environmental impacts such as ozone layer depletion, human toxicity, aquatic ecotoxicity, eutrophication, fossil depletion, etc. *(63,70,71),* the quantification of these impact categories showed a 30% overall improvement of RMA compared to conventional asphalt *(70).*

Further, Table 6.1 presents a summary of the relevant literature containing research findings that facilitated identifying general knowledge gaps in existing sustainability and life cycle studies of rubber-modified asphalt pavements.

Table 6.1 Literature review on LCA of Rubber-Modified Asphalt

Author, year	**System boundaries**	**Relevant findings**
Jung, 2002 *(69)*	Construction, maintenance, and user cost comparison	• Rubberized pavements were more cost-effective compared to conventional pavements.
Chiu et al., 2007 *(64)*	End of construction phase, operation phase to maintenance phase	• Decrease in heat requirements dthe manufacturing process of pavement production was the most effective means of lowering the eco-burden.
Bartolozzi et al., 2012 *(70)*	Construction phase to end-of-life phase (15-year lifespan)	• The environmental advantages of RMA pavements were about 33% more than for HMA pavements.

	(Use phase was excluded)	- Benefits of RMA include significant noise reduction, higher life expectancy and more durable in high-traffic conditions.
Feraldi et al., 2013 *(67)*	Consequential LCA of tire-derived fuel and crumb rubber from ELT scrap tires	- Crumb rubber treatment of scrap tires involved significant reduction in environmental effects.
Li et al., 2014 *(73)*	Scrap tire collection to GTR production	- Devulcanization process of ground rubber had the highest environmental load. - The highest impact factor was human health in the production phase of GTR life cycle.
Zhu et al., 2015 *(62)*	Resource extraction to construction phase	- In asphalt mixture life cycle, the mixing process consumed most energy, whereas the paving and compaction processes consumed comparatively much less. - Asphalt Rubber pavements had significant advantage over SBS-modified asphalt pavement with respect to energy conservation.
Bartolozzi et al., 2015 *(63)*	Construction phase to end-of-life phase (15-year lifespan)	- The longer service-life and low maintenance of RMA pavements was the main environmental advantage. - Binder production in the construction phase was the most damaging process.
Soulimana et al., 2016 *(68)*	Comparison of thick and thin pavement structures	- Cost-effectiveness of RMA mixtures was 4.1 times higher than unmodified HMA mixture.
Thives et al., 2017 *(72)*	Resource extraction to construction phase	- The heating and drying process of aggregates were the main source of GHG emissions, due to the fuel usage. - Carbon dioxide (70%), carbon monoxide (40%) and methane (60%) emissions are significantly lower for rubberized asphalt mixes than for portland cement concrete.

Yang et al., 2018 *(38)*	Emission analysis of mixes in laboratory	• Mixing temperature of asphalt mixture was predominantly responsible for toxic gas emissions. • Warm mix technology can reduce the emission level of CR mixtures significantly.
Wang et al., 2018 *(8)*	Resource extraction to maintenance phase (40-year lifespan)	• The tire-to-pavement noise reduction was between 40-88% for RMA. • The maintenance phase had lower energy consumption compared to the other phases in the life cycle. • During rehabilitation phase, RMA pavements showed substantial reduction in environmental burden.
Bressi et al., 2019 *(65)*	Resource extraction to construction phase	• Crumb rubber-modified mixes yielded higher environmental impact due to devulcanization process of rubber. • The 40% addition of recycled asphalt pavement (RAP) to the asphalt mix improved all sustainability indicator scores. • Higher durability was required for CR-modified mixes to be more advantageous.
Pratico et al., 2020 *(66)*	Resource extraction to maintenance phase (20-year lifespan)	• Production of raw materials had the highest contribution to overall impact categories. • Major part of energy consumption is in the construction phase. • Implementation of warm mix asphalt technology to the pavement resulted in lower energy consumption.
Landi et al., 2020 *(71)*	Resource extraction to construction phase	• The production and acquisition of raw materials contributed the most to the global warming potential (78%). • Main benefit of RMA is increased service life, leading to decreased maintenance.

6.4 KNOWLEDGE GAPS AND RECOMMENDATIONS

Based on the comprehensive literature review of rubber-modified asphalt conducted in the previous section, the following knowledge gaps could be identified:

1. Over the last decade, there has been an acceleration in rubber modification technology, in both wet and dry processes. However, current sustainability reports still rely on outdated data, while numerous reports on RMA mixtures have shown that they perform adequately and are comparable to polymer modified mixtures. This has reflected tremendously on increased life expectancy of rubberized pavements and therefore, it is imperative that LCA studies account for these developments. The maintenance intervals of RMA pavements significantly exceed those of conventional asphalt pavements. The use phase of the pavement must account for maintenance operations and base its assumptions on up-to-date performance records of RMA.

2. Ground tire rubber is an efficient way to mitigate scrap tire accumulation in landfills, as a secondary raw material for asphalt pavement. There is a need to establish a standardized approach to incorporate the eco-credit associated with recycling scrap tire stockpiles in pavement LCA; current LCA studies do not account for the recycle phase of scrap tires, negatively impacting the overall environmental effects. This can be done by broadening the system boundaries of RMA pavements to include the end-of-life phase of rubber tires in the pavement life cycle.

3. RMA technology has shown to impart enhancements in certain functional characteristics in tire-to-pavement interactions, such as noise reduction, skid resistance, lower tire wear, etc., in contrast to other pavement types. These advantages and their impact on the

environmental consequences of RMA are not fully quantified in existing pavement LCAs. These considerations could result in a net positive effect.

4. Majority of LCA reports focus on evaluating prime impact categories, such as global warming potential, energy consumption and greenhouse gas emissions. Recent studies have inferred that a vast amount of rubber particles from tire wear deposit in water streams. However, rubberized pavements have smoother surfaces, which have proved to produce less tire wear. These benefits can be realized by quantifying and comparing other impact factors, such as eco-toxicity, water pollution, chemical leaching, etc., of various pavement mixtures.

6.5 SUMMARY

The sustainability studies in this thesis chapter were summarised with the intention to understand and analyse the potential of rubber-modified asphalt from an environmental aspect. A vast and comprehensive literature review was performed on studies that ranged from the early 2000s that used traditional RMA mixing techniques and based their studies on now outdated knowledge, to more contemporary literature that applied modern life cycle assessment approaches on pavements that used advanced RMA practices. To obtain significant findings and learn the varied approaches in these pavement LCAs, the defining aspects such as goal, functional unit, system boundaries and impact categories were analyzed and compared. This study established the following knowledge gaps and recommendations; inclusion of the maintenance phase of pavements and end-of-life phase of scrap tires in the system boundaries are critical for RMA pavements, there is a need to assign standardized eco-credit for RMA, using up-to-date performance data including functional characteristics, and quantifying additional and more specific impact categories can significantly improve sustainability analysis outcomes for rubber-modified pavements. Addressing such gaps in the knowledge could contribute to apprehend the full sustainability potential of rubber as a recycled material and its responsible use for pavement application.

CHAPTER 7 CONCLUSIONS AND FUTURE WORK

7.1 GENERAL CONCLUSIONS

The work presented in this thesis assessed the use of recycled ground tire rubber in stone mastic asphalt mixtures via the dry process, as a sustainable material. A suite of tests was conducted to study the performance, particularly high-temperature rutting, and intermediate- and low-temperature fracture. The Performance-Space diagram plotted with the DC(T) fracture energies and Hamburg rut depths, demonstrated the ideality or balance of the SMA mixes in terms of resistance to specific pavement distresses. In addition to assessing the benefits of GTR-modified SMA in terms of mechanical properties, it was found equally important to understand the environmental impact of rubber-modified asphalt on pavement sustainability. The life cycle assessment tool was selected as a method of analysis for sustainability studies, where the first step was taken to identify the knowledge gaps in existing literature.

7.2 SPECIFIC CONCLUSIONS

- From the detailed literature survey, it was seen that that rubber-modified asphalt mixes using the dry process presented improved mixture performance, in terms of high-temperature rut resistance and low-temperature cracking. Further, pre-treated crumb rubber products are available in the market for use with this mixing technique.

- It was also seen from the literature that crumb rubber has been a successful means of modification for stone mastic asphalt (SMA) mixes, since they work well with gap-graded mixes. The main benefits of using ground tire rubber (GTR) in SMA mixes included enhanced fatigue resistance leading to better cracking and rutting characteristics, improvement in the overall stability of the mix, prevention of binder drain-down, and lower influence of high temperatures on the stiffness modulus. Further, SMA mixes modified with fibers or polymers exhibit less drain-down of the asphalt.

- Two types of GTR with different chemical compositions and/or treatments, denoted as GTR-I and GTR-II, were chosen for this performance testing suite (by 10% modification by weight of binder). The nominal maximum aggregate size of the blend was 12.5 mm, and all blends consisted of limestone and granite stockpiles. The mineral filler employed in the GTR-modified SMA mixes was composed of ASTM Class C fly ash, whereas limestone filler was used for the virgin SMA mix. Also, a proprietary chemical WMA additive, Evotherm-P14, was added in the SMA mixes, at 0.5% by weight of the asphalt binder. Further, the SMA mixes had cellulose fibers at 0.3% weight of the whole mix. All the SMA mixes were found to be workable though they required more compactive effort compared to dense-graded mixes.

- A performance test suite consisting of the DC(T) test to assess thermal cracking, the IDEAL-CT test to analyze fracture energy of the asphalt at intermediate temperature, and the Hamburg wheel-tracking test was done to determine the rutting susceptibility, was chosen to address all the major distresses in asphalt pavements.

- In the DC(T) tests, the GTR-modified SMA mixes satisfied the passing fracture energy criteria of 690 J/m^2. The Hamburg test results of all three SMA mixes were found to be within the range of desirable performance, though the GTR mixtures did perform better than the control SMA mix, by a small margin. This shows that the SMA mixes have good durability to continually withstand plastic deformations caused by high-traffic volume. From the IDEAL-CT test, the fracture indexes for the GTR-modified SMA mixtures indicated better resistance against pavement distresses at intermediate temperature such as fatigue cracking. The performance space diagram consisting of the DC(T) fracture energies and HWTT rut depths showed that the SMA mixes modified with GTR proved to be ideal, in terms of good resistance to high and low-temperature pavement distresses.

- Overall, from the performance tests conducted, the 10% addition of ground tire rubber in SMA mixes by the dry process was successful, for the climatic conditions of Missouri and proved to better than unmodified SMA.

- The comprehensive literature review of sustainability studies ranged from the early 2000s that used traditional RMA mixing techniques and based their studies on now outdated knowledge, to more contemporary literature that applied modern life cycle assessment approaches on pavements that used advanced RMA practices. Significant findings from the varied approaches in the pavement LCAs included the defining aspects such as goal, functional unit, system boundaries and impact categories. The knowledge gaps identified included: the inclusion of the maintenance phase of pavements and end-of-life phase of scrap tires in the system boundaries are critical for RMA pavements, there is a need to assign standardized eco-credit for RMA, using up-to-date performance data including functional characteristics, and quantifying additional impact categories can significantly improve sustainability analysis outcomes for rubber-modified pavements.

7.3 RECOMMENDATIONS FOR FUTURE WORK

- This study further encourages the incorporation of recycled rubber to enhance the performance of stone mastic asphalt mixes and contribute to sustainable development. Continuing work with MoDOT, upcoming phases of this project are expected to focus on optimizing the GTR content in SMA mixes. Future research could assess the viability of other recycled materials, such as waste plastics, suitable for SMAs and help state agencies develop a standardized performance specification for stone mastic asphalt pavements in Missouri.
- The GTR modified SMA mixes assessed in this work have been employed in demonstration projects on interstate highway I-44 by MoDOT, these pavement sections will be monitored for long-term field performance.
- Based on insights drawn from the sustainability study, it is recommended to further advance and promote the usage of RMA as an effective performance and sustainable solution for pavements. A standardized guide for pavement LCA would enable more efficient and comparable assessments among different studies. Through this, the responsible use of RMA technology can be put into effect in the asphalt industry, and contractors and state highway agencies may also be more likely to implement rubber modification with the availability of national specifications, as they currently have very limited experience with modern RMA materials.
- The closure of the RMA-related knowledge gaps will facilitate more accurate information for the decision makers in various sustainability and pavement institutions, to drive the use of recycled rubber in asphalt mixtures worldwide.

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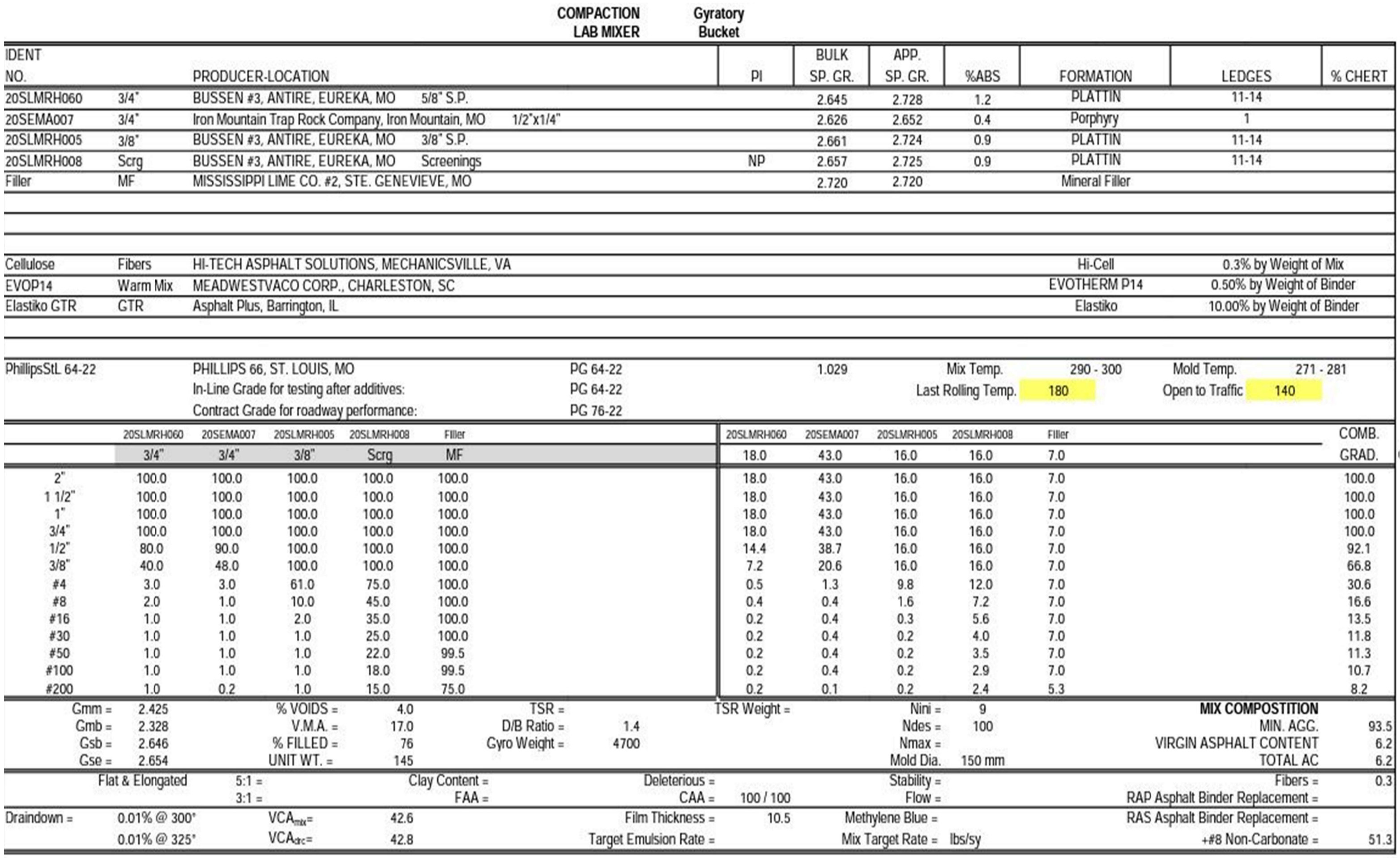
APPENDIX A: MIX DESIGNS



COMPACTION Gyratory
LAB MIXER Bucket

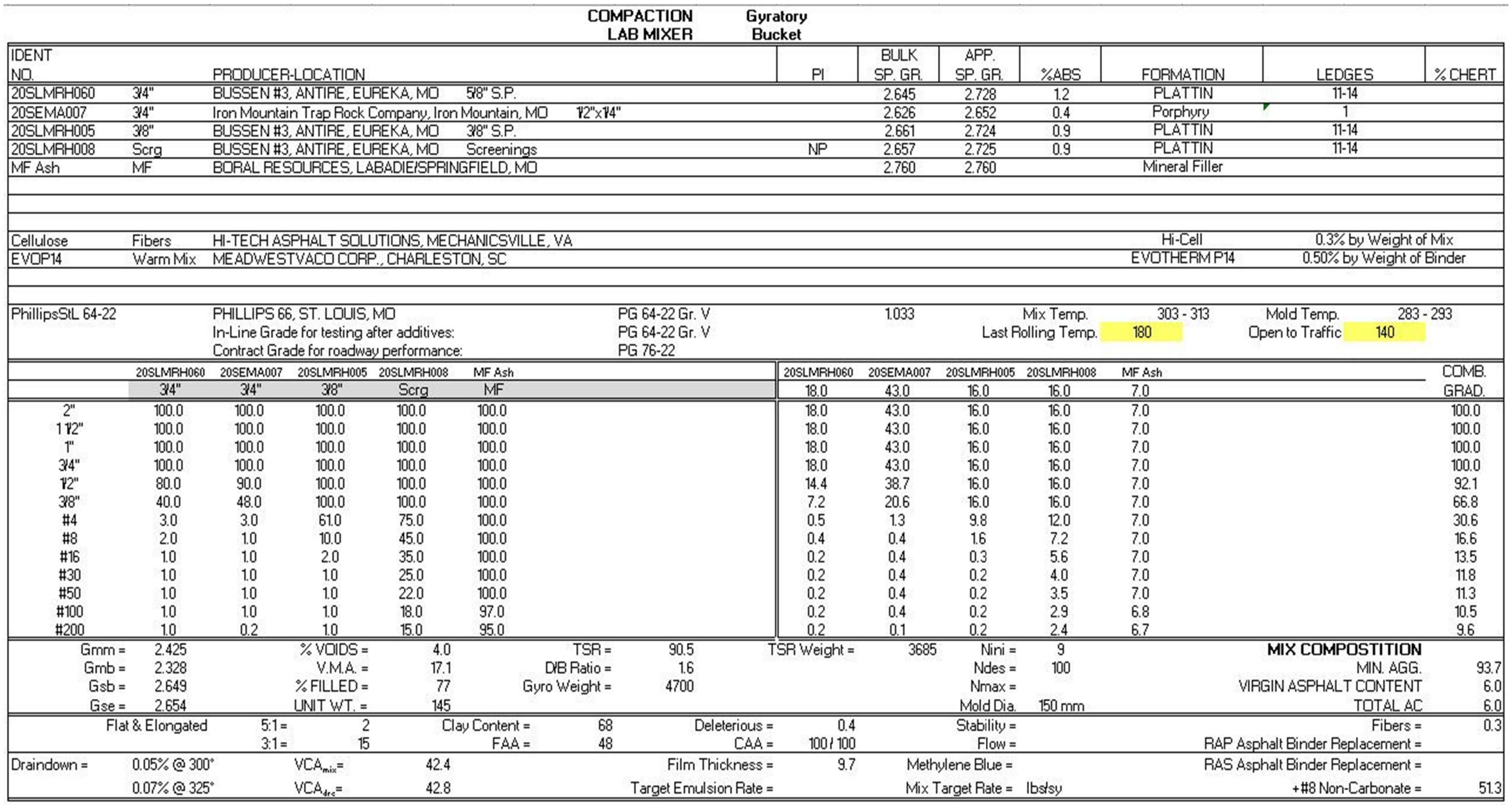
IDENT NO.		PRODUCER-LOCATION		PI	BULK SP. GR.	APP. SP. GR.	%ABS	FORMATION	LEDGES	% CHERT
20SLMRH060	3/4"	BUSSEN #3, ANTIRE, EUREKA, MO	5/8" S.P.		2.645	2.728	1.2	PLATTIN	11-14	
20SEMA007	3/4"	Iron Mountain Trap Rock Company, Iron Mountain, MO	1/2"x1/4"		2.626	2.652	0.4	Porphyry	1	
20SLMRH005	3/8"	BUSSEN #3, ANTIRE, EUREKA, MO	3/8" S.P.		2.661	2.724	0.9	PLATTIN	11-14	
20SLMRH008	Scrg	BUSSEN #3, ANTIRE, EUREKA, MO	Screenings	NP	2.657	2.725	0.9	PLATTIN	11-14	
Filler	MF	MISSISSIPPI LIME CO. #2, STE. GENEVIEVE, MO			2.720	2.720		Mineral Filler		

Cellulose	Fibers	HI-TECH ASPHALT SOLUTIONS, MECHANICSVILLE, VA	Hi-Cell	0.3% by Weight of Mix
EVOP14	Warm Mix	MEADWESTVACO CORP., CHARLESTON, SC	EVOTHERM P14	0.50% by Weight of Binder
Elastiko GTR	GTR	Asphalt Plus, Barrington, IL	Elastiko	10.00% by Weight of Binder

PhillipsStL 64-22	PHILLIPS 66, ST. LOUIS, MO	PG 64-22	1.029	Mix Temp.	290 - 300	Mold Temp.	271 - 281
	In-Line Grade for testing after additives:	PG 64-22		Last Rolling Temp.	180	Open to Traffic	140
	Contract Grade for roadway performance:	PG 76-22					

	20SLMRH060	20SEMA007	20SLMRH005	20SLMRH008	Filler	20SLMRH060	20SEMA007	20SLMRH005	20SLMRH008	Filler	COMB.
	3/4"	3/4"	3/8"	Scrg	MF	18.0	43.0	16.0	16.0	7.0	GRAD.
2"	100.0	100.0	100.0	100.0	100.0	18.0	43.0	16.0	16.0	7.0	100.0
1 1/2"	100.0	100.0	100.0	100.0	100.0	18.0	43.0	16.0	16.0	7.0	100.0
1"	100.0	100.0	100.0	100.0	100.0	18.0	43.0	16.0	16.0	7.0	100.0
3/4"	100.0	100.0	100.0	100.0	100.0	18.0	43.0	16.0	16.0	7.0	100.0
1/2"	80.0	90.0	100.0	100.0	100.0	14.4	38.7	16.0	16.0	7.0	92.1
3/8"	40.0	48.0	100.0	100.0	100.0	7.2	20.6	16.0	16.0	7.0	66.8
#4	3.0	3.0	61.0	75.0	100.0	0.5	1.3	9.8	12.0	7.0	30.6
#8	2.0	1.0	10.0	45.0	100.0	0.4	0.4	1.6	7.2	7.0	16.6
#16	1.0	1.0	2.0	35.0	100.0	0.2	0.4	0.3	5.6	7.0	13.5
#30	1.0	1.0	1.0	25.0	100.0	0.2	0.4	0.2	4.0	7.0	11.8
#50	1.0	1.0	1.0	22.0	99.5	0.2	0.4	0.2	3.5	7.0	11.3
#100	1.0	1.0	1.0	18.0	99.5	0.2	0.4	0.2	2.9	7.0	10.7
#200	1.0	0.2	1.0	15.0	75.0	0.2	0.1	0.2	2.4	5.3	8.2

Gmm = 2.425	% VOIDS = 4.0	TSR =		TSR Weight =	Nini =	9	MIX COMPOSTITION	
Gmb = 2.328	V.M.A. = 17.0	D/B Ratio =	1.4		Ndes =	100	MIN. AGG.	93.5
Gsb = 2.646	% FILLED = 76	Gyro Weight =	4700		Nmax =		VIRGIN ASPHALT CONTENT	6.2
Gse = 2.654	UNIT WT. = 145				Mold Dia.	150 mm	TOTAL AC	6.2
Flat & Elongated	5:1 =	Clay Content =	Deleterious =		Stability =		Fibers =	0.3
	3:1 =	FAA =	CAA =	100 / 100	Flow =		RAP Asphalt Binder Replacement =	
Draindown = 0.01% @ 300°	VCA$_{mix}$= 42.6		Film Thickness =	10.5	Methylene Blue =		RAS Asphalt Binder Replacement =	
0.01% @ 325°	VCA$_{drc}$= 42.8		Target Emulsion Rate =		Mix Target Rate =	lbs/sy	+#8 Non-Carbonate =	51.3



COMPACTION Gyratory
LAB MIXER Bucket

IDENT NO.		PRODUCER-LOCATION		PI	BULK SP. GR.	APP. SP. GR.	%ABS	FORMATION	LEDGES	% CHERT
20SLMRH060	3/4"	BUSSEN #3, ANTIRE, EUREKA, MO	5/8" S.P.		2.645	2.728	1.2	PLATTIN	11-14	
20SEMA007	3/4"	Iron Mountain Trap Rock Company, Iron Mountain, MO	1/2"x1/4"		2.626	2.652	0.4	Porphyry	1	
20SLMRH005	3/8"	BUSSEN #3, ANTIRE, EUREKA, MO	3/8" S.P.		2.661	2.724	0.9	PLATTIN	11-14	
20SLMRH008	Scrg	BUSSEN #3, ANTIRE, EUREKA, MO	Screenings	NP	2.657	2.725	0.9	PLATTIN	11-14	
MF Ash	MF	BORAL RESOURCES, LABADIE/SPRINGFIELD, MO			2.760	2.760		Mineral Filler		

Cellulose	Fibers	HI-TECH ASPHALT SOLUTIONS, MECHANICSVILLE, VA	Hi-Cell	0.3% by Weight of Mix
EVOP14	Warm Mix	MEADWESTVACO CORP., CHARLESTON, SC	EVOTHERM P14	0.50% by Weight of Binder

PhillipsStL 64-22 — PHILLIPS 66, ST. LOUIS, MO — PG 64-22 Gr. V — 1.033 — Mix Temp. 303 - 313 — Mold Temp. 283 - 293
In-Line Grade for testing after additives: PG 64-22 Gr. V — Last Rolling Temp. 180 — Open to Traffic 140
Contract Grade for roadway performance: PG 76-22

	20SLMRH060	20SEMA007	20SLMRH005	20SLMRH008	MF Ash	20SLMRH060	20SEMA007	20SLMRH005	20SLMRH008	MF Ash	COMB.
	3/4"	3/4"	3/8"	Scrg	MF	18.0	43.0	16.0	16.0	7.0	GRAD.
2"	100.0	100.0	100.0	100.0	100.0	18.0	43.0	16.0	16.0	7.0	100.0
1 1/2"	100.0	100.0	100.0	100.0	100.0	18.0	43.0	16.0	16.0	7.0	100.0
1"	100.0	100.0	100.0	100.0	100.0	18.0	43.0	16.0	16.0	7.0	100.0
3/4"	100.0	100.0	100.0	100.0	100.0	18.0	43.0	16.0	16.0	7.0	100.0
1/2"	80.0	90.0	100.0	100.0	100.0	14.4	38.7	16.0	16.0	7.0	92.1
3/8"	40.0	48.0	100.0	100.0	100.0	7.2	20.6	16.0	16.0	7.0	66.8
#4	3.0	3.0	61.0	75.0	100.0	0.5	1.3	9.8	12.0	7.0	30.6
#8	2.0	1.0	10.0	45.0	100.0	0.4	0.4	1.6	7.2	7.0	16.6
#16	1.0	1.0	2.0	35.0	100.0	0.2	0.4	0.3	5.6	7.0	13.5
#30	1.0	1.0	1.0	25.0	100.0	0.2	0.4	0.2	4.0	7.0	11.8
#50	1.0	1.0	1.0	22.0	100.0	0.2	0.4	0.2	3.5	7.0	11.3
#100	1.0	1.0	1.0	18.0	97.0	0.2	0.4	0.2	2.9	6.8	10.5
#200	1.0	0.2	1.0	15.0	95.0	0.2	0.1	0.2	2.4	6.7	9.6

Gmm = 2.425 % VOIDS = 4.0 TSR = 90.5 TSR Weight = 3685 Nini = 9
Gmb = 2.328 V.M.A. = 17.1 D/B Ratio = 1.6 Ndes = 100
Gsb = 2.649 % FILLED = 77 Gyro Weight = 4700 Nmax =
Gse = 2.654 UNIT WT. = 145 Mold Dia. 150 mm

MIX COMPOSTITION
MIN. AGG. 93.7
VIRGIN ASPHALT CONTENT 6.0
TOTAL AC 6.0

Flat & Elongated 5:1 = 2 Clay Content = 68 Deleterious = 0.4 Stability = Fibers = 0.3
3:1 = 15 FAA = 48 CAA = 100 / 100 Flow = RAP Asphalt Binder Replacement =

Draindown = 0.05% @ 300° VCA$_{mix}$= 42.4 Film Thickness = 9.7 Methylene Blue = RAS Asphalt Binder Replacement =
0.07% @ 325° VCA$_{drc}$= 42.8 Target Emulsion Rate = Mix Target Rate = lbs/sy +#8 Non-Carbonate = 51.3

APPENDIX B: AIR VOIDS OF LAB MIX SPECIMENS

CONTROL MIX												
(A) Gmm	2.432											
	DC(T)			IDEAL-CT			Hamburg					
Sample Name	Rep1	Rep2	Rep3	Rep1	Rep2	Rep3	Rep1-a	Rep1-b	Rep2-b	Rep2-a	Rep3-a	Rep3-b
Diameter (mm)	150mm											
Height (mm)	140mm			62mm			62mm					
(B) Dry mass in air, g	2005.7	1965.6	1984.5	2358.9	2362.8	2363.2	2376.2	2362.9	2359.1	2356.9	2361.5	2361.2
(C) Saturated sarface dry mass, g	2009.8	1970.5	1988.4	2369	2371.1	2372.1	2384.4	2371.5	2368	2366.7	2373	2373.7
(D) Mass in water, g	1132.6	1107.9	1124.9	1335.3	1336.1	1339.2	1349.9	1339.5	1333.7	1332.9	1337.3	1339.2
(E) Volume (C-D), cm^3	877.2	862.6	863.5	1033.7	1035	1032.9	1034.5	1032	1034.3	1033.8	1035.7	1034.5
(F) Bulk specific gravity (B/E)	2.286	2.279	2.298	2.282	2.283	2.288	2.297	2.29	2.281	2.28	2.28	2.282
(G) Percent Absorption, (C-A/C-D)*10	0.5	0.6	0.5	1	0.8	0.9	0.8	0.8	0.9	0.9	1.1	1.2
(H) Percent compaction (F / A * 100),	94	93.7	94.5	93.8	93.9	94.1	94.4	94.1	93.8	93.7	93.8	93.9
Air voids (100 - H), %	6.0	6.3	5.5	6.2	6.1	5.9	5.6	5.9	6.2	6.3	6.2	6.1

GTR-I MIX												
(A) Gmm	2.408											
	DC(T)			IDEAL-CT			Hamburg					
Sample Name	Rep1	Rep2	Rep3	Rep1	Rep2	Rep3	Rep1-a	Rep1-b	Rep2-b	Rep2-a	Rep3-a	Rep3-b
Diameter (mm)	150mm											
Height (mm)	140mm			62mm			62mm					
(B) Dry mass in air, g	1957.3	1975.8	1955.1	2342.1	2341.6	2343.3	2342.8	2343.7	2332.5	2343	2341.2	2343.3
(C) Saturated sarface dry mass, g	1965	1980.9	1961.2	2353.5	2352.9	2357.6	2353.5	2356.9	2344.8	2353.2	2353	2357.6
(D) Mass in water, g	1095.4	1110.1	1098.1	1324	1319.2	1322.5	1316.5	1317.8	1309	1312.4	1317.4	1322.5
(E) Volume (C-D), cm^3	869.6	870.8	863.1	1029.5	1033.7	1035.1	1037	1039.1	1035.8	1040.8	1035.6	1035.1
(F) Bulk specific gravity (B/E)	2.251	2.269	2.265	2.275	2.265	2.264	2.259	2.256	2.252	2.251	2.261	2.264
(G) Percent Absorption, (C-A/C-D)*10	0.9	0.6	0.7	1.1	1.1	1.4	1	1.3	1.2	1	1.1	1.4
(H) Percent compaction (F / A * 100),	93.5	94.2	94.1	94.5	94.1	94	93.8	93.7	93.5	93.5	93.9	94
Air voids (100 - H), %	6.5	5.8	5.9	5.5	5.9	6.0	6.2	6.3	6.5	6.5	6.1	6.0

GTR-II MIX												
(A) Gmm	2.408											
	DC(T)			IDEAL-CT			Hamburg					
Sample Name	Rep1	Rep2	Rep3	Rep1	Rep2	Rep3	Rep1-a	Rep1-b	Rep2-b	Rep2-a	Rep3-a	Rep3-b
Diameter (mm)	150mm											
Height (mm)	140mm			62mm			62mm					
(B) Dry mass in air, g	1946.1	1956.2	1935.4	2342.8	2344.9	2344	2342	2342.9	2341.6	2343.7	2343.5	2344.2
(C) Saturated sarface dry mass, g	1950.1	1961.5	1942.6	2356.7	2358.8	2355.5	2354.3	2353.1	2353.8	2357.2	2354.9	2355.9
(D) Mass in water, g	1092.3	1098.9	1083.1	1321.5	1323.1	1320	1316.8	1316.7	1316.3	1319.5	1321.9	1322.2
(E) Volume (C-D), cm^3	857.8	862.6	859.5	1035.2	1035.7	1035.5	1037.5	1036.4	1037.5	1037.7	1033	1033.7
(F) Bulk specific gravity (B/E)	2.269	2.268	2.252	2.263	2.264	2.264	2.257	2.261	2.257	2.259	2.269	2.268
(G) Percent Absorption, (C-A/C-D)*10	0.5	0.6	0.8	1.3	1.3	1.1	1.2	1	1.2	1.3	1.1	1.1
(H) Percent compaction (F / A * 100),	94.2	94.2	93.5	94	94	94	93.7	93.9	93.7	93.8	94.2	94.2
Air voids (100 - H), %	5.8	5.8	6.5	6.0	6.0	6.0	6.3	6.1	6.3	6.2	5.8	5.8