Evaluation of Recycled Components in Stone Matrix Asphalt Mixes

December 2023
Final Report

Project number TR202020
MoDOT Research Report number cmr 23-016

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TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
cmr 23-016		

4. Title and Subtitle	5. Report Date
Evaluation of Recycled Components in Stone Matrix Asphalt Mixes	September 2023 Published: December 2023
	6. Performing Organization Code
7. Author(s) William Buttlar[1], Ph.D., P.E. https://orcid.org/0000-0002-1545-0165, Magdy Abdelrahman[2], Ph.D. https://orcid.org/0000-0002-8722-0203, Punyaslok Rath[1], Ph.D. https://orcid.org/0000-0002-6546-5429, Jim Meister[1], Nandita Gettu[1], Ahmed S. El-Ashwah[2]	**8. Performing Organization Report No.**
9. Performing Organization Name and Address [1]Department of Civil and Environmental Engineering University of Missouri Columbia, MO 65201 [2]Department of Civil and Environmental Engineering Missouri University of Science and Technology Rolla, MO 65409	**10. Work Unit No.** **11. Contract or Grant No.** MoDOT project # TR202020
12. Sponsoring Agency Name and Address Missouri Department of Transportation (SPR-B) Construction and Materials Division P.O. Box 270 Jefferson City, MO 65102	**13. Type of Report and Period Covered** Final Report (July 2020-October 2023) **14. Sponsoring Agency Code**

15. Supplementary Notes

Conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration. MoDOT research reports are available in the Innovation Library at https://www.modot.org/research-publications.

16. Abstract

Currently, Missouri DOT (MoDOT) does not allow use of recycled materials in SMAs. MoDOT commissioned this study to investigate the effect of incorporation of recycled materials such as RAP and GTR in SMAs. In Phase 1, plant-produced mixtures were collected, and recreated under BMD methodology to determine acceptable upper-limit on RAP for initial implementation. In Phase 2, friction properties of mixtures were obtained by testing aggregates, lab and plant produced mixtures, and a field section containing GTR. Based on the results, the following conclusions were drawn: 1) The current use of conglomerate, unfractionated RAP stockpiles poses practical limitations in achieving passing BMD thresholds at higher levels of RAP, 2) Suitable frictional characteristics were achieved at lower levels of RAP but results indicated that the softer aggregates present in current RAP stockpiles tended to reduce skid resistance, and 3) Use of GTR appears to be promising option for incorporating recycled materials into Missouri pavements, based on lab BMD and skid resistance results in the lab and field. Based on the findings, the following recommendations were made :1) MoDOT should consider allowing RAP in SMA mixtures but, an upper limit of 15% asphalt binder replacement (ABR) from RAP is recommended at this time, 2) If greater than 15% ABR by RAP is considered, a value engineering proposal should be provided, accompanied with BMD tests, 3) The research supports the continued and increased usage of GTR as a possible approach towards achieving good mixture durability, skid resistance, and mixture sustainability.

17. Key Words	18. Distribution Statement
Reclaimed stone pavement; Recycled asphalt pavement; Recycled materials; Stone matrix asphalt	No restrictions. This document is available through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified.	Unclassified.	67	

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MoDOT MCTI Project #TR202020

9/12/2023

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Acknowledgements

The research team would like to thank the Missouri Department of Transportation for their generous support of this research. We would especially like to thank Dan Oesch, Jason Blomberg, Jen Harper, Jonathan Varner, Treasa Porter and Dave Ahlvers from MoDOT. The research team would also like to express gratitude to the Capital Paving Co. and to NB West Contractors.

Executive Summary

The use of Stone Matrix Asphalt, or SMA (also known as Stone Mastic Asphalt), has been quite popular on interstates and other routes with heavy traffic – developed in Europe and then introduced in the US roughly 30 years ago. Well-designed SMAs exhibit higher cracking resistance compared to standard Hot Mix Asphalt (HMA) due to thicker asphalt films on aggregates, and superior rutting resistance due to stone-on-stone contact, which is a result of its gap gradation. Conventionally, most agencies limit incorporation of recycling in SMA mixtures due to strict requirements for the use of high-quality aggregates that are resistant to abrasion to be able to achieve adequate stone-on-stone contact and frictional characteristics for skid resistance. However, numerous studies have shown laboratory as well as field data on the effective use of recycled materials in SMAs, such as Reclaimed asphalt Pavement (RAP), Ground tire Rubber (GTR, or also known as Recycled Tire Rubber (RTR)), and Recycled Asphalt Shingles (RAS). Incorporation of the aforementioned recycled materials into SMA mixtures in moderation has been shown to improve various performance characteristics (cracking and rutting resistance), along with significant cost savings. Moreover, the use of recycled materials is in line with the ongoing national efforts of enhancing the sustainability of pavement infrastructure.

Missouri is one of the states which currently does not allow use of recycled materials in the SMAs despite the routine inclusion of recyclates in dense-graded Superpave and non-Superpave (BP1, BP2, and BP3) mixtures. BP1-3 mixtures are used for low-to-moderately trafficked roadways. Within that backdrop, MoDOT commissioned this study with the following overarching goals and objectives:

1. To evaluate the performance of Missouri SMA mixtures incorporated with RAP and GTR, based on mixture tests for cracking and rutting. Per MoDOT's recommendation, the IDEAL-CT test was used to control cracking resistance, while the Hamburg Wheel Track test was used to control rutting resistance.
2. To explore various Balanced Mix Design (BMD) strategies, such as air void regression and the use of softer binder grade, particularly as a means to produce mix designs with passing cracking test results.
3. Investigate the effect of incorporation of recycled components on the frictional properties of SMA mixtures, including assessing the abrasion resistance of aggregates, quantifying the shape characteristics, and measuring skid resistance using a suite of laboratory tests, along with a field experiment involving skid trailer testing.

This study was comprised of two phases: Phase 1 included mixture design and laboratory testing, while Phase 2 exclusively focused on friction testing. In Phase 1, the research team obtained three SMA mixtures from two projects (plant-produced), replicated them in the lab. The mixtures included SMAs placed on I-44 in Franklin County (MO) and on I-70 in Callaway County (MO). The I-44 project involved two SMAs – one with polymer-modified PG64V-22 binder and other with GTR modification via dry process (base mix used a PG64-22 binder). Both of the unmodified mixtures (I-44 Control and I-

70 Control) were later re-designed with RAP at various dosages as guided by various BMD strategies to ascertain maximum RAP contents. In Phase 2, the aggregate stockpiles were tested for abrasion using Micro-Deval test and mixtures were then tested to determine the frictional properties using the British Pendulum Test and the Dynamic Friction Test. Finally, a field investigation on the effect of GTR inclusion on skid resistance was carried out.

Based on the findings of the study, the following conclusions were drawn:

1. The current use of conglomerate (non-homogeneous), unfractionated RAP stockpiles poses practical limitations in achieving passing balanced mix designs at higher levels of RAP. The key findings supporting this conclusion were:
    a. At RAP levels above 15%, difficulties were encountered in passing both cracking and rutting BMD tests, despite efforts to incorporate softer base binder grades and/or modifiers such as warm-mix asphalt additives. One mixture (I-44 Control), in particular, required multiple design iterations to achieve both passing cracking and rutting test scores.
    b. Skid/friction tests also indicated that the softer aggregates present in current RAP stockpiles tended to reduce parameters associated with skid resistance; however, suitable frictional characteristics were achieved at lower levels of RAP.
2. The use of recycled ground tire rubber, or GTR (engineered crumb rubber introduced by the dry process was studied herein) appears to be a viable avenue for incorporating recycled materials into Missouri pavements. The key findings supporting this conclusion were:
    a. A balanced mix design for an SMA mixture placed in Cooper County, MO on I-70 was successfully designed and produced in the summer of 2022 and is performing very well to date.
    b. Skid trailer testing displayed a potential added benefit of using GTR in flexible pavement surface materials, namely, an approximately 12% increase in skid resistance in the test section containing GTR was measured relative to the control section, which did not contain GTR.

Based on the findings and conclusions of this study, the following recommendations were drawn:

1. It is recommended that MoDOT consider allowing RAP in SMA mixtures; however, at this time, with the use of conglomerate and unfractionated RAP stockpiles, an upper limit of 15% asphalt binder replacement (ABR) from RAP is also recommended. Alternatively, for simplicity, an upper limit of 20% RAP by weight of mixture could be established.
2. MoDOT has recently begun allowing the use of GTR in Superpave and SMA mixtures. The research conducted herein supports the continued and increased usage of GTR as a possible approach towards achieving good mixture durability, skid resistance, and economics while promoting mixture sustainability.

3. It is recommended that additional research be conducted to address the following open research questions:
    a. Can the use of homogeneous and fractionated RAP stockpiles lead to the possibility of specifying even higher RAP levels in the future? Such practices have shown the possibility of driving towards 30% RAP usage at the Illinois Tollway; however, it is acknowledged that the RAP in Missouri is likely a bit stiffer than the RAP in the Chicago area.
    b. The use of modifiers such as recycling agents (rejuvenators) and various warm-mix products present convenient approaches to achieving BMD requirements for SMA mixes; however, the long-term performance benefits of these products should be further investigated through field studies.
    c. In addition to RAP and GTR, other recycled materials offer potential economic, sustainability and even performance benefits for SMA mixes. These include recycled, post-consumer waste plastic (PCR-P) and recycled asphalt shingles (RAS). These should be further investigated. PCR-P inclusion in SMAs can be evaluated once long-term field performance results are obtained for test sections constructed on I-155 near Hayti, MO. The I-155 sections were constructed under a separate research project, where material was placed in the summer of 2023.
    d. Additional lab and field friction testing is recommended as MoDOT begins to modify specifications to allow recycled materials in SMA mixes.
    e. MoDOT may wish to consider allowing greater than 15% asphalt binder replacement in SMA mixes (or greater than 20% RAP by weight of mix), provided that a value engineering proposal accompanies the mix design showing that: (1) Additional RAP stockpiling techniques are being used to improve the quality and consistency of the RAP product, such as the use of homogeneous stockpiles and fractionated RAP stockpiles; (2) BMD requirements can be satisfied, and (3) an added requirement for a laboratory skid test should also be considered as part of the BMD for SMA mixtures containing more than 15% ABR from RAP (more than 20% RAP by weight of mix).

Table of Contents

List of Figures

List of Tables

Chapter 1
Introduction

1.1. Background and Motivation

In recent times, America's pavement infrastructure has witnessed increasing traffic loads, heavier vehicles, and challenging environmental conditions, which has prompted paving agencies to adopt various strategies to enhance durability of the pavements. One such strategy, often utilized for interstate pavements, is the use of Stone Matrix Asphalt (also known as Stone Mastic Asphalt, or SMA). SMA is a specialty gap-graded mixture that is characterized by its stone-to-stone skeleton structure and high asphalt content. SMA mixes were initially developed in Germany in the late 1960s with the original intention of creating asphalt mixes with a structural integrity to resists wear-and-tear from studded tires, and consequently designed with coarser, high-quality aggregates (Brown and Manglorkar 1993; Yin and West 2018). By the 1990s, the use of SMAs was adopted by many states in the U.S. following the European asphalt study tour by the Federal Highway Administration (FHWA). 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.

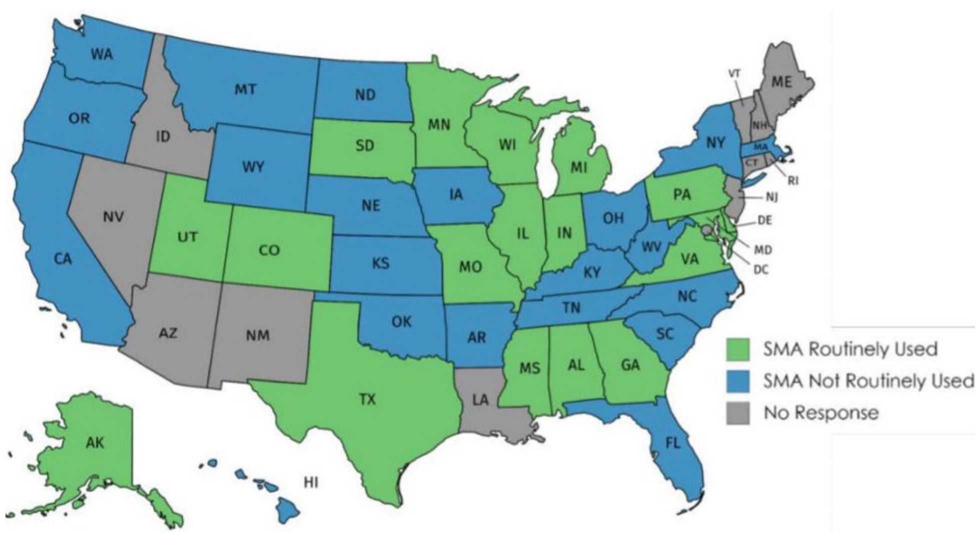


Figure 1-1 Use of SMA mixes in USA

Conventionally, most agencies limit incorporation of recycling in SMA mixtures due to requirement of high-quality aggregates that are resistant to abrasion to be able to achieve adequate stone-on-stone contact (2022). For instance, Georgia DOT limits RAP usage in their SMA mixtures to 15% as opposed to allowing up to 40% RAP in their conventional dense-graded mixtures (Yin and West 2018). MoDOT currently does not allow any RAP in their SMAs whereas Missouri dense graded mixtures are routinely produced with RAP incorporation. However, numerous studies and demonstration projects have shown that recycled materials such as RAP, RAS, GTR, and others can be effectively used in SMAs without any compromise on durability. Moreover, the use of recycled materials also results in significant cost-savings and is in line with the ongoing national efforts of enhancing sustainability of pavement infrastructure. To that end, MoDOT initiated this study to investigate the use of recycling components in Missouri SMA mixtures.

Apart from improving the durability of roads, SMAs are also known to provide benefits such as improved frictional characteristics, reduction in spray in wet conditions, and reduction in noise. The benefit of improved friction provided by SMAs is critical for interstate pavements with high and fast-moving traffic, especially in wet conditions as characterized by skid resistance. The use of certain recycled components such as RAP and RAS in high quantities could affect the skid resistance since it is a function of aggregate microstructure and macrostructure. In addition, the long-term frictional performance depends on the aggregates' abrasion and degradation resistance, as well as the internal aggregate texture. Hence, it is critical to evaluate the frictional performance of SMA mixtures with recycled components.

In this project, SMA mixes were designed using the Balanced Mix Design (BMD) methodology, considering that MoDOT is slowly transitioning to adopting BMD over Superpave. Appropriate tests, and corresponding thresholds were used in consultation with MoDOT, and are described in Chapter 3. Various BMD strategies were also explored to ensure performance of the produced SMA mixtures. A detailed literature review on pertinent topics is included in Appendix A. The upcoming sections outline the objectives of the study in greater detail.

1.2. Goals and Objectives

The overarching goal of this project, as the project name suggests, is to evaluate the effect of incorporation of recycled components in SMA mixtures. The main objectives of this study can be described as follows:

1. Evaluate the performance of Missouri SMA mixtures incorporated with RAP and GTR, based on mixture tests for cracking and rutting. Per MoDOT's recommendation, IDEAL-CT was used for cracking resistance and Hamburg Wheel Track test was used for rutting resistance.
2. Explore various BMD strategies, such as air voids regression and use of softer binder grade, to ensure adequate performance of SMA mixtures with and without recycled components.
3. Investigate the effect of incorporation of recycled components on the frictional properties of SMA mixtures, including assessing the abrasion resistance of aggregates, quantifying the shape characteristics, and measuring skid resistance in laboratory and field.

1.3. Organization of Report

This remainder of this report is organized in the following manner:

- Chapter 2 – Materials;
- Chapter 3 – Testing and Analysis Methods;
- Chapter 4 – Mixture Design and Test Results;
- Chapter 5 – Friction Testing;

- Chapter 6 – Summary, Conclusions and Recommendations.

Chapter 2
Materials

2.1. Overview

This study was conducted in two phases. In Phase 1, the Mizzou team obtained three SMA mixtures from two projects (plant-produced), replicated them in the lab, and added RAP to two of those three mixtures. The RAP mixtures were put through BMD test thresholds to determine the optimum RAP content, after which the mixtures were sent to the S&T team for friction testing (Phase II). This section will cover the materials for the mixtures collected from the two projects. Subsequent sections will discuss the methods followed for BMD testing, and the number of BMD strategy iterations undertaken to optimize the RAP amount.

2.2. Project and Mixture Information

Two stone matrix asphalt mixes were sampled for mixture performance testing, including control sections (no recyclates) those containing recycled materials. The mixes were produced by two different contractors on two different interstates in Missouri. One of the mixtures was paved on I-44 in Franklin County. The majority of the I-44 project was paved with a GTR-modified SMA that used dry-process incorporation of Engineered Crumb Rubber (ECR) as a mixture additive. Only small sections (ramps) were paved with non-ECR mix with a polymer modified PG64V-22 binder. Details on material sampling are included in Section 2.3. Material Sampling. The mixes were produced at a portable plant setup in a former trailer sales lot. The SMA was placed on interstate 44 in both directions between the St. Louis County line and Route 30. The other mixture was paved in Callaway County on I-70. It was produced by a portable asphalt plant set up in a gravel lot. This mix was paved in both directions on I-70 from the Boone/Callaway County line at Cedar Creek to Kingdom City.

All three mixtures paved on the interstates were sampled by the Mizzou Asphalt Pavement and Innovation laboratory (MAPIL) at the University of Missouri, Columbia, and were referred to as baseline mixtures. These baseline mixtures were re-produced in the MAPIL lab per the Job Mix Formula (JMF) provided by the contractors and were assessed for volumetric and performance properties. The naming convention followed was as follows:

Table 2-1 Mix information

Mix	Mix ID	Binder Grade	AC Content	Additives
I-44 Control	SP125BSM 20-85	PG64V-22	6.0	cellulose fibers, warm-mix additive
I-44 10ECR	SP125BSM 20-82	PG64-22	6.2	ECR*, cellulose fibers, warm-mix additive
I-70 Control	SP125BSM 21-05	PG64V-22	6.2	cellulose fibers, ant-strip agent
ECR =	Engineered Crumb Rubber			

The two baseline mixtures which did not include GTR were modified with various amounts of RAP, as discussed in Section 5.2. Further, various BMD strategies were implemented in the RAP-modified mixtures to obtain the optimum RAP dosage with adequate performance.

2.2.1. Aggregate Stockpiles

The aggregate stockpiles used for mixes I-44 Control and 10ECR are presented in Table 2-2 and the stockpiles for I-70 mix are in Table 2-3. Figure 2-1 shows the blend gradations for the three mixtures listed in Table 2-1.

Table 2-2 Individual stockpile gradations for I-44 Control and ECR mixes (SP125BSM 20-85 and 20-82, respectively)

Sieve Size (No.)	Sieve Size (mm)	3/4"A	3/4"IM	3/8A"	Screenings	Mineral Filler
Aggregate Blend		18%	43%	16%	16%	7%
2 inches	50.00	100.00	100.00	100.00	100.00	100.00
1 1/2 inches	37.50	100.00	100.00	100.00	100.00	100.00
1 inch	25.00	100.00	100.00	100.00	100.00	100.00
3/4 inch	19.00	100.00	100.00	100.00	100.00	100.00
1/2 inch	12.50	80.00	90.00	100.00	100.00	100.00
3/8 inch	9.50	40.00	48.00	100.00	100.00	100.00
No. 4	4.75	3.00	3.00	61.00	75.00	100.00
No. 8	2.36	2.00	1.00	10.00	45.00	100.00
No. 16	1.18	1.00	1.00	2.00	35.00	100.00
No. 30	0.60	1.00	1.00	1.00	25.00	100.00
No. 50	0.30	1.00	1.00	1.00	22.00	100.00
No. 100	0.15	1.00	1.00	1.00	18.00	97.00
No. 200	0.075	1.00	0.20	1.00	15.00	95.00

Table 2-3 Individual stockpile gradations for I-70 Control mix (SP125BSM 21-05)

Sieve Size (No.)	Sieve Size (mm)	1/2" minus	3/4" clean	9/16" clean	9/16"	3/8"#4	Mineral Filler
Aggregate Blend		13.5%	21%	20%	5.5%	34%	6%
2 inches	50	100	100	100	100	100	100
1 1/2 inches	37.5	100	100	100	100	100	100
1 inch	25	100	100	100	100	100	100
3/4 inch	19	100	100	100	100	100	100
1/2 inch	12.5	95	63	97	98	100	100
3/8 inch	9.5	83	25	78	86	97	100
No. 4	4.75	52	6	31	64	32	100
No. 8	2.36	31	5	8	50	6	100
No. 16	1.18	18	5	6	39	2	100
No. 30	0.6	12	4	6	30	1	99.9
No. 50	0.3	8	3	5	22	1	99.7
No. 100	0.15	5	3	4	15	1	99
No. 200	0.075	4	2	3	12	0.2	95.6

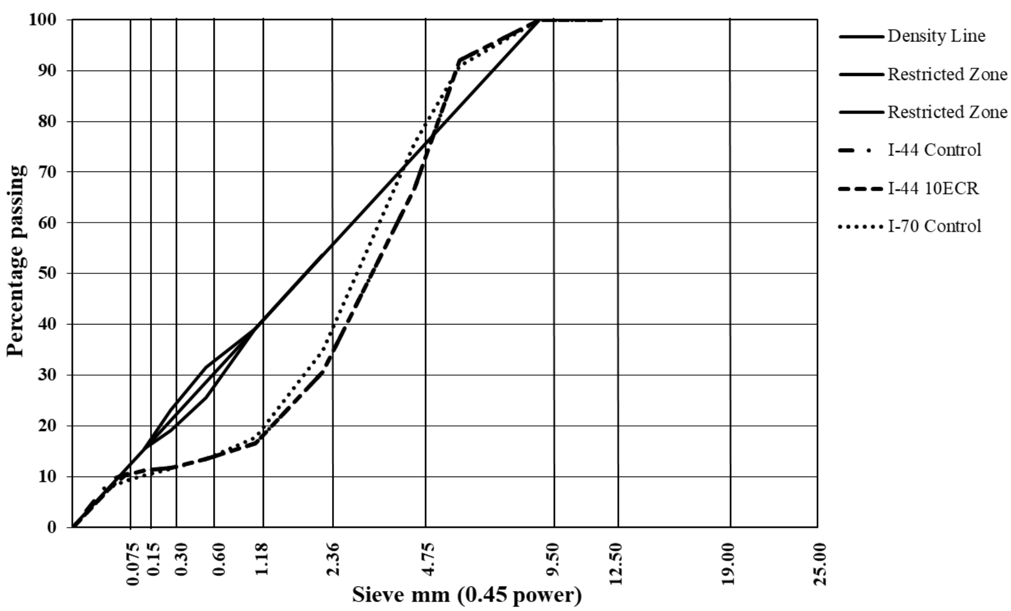


Figure 2-1 Aggregate gradation used for all mixes

2.2.2. RAP Stockpile

The RAP gradation is shown in Figure 2-2. Based on contractor data, the RAP stockpile had 4.7% available binder contributing to the total asphalt binder content of the mixes. Through conversation with several quality control personnel working for different contractors in the state, RAP in Missouri is most often processed and screened at a contractor's central yard and then trucked to the plant making the mix. The RAP stockpile at the central yard is comprised of material from multiple milling jobs and therefore contains multiple binder sources, binder grades, and a variety of aggregate sources. The contractors frequently sample and test the RAP to determine if adjustments are needed in the current JMF being produced with the highly conglomerate (heterogeneous) RAP material.

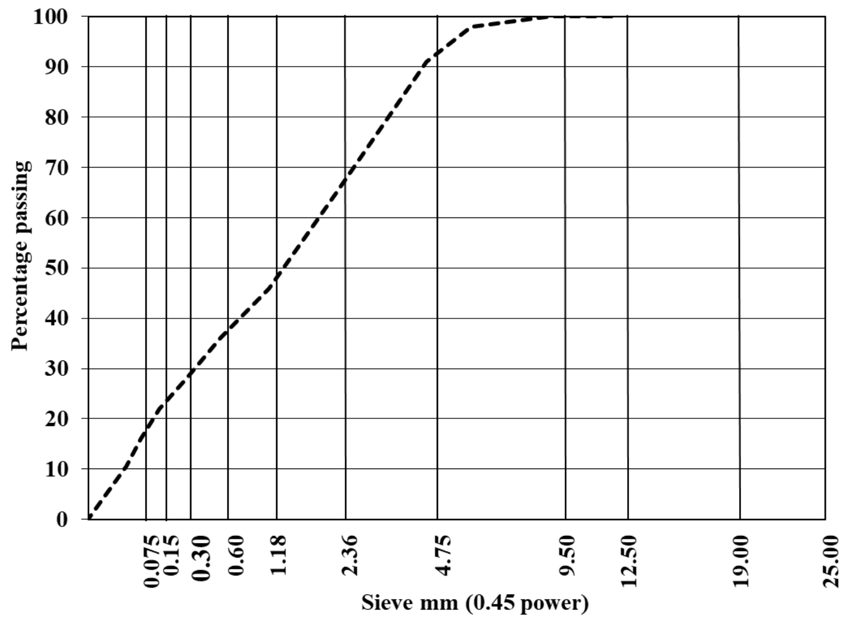


Figure 2-2 Aggregate gradation used for RAP stockpile

A second conglomerate RAP source was sampled for this project (pictured in Figure 2-3). When the material was sampled, no gradation or asphalt content was provided. The university performed appropriate test methods to obtain the gradation data and binder content, but results were widely variable between several replicates. Thus, this particular RAP source was not further used in this study.

Figure 2-3 RAP stockpiles sampled for this project

2.3. Material Sampling

For the I-44 mixtures, aggregates were sampled on August 13, 2020. Sample pads were prepared by a bucket loader. University personnel then shoveled the aggregates from the pads into plastic buckets. The stockpiles were fairly wet from recent thunderstorms. A total of seventy-five, 5-gallon buckets were filled in proportion to the job mix formula. The aggregate proportions are the same for both mixes. 5-gallon steel pails of both binders were obtained from the supplier by the contractor. The fly ash was also obtained by the contractor and provided to the university. Evotherm P14 was obtained from Ingevity. A bale of cellulose fibers was provided by the contractor from the plant. Plant mix samples were sampled from the delivery trucks hauling the mix to the paving site. The plant had a truck sampling platform. University personnel and plant personnel worked quickly to fill ten steel pails during each sampling event. The top six inches of the load was moved aside and the samples were shoveled from the newly exposed asphalt mix surface.

Several trips were needed to obtain all required samples of the plant mix. For instance, the research team was scheduled to sample the ECR mix the same night as the aggregate sampling, but there were equipment issues that prevented paving that night. Ten, 5-gallon steel pails of plant mix 20-82 (I-44 10ECR mix) were sampled the following night (August 14, 2020). Unfortunately, the produced mix did not follow the JMF and could not be used. The loader operator was loading an incorrect stockpile into one of the bins. On August 20, 2020, sampling of mix 20-82 was planned (the I-44 10ECR mix), but the plant was having issues with binder content. Therefore, the mix sampled that night was ultimately unrepresentative. Finally, on September 17, 2020, representative samples for mix 20-82 (I-44 10ECR mix) were obtained.

The samples for mix 20-85 (I-44 Control) were pulled by the plant personnel as MODOT QC split samples. They only produced a small amount of mix 20-85 (I-44 Control). This was made in August during a time the university could not visit the plant. The contractor was able to set aside several boxes of QC splits that were not needed. The university used this material as the plant mix for section 20-85 (I-44 Control).

For the I-70 mix (SP125BSM 21-05), aggregates were sampled on June 2, 2021. The stockpiles were cut and sample pads created by the plant's bucket loader. Sixty-three 5-gallon plastic buckets were filled by university personnel from the sample pads. The number of buckets per stockpile was in proportion to the job mix formula. The liquid binder was obtained from an asphalt terminal in St. Louis. The contractor provided a small amount of 'Fastac' antistrip. The plant mix was sampled into ten, 5-gallon steel pails by the plant personnel and then given to the university in July. The RAP for this project was sampled on March 10, 2022. Sample pads were created by the plant's bucket loader and university personnel filled fifty, 5-gallon plastic buckets.

Chapter 3
Testing and Analysis Methods

3.1. Overview

In this study, MoDOT prescribed the IDEAL-CT test for cracking and the Hamburg wheel tracking test to control the rutting performance of the mixtures. The minimum threshold for the IDEAL-CT index was 165 (the current minimum criteria for SMA mixes), with the assumption that the tested mix would be short-term oven aged, cooled, then reheated prior to lab compaction and testing. For the Hamburg test a 12.5 mm maximum rut depth requirement at 20,000 passes was imposed (at a test temperature of 50°C (122°F)). The performance tests are described briefly below. Phase 2 of this study included friction testing, where the methods used are described in Chapter 5.

3.2. IDEAL-CT Testing

The IDEAL-CT cracking test is a recent mix cracking test developed by the Texas Transportation Institute (TTI). The test is developed for routine quality control (QC) and quality assurance (QA). The test set-up is similar to the traditional indirect tensile strength test, but it is performed at 25°C (77°F) at a constant loading rate of 50 mm/min until failure occurs. The specimen does not require gluing, notching, drilling or additional cutting. The test procedure is detailed in ASTM D8225 (ASTM D8825-19 2019). In this project, the specimens (150 mm diameter and 62 mm height) were conditioned in a temperature-controlled chamber for a minimum of 2 hours at 25°C (77°F). After conditioning, the specimens were centered between loading platens (see **Error! Reference source not found.**(a)). A seating load of 0.1 kN was applied in order to make appropriate contact between the loading platens and the sample. The sample was then loaded under a displacement control mode of 50 mm/min while the loading level was measured and recorded by the device. **Error! Reference source not found.**(b) shows a sample of the software output, i.e., the load-displacement curve.

The cracking parameter for the IDEAL-CT test, called the CT-Index, is derived from the load-displacement curve, as described in Equation 1.

$$CT_{index} = \frac{G_f}{|m_{75}|} \times \left(\frac{l_{75}}{D}\right) \times \left(\frac{t}{62}\right) \quad [1]$$

where,

G_f = Fracture energy (area under the curve normalized by the AREA fractured)

$AREA$= Area under the load – displacement curve, until the terminal load of 0.1 kN is reached

m_{75} = Modulus parameter (absolute value of the slope at 75% of peak load)

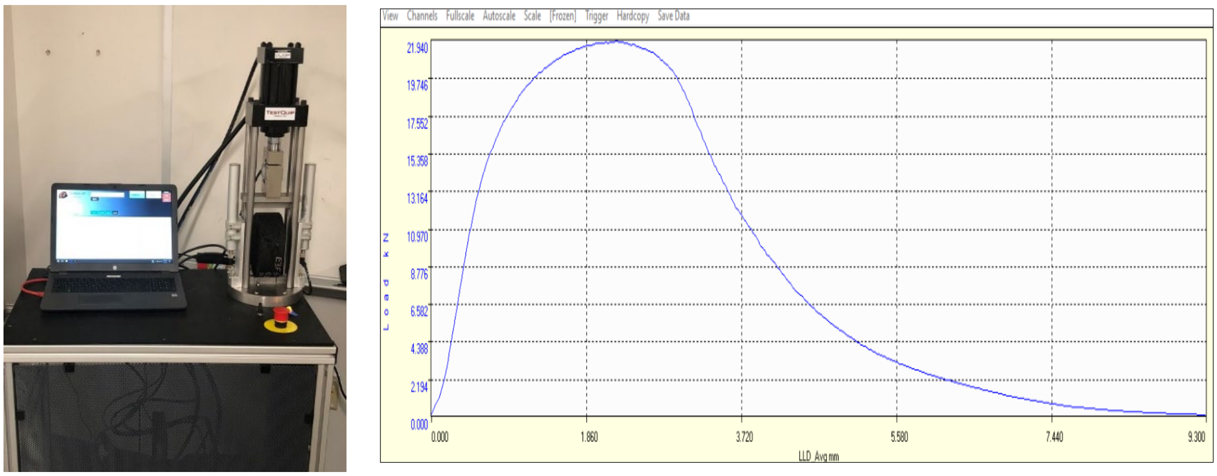
$\frac{l_{75}}{D}$ = Strain tolerance parameter (when load is reduced to 75% of peak load)

l_{75} = Vertical displacement when the load is reduced to 75% of peak load

D = Diameter of the sample

t = Specimen thickness

The larger the CT-index, the better cracking resistance of the mixture.



(a) (b)

Figure 3-1. (a) The Test Quip IDEAL-CT apparatus at MAPIL, (b) Typical load-displacement curve from Test Quip software

3.3. Hamburg Wheel Track Testing

Permanent deformation (rutting) in an asphalt pavement is a result of consolidation and shear flow caused by traffic loading in hot weather. This results in gradual accumulation of volumetric and shear strains in the HMA layers. The measured deformation of different layers of flexible pavement revealed that the upper 100 mm (4in.) serves the main portion of the pavement rut depth such that the asphalt layer accumulates up to 60 percent of total permanent deformation. Lack of shear strength of the asphalt layer to resist the repeated heavy static and moving loads results in downward movement of the surface and provides the potential for upheaval and microcracks along the rut edges. In addition to the structural failure issues, safety concerns rise when steering becomes affected by the non-planarity of the riding surface and standing water creates the potential for vehicle hydroplaning and longer stopping distances.

Wheel load tracking (WLT) tests are the most common performance tests for the controlling the rutting potential of HMA mixes. The WLT methods simulate traffic by passing over standardized wheels simulating real-life traffic loads on HMA specimen at a given temperature. The two most common WLT test devices are Hamburg Wheel Tracking Test (HWTT) and the Asphalt Pavement Analyzer (or APA, formerly known as the Georgia-loaded wheel tester). The HWTT is performed in accordance to AASHTO T324 standard (AASHTO-T324 2017). A loaded steel wheel, weighing approximately 71.7 kg tracks over the samples placed in a water bath at 50°C (122°F) (Figure 3-2). The vertical deformation of the specimen is recorded along with the number of wheel passes. The test is generally stopped when either the specimen deforms by

20mm or the number of passes exceeds 20,000. A Cooper Hamburg device (Figure 3-2) was used in this study.

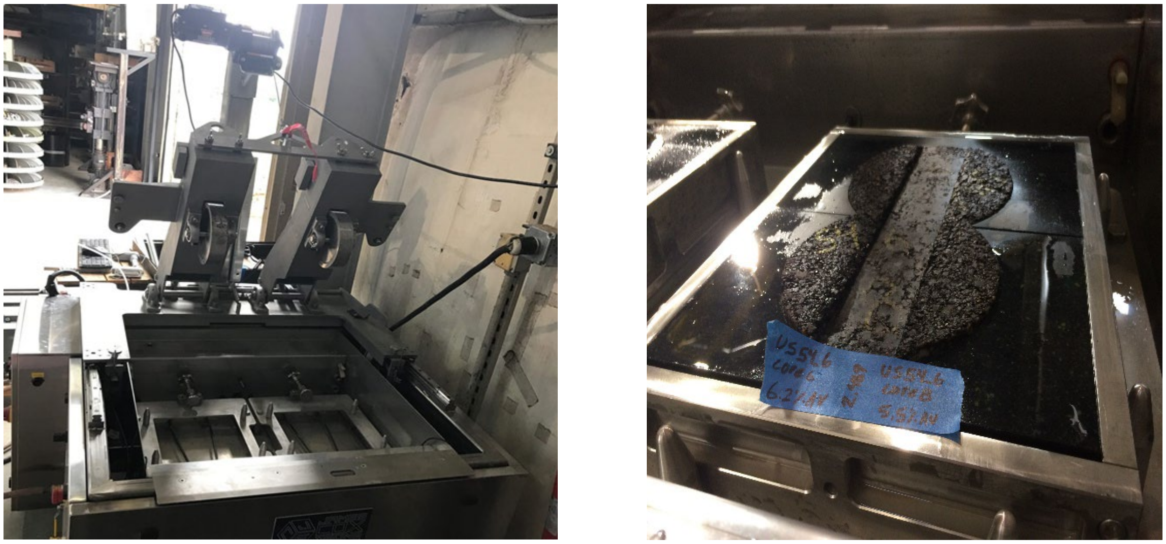


Figure 3-2 Hamburg Wheel Tracking Device: a) Test device b) Mixtures after test

Chapter 4
Mixture Design and Test Results

4.1. Overview

In this section, mix design iterations and steps taken to arrive at final I-44 and I-70 RAP mixes through balance mix design methodology are described.

4.2. Mix Design Iterations

<u>Iteration 1</u>: Baseline RAP Mixes (15%, 30% ABR, PG 64-22, 4.0%AV)

The initial RAP mixes were designed based off the contractor's job mix formulas for I-44 and I-70 control mixes. These mix gradations (shown in Figure 2-1) were redesigned to incorporate the RAP stockpile gradation whilst attempting to introduce minimal changes to the combined gradation of the control mix. This was done by removing small quantities of the finer stockpiles. To begin, two different ABR contents were decided for evaluation - 15% ABR and 30% ABR. The I-44 15% ABR mix was designed with 19% RAP in the aggregate blend while the I-70 15% ABR mix had 20% RAP. Typically, the binder content in RAP stockpiles is lower than the eventually determined optimum binder content for a newly designed mix. Hence, the %RAP used in a mix is slightly greater than the computed ABR for the mix. Both I-44 and I-70 30% ABR aggregate blends incorporated 40% RAP. Binder contents were then selected by trial and error to achieve 4.0% air voids at the design compaction level of 100 gyrations. A softer binder grade, PG64-22, was used for the RAP mixtures to counter the stiffness of the RAP binder. Results from the tests are shown in Table 4-1. For the 15% ABR mixes, the I-44 Control mix yielded an average CT-score of 96 and 120 for the I-70 Control mix, both failing to meet the threshold for SMA mixes of 165. The 30% ABR mixes exhibited better rutting resistance but lower CT-Index, as expected. The introduction of RAP, even at low levels (15%) stiffened the mixture enough to bring the CT-Index below the allowable CT index test threshold of 165.

Table 4-1 Mix design iteration 1 details

Mix	ABR	Binder grade	Total AC (Virgin AC)	CT Index	Rut Depth @ 20,000 passes (mm)
I-44	15	PG64-22	5.5 (4.6)	96.5	4.14
I-44	30	PG64-22	5.2 (3.3)	35.2	3.13
I-70	15	PG64-22	6.1 (5.2)	120.7	5.29
I-70	30	PG64-22	5.9 (4.0)	50.1	3.30

<u>Iteration 2</u>: Softer Binder Grade (10%, 15%, 30% ABR, PG58-28, 4.0%AV)

Binder contents of 5.2% for the I-70 mix and 4.6% for the I-44 mix were obtained from the first iteration of 15% ABR mixes. In an effort to achieve desirable CT-scores, a softer binder grade, PG58-28, was selected to be evaluated. With this approach, the I-44 mixtures still did not meet the cracking requirements, as shown in Table 4-2 Mix design iteration 2 details. As a next step, the RAP amount was brought down to 10% with the expectation of a higher CT-Index. However, the lower RAP amount did not yield the desired cracking resistance and was, in fact, statistically similar to the15% ABR mixture.

On the other hand, the I-70 Control mix with 15% ABR mix yielded satisfactory CT-Index of 172.1 and rut depth of 8.16 mm. Although the CT-Index was close to the threshold, no further changes in RAP amounts were made in order to retain adequate rutting resistance of the mix. Since an optimum RAP content was obtained for the I-70 mix, subsequent iterations were focused on the I-44 mixture only.

Table 4-2 Mix design iteration 2 details

Mix	ABR	Binder grade	Total AC (Virgin AC)	CT Index	Rut Depth @ 20,000 passes (mm)
I-44	10	PG58-28	5.5 (4.9)	138.7	6.92
I-44	15	PG58-28	5.5 (4.6)	135.9	5.00
I-70	15	PG58-28	6.1 (5.2)	172.1	8.16

<u>Iteration 3</u>: Regressed Air Voids (I-44, 15%ABR, PG58-28, 3.0%AV)

A regressed air voids approach was used in this iteration with a PG58-28 binder, in an effort to increase the binder content and consequently the CT-Index. The air voids were regressed to 3.0% and AC content was increased to 4.7%, with 15% ABR. However, this approach did not impact the CT-Index significantly, as the mix recorded a CT-Index of 134.6, as shown in Table 4-3 Mix design iteration 3 details. This score was close to the results obtained in the previous iteration without air voids regression (see Table 4.2).

Table 4-3 Mix design iteration 3 details

Mix	ABR	Binder grade	Total AC (Virgin AC)	Air voids	CT Index	Rut Depth @ 20,000 passes (mm)
I-44	15	PG 58-28	5.6 (4.7)	3.0	134.6	5.64

<u>Iteration 4</u>: Binder Additives (I-44 15%RAP, PG 58-28, 4.0%AV, 4% warm-mix additive)

The final RAP mix iteration for I-44 was designed with the increase of the Evotherm P14 warm mix additive from 0.5% to 4.0% (see Table 2-1 Mix information for control mix details). This approach resulted in a 55% increase in the CT-scores in comparison to the mix without additives i.e., I-44 PG58-28 RAP mix in iteration 2. The rut depth results were high (9.1mm) but within the maximum of 12.5mm at 20,000-wheel passes requirement. This mix was established as the final I-44 RAP mix, namely, I-44 15ABR.

Table 4-4 Mix design iteration 4 details

Mix	ABR	Binder grade	Total AC (Virgin AC)	Air voids	CT score	Rut Depth @ 20,000 passes (mm)
I-44	15	PG 58-28	5.5 (4.6)	4.0	211.3	9.09

<u>Other Iterations</u>: Use of PG46-34 (I-44 15%, 30% ABR, PG 46-34)

While the researchers used PG58-28 as the softer binder grade, the possible use of PG46-34 was also evaluated. It must be noted that since PG46-34 is not commonly used in Missouri climates, recommending this softer grade binder for RAP mixtures could have significant economic implications. Nevertheless, from a research standpoint, this evaluation was of interest and is being reported herewith. As shown in Table 4-5, the mix with 15% ABR yielded an improvement in the cracking resistance and produced CT-scores (155.5) fairly close to the minimum CT-index requirement (165.0). However, the recorded average rut depth for the 15% ABR mix was 16.8mm. Although the CT-Index was below the threshold for 15% ABR, the researchers also investigated 30% ABR mix, albeit with regressed air voids of 3.5%. Compared to the 30% ABR mix with PG58-28 (at 4.0% air voids), the CT-Index improved but it was still below the required threshold, as shown in Table 4.5.

Table 4-5 Other mix design iteration details

Mix ID	ABR	Binder grade	Total AC (Virgin AC)	Air voids	CT Index	Rut Depth @ 20,000 passes (mm)
I-44	15	PG46-34	5.5 (4.6)	4	155.5	16.78
I-44	30	PG46-34	5.2 (3.3)	3.5	85.8	N/A

<u>Final Recommendation:</u>

Based on the iterations discussed above, the final mixture recommendations are listed in Table 4-6, with individual cracking and rutting results plotted in Figure 4-1, and Hamburg-CT interaction plot shown in Figure 4-2. As seen in the table, both the I-44 and the I-70 control mixtures were modified with 15% recycled binder sourced from 20% RAP, and the I-44 mix was additionally modified with recycled crumb rubber (referred to as Engineered Crumb Rubber or ECR). The CT-Index and rut depth results were 'passing' for all mixtures except the I-70 Control mix (see Figure 4-2). Notably, MoDOT did not have a CT-Index threshold of 165 during the production of the I-70 mix (Superpave design).

The I-44 Control mix benefited from the introduction of ECR as the rutting resistance increased without any significant effects on the cracking index score. However, addition of 15% recycled binder from RAP resulted in a drop in cracking as well as rutting resistance compared to the control mix. As discussed in prior sections, both the 144 10ECR and I-44 15ABR mix had softer base binder compared to the control mix. The drop in rutting resistance with addition of RAP was unexpected but could have been a result of the properties of the RAP source. As discussed in Section 2.2.2. RAP Stockpile, the RAP stockpiles are often made up of multiple binder sources and grades, which could have influenced the result.

The I-70 Control mix was also modified with the same RAP resulting in 15% ABR. Unexpectedly, the CT Index increased but the rutting resistance decreased. This is likely caused by the conflation of two factors – RAP source and binder type, i.e., softer binder with 4% Evotherm P14 (warm mix additive).

Table 4-6 Summary of performance results

Mix*	Binder Grade	Virgin Binder content	Additives	Hamburg Rut Depth @20,000 passes (mm)	CT Index
I-44 Control	PG64V-22	6.0	0.5% warm mix additive#	6.02	252.1
I-44 10ECR	PG64-22	6.2	0.5% warm mix additive	5.17	250.6
I-44 15ABR	PG58-28	4.6	4% warm mix additive	9.09	211.3
I-70 Control	PG64V-22	6.2	0.5% antistrip agent**	3.47	103.7
I-70 15ABR	PG58-28	5.2	N/A	8.16	172.1

*All mixes contained 0.3% cellulose fibers by weight of mix. # Evotherm P14. **FASTAC antistrip

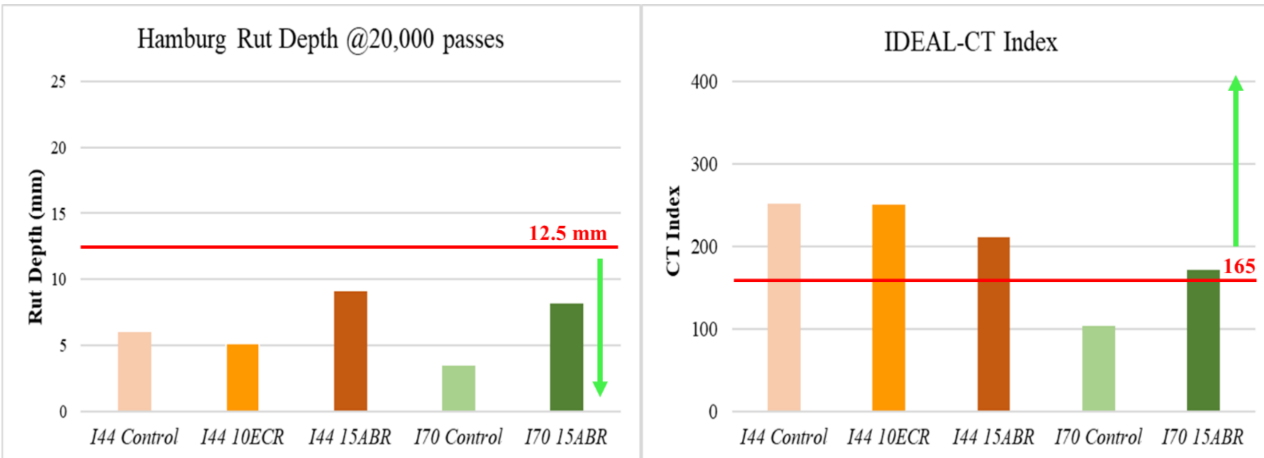


Figure 4-1 Performance of mixes in (a) IDEAL-CT test and (b) Hamburg rutting test (red line represents the threshold)

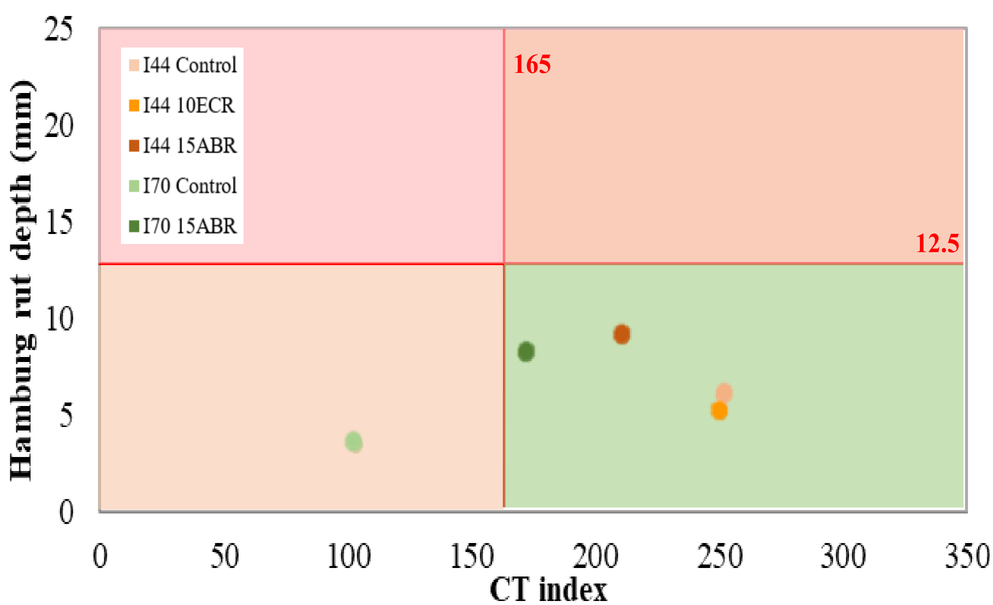


Figure 4-2 Hamburg-CT interaction plot

4.3. Volumetric Properties of Final Designs

Although this project used BMD methodology to produce mixtures, the volumetric properties for all the mixtures are also reported for informational purposes in Table 4-7. The appropriate volumetric tolerances for the respective stone matrix asphalt mixes along with the baseline mixes are included in the table.

Table 4-7 Volumetric properties of mixes

Mix ID	%Total AC (%Virgin AC)	%AV	%VMA	%VFA	DP
Limits	N/A	N/A	>17	>75	N/A
I-44 Control*	6.0 (6.0)	4.0	17.10	77.0	1.6
I-44 ECR*	6.2 (6.2)	4.0	17.60	77.0	1.4
I-44 15ABR	5.5 (4.6)	4.0	15.98	75.2	1.5
I-70 Control*	6.2 (6.2)	4.0	17.30	77.0	1.0
I-70 15ABR	6.1 (5.2)	4.0	17.46	75.7	1.0

*volumetrics reported from JMFs

Chapter 5
Friction Testing

5.1. Overview

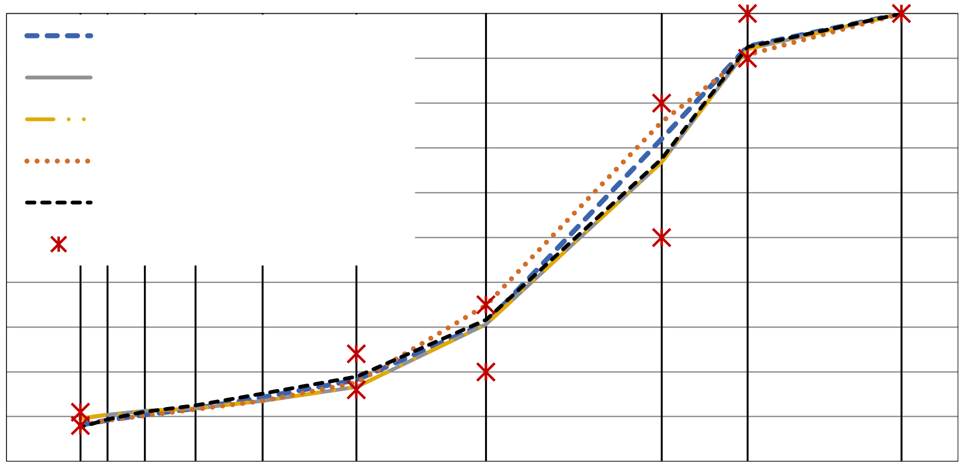
One of the main benefits of SMA mixtures are to provide a surface with high skid resistance. The skid resistance of a pavement surface relies on the aggregate microstructure and macrotexture of the pavement surface. In addition, the long-term frictional performance depends on the aggregates' abrasion and degradation resistance, as well as the internal aggregate texture. Incorporating reclaimed asphalt pavement (RAP) materials in asphalt mixtures may negatively impact the skid performance of SMA mixtures depending on the RAP aggregate quality and design parameters. The frictional performance of SMA mixtures with recycled components must be evaluated. To that end, this phase of the study looked at the following objectives:

A. Assess the abrasion resistance of applied aggregates,
B. Quantify aggregate shape characteristics using aggregate imaging system (AIMS) techniques,
C. Measure frictional characteristics of the SMA mixtures and compare them to the dense-graded mixtures.

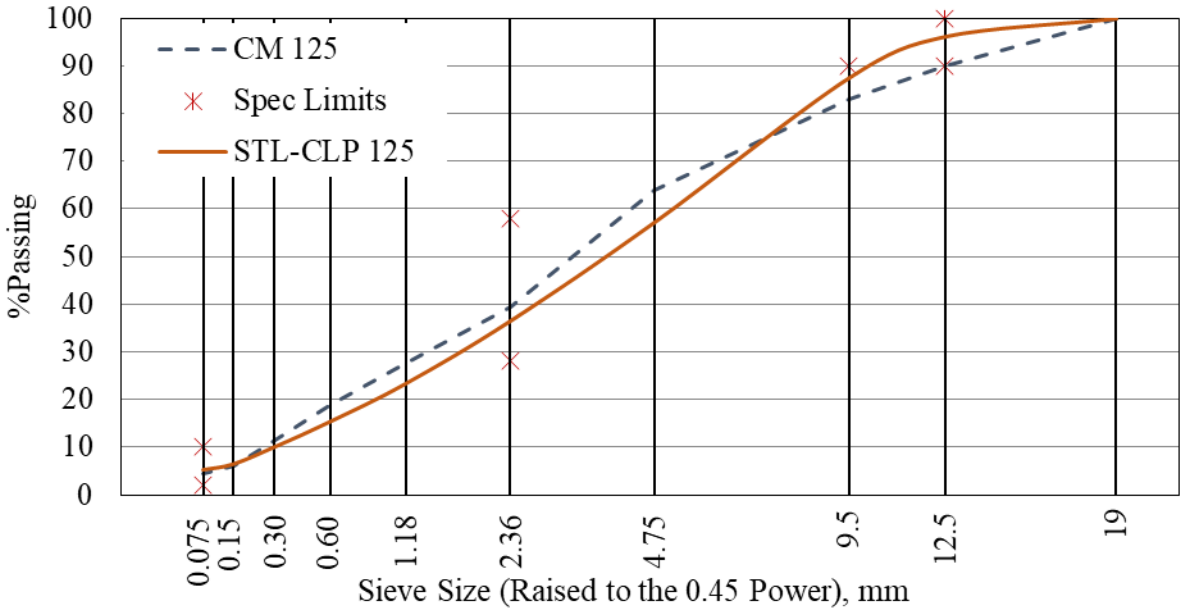
The following sections will cover the materials and test methods used on this phase of the study, as carried out at Missouri S&T University. In addition, a detailed literature review is included in Appendix A.

5.2. Materials

In this phase of the study, five different stone matrix asphalt (SMA) types - SP125BSM 20-54, 20-82 (I-44 10ECR), 20-85 (I-44 Control), 20-85 with 15% ABR (I-44 15ABR), and 21-05 (I-70 Control). In addition, two Superpave mixes, namely, CM 125 and STL-CLP 125, were investigated. Figure 5-1 presents the job mix formula (JMF) of all the SMA and dense graded mixes.



(a) SMA mixtures



(b) DG mixtures

Figure 5-1 Job mix formula (JMF) of investigated mixtures

5.3. Methodology and Experimental Work

Figure 5-2 presents the proposed methodology of friction testing for aggregates and asphalt mixtures. Aggregate testing included Micro-Deval, and AIMS analysis, while mixture testing included British Pendulum Tester, Dynamic Friction Tester, and Circular Track Meter. The aggregates were also put through sieve analysis and detailed results including scale and shape parameters obtained from Weibull distribution function are included in Appendix B for brevity.

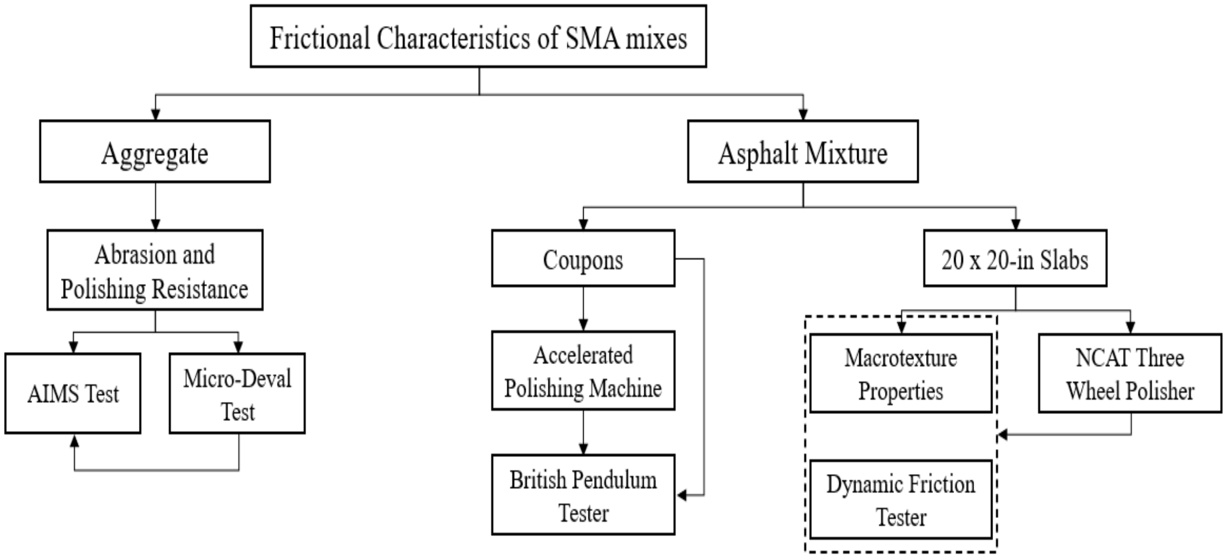


Figure 5-2 Proposed experimental plan

5.3.1. Aggregate Friction Testing

In this research study, several test methods were used to evaluate the frictional properties and polishing resistance of aggregates as follows:

5.3.1.1. Micro-Deval Test

The Micro-Deval (M-D) test ("Micro-Deval Test for Evaluating the Quality of Fine Aggregate for Concrete and Asphalt Micro-Deval Test for Evaluating the Quality of Fine Aggregate for Concrete and Asphalt.Pdf," n.d.) was used to evaluate the abrasion resistance of the investigated aggregates at different run times (105, 180, and 240 minutes). A 1500 ± 5 g aggregate sample with a specific grading was placed in a steel container with 2.0 ± 0.05 L of tap water for at least an hour following the ASTM D6928-17 standard (ASTM 2017) ("ASTM D6928-17Standard Test Method for Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus" 2017). After that, 5,000 ± 5 g of steel balls were placed gently in the container. After contacting the M-D test for the desired run time, the polished aggregate sample was screened over a 4.75-mm (#4) sieve superimposed on a 1.18-mm (#16) sieve. The percentage of the M-D abrasion loss is calculated by $\%\text{MD Loss} = \frac{\text{A -B}}{\text{A}} \times 100$ Equation **5.1**. Two different grades were investigated in this research study, as presented in

Table 5-1 Proposed Micro-Deval gradation is provided in

Table 5-1**.**

$$\%\boldsymbol{MD\ Loss} = \frac{\boldsymbol{A-B}}{\boldsymbol{A}} \times \mathbf{100} \qquad \text{Equation 5.1}$$

where:

A : The dry weight of a sample
B : The dry weight of material retained on the 4.75 mm and 1.18 mm sieves

Table 5-1 Proposed Micro-Deval gradation

Sieve Size		Grade A	Grade B
Passing	Retained	Mass	Mass
12.5-mm	9.5-mm	750 g	-
9.5-mm	6.3-mm	375 g	750 g
6.3-mm	4.75-mm	375 g	750 g
Total		1500±5g	1500±5g

5.3.1.2. Aggregate Imaging Measurement System (AIMS)

This research used the AIMS technique to investigate the aggregate angularity and surface texture before and after different run times in the M-D device. The AIMS device has a camera with two lighting options to capture the aggregate particles at different resolutions. It can also quantify an aggregate form from a size of 37.5 mm to 150 mm. Such a technique is used to quantify the angularity, texture, and 3-D shape of coarse aggregate particles ($R_{\#4}$) and the angularity of fine aggregates ($P_{\#4}$) (2005; 2011). The recommended number of particles is 50 particles for coarse aggregates (R#4) for AIMS analysis ("Field Evaluation of Asphalt Mixture Skid Resistance and Its Relationship to Aggregate Characteristics" 2011). More details about the method of quantifying aggregate surface texture and angularity can be found in Masad et al., 2006 (2006).

5.3.2. Asphalt Mixture Friction Testing

Three frictional testing techniques were used to assess the frictional properties of the fabricated SMA slabs and coupons including the British Pendulum Tester, The Circular Track Meter, and the Dynamic Friction tester (DT). The fabricated SMA slabs and coupons were polished with a Three-Wheel Polishing Device (TWPD) in the first stage and an accelerated polishing machine in the final stage. Brief details of the tests and equipment are included in the sections below.

5.3.2.1. British Pendulum Tester

The British pendulum tester (BPT) is used to evaluate the micro-texture properties of either curved samples (coupons) or flat surfaces at low speeds (six mph), according to ASTM-E0303-22 (ASTM 2022) (ASTM 2022). The British pendulum number (BPN) represents the kinetic energy loss by dragging the rubber slider over the test surface.

5.3.2.2. Circular Track (CT) Meter

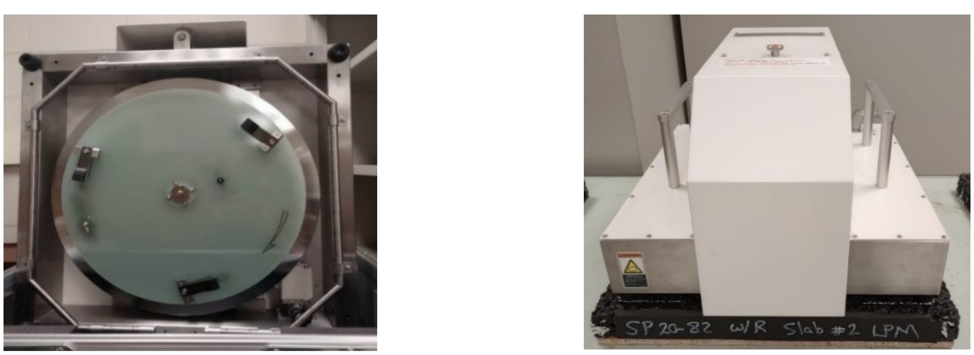
The CT meter (Figure 5-3) is used to quantify the macrotexture of the pavement surface. It has an arm with a charge-coupled device (CCD) laser-displacement sensor that measures the profile of a circle track up to a radius of 142 mm (5.6 in) or a circumference of 892 mm (35 in). The measured profile is segmented into eight arcs with 111.5 mm (4.4 in). The average mean profile depth (MPD) is calculated for each segment, which has an average of 124 points each. Finally, the average of all eight-segment depths is the final MPD.

(a) (b)

Figure 5-3 The CT meter shown (a) on a fabricated slab and (b) from a bottom view

5.3.2.3. Dynamic Friction Tester (DFT)

The dynamic friction tester (DFT) was used to measure the surface frictional characteristics of the fabricated SMA slabs at different three-wheel polishing cycles in wet conditions according to ASTM E1911-19 (ASTM 2019) (ASTM 2019). The DFT consists of three spring-loaded rubber sliders mounted on a 335-mm horizontal spinning disk. A disk rotates parallel to the test surface until it reaches the desired rotational speed corresponding to the sliders' tangential velocity (90 km/hr maximum); then, the disk is lowered, and the sliders contact the test surface. The DFT converts the measured traction force in each slider to the surface friction coefficient. The DFT provides the dynamic friction coefficient (μ) at speeds between10 and 60 km/hr). The μ at 20k m/hr represents the micro-texture properties of the test surface, indicating the contribution of aggregates to pavement skid resistance (2009; 2023). Therefore, the DFT value at 20 km/hr was monitored at different TWPD cycles.



(a) (b)

Figure 5-4 The dynamic friction tester (DFT). (a) DFT bottom view and (b) DFT on prepared slab

5.3.2.4. NCAT Three-Wheel Polishing Device (TWPD)

A three-wheel polishing device (TWPD) was used to polish the fabricated SMA slabs. The polishing device consists of three patterned pneumatic tires (tread sawtooth), as shown in Figure 5-5(a). The wheel assembly can exert 0.65 ± 0.02 kN (146 ± 5lb) on the test surface through the pneumatic tires. The pneumatic tire size should be 2.80/2.50–4 with 240 ± 34 kPa (35 ± 5 psi) according to AASHTO PP104-21 (AASHTO 2021) *(16)*. The wheel assembly rotates in a circular path with a diameter of 284 mm (11.2 in) at a speed of 60 ± 5 rpm. This research study used 47.6 kN (105 lb.) total applied load on test slab surfaces with a tire pressure of 241.3 ± 34.5 kPa (35 ± 5 psi) and with a speed of 60.2 rpm. A water spray was applied during the polishing process to mitigate the wear of the pneumatic tires and wash away the abraded aggregate and rubber particles from the slab surface. In this research, the friction characteristics of the test slabs were evaluated at different TWPD polishing cycles of 1000, 2000, 5000, 10,000, 30,000, 50,000, and 100,000 cycles.

(a) Tire tread pattern (b) Loaded wheel assembly (c) TWPD during Polishing

Figure 5-5 NCAT three-wheel polishing device

5.4. Sample Preparations

5.4.1. Laboratory Produced Mix (LPM) Preparation

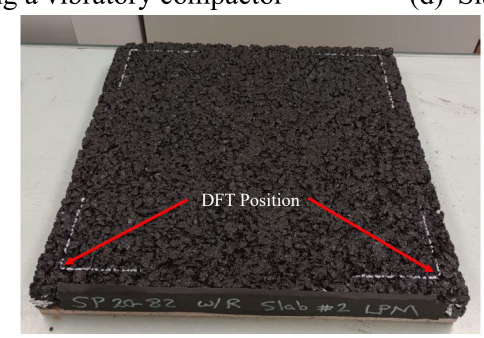
All friction samples were fabricated at the Missouri University of Science and Technology laboratory, except for the SP125 20-82 and SP125 20-85 with 15% ABR mixes, which were mixed at the University of Missouri-Columbia Mizzou Lab. All the aggregate sources were screened over the standard sieve set to control the gradation of the LPM, as shown in Figure 5-6(a). The weight of the mixture components (aggregate, asphalt binder, and fiber) was estimated based on the mix design sheet. The total aggregate weight was divided into four equal batches (around 6,900 gm for each aggregate batch) following the AASHTO PP104-21 standard (AASHTO 2021), as presented in Figure 5-6(b) (AASHTO 2021). Then, a specific weight of the screened-oven dried aggregates was collected to achieve the contractor-supplied job mix formula (JMF). The batched aggregates were kept in the oven overnight at 20°C over the mixing temperature. A bucket-style laboratory mixer was used to produce the LPM. The mixing process lasted two minutes, and the fluffed fiber was spread gradually on the mixture during the mixing process once the aggregates were coated with asphalt (within the first 30 seconds). Finally, the produced mix batches were placed in the oven at compaction temperature for 2 hours before the compaction step to simulate the short-term aging (AASHTO 2021).

(a) Aggregate source batch for I-44 mix

(b) An I-44 mix aggregate batch

(c) Slab compaction using a vibratory compactor

(d) Slab after compaction



(e) Labeled and marked slab for friction testing

Figure 5-6 Procedure of fabricating LPM SMA mixtures and slabs

5.4.2. Plant Produced Mix (PPM) Samples

Plant-produced mixtures were brought to the lab in either carton boxes or 5-gallon steel pails, as seen in Figure 5-7, and reheated until the mix was workable. After that, the mixture was reduced to a slab sample and gyratory sample following the quartering method described in AASHTO R47 AASHTO 2023) ("AASHTO R47 Standard Practice for Reducing Samples of Asphalt Mixtures to Testing Size" 2023). Regarding the PPM, the compaction temperatures were like the provided JMF.

(a) (b)

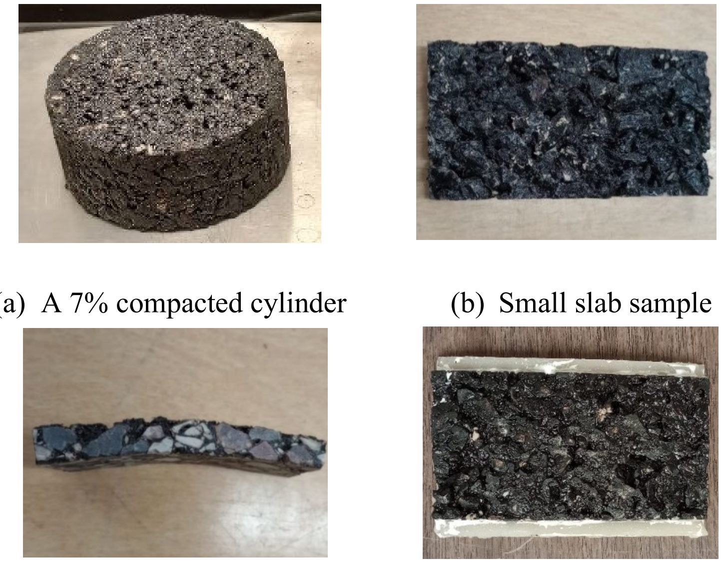
Figure 5-7 Plant-produced mix samples. (a) Cartons and (b) 5-gallon steel pails

In this research study, two different friction testing protocols, the British pendulum tester (BPT) and dynamic friction tester (DFT), were used to evaluate the friction characteristics of the proposed SMA mixes. Therefore, two different sample geometries were fabricated to fit the testing methods.

5.4.3. British Pendulum Tester Samples

For the BPT specimens, the sample preparation consists of five main steps:

(1) A gyratory compactor was used to prepare a 65-mm height and 150-mm diameter cylinder for each mix at 7 ± 1% air voids Figure 5-8(a)
(2) The bottom and top surfaces were sawed to prepare four flat samples of dimensions 88.9 by 44.4 by approximately 10 mm (3.5 by 1.75 by approximately 0.4 in.) as shown in Figure 5-8(b).
(3) The sawed samples were placed in the BPT mold with the suitable placer thickness to avoid further compaction in the oven at the compaction temperature (around 140°C) to curve the sample surface Figure 5-8(c).
(4) After cooling down to room temperature, a thin layer of plaster was spread on the mold, and then the curved sample was placed on the plaster to prevent getting the epoxy agent into the sample surface.
(5) After the epoxy's curing time, the sample was de-molded and washed carefully to remove any plaster adhered to the mixture surface, Figure 5-8(d).



(a) A 7% compacted cylinder (b) Small slab sample

(c) Curved sample (d) Fabricated coupon

Figure 5-8 Preparation steps of asphalt mixture coupons

5.4.4. Dynamic Friction Tester Samples

For the DFT testing, square slabs were fabricated in the laboratory and compacted by a vibratory compactor. Two different slab geometries were prepared: 508 x 50.8 x 50.8 mm (20 x 2 x 2-in.) for laboratory-produced mix (LPM) and 508 x 50.8 x 38.1 mm (20 x 2 x 1.5-in.) for plant-produced mix (PPM). The total weight of the mix is calculated based on the slab dimensions, the maximum theoretical specific gravity of the mixture (G_{mm}), and the desired air voids (7±1%) using $\text{Mix Wt.} = (\text{lwt})(G_{mm} \cdot \rho_w)\left[\frac{(100\text{-}V_a)}{100}\right]$ Equation **5.2** according to AASHTO PP104-21 (AASHTO 2022) (AASHTO 2021). A vibratory plate compactor was used to compact the slabs, as shown in Figure 5-6(e) in next section.

$$\boldsymbol{Mix\ Wt.} = (\boldsymbol{lwt})(\boldsymbol{G_{mm}} \cdot \boldsymbol{\rho_w})\left[\frac{(\mathbf{100}-\boldsymbol{V_a})}{\mathbf{100}}\right] \qquad \text{Equation 5.2}$$

where:

l, w, and t	:	Length, width, and thickness of the slab, mm
G_{mm}	:	The maximum theoretical specific gravity of the mixture
ρ_w	:	The density of water, 0.001 g/mm^3
Va	:	Desired % air voids of slab

5.5. Testing Results, Analysis, and Discussion

5.5.1. Aggregate Frictional Characteristics

5.5.1.1. Degradation Resistance of Aggregates

The micro-Deval (M-D) test was conducted at three-run times (105, 180, and 240 minutes) to study the degradation rate of investigated aggregates. In addition, two different gradings were used to assess the impact of sample grading on the degradation rate. For RAP material, since the ignition oven may damage or degrade the surface texture of the RAP aggregates, an extraction test was conducted following ASTM D2172/D2172M (ASTM 2018) using trichloroethylene (TCE). After that, the M-D test was run on the extracted aggregate at two-run times (105 and 180 minutes) (ASTM 2017; 2012) .

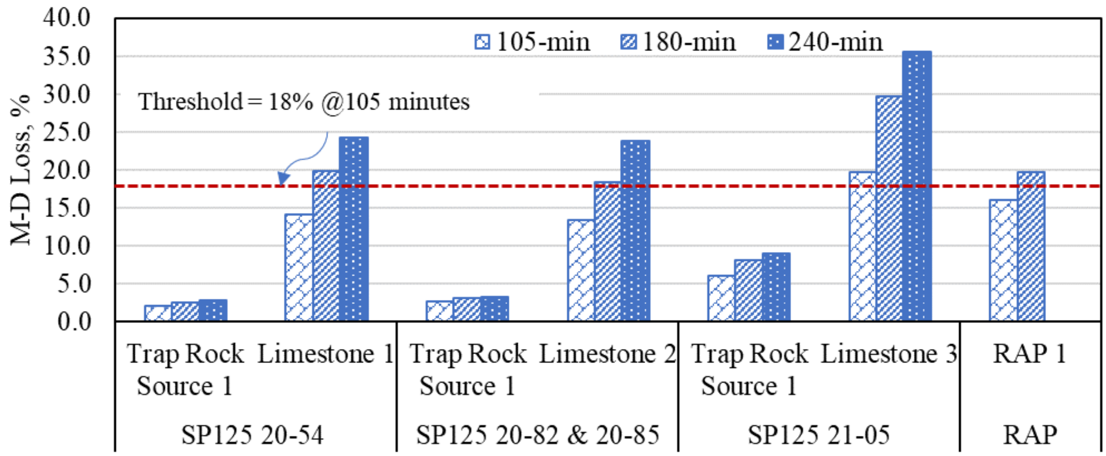


Figure 5-9 MD abrasion loss percentage for investigated aggregates

The trap rock sources had a good degradation resistance (lowest abrasion loss percentage), as demonstrated in Figure 5-9, while the Limestone 3 stone had the highest abrasion loss indicating poor resistance to wearing. Limestones 1 and 2, and RAP aggregate material sources had moderate degradation resistance. Similar results have been obtained in previous studies wherein track rock sources have higher abrasion resistance compared to limestone sources (Wu et al. 1998).

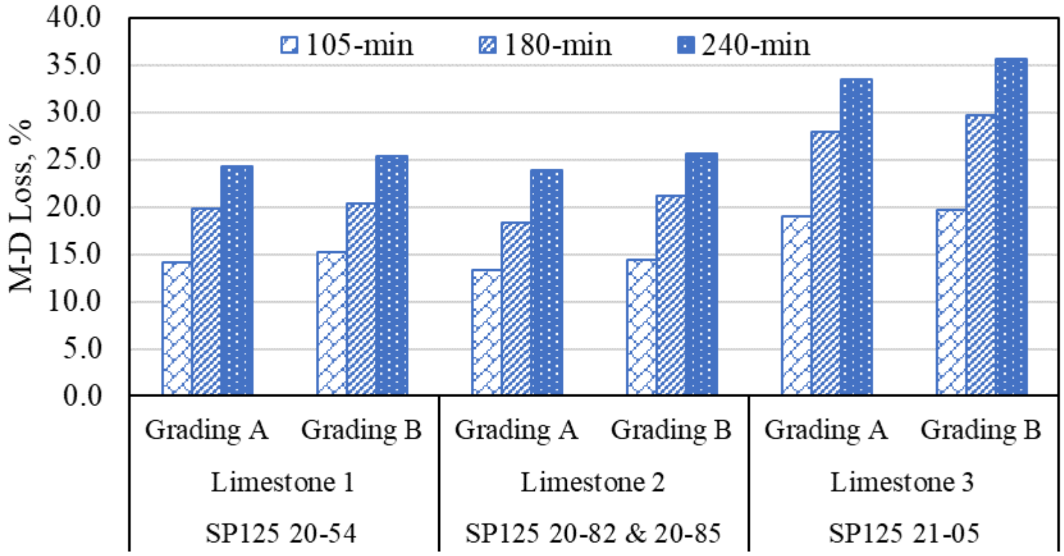


Figure 5-10 MD abrasion loss percentage for different gradings at different run times

Figure 5-10 shows an insignificant effect on the sample grading based on the degradation rate and resistance. However, the coarser grading (grading A) had a higher degradation resistance.

5.5.1.2. Shape, Texture, and Angularity Characteristics of Aggregates

The aggregate texture and angularity of six aggregate sources (extracted RAP aggregates, Limestone 1, 2, and 3 (used in 20-54, 20-82/85, 21-05 mixtures respectively), Trap Rock Source 1, and Limestone 4 (used in CM Superpave mixture) were examined in this research study.

The AIMS II device was used to measure the surface texture and angularity of three sizes: passing ½" sieve and retained on 3/8" sieve, passing 3/8" and retained on ¼", and passing ¼" and retained on #4—all at different M-D run times: (1) before M-D (BMD), (2) after 105-min of M-D polishing time (AMD105), and (3) after 180-min of M-D polishing time (AMD180). After that, the weighted average of texture and angularity indices of each aggregate source were estimated. Figure 5-11 presents an example of the impact of aggregate source gradation on aggregate angularity and texture. It was observed that the same aggregate sources with different grading slightly differed in the distributions of texture and angularity index. The changes in the aggregate texture and angularity with time was found using the Micro-Deval test as evaluated by using$TX(t) = a_{TX} + b_{TX} \times Exp(-c_{TX}{*}t)$ Equation **5.3** and $GA(t) = a_{GA} + b_{GA} \times Exp(-c_{GA}{*}t)$ Equation **5.4**, respectively.

$$\boldsymbol{TX(t) = a_{TX} + b_{TX} \times Exp(-c_{TX} * t)} \qquad \text{Equation 5.3}$$

$$\boldsymbol{GA(t) = a_{GA} + b_{GA} \times Exp(-c_{GA} * t)} \qquad \text{Equation 5.4}$$

where:

$TX(t)$ & $GA(t)$	:	Aggregate texture and angularity with time, respectively
a_{TX}, b_{TX}, & c_{TX}	:	The regression coefficients of the aggregate texture model
a_{GA}, b_{GA}, & c_{GA}	:	The regression coefficients of the aggregate angularity model
T	:	Micro-Deval run time

The Trap Rock 1 had the highest initial and terminal aggregate texture and angularity, followed by Limestone 2 and 3, indicating that mixes containing trap rock and/or one of the two limestones should have better frictional performance. Finally, the weighted average of the aggregate angularity and texture parameters of the investigated mixtures are presented in Figure 5-11.

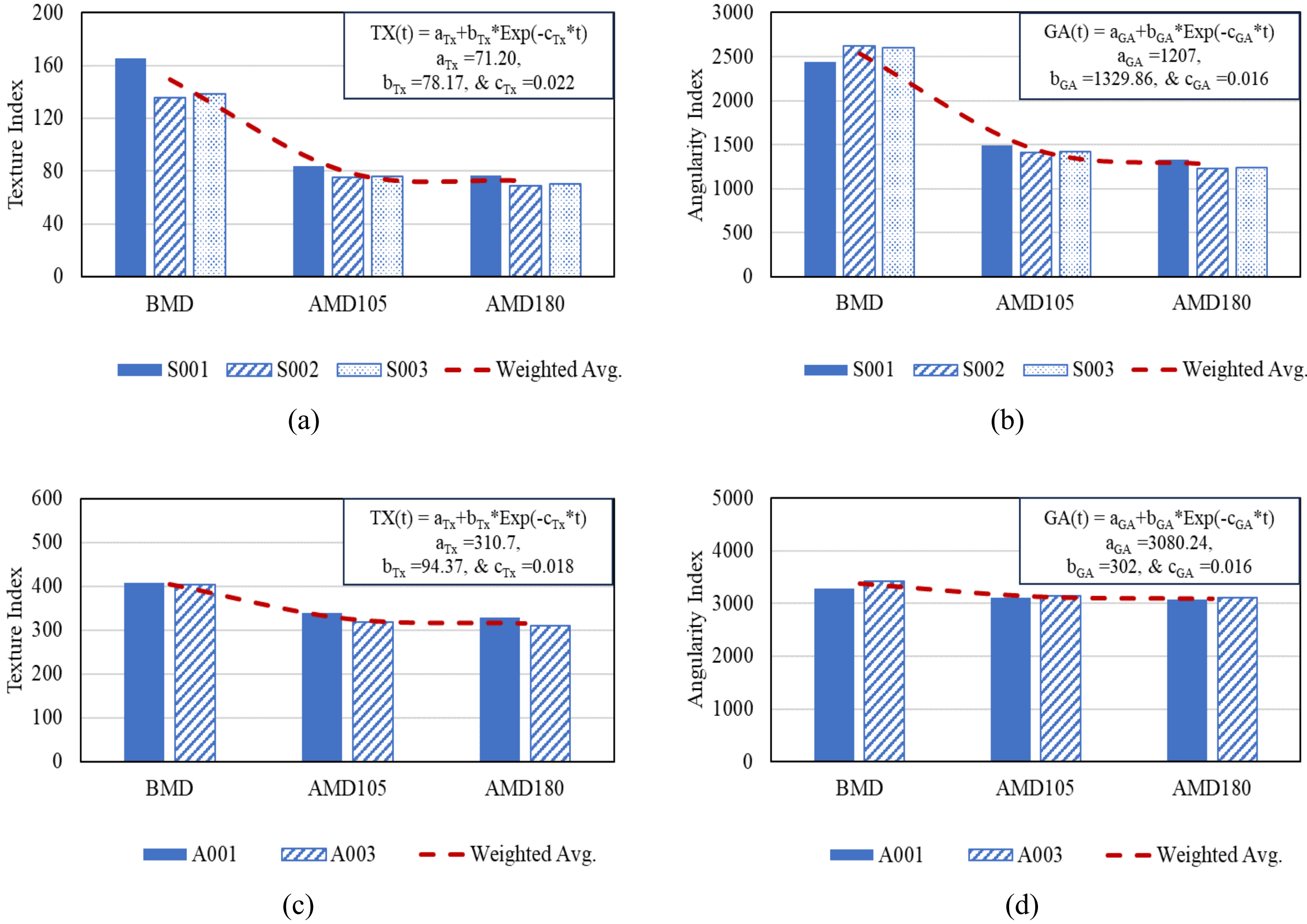


Figure 5-11. The Texture and Angularity Indices of aggregate sources of SP125 21-05 (I-70) (BMD = Before M-D polishing, AMD = After M-D polishing). (a) Texture Index of Trap Rock 1, (b) Angularity Index of Trap Rock 1, (c) Texture Index of Limestone 3, (d) Angularity Index of Limestone 3,

As shown in Figure 5-12, the investigated RAP material had two aggregate sources (trap rock and limestone), and the texture and angularity indices of both sources were measured; then, the weighted average indices were estimated accordingly. The extracted RAP aggregate sources had good to excellent texture and angularity indices compared to other investigated aggregate sources. However, the aggregate of the pavement surface is exposed to polishing and degrading due to environmental and traffic conditions. The RAP material crushing process would be expected to produce high-quality aggregates with good surface characteristics. Finally, in light of the results of the full testing suite, it was concluded that the RAP material would not be expected to have a significant, negative effect on the frictional performance of recycled asphalt mixtures.

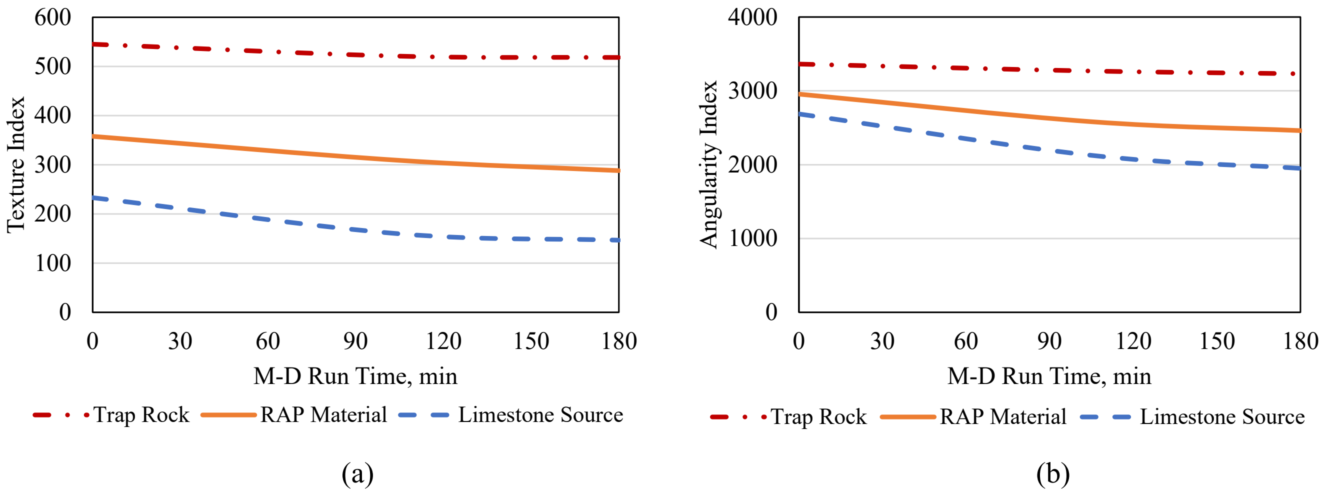
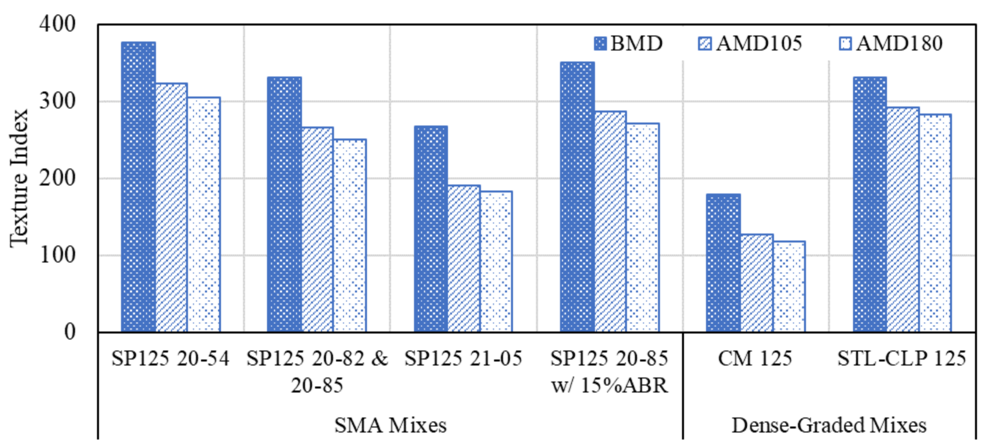
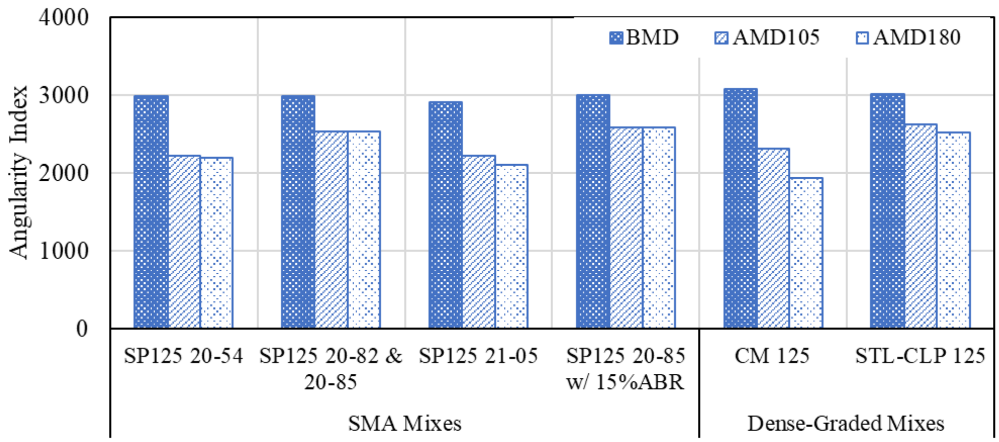


Figure 5-12 (a & b) Texture and angularity indices of RAP aggregate material source which included trap rock and limestone.



(a)



(b)

Figure 5-13 (a) Aggregate angularity and (b) texture indices of the investigated mixtures

The texture and angularity indices of the mixtures investigated in this study are shown in Figure 5-13. The superiority of the trap rock was observed, followed by Limestone 1, compared to the other investigated aggregate sources in terms of the texture and angularity characteristics. The terminal texture and angularity of the trap rock were higher than the initial texture and angularity of the limestone sources, indicating that the mixes with trap rock, either SMA or Superpave mixtures would have a satisfactory long-term frictional performance.

5.5.2. Mixture Frictional Characteristics

The frictional performance of the fabricated slabs were evaluated at different TWPD cycles (1, 2, 5, 10, 30, 50, and 100 thousand) using a dynamic friction tester (DFT) and circular texture (CT) meter. The results of the DFT and CT-meter tests were then used to calculate the international friction index (IFI), following ASTM E1960-07 (ASTM 2015) (ASTM 2015).

5.5.2.1. British Pendulum Tester Results

Two coupons from the gyratory compacted cylinders were prepared for BPT measurement from each mixture. The BPT was conducted before and after applying an accelerated polishing device for 10 hours, as presented in Figure 5-14. It was found that the dense-graded mixtures had a high initial BPN of 45. In addition, the PPM for all SMA mixtures had a higher BPN than the LPM, which matches the DFT20 results.

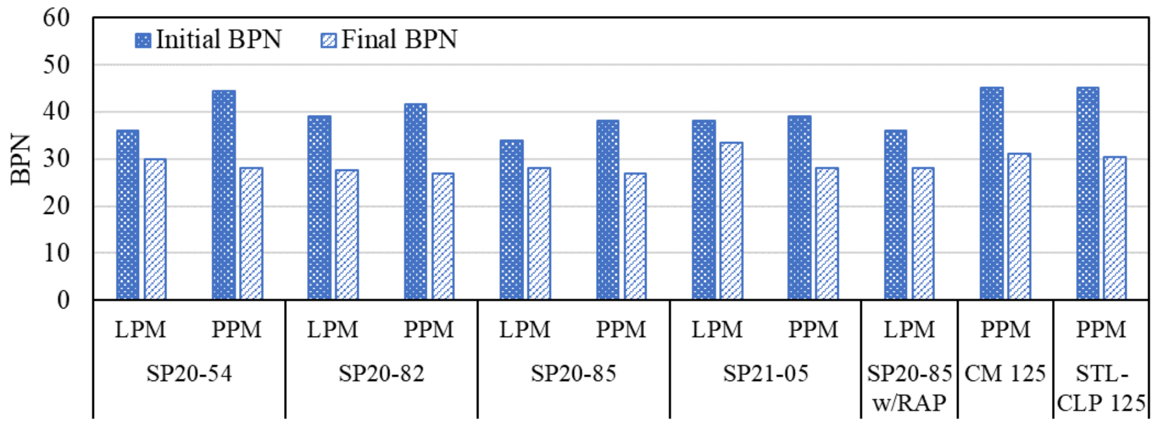
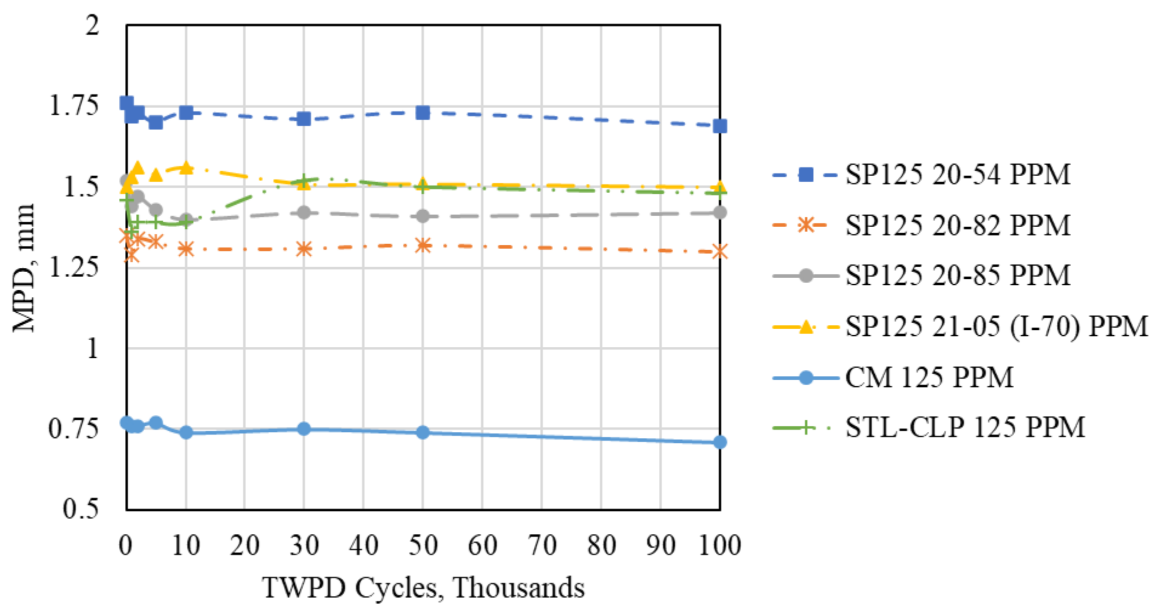


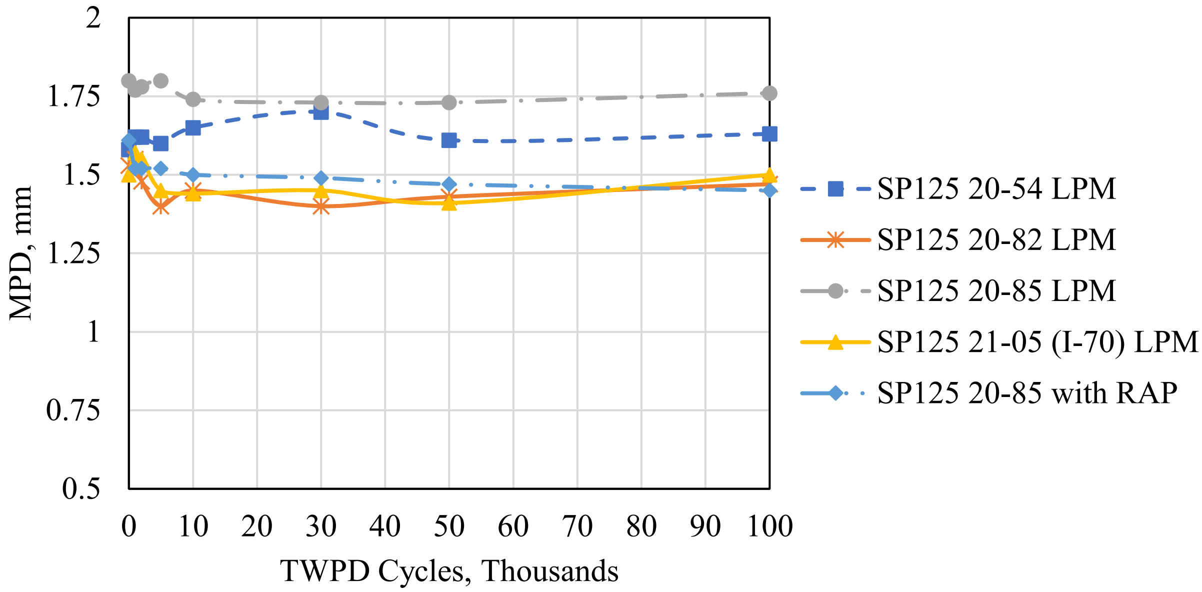
Figure 5-14 BPT results of investigated mixtures

5.5.2.2. CT Meter Results

The measured mean profile depth (MPD) using the CT meter, for the fabricated SMA slabs varied between 1.35 mm and 1.75 mm for the SMA mixtures and 0.75 mm and 1.45 mm for dense-graded mixtures. However, the SMA mixtures have almost the same gradation, as illustrated in Figure 5-1 (a). Notably, pavement surfaces with a high macrotexture mixture have a high skid resistance (friction number) at higher speeds as the water drains faster away from the tire-pavement interface. It was observed that the MPD changed at the first few thousand polishing cycles and then remained almost constant, as shown in Figure 5-15.



(a)

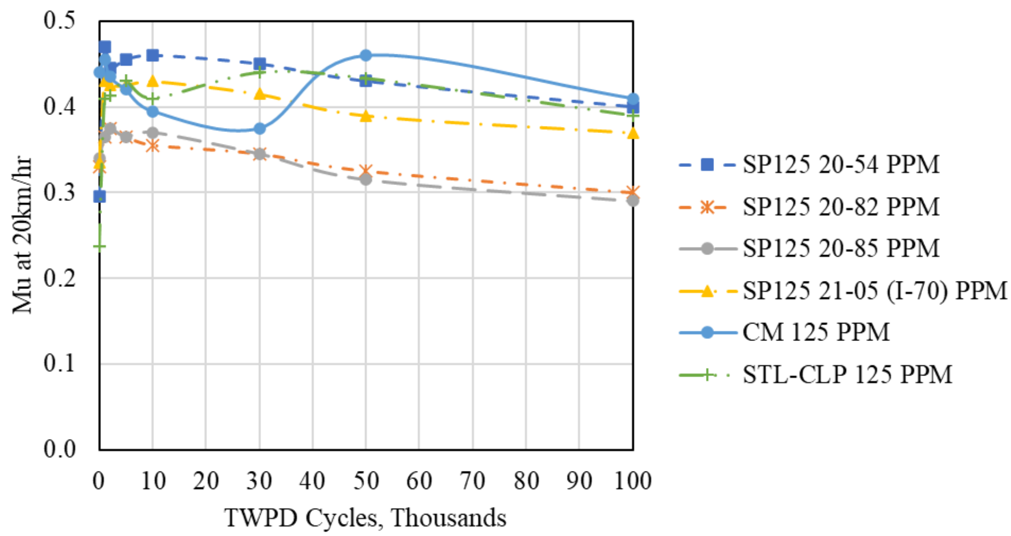


(b)

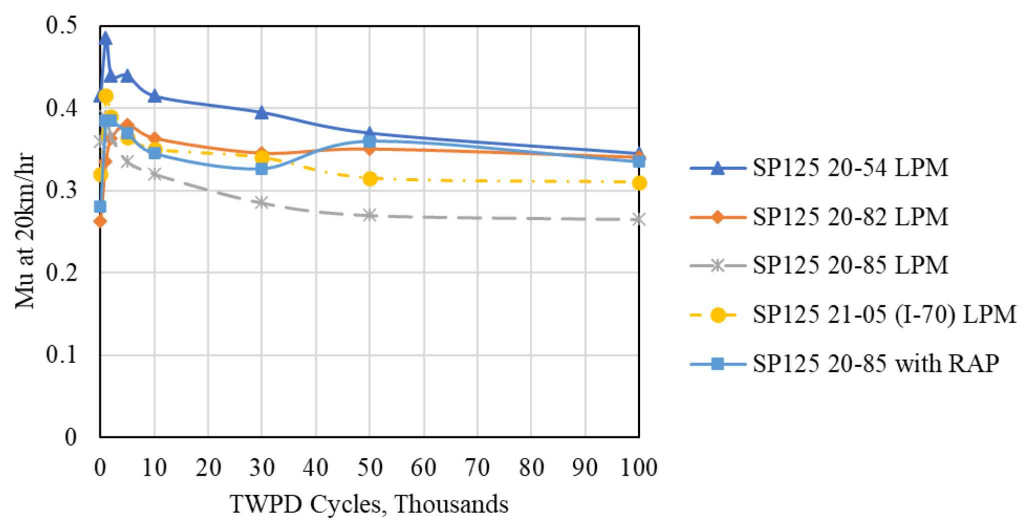
Figure 5-15 MPD of fabricated slabs at different TWPD cycles for, (a) plant produced mixes, and (b) lab produced mixtures

5.5.2.3. Dynamic Friction Test Results

Figure 5-16 presents the DFT_{20} values of the investigated asphalt mixtures in wet conditions at different TWPD cycles. Notably, the DFT20 values of all investigated mixtures increase significantly within the first few thousand polishing cycles due to wearing the binder film off the surface aggregates and exposing the aggregate texture; then, the wheel starts polishing the aggregates till reaching the terminal friction number. It was observed that the SP125 20-54 mix had the highest DFT20 values, which matches the Micro-Deval test and AIMS results, indicating that the DFT20 could differentiate between the mixtures in terms of the micro-texture of the pavement surface.



(a)



(b)

Figure 5-16 DFT values at 20 km/hr at different TWPD cycles. (a) Plant produced mixtures and (b) laboratory produced mixtures

5.6. Preliminary Field Results

Apart from the laboratory analysis, the research team was also able to gather skid resistance measurements from a field section. Although MoDOT currently does not allow recyclates like RAS or RAS in the SMAs, recently, the addition of GTR via dry process has been allowed per MoDOT's latest specifications (JSP 1801). A small 2-mile section of SMA (referred to as SP125BSM 22-84) modified with Engineered Crumb Rubber, or ECR, was paved on I-70 in Cooper County, with the rest of the project using a polymer-modified (PG64V-22) mixture. Note that previous sections of this study (see Section 2.2, Page 4) referred to the I-70 mix obtained from a project in Callaway County. As shown in Figure 5-17, MoDOT employed a locked-wheel skid trailer towed on the back of a pick-up truck fitted with data acquisition systems to measure the skid number on the two surfaces – one paved with polymer-modified mix and other with ECR mix. The following sections include information on the mix and subsequently a discussion of skid resistance results.

Figure 5-17 Locked-wheel skid trailer

5.6.1. Aggregate Stockpiles

This mix consisted of seven different aggregate stockpiles, with the individual stockpile gradations shown in Table 5-2 and the aggregate blend for this mix is represented in Figure 5-18. The polymer-modified SMA used PG64V-22 binder while the ECR-modified SMA used PG64-22 with 10% ECR added by weight of virgin binder.

Table 5-2 Aggregate stockpiles for I-70 Cooper County mix (SP125BSM 22-84)

		3/4"	1/2"×	1/2"	3/8"		3/8"	MF

Sieve Size (No.)	Sieve Size (mm)		1/4"		(A)	3/8" (B)	(C)	
Aggregate Blend		18%	23.5%	5%	30%	5%	11%	7.5%
2 inches	50.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
1 1/2 inches	37.50	100.00	100.00	100.00	100.00	100.00	100.00	100.00
1 inch	25.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
3/4 inch	19.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
1/2 inch	12.50	78.00	90.00	100.00	100.00	100.00	100.00	100.00
3/8 inch	9.50	59.00	48.00	92.00	97.00	100.00	100.00	100.00
No. 4	4.75	26.00	3.00	65.00	32.00	52.00	61.00	100.00
No. 8	2.36	9.00	1.00	47.00	6.00	16.00	17.00	100.00
No. 16	1.18	5.00	1.00	35.00	2.00	7.00	7.00	100.00
No. 30	0.60	4.00	1.00	27.00	1.00	6.00	6.00	99.90
No. 50	0.30	4.00	1.00	20.00	1.00	5.00	5.00	99.70
No. 100	0.15	3.00	1.00	16.00	1.00	4.00	4.00	99.00
No. 200	0.075	2.50	0.20	12.00	0.20	3.00	3.50	95.60

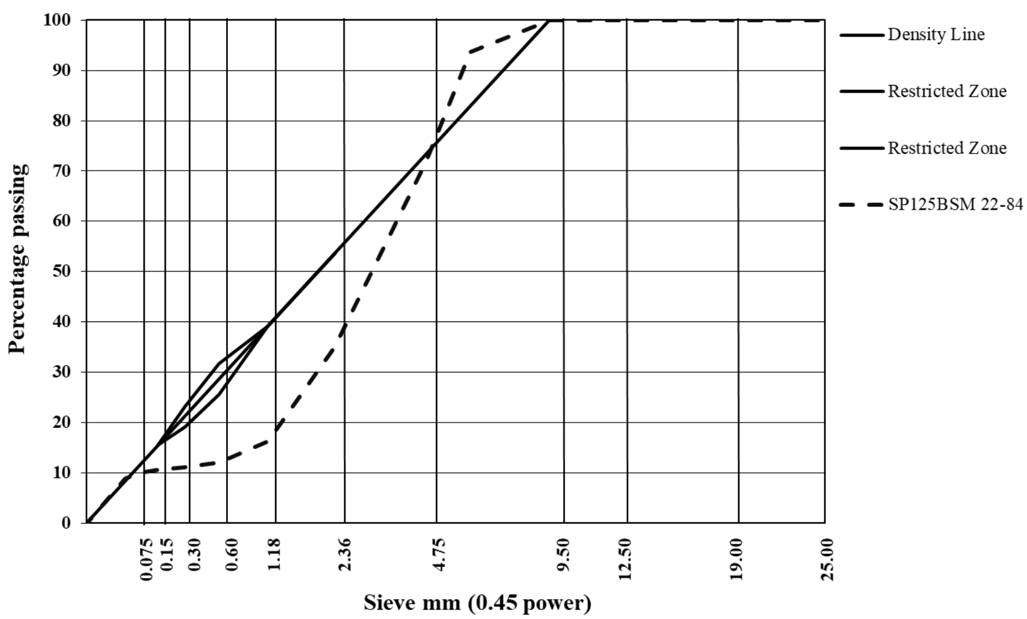


Figure 5-18 Aggregate gradation for I-70 Cooper County mix (SP125BSM 22-84)

5.6.2. Skid Resistance Results

Skid resistance of a pavement is dependent on multiple factors that affect the interaction of pavement and vehicle. In this study, skid number for the pavement sections was adjusted for 40 mph driving speed. The skid number for the PG64V-22 binder (or ‘polymer’) section was measured 0.8 miles west of ECR section and approximately 2 miles east of ECR section. A bridge was located towards the east-end of the ECR section and the skid number readings for the bridge were discarded from calculations. On average, the ECR section exhibited a 12% increase in skid resistance compared to the polymer-modified (PG64-22V) sections. The measurements were obtained only a week after construction. Both sections of the pavement are expected to become rougher (possess higher friction) as they experience more traffic and the surface film of binder is abraded away. In the long term, the skid resistance will likely diminish slightly from the peak, depending on the level of traffic and polish resistance of the aggregates. That notwithstanding, the early skid resistance increase afforded by the presence of ECR during the early life of the pavement when the slippery film of asphalt from initial construction is still intact is of significant benefit from a safety perspective.

Chapter 6
Summary, Conclusions and Recommendations

6.1. Summary and Conclusions

A comprehensive research investigation was carried out to investigate the potential use of recycled materials in Stone Matrix Asphalt (SMA) mixtures in Missouri, with a focus on the use of reclaimed asphalt pavement (RAP). A field investigation involving the use of ground tire rubber as another recycled material source for SMA was also studied herein. The methods used involved a Balanced Mix Design (BMD) approach, along with advanced friction testing in the lab and field. Friction testing was included in the research due to the concern over friction reduction leading to increased stopping distances when potentially softer aggregates are introduced into SMA mixtures via RAP sources stemming from non-SMA mixes with lower aggregate quality requirements. Based on the findings of the study, the following conclusions were drawn:

1. The current use of conglomerate (non-homogeneous), unfractionated RAP stockpiles poses practical limitations in achieving passing balanced mix designs at higher levels of RAP. The key findings supporting this conclusion were:
    a. At RAP levels above 15%, difficulties were encountered in passing both cracking and rutting BMD tests, despite efforts to incorporate softer base binder grades and/or modifiers such as warm-mix asphalt additives. One mixture (I-44) in particular required multiple design iterations to achieve both passing cracking and rutting test scores.
    b. Skid/friction tests also indicated that the softer aggregates present in current RAP stockpiles tended to reduce parameters associated with skid resistance; however, suitable frictional characteristics were achieved at lower levels of RAP.
2. The use of recycled ground tire rubber, or GTR (engineered crumb rubber introduced by the dry process was studied herein) appears to be another viable avenue for incorporating recycled materials into Missouri pavements. The key findings supporting this conclusion were:
    a. A balanced mix design for an SMA mixture placed in Cooper County, MO on I-70 was successfully designed and produced in the summer of 2022 and is performing very well to date.
    b. Skid trailer testing displayed a potential added benefit of using GTR in flexible pavement surface materials, namely, an approximately 12% increase in skid resistance in the test section containing GTR was measured relative to the control section, which did not contain GTR. The early skid resistance increase afforded by the presence of ECR (Engineered Crumb Rubber, or dry process GTR) during the early life of the pavement when the slippery film of asphalt from initial construction is still intact is of significant benefit from a safety perspective.

6.2. Recommendations

Based on the findings and conclusions of this study, the following recommendations are made:

1. It is recommended that MoDOT consider allowing RAP in SMA mixtures; however, at this time, with the use of conglomerate and unfractionated RAP stockpiles, an upper limit of 15% asphalt binder replacement (ABR) from RAP is also recommended. Limiting RAP to this level at this point in time is supported by three findings: (1) difficulty in achieving balanced mix designs may likely arise when driving towards ABR levels above 15% with current RAP stockpiles in Missouri; (2) limiting ABR to 15% will avoid the need for the use of excessively soft base binder grades, which typically are more costly and in short supply, and; (3) the use of relatively low to moderate RAP levels provides a factor of safety with respect to pavement skid resistance, at least until more research is conducted and/or improved RAP stockpile specifications are developed. Alternatively, an upper limit of 20% RAP by weight of the mixtures could be established, if an ABR-based upper threshold not desired.
2. MoDOT has recently begun allowing the use of GTR in Superpave and SMA mixtures. The research conducted herein supports the continued and increased usage of GTR as a possible approach towards achieving good mixture durability, skid resistance, and economics while promoting mixture sustainability.
3. It is recommended that additional research be conducted to address the following open research questions:
   a. Can the use of homogeneous and fractionated RAP stockpiles lead to the possibility of specifying even higher RAP levels in the future? Such practices have shown the possibility of driving towards 30% RAP usage at the Illinois Tollway; however, it is acknowledged that the RAP in Missouri is likely a bit stiffer than the RAP in the Chicago area.
   b. The use of modifiers such as recycling agents (rejuvenators) and various warm-mix products present convenient approaches to achieving BMD requirements for SMA mixes; however, the long-term performance benefits of these products should be further investigated through field studies.
   c. In addition to RAP and GTR, other recycled materials offer potential economic, sustainability and even performance benefits for SMA mixes. These include recycled, post-consumer waste plastic (PCR-P) and recycled asphalt shingles (RAS). A recent test bed constructed on I-155 near Hayti, Missouri as a collaboration between MoDOT and the research team leading the study presented herein will provide valuable information with regards to the use of GTR and PCR-P in Missouri SMA mixture. Although RAS has been successfully deployed at the Illinois Tollway in SMA mixtures, more research is needed to validate the potential use of RAS in Missouri mixtures, given the hotter climatic conditions leading to stiffer RAS materials in the area, which may lead to challenges in meeting cracking test requirements for SMAs design with BMD.

d. Additional lab and field friction testing is recommended as MoDOT begins to modify specifications to allow recycled materials in SMA mixes.
e. MoDOT may wish to consider allowing greater than 15% asphalt binder replacement (or, alternatively, 20% RAP by weight of the mixture) in SMA mixes, provided that a value engineering proposal accompanies the mix design showing that: (1) Additional RAP stockpiling techniques are being used to improve the quality and consistency of the RAP product, such as the use of homogeneous stockpiles and fractionated RAP stockpiles; (2) BMD requirements can be satisfied, and (3) an added requirement for a laboratory skid test should also be considered as part of the BMD for SMA mixtures containing more than 15% ABR from RAP.

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Appendix A

Literature Review

Early literature defined stone matrix asphalt as hot mix asphalt mixtures (HMA) prepared with gap-graded aggregate gradation in order to maximize the asphalt binder content and coarse aggregate fraction (E. R. Brown and L. A. Cooley, Jr 1999). By 1991, the first SMA mixes had been placed in the U.S. as a premium mixture used in projects with high traffic, 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 (n.d.). Although SMA mixtures are initially expensive compared to the usual dense-graded mixtures, the delay in maintenance activities due to prolonged pavement life justifies the initial investment (*25*, *2, 26,*) 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.

Use of Recycled Materials in SMA

Most state agencies in the U.S. do not allow any recycled contents in their SMA mixes. However, few states have specifications on the percentage by weight of mixture or asphalt binder replacement and quality of RAP permitted in SMAs produced in their respective states. Georgia and Alabama have a limit of 15% by weight of mix incorporation of RAP ("Standard Specifications for Highway Construction" 2022; "Standard Specifications Construction of Transportation Systems" 2021). According to Illinois specifications, SMA pavement surfaces can be incorporated with 15% of fractioned RAP (FRAP) or 25% with combination of FRAP and RAS. The Virginia Department of Transportation (VDOT) permits the use and quantity of RAP as per the binder used for the mix i.e., up to 20% for mixes using PG70-22 and up to 15% for PG76-22 mixes (2007a). Other mix property and mix design considerations have to be accounted for while including RAP in SMA mixes, to name a few: the need to use a softer binder grade to counteract the stiffness effect due to RAP usage, addition of rejuvenators to activate aged binder in RAP, the different effects using fine RAP or coarse RAP to the final mix properties, etc.

Recycled materials not only save cost in terms of materials, but also impart various performance benefits. A popular recycled material used in SMA modification is Ground Tire Rubber (GTR). Traditionally, rubber-modification has been successful in gap-graded mixtures, which makes SMA an ideal candidate to be modified with rubber. Numerous research studies have reported on the benefits of using GTR in SMAs, such as enhanced fatigue and overall crack resistance, low rutting potential, and prevention of drain-down without use of fibers. Table A-8-1 presents multiple such studies covering the usage of recycled materials in SMAs.

Table A-8-1 Studies on use of recycled materials in Stone Matrix Asphalt mixtures

Authors	Modifications	Findings
Watson et al. 2008 (2008)	RAP (four different sources; 10, 20, 30, 40% in quantity)	20% RAP can be used without significant effect on fatigue performance Enhanced rutting resistance No effect on low-temperature performance with increase in RAP.
Manosalvas-Paredes et al. 2015 (2016)	GTR + SBS	GTR-SBS can be used to replace cellulose fibers to prevent draindown
Sarang et al., 2015 (Sarang, G., B. M. Lekha, G. Krishna, and A. U. Ravi Shankar 2016)	Waste Plastic	Waste plastic is suitable dosage can be used as stabilizing additive in SMA
Cascione et al. 2015(Cascione, A. A., R. C. Williams, and J. Yu 2015)	RAS	5% RAS in SMA in Illinois showed good performance
Mashaan et al. 2014 (Mashaan, N. S. 2014)	GTR	Improved fatigue life
Diefenderfer 2017 (Diefenderfer, S. D 2017)	RAS	Excellent rutting performance RAS mixtures more susceptible to fatigue
Wang et al. 2017 (Wang, Z., Z. Li, H. Liu, and L. Yang. 2017)	RAP (0, 10, 20, 30%) in SMA and modified HMA	RAP inclusion did not affect surface properties significantly Excellent fatigue performance, comparable to modified HMA with no RAP
Baaj and Paradis 2008 (Baaj, H., and M. Paradis 2008)	RAS (4%)	RAS could be used to replace asbestos fibers in SMA and reduce virgin binder content 2-year field study shows no distress on RAS section
Devulapalli et al. 2020 (Devulapalli, L., S.	RAP (up to 40%) with rejuvenators	40% RAP can be used in SMA with proper gradation

Kothandaraman, and G. Sarang 2020)		
Wang and Buttlar 2018 (39. 2019)	RAP, RAS, GTR	Excellent rutting and good cracking resistance
Rath et al. 2019a (40. 2019)	RAP, RAS, GTR	Excellent performance in rutting and cracking resistance Up to 47% binder replacement with use of softer binder and GTR
Rath et al. 2019b (40. 2019)	GTR	Better performance in cracking and rutting laboratory tests than control PPA-modified mixture

Evaluation of Reduced Air Void Design Targets

Due to the coarse aggregate skeleton of SMA mixtures, there exists a possibility of interconnected air voids, which makes the SMAs permeable at relatively lower air voids content (Xie, H., and D. E. Watson 2004). This prompted a recommendation for a compaction level of 6% air voids or less for SMAs with 12.5 NMAS or less (2002). More recently, studies have shown that regressing air voids in asphalt mixtures result in an increase in cracking resistance without compromising rutting resistance (West, R., C. Rodezno, F. Leiva, and A. Taylor 2018).

Superpave design dictates designing mixtures at 4% air voids to avoid adding excess binder in the mixtures that would increase the risk of rutting, bleeding, and shoving. However, two decades worth of observations have shown that since the implementation of Superpave, pavements have failed predominantly by cracking (West, R., C. Rodezno, F. Leiva, and A. Taylor 2018; Maupin Jr., G. W 2003). Cracking resistance increases with an increase in asphalt binder content and there are only two ways to increase the effective asphalt content in an asphalt mixture- by regressing air voids or by increasing minimum VMA. Increasing the minimum VMA would require a change in aggregate blend and is difficult to enforce due to poor repeatability of specific gravity values. Wisconsin DOT investigated the regressing of air voids in mixtures and observed an increase in cracking resistance of mixtures with two popular cracking tests (West, R., C. Rodezno, F. Leiva, and A. Taylor 2018). The report also shows that the rutting values, measured by Hamburg wheel tacking device, and was not affected drastically by regression of air voids. This approach has also been adopted by Colorado, Michigan, South Carolina, and Illinois paving agencies (Tran, N., G. Huber, F. Leiva, B. Pine, and F. Yin 2019).

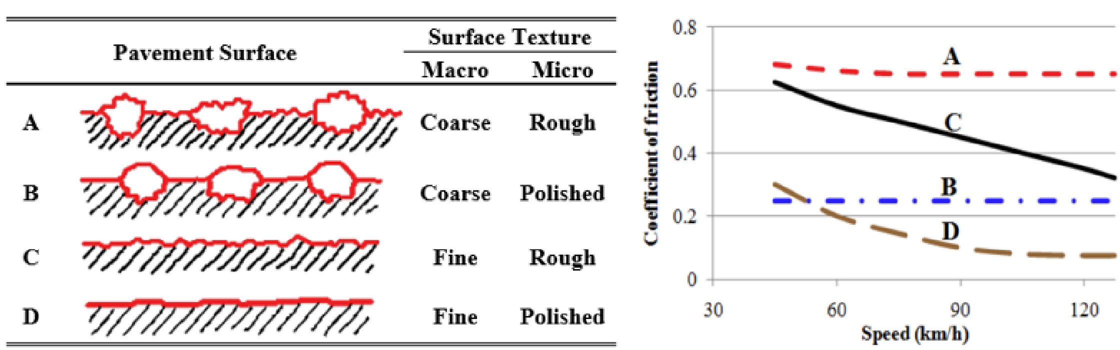
A recent NCAT report listed regression of air voids by increase in binder content as one of the mix design strategies in Balanced Mix Design (BMD) method for improving mixture performance (Tran, N., G. Huber, F. Leiva, B. Pine, and F. Yin 2019). With an increase in recycled content in asphalt mixtures, BMD approach is gaining popularity among the states and design of highly recycled specialized mixtures, such as SMAs. Illinois Tollway has placed multiple SMA designs with high recycled content (up to 36% asphalt binder replacement) and

GTR on its interstate routes back in 2009 and used a 3.5% air void design target to promote mix durability (39. 2019). In 2016, they placed nine experimental SMA sections on I-88 with different rubber technologies, RAP, and RAS (up to 47% asphalt binder replacement). These SMA sections performed exceptionally in laboratory testing and on field, having survived the harsh winter of 2019 (40. 2019).

Friction Testing

Pavement skid resistance is affected by adhesion characteristics in the micro-texture mechanism and by hysteresis in the macrotexture mechanism. Both micro-texture and macrotexture surfaces are affected by the asphalt mix aggregates and binder. Pavement macrotexture aggregate properties are governed by aggregate gradation, maximum aggregate size, characteristics of both coarse and fine aggregates, air voids, mix binder type and content. Coarse aggregate characteristics are particle shape, angularity, and texture. These characteristics govern the pavement surface's micro-texture features. As a result, the asphalt mix components (e.g., aggregate characteristics, recycled material content, and type) significantly impact pavement performance. In addition, the pavement surface experiences polishing and wear by traffic, leading to pavement degradation and skid resistance.

Generally, the initial pavement surface friction is low because the aggregate particles are coated with asphalt binder. Over time, traffic wears off the film binder to expose the actual friction of the aggregates. Heavy traffic causes a reduction in friction levels and sometimes changes in the pavement surface texture as the aggregate particles undergo repetitive wheel induced polishing. Finally, the friction levels off at the terminal friction value. This happens when surface aggregates are polished/ worn to their terminal level; hence, further wheel passes do not produce further friction loss. Hogervorst (1974) presented skid resistance as a function of vehicle speed on pavements with micro- and macro-texture surfaces (Hogervorst, D 1974). Notably, skid resistance is almost constant with vehicle speed on coarse macro-texture surface pavements (i.e., SMA and open graded friction course OGFC pavements regardless of the micro-texture condition (Mallick, R. B., Kandhal, P. S., Cooley Jr., L. A., Watson, D. E 2000). Moreover, skid resistance reduces with vehicle speed on fine pavement surfaces, as shown in Figure A-8-1.



(a) (b)

Figure A-8-1 (a) Pavement friction with different speeds at different surface textures (Hogervorst 1974) and (b) Laboratory and field measurements of pavement friction

Laboratory/Field Measurement Techniques of the Pavement Friction

British pendulum tester (BPT)
Generally, the BPT is a laboratory and field technique that can evaluate the micro-texture properties of pavement surfaces at low speed (typically 6-11 mph) following ASTM E303 (ASTM 2022) (ASTM 2022). The BPT measures the relative friction between the test surface and a rubber slider and is reported as the British pendulum number (BPN). Two rubber slider dimensions are typically used: 1.25” for aggregate coupons and 3" for level surfaces.

The method operates by swinging a pendulum from a certain height under the gravity force. The pendulum ends with a rubber slider, which contacts the pavement surface or the aggregate coupon upon release. As the pendulum makes contact and swings down, a pointer is pushed up along a calibrated scale and maintained at the highest position reached by the pendulum. A lower value on the scale indicates that the rubber slider faced less friction, causing the pendulum to swing higher.

Dynamic friction tester (DFT)
To overcome the BPT limitation, the DFT was introduced to measure the test surface friction in the laboratory and/or field at a wide range of speeds (0-90 km/hr) per ASTM E1911 (ASTM 2019) (ASTM 2019). The DFT is a portable instrument consisting of a rotating disc with three rubber sliders attached to its bottom, similar to the BPT slider. The disc spins at tangential velocities equivalent to traffic speeds of 0-90 km/hr and then is lowered onto the test surface to measure its friction. The friction coefficient is typically measured in wet conditions by dividing the torque force by the spinning disc weight.

Unlike the BPT, the DFT quantifies surface friction at speeds ranging from 10 to 90 km/hr, whereas the BPT can only measure the speed at which gravity pulls the pendulum arm downwards (to approx. eight mph). The LWST at 40 mph also correlates better with the DFT value at 20 km/hr compared to BPT (Aldagari, S., Al-Assi, M., Kassem, E., Chowdhury, A.R., & Masad, E 2022). Secondly, the DFT has the same testing footprint as the CTMs, which allows combining their values to calculate a harmonized friction number developed by the International Friction Index (IFI)) as per ASTM E1960-07 (ASTM 2015) (ASTM 2015).

Circular texture (CT) meter
The CT meter has an arm with a charge-coupled device (CCD) laser-displacement sensor that measures the profile of a circle track with a radius of 142 mm (5.6 in) or a circumference of 892 mm (35 in). The measured profile is segmented into eight arcs with 111.5 mm (4.4 in). The average mean profile depth (MPD) is calculated for each segment and has an average of 124 points. Finally, the average of all eight-segment depths is the final MPD.

Current Practice for Evaluating the Pavement Friction

Several highway agencies evaluate pavement frictional performance periodically or as needed to ensure adequate skid resistance. Elkhazindar et al. (2022) conducted a comprehensive survey to identify the current practices in managing pavement friction to develop an appropriate PFM framework for state DOTs (Elkhazindar, A., Hafez, M., and Ksaibati, K 2022). Based on such a survey, 26 U.S. states utilized a locked-wheel friction tester following ASTM E274/E274M-15 (ASTM 2020) (ASTM 2020).

Table A-8-2 Current pavement friction evaluation practices

State DOT	Device*	Speed, mph	Tire type**	Standard
Arizona	HFT	40 or 60	Smooth Tread	ASTM E-1551
Arkansas	LWST, DFT, & CT meter	-	-	ASTM E274
Idaho	LWST	40	Smooth	ASTM E274
Illinois	Skid trailer	40	Smooth & Ribbed	ASTM E274
Kentucky	LWST& SCRIM	-	Ribbed Tire	ASTM E274
Maryland	LWST	-	Ribbed Tire	ASTM E274
Minnesota	LWST	40	Ribbed & Smooth	ASTM E274
New York	LWST	40	Ribbed	ASTM E274
North Carolina	LWST, SCRIM, & GT	It is corrected to 40 mph	Ribbed	ASTM E274 & ASTM E1844
Ohio	LWST	40	Smooth Tire	ASTM E274
Pennsylvania	SFT	25 to 50	Ribbed & Smooth	ASTM E274
Texas	LWST	50	Smooth & Ribbed	ASTM E274
UTAH	LWST	-	-	ASTM E274
Virginia	LWST	-	Smooth	ASTM E274
Washington	LWST	-	Ribbed	ASTM E274

*SFT is skid friction tester, LWST is locked wheel skid tester, GT is grip tester, SCRIM is sideways force research investigatory machine

**Smooth tire follows ASTM E524-08 (ASTM 2020) and ribbed tire follows ASTM E501-08 (ASTM 2020).

Threshold of Pavement Skid Resistance

The investigatory level and intervention level are the two friction assessment categories. The investigatory level, generally used for developing a pavement maintenance and rehabilitation (M&R) plan, monitors the pavement skid resistance when it reaches a low value to detect the accurate preventive treatment date. Meanwhile, the intervention level is the threshold limit at which an immediate corrective treatment action can be applied. Formerly, Henry (2000) designed a questionnaire to classify the current practices for measuring the frictional characteristics of pavements in the U.S., as presented in **Table A-8-3** (Henry, J. J. 2000).

Table A-8-3 Threshold skid number of intervention levels *(51)*

State DOTs	Roadway Functional Classification			
	Interstate	Primary	Secondary	Local
Arizona	34 (Mu Meter)	34 (Mu Meter)	34 (Mu Meter)	
Idaho	SN40S > 30	SN40S > 30	SN40S > 30	
Illinois	SN40R > 30	SN40R > 30	SN40R > 30	
Kentucky	SN40R > 28	SN40R > 25	SN40R > 25	SN40R > 25
New York	SN40R > 32	SN40R > 32	SN40R > 32	SN40R > 32
Puerto Rico	SN40R > 40	SN40R > 40		
South Carolina	SN40R > 41	SN40R > 37	SN40R > 37	
Texas	SN40R > 30	SN40R > 26	SN40R > 22	
Utah	SN40R > 30-35	SN40R > 35	SN40R > 35	
Washington	SN40R > 30	SN40R > 30	SN40R > 30	SN40R > 30
Wyoming	SN40R > 35	SN40R > 35	SN40R > 35	

Recently, Elkhazindar et al. (2022) conducted a comprehensive survey to define the recommended threshold of roadway friction *(49)*. Five of the participating states reported the recommended minimum intervention skid resistance levels using a locked-wheel tester, as summarized in Table A-8-4. Finally, there is an excellent correlation between the skid resistance measured by the locked-wheel or grip tester and the dynamic friction tester (DFT_{20}) and the pavement surface texture (MPD).

Table A-8-4 Threshold friction number of intervention levels *(49)*

State DOT	Recommended friction number (FN)		
	Interstate	National Highway	Non-National Highway
Maryland*	FN = 0.46 and 0.49 for Urban and Rural Areas, respectively.	N/A	N/A
Florida*	FN = 40		
Idaho*	Speed limit > 45 mph; FN = 35 & speed limit ≤ 45 mph >> FN =30		
Indiana	FN40S = 20		
Wyoming	FN40R = 40		

*Test speed and tire type were not provided.

Appendix B

Mix Gradation Analysis

As a part of Phase 2 of the study, an analysis of the aggregate blends for the various mixtures tested was conducted and reported herewith.

The mixture's job mix formula (JMF) affects the pavement surface's macrotexture. The cumulative two-parameter Weibull distribution ($F(x; \lambda, \kappa) = 1\text{-exp}(-(x/\lambda)^{\kappa})$ Equation B.**1**) quantifies the aggregate mix gradation precisely (ASTM 2020; Kassem, E., Masad, E., Awed, A., and Little, D 2012; Kogbara, R. B., Masad, E. A., Kassem, E., Scarpas, A. T., and Anupam, K., n.d.). Figure B-9-1 illustrates how the Weibull distribution parameters reflect the mix gradation. High scale and shape factors (λ and κ parameters) represent coarser mix gradation and uniform mix, respectively. The closer the κ parameter is to 1 is associated with a well-graded mix. A nonlinear least square method is generally used to calculate the Weibull distribution function. Figure B-9-2 and Table B-9-1 present the calculated Weibull distribution parameters at the minimum sum of square error (SSE) and the goodness of fit.

$$\boldsymbol{F(x; \lambda, \kappa) = 1 - exp(-(x/\lambda)^{\kappa})} \qquad \text{Equation B.1}$$

Where:

x	:	Aggregate/ sieve size, mm
λ and κ	:	The scale and shape parameters of the Weibull distribution

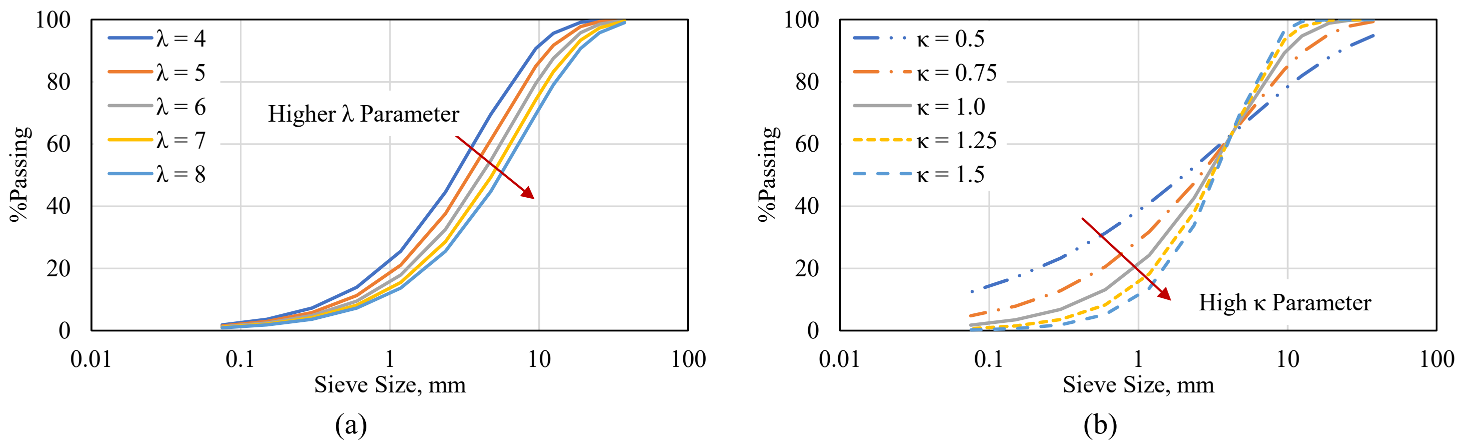


Figure B-9-1 Mix gradation impact on value of Weibull distribution parameters. (a) Impact of mix gradation, λ parameter and (b) impact of mix gradation, κ parameter

Table B-9-1 Weibull distribution parameters and statistical parameters

Mix Type	Mix ID	Weibull Distribution Parameters		Statistical Parameters		
		λ	κ	SSE	R^2	RMSE
SP125 SMA mixes	SP125 20-54	7.743	1.417	0.04994	0.9538	0.0790
	SP125 20-82	8.116	1.43	0.05776	0.9504	0.085
	SP125 20-85 (I-44)	8.116	1.429	0.05815	0.9501	0.0853
	SP125 21-05 (I-70)	7.444	1.368	0.03941	0.9679	0.0700
	SP125 20-85 W/ 15%ABR	7.901	1.323	0.05468	0.9533	0.0827
SP 125 Dense Graded Mixes	CM 125	4.578	0.7983	0.00227	0.9981	0.01686
	STL-CLP 125	4.858	0.9663	0.01108	0.9917	0.03722

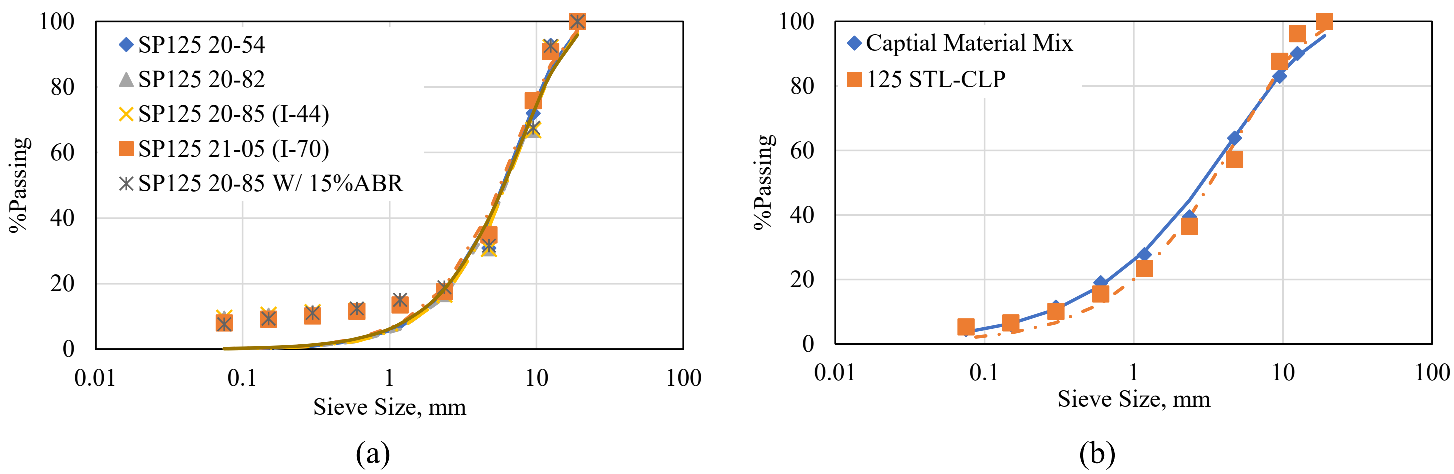


Figure B-9-2 Weibull distribution of aggregate mix gradation