Field Demonstration of Post-Consumer Waste Plastics and Ground Tire Rubber in Columbia, Missouri

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16. Abstract

Research has shown that asphalt pavements can serve as a destination for some of the major streams of waste materials around the globe, such as scrap tires and plastics. Heightened restrictions imposed by China in terms of waste stream contamination in 2018 has catalyzed research on incorporating post-consumer recycled (PCR) plastics into asphalt pavements. On the other hand, Ground tire rubber (GTR) from scrap tires have been used in asphalt pavements since the 1960s, but has not achieved its full potential in terms of market adoption. A field demonstration project is underway in Columbia, MO, to evaluate the incorporation of modern recycled plastic and GTR in asphalt mixtures. The project focused on dry-process modification which requires minimal alterations to an existing asphalt plant and allows a higher amount of the recyclates to be added. The project was designed to assist in Missouri DOT's early roll-out of Balanced Mix Design (BMD) specifications. Among the strategies investigated, it was found that a softer virgin binder grade led to the best improvement in BMD cracking test scores. From a production and construction point of view, the operations went smoothly and closely mirrored the equipment, procedures and results observed early in the project during the control mixture production and laydown stage. After the first two winters, a moderate amount of reflective cracking was noted in all test sections and in the control section. The results of the study suggest the viability of dry-process, GTR and PCR plastic as a greener alternative to binders modified with virgin polymers and/or chemical treatments. Future studies will be needed to examine additional PCR plastic streams, especially more highly mixed streams.

17. Key Words
Asphalt pavements, Recycling, Waste plastics, Ground tire rubber, Balanced mix design (BMD), Sustainability, Demonstration

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The findings and conclusions of this study were arrived at by the research team, and do not necessarily reflect the views and opinions of the Missouri Department of Transportation.

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Executive Summary

The issue of waste plastics has emerged as one of the most pressing environmental crises in recent times. Over the past five years, one of the more popular ways identified with the potential to recycle vast amounts post-consumer waste plastics is their incorporation into asphalt pavement mixtures. Preliminary research into the use of waste plastics as either an asphalt binder or mixture modifier have shown positive results in laboratory trials, but at this point very limited field data is available. To remedy this, various state and private agencies have supported or commissioned the construction of field demonstration projects featuring asphalt mixtures incorporating post-consumer recycled (PCR) plastics, including Missouri, Virginia, California, Ohio, Alabama, and Pennsylvania. Active and planned demonstration projects in many more states are also underway.

It has been reported that about 60% of the existing literature on plastic use in asphalt is focused on wet process modification, but the use of waste plastic additives, or the 'dry process' is generally less expensive and opens the door for the use of higher amounts of recycled plastics in asphalt. In 2021, University of Missouri-Columbia (Mizzou) researchers partnered with the Missouri DOT (MoDOT) and other stakeholders to design and construct a field demonstration project with dry-process post-consumer recycled (PCR) plastics. The project was undertaken to better understand the constructability and performance of asphalt mixtures modified with PCR plastics. The Mizzou research team had extensive prior experience in incorporating ground tire rubber (GTR) in asphalt mixtures via the dry process and surmised that the same asphalt plant equipment and general design methodologies could be used for the use of dry PCR plastic additives in asphalt. Pavements constructed with modern dry process GTR in Missouri and around the United States over the past two decades have shown good performance, and a new materials specification was recently developed and implemented in Missouri for dry process GTR mixtures. Accordingly, the project included a test section with dry process GTR as a secondary control section, along a primary control section using a stiff asphalt binder not containing virgin or recycled polymer. In addition, the project also provided an opportunity for a real-world experience in implementing balanced mix design (BMD) while promoting the use of modern, heterogeneous recycled asphalt mixtures.

For the demonstration project, 1.64 miles (centerline) (2.64 km) of a four-lane road on Route 740, also known as Stadium Boulevard, in Columbia, MO was selected from the eastern side of the 7.2 mile (11.6 km) resurfacing project. The lanes were divided into four sections to include four mixture types including three mixtures modified with polyethylene and one with engineered crumb rubber (ECR). For the PCR plastic mixes, a post-consumer recycled pellet comprised mainly of linear, low-density polyethylene (LLDPE), obtained from Avangard Innovative (Houston, TX) was used. For dry process GTR modification, as mentioned earlier, an engineered crumb rubber (ECR) product (marketed as Elastiko^{TM}) was used. Apart from the recycled additives, the mix also used recycled aggregate stockpiles – coarse RAP (4.9% asphalt content), and boiler slag. The remainder of the project was paved with "control" mix as designed by the contractor. In general, most mixes were designed and ultimately constructed with 30% RAP and 30% slag.

For this project, MoDOT specified that Balanced Mix Design (BMD) be used in all mixture designs and for quality control. The IDEAL-CT test was prescribed to control cracking, while the Hamburg wheel tracking test was prescribed to control the rutting performance of the mixtures. The minimum threshold for the IDEAL-CT index was 32.0, and for the Hamburg test a 12.5 mm (~ 0.5") maximum rut depth requirement at 20,000 passes was imposed (at a test temperature of 50 ºC (122 ºF)). After several design iterations by the Mizzou research team employing various BMD strategies such as change in base binder, aggregate gradation, binder content and use of other modifiers, MoDOT was provided with two sets of recommendations for final mix designs. Based on practical considerations, such as using the same gradation in the modified mixes as the control mix, and the availability of some critical modifiers, the selected designs were:

1. 25PE mix with 0.25% Polyethylene (PE) by mix weight,
2. 50PE mix with 0.50% PE by mix weight,
3. 10ECR mix with 10% Engineered Crumb Rubber (ECR) by weight of virgin binder, and
4. 50PEL mix with 0.50% PE (by mix weight) incorporated in a mix using ELVALOY^{TM}-modified binder. Elvaloy^{TM} is a reactive elastomeric terpolymer which was used as a compatibilizer in one of the mixtures containing PCR plastic. A dosage rate of 0.90% Elvaloy^{TM} by weight of binder was used.

From a production and construction point of view, the operations went smoothly and closely mirrored the equipment, procedures and results observed early in the project during the control mixture production and laydown stage. The main difference in GTR and PCR plastics incorporation was their flow characteristics through the feeder system used. While rubber particles were much finer and had a higher angle of repose due to particle roughness, the LLDPE plastic feed stock used was in the form of small pellets, formed by extrusion and chopping. The pellets were visually smooth and clearly possessed a significantly lower angle of repose, flowing more readily through the feeder system. The absence of significant particle contact friction initially led to an overload in one of the feeder system drive motors, which was resolved through a minor modification to the feeder unit. The produced mixtures were found to be quite workable, and no issues were reported at the plant or in the field with regards to odors or emissions. An in-place field density of greater than 95.0% on average was achieved with less than 1.0% variation.

As noted, this project specified IDEAL-CT and Hamburg tests as part of BMD methodology. Both the tests were conducted on plant-produced mixtures obtained and compacted on the night of production, and on mixtures that were stored, reheated and compacted at a later date. Apart from these two tests, the research team also conducted Disc-shaped Compact Tension (DC(T)) test and Rapid Rutting Test (RRT, or also known as IDEAL-RT). The DC(T) was only conducted on reheated plant-produced mix, but the RRT was conducted on the reheated plant-produced mixtures as well as lab-produced mixes.

The CT-Index results showed that all the mixtures passed the threshold of 32.0, even upon reheating. The modified mixes all significantly outperformed the control mix in terms of cracking resistance, likely due to the higher virgin binder content used.

Comparing the CT-Index obtained from testing mixture on the night of production to reheated plant-produced mixtures, all modified mixtures except the 25PE mix showed only a marginal drop in CT-index upon reheating. In Hamburg tests, the 10ECR and 25PE mix failed the rutting threshold of 12.5 mm at 20,000 passes. The high rutting of the 25PE mix tracks with the fact that it has the least amount of modification and is close to a PG58-28 binder system (also resulting in a high CT-Index). However, it should also be noted that none of the mixtures have shown any sign of rutting on the field as of the date of this report. The portion of the project where the test sections were located (east) have a lower traffic level as compared to the western portion of the project, and more likely receive closer to the equivalent of a 10,000 pass Hamburg traffic level. It was observed that all of the modified mixtures except the 10ECR mix showed a decrease in rutting when testing a reheated sample. The RRT results, in general, tracked with the Hamburg results, with R^2 correlation coefficients generally above 0.5. In the DC(T) test, all modified mixtures exceeded the threshold recommended for a mix to be used in moderate traffic road, with the 10ECR mix being on the borderline for acceptance when compared to the recommended fracture energy threshold for high project criticality.

A Smart Pavement Monitoring (SPM) tool was used to identify cracks/distresses from a continuous stream of GPS-tagged images collected with a simple, downward facing HD camera placed on a boom-type support mounted to a trailer hitch. The tool uses an in-house developed machine learning algorithm. After the first winter, the reflective crack severity was found to be low and the ride quality and overall appearance of the test sections is still in excellent condition. The 50PEL section performed the best followed by the 10ECR section in terms of reflective cracking resistance.

The findings from this study show that both waste plastics and ground tire rubber modified asphalt mixtures perform well and can enhance mixture performance. More demonstration projects in different geographical locations and traffic conditions will be helpful in reinforcing the findings of this study and increase the use of these recyclates in asphalt mixtures making them more sustainable. It is envisioned that a similar specification as recently developed for dry process GTR mixes can be developed for the routine design and control of asphalt mixtures containing waste plastic additive.

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Chapter 1

Introduction

1.1. Overview

The issue of waste plastics has emerged as one of the most pressing environmental crises in recent times. Plastics are incredibly tough and durable materials by design, which explains its widespread usage in virtually all walks of life – consumer products, food packaging, heath care, automotive and a myriad of other applications. However, being non-bio-degradable, dealing with post-consumer plastics in ways that minimize environmental damage, and moreover, promote sustainable and circular solutions are serious global engineering, government and societal challenges. There are clearly more waste plastics being produced annually than established recycling streams can handle, which is evident from media coverage on the Great Pacific Garbage Patch (an accumulation of plastic debris floating in Pacific Ocean). In addition, recent changes in international policies and disruptions in the global transportation systems due to the pandemic has compelled the US stakeholders to look inwards for solutions to re-use and recycle post-consumer waste plastics.

Over the past five years, one of the more popular ways identified with the potential to recycle vast amounts post-consumer waste plastics is with regards to road infrastructure. In the US road, about 94% of all paved roads are surfaced with asphalt. Research from other countries on the incorporation of post-consumer recycled plastics (or PCR plastics) in asphalt mixtures showed improvement in the mechanical properties of the mixtures (Grady, 2021; Wu & Montalvo, 2021). It has been reported that about 60% of the existing literature on plastic modification is on wet process modification (Willis, Yin, & Moraes, 2020). Typically, 1 to 8% by weight of asphalt binder, but most commonly no more than 4%, is added to tanks with a mechanical mixer to achieve a homogenous blend of modified binder. Polyethylene, or PE (both High Density PE and Low Density PE variants) is particularly suitable for wet process modification due to its low melting point. However, separation is a commonly reported issue, as plastics have a lower specific gravity as compared with asphalt. The use of specialized compatibilizers such as reactive elastomeric terpolymer (RET) has been reported to alleviate compatibility issues and enhance mixture performance, not only with plastics but also with crumb rubber mixes (Geckil & Seloglu, 2018; O. Xu, Xiao, Han, Amirkhanian, & Wang, 2016).

On the other hand, dry process modification is more versatile in terms of the different plastics that can be potentially incorporated when used as a dry-process additive. It has been reported that low melting point PCR plastics will typically melt when mixed with hot aggregates and will even coat the aggregate, producing potentially better physical characteristics (Wu & Montalvo, 2021) (Patel, Popli, & Bhatt, 2012). The dry process also permits a higher amount of PCR plastic content to be recycled, with typical dosage rates generally falling between 0.2-1.0% by weight mix (or about 5-20% by weight of binder) (Wu & Montalvo, 2021).

1.2. Literature Review

A detailed literature review was completed in the first quarter of this project, and is included in Appendix A.

1.3. Organization of Report

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

- Chapter 2 – Project Information;
- Chapter 3 – Materials;
- Chapter 4 – Testing and Analysis Methods;
- Chapter 5 – Mixture Design;
- Chapter 6 – Mixture Production and Placement;
- Chapter 7 – Mixture Test Results;
- Chapter 8 – Field Performance Evaluation;
- Chapter 9 – Summary, Conclusions and Recommendations;
- Appendix A – Literature Review.

Chapter 2

Project Information

2.1. Overview

In this portion of the study, the project layout including geographical location, information on the mixture designs, and visual survey of the post-milled surface will be discussed.

2.2. Project Layout and Mix Design Changes

The project was undertaken to demonstrate the constructability and performance of asphalt mixtures modified with recycled ground tire rubber and plastic, both via a similar dry process approach. It should be noted that a standard MoDOT "Control" mixture was used on the remainder of the 7.2-mile (11.6 km) resurfacing project. The geographical location of the whole project with respect to important landmarks is shown in in Figure 2-1. For the demonstration project, 1.64 miles (centerline) (2.64 km) of a four-lane road on Route 740, also known as Stadium Boulevard, in Columbia, MO was selected from the eastern side of the 7.2 mile (11.6 km) resurfacing project. The project called for removal by milling of 0.75"-1.5" (19.1 – 38.1 mm) of the existing asphalt surface and replacing it with a 1.5" (38.1 mm) thick new surface layer. The lanes were divided into four sections to include four mixture types, initially to be composed as follows-

1. 10ECR: Dry process ground tire rubber mix, which used an Engineered Crumb Rubber (ECR) product, included by 10% of virgin binder weight
2. 25PE: Recycled Polyethylene (PE) (or PCR plastic) mix, included by 0.25% of mix weight
3. 25PEL: 25PE mix modified with 0.9% ELVALOY™ RET, used as both a binder-plastic compatibilizer and elastomeric polymer
4. 50PE: PE mix, including 0.50% PE by mix weight

The research team at Mizzou based their design recommendations based on the plastics dosage rates described above, and the layout of test sections is shown in Figure 2-2.

However, due to some unavoidable circumstances, the 25PEL mix design (0.25% PE with ELVALOY™ RET) had to be switched with a 50PEL (0.50% PE with ELVALOY™ RET) mix. The final layout with the 50PEL mixture is shown in Figure 2-3. Finally, the test sections were composed of the following mix designs-

1. 10ECR: 10% Engineered Crumb Rubber by weight of virgin binder
2. 25PE: 0.25% PE by weight of mix
3. 50PEL: 0.50% PE by weight of mix with 0.9% ELVALOY™ RET
4. 50PE: 0.50% PE by weight of mix

Details of the design changes are discussed in Section 5.2 and 5.3.

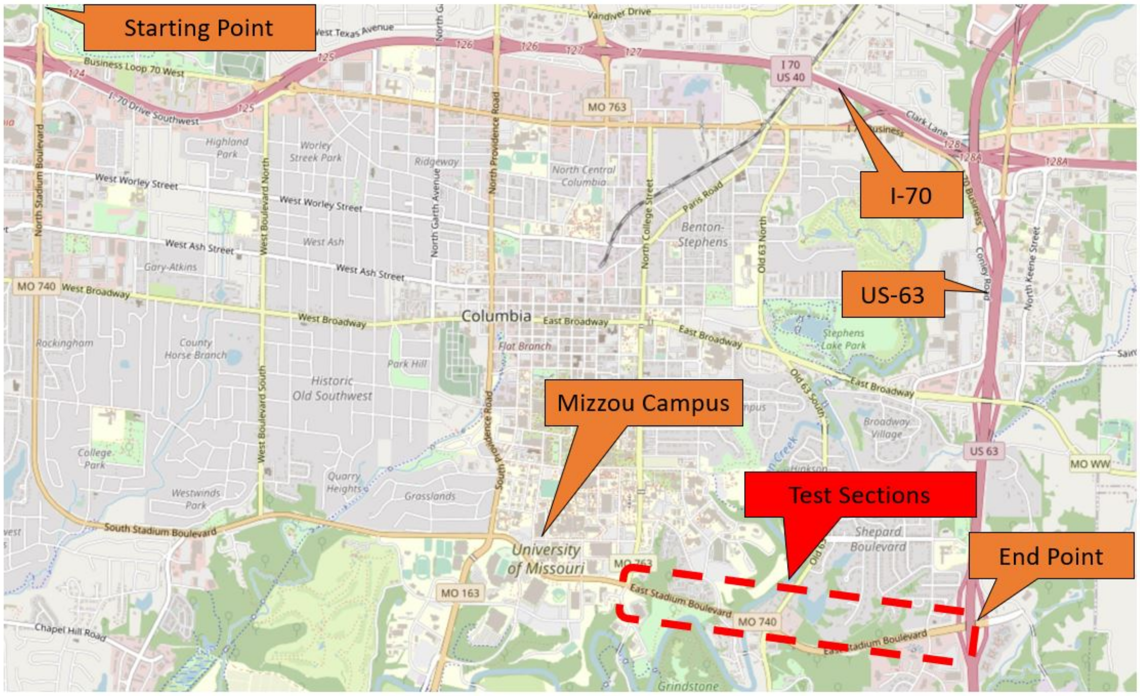
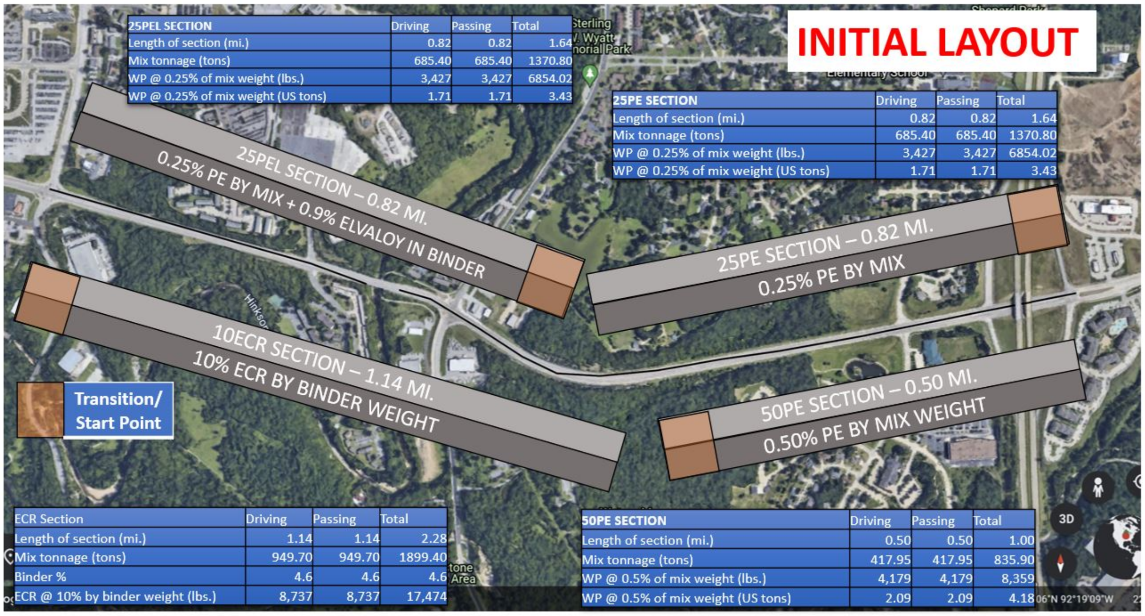


Figure 2-1. Layout of test sections for the Stadium Blvd, Rt. 740 resurfacing project



25PEL SECTION	Driving	Passing	Total
Length of section (mi.)	0.82	0.82	1.64
Mix tonnage (tons)	685.40	685.40	1370.80
WP @ 0.25% of mix weight (lbs.)	3,427	3,427	6854.02
WP @ 0.25% of mix weight (US tons)	1.71	1.71	3.43

25PE SECTION	Driving	Passing	Total
Length of section (mi.)	0.82	0.82	1.64
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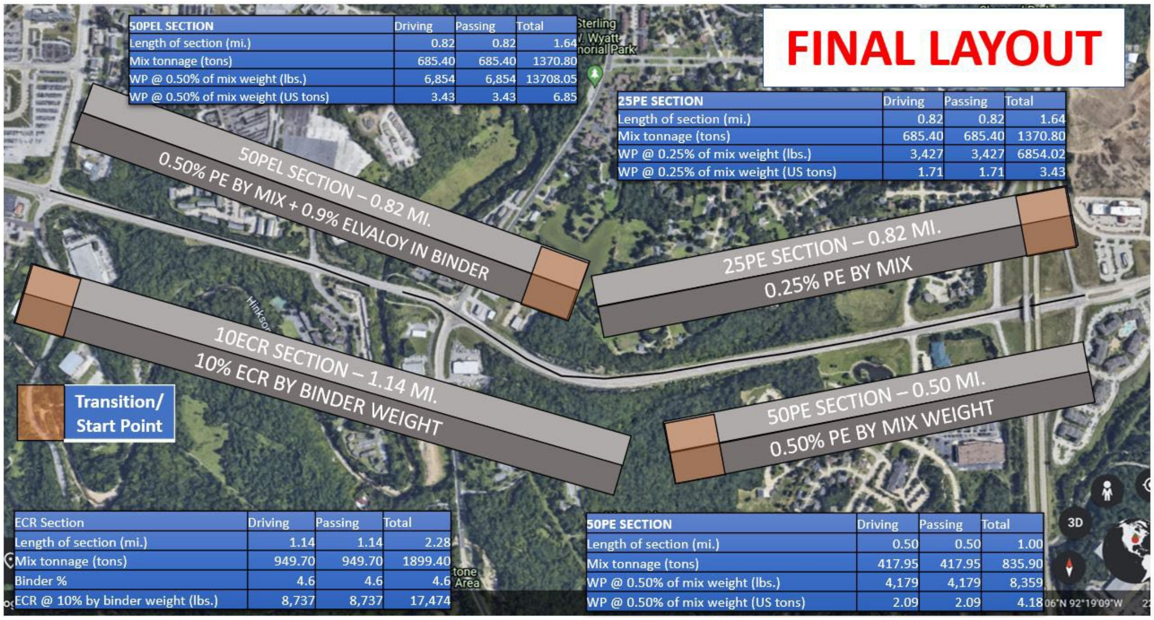
WP @ 0.25% of mix weight (lbs.)	3,427	3,427	6854.02
WP @ 0.25% of mix weight (US tons)	1.71	1.71	3.43

ECR Section	Driving	Passing	Total
Length of section (mi.)	1.14	1.14	2.28
Mix tonnage (tons)	949.70	949.70	1899.40
Binder %	4.6	4.6	4.6
ECR @ 10% by binder weight (lbs.)	8,737	8,737	17,474

50PE SECTION	Driving	Passing	Total
Length of section (mi.)	0.50	0.50	1.00
Mix tonnage (tons)	417.95	417.95	835.90
WP @ 0.5% of mix weight (lbs.)	4,179	4,179	8,359
WP @ 0.5% of mix weight (US tons)	2.09	2.09	4.18

Figure 2-2. Initial, detailed layout of the test sections and material quantities



50PEL SECTION	Driving	Passing	Total
Length of section (mi.)	0.82	0.82	1.64
Mix tonnage (tons)	685.40	685.40	1370.80
WP @ 0.50% of mix weight (lbs.)	6,854	6,854	13708.05
WP @ 0.50% of mix weight (US tons)	3.43	3.43	6.85

25PE SECTION	Driving	Passing	Total
Length of section (mi.)	0.82	0.82	1.64
Mix tonnage (tons)	685.40	685.40	1370.80
WP @ 0.25% of mix weight (lbs.)	3,427	3,427	6854.02
WP @ 0.25% of mix weight (US tons)	1.71	1.71	3.43

ECR Section	Driving	Passing	Total
Length of section (mi.)	1.14	1.14	2.28
Mix tonnage (tons)	949.70	949.70	1899.40
Binder %	4.6	4.6	4.6
ECR @ 10% by binder weight (lbs.)	8,737	8,737	17,474

50PE SECTION	Driving	Passing	Total
Length of section (mi.)	0.50	0.50	1.00
Mix tonnage (tons)	417.95	417.95	835.90
WP @ 0.50% of mix weight (lbs.)	4,179	4,179	8,359
WP @ 0.50% of mix weight (US tons)	2.09	2.09	4.18

Figure 2-3. Final layout of the test sections and details of mix tonnage

2.3. Visual Survey

A visual survey conducted after milling revealed that a majority of the test section areas had an exposed jointed Portland cement concrete (PCC) underlying pavement structure, with the exception of the West-most portion of the section. The West side of the test sections (East of the intersection with College Avenue with 10ECR and 50PEL mixes) evidently had thicker and/or additional asphalt overlay layers, although the reflective cracking pattern indicated that this section was also underlain by jointed PCC at some depth, and most likely jointed-plain concrete. In the future, it is recommended that full-depth cores be cut to clearly identify underlying pavement layering. Most of the joints exhibited some form of cracking, as shown in Figure 2-4(a). A number of failed and spalled transverse joints were improved with full-depth repair with concrete and dowel bars, while less severely deteriorated joints and isolated potholes were addressed with partial-depth patches and crack sealing. For larger patches, a quick-setting, modified concrete patch material was used, while hot-mix asphalt was used to fill small potholes and underlying pavement defects.

(a)

(b)

Figure 2-4. (a) Concrete joints post-milling, (b) Milling operations

Chapter 3

Materials

3.1. Overview

In this portion of the study, details on the materials used in this study including aggregate stockpiles and the additives (PE and GTR) will be described and discussed. In addition, material sampling and a step-by-step account of mix handling during production is also described.

3.2. Aggregate Stockpiles and Mix Additives

The aggregate stockpiles available for the project were: two ½” (12.7 mm) stockpiles (one was ‘dirty’, i.e., containing significant fines content, while the other was washed and considerably cleaner of fines), 3/8” (9.5 mm) , ¼” (6.35 mm) chips, baghouse fines, coarse RAP (4.9% asphalt content), and boiler slag. All individual stockpile gradations are shown in Table 3-1. In terms of modifiers/additives, Evoflex CA-4 rejuvenator and LOF-65 anti-strip were made available by the contractor. The contractor also provided two binders: PG64-22 and PG58-28, for use along with specifics on stockpile percentages for a control mix design (no modifiers).

Table 3-1. Individual stockpile gradations

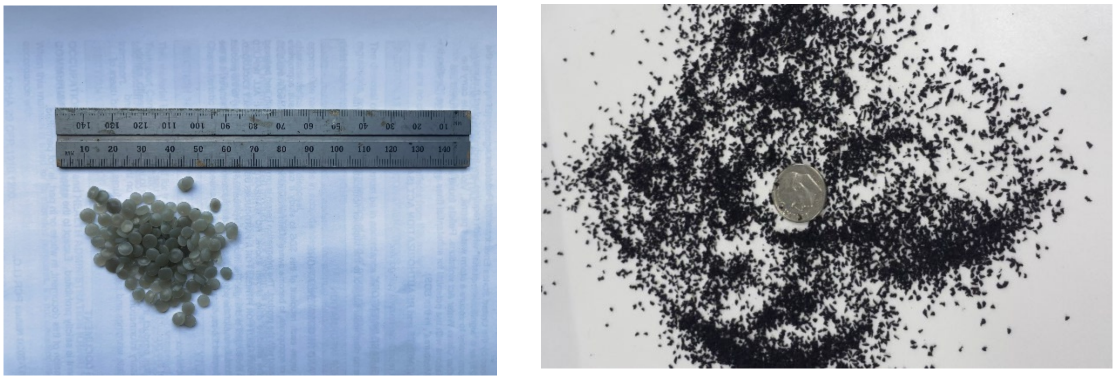
Sieve Size (No.)	Sieve Size (mm)	1/2" Dirty	1/2" Clean	3/8" Clean	1/4" Chips	Boiler Slag	Coarse RAP	Baghouse Fines
1/2 inch	12.50	100.00	100.00	100.00	100.00	100.00	100.00	100.00
3/8 inch	9.50	99.00	96.00	100.00	100.00	100.00	100.00	100.00
No. 4	4.75	74.00	32.00	60.00	79.00	97.00	80.00	100.00
No. 8	2.36	48.00	5.00	19.00	13.00	82.00	56.00	100.00
No. 16	1.18	31.00	4.00	12.00	8.00	40.00	42.00	100.00
No. 30	0.60	22.00	4.00	10.00	7.00	15.00	32.00	100.00
No. 50	0.30	16.00	3.00	8.00	6.00	6.00	23.00	99.00
No. 100	0.15	13.00	3.00	7.00	6.00	2.00	16.00	98.00
No. 200	0.075	11.00	2.50	6.00	5.70	1.30	12.00	97.00

1” = 25.4 mm

For dry process plastic modification of asphalt mixtures, a post-consumer recycled pellet comprised mainly of linear, low-density polyethylene (LLDPE), obtained from Avangard Innovative (Houston, TX) was used, as shown in Figure 3-1(a). The aggregates were heated to 190 °C (374 °F)and the binder was heated to 155 °C (311 °F), matching the plant’s mixing temperature for the plan grade of PG64V-22. Once aggregates were heated to 190 °C (374 °F), the dry LLDPE pellets were mixed with the superheated aggregates in a mixing bucket for one minute before being returned to the oven. After 15 minutes, asphalt binder was added to the aggregate-PE batch and mixed in a bucket mixer for two minutes. The aforementioned procedure was developed by trial-and-error after more than 1 year of laboratory experimentation, observation and measurement. It is hoped that the procedure can be validated and/or improved after the completion of the demonstration project described herein. In this project, short-term aging was simulated by aging the mix for 2 hours at the compaction temperature (145 ºC (293 ºF)for the mixes containing the LLDPE dry additive) with stirring at the end of each hour.

For the hybrid LLDPE mix, the above process was followed with the exception of the introduction of a polymer modified asphalt. ELVALOY™ RET, a reactive elastomeric terpolymer, was provided by Dow. A total of 75 liquid tons of the wet process RET binder was produced at Coastal FMC Willow Springs facility using a base PG58-28 binder. The target modification level was less than that of a traditional PMA due to the anticipated grade bumping from the 10 wt % PCR to be added in the dry process step. The base binder was modified with 0.9% wt % of RET prior to the day of mixing with the dry process materials. The RET PMA was processed like other elastomers. The elastomer was fed into a wetting tank at 120 lbs (54.5 kg) per minute concurrently with liquid asphalt which was at 202 ºC (395 ºF). The authors note this is an elevated temperature compared to normal RET processing with liquid asphalt at 163 ºC (325 ºF) to 185 ºC (365 ºF) but in this case was due to processing conditions at the terminal. The combined RET and asphalt was then fed through a single-pass shear mill into a standard PMA mixing tank. Total addition time of the 1400 lbs (635 kg) of RET was approximately 11 minutes. At this time a sample was obtained from the mixing and passed through wire mesh. No pellets were observed indicating the polymer had fully dissolved. The material was held for an additional 3.5 hours before moving to storage. Note that typically a co-reactant is used to accelerate the chemical reaction of RET with the asphalt's functional groups. In this case only a thermal reaction was used which was determined to be complete after 3.5 hours.

For dry process GTR modification, as mentioned earlier, an engineered crumb rubber (ECR) product (marketed as Elastiko™) was used, as shown in Figure 4(b). The aggregates were heated at 190 ºC (374 ºF) and the binder was heated to 170 ºC (338 ºF). The rubber was pre-blended with binder at 163-170 ºC (325 – 338 ºF) for 30 minutes in a high-shear mixer (slotted screen used). This was done to properly simulate the thermodynamic and physical conditions in a mixing drum, wherein a large mass of superheated aggregates have the effect of softening and tearing rubber particles while it swells and interacts with the binder. The pre-blended binder was then added to the superheated aggregates and tumbled in a bucket mixer for two minutes. Also following ECR manufacturer recommendations, an appropriate dose of supplemental binder was added to the virgin binder content from the base (unmodified) mixture design to compensate for the binder absorbed by the rubber particles. In this project, 10% ECR modification was used and 0.2% supplemental binder (by mix weight) was added to the base (unmodified) mixture design. In terms of short-term oven aging, the mix was aged for two hours at 170 ºC (338 ºF) with no stirring to allow uninterrupted interaction of rubber and binder during the simulation of plant-aging.



(a) (b)

Figure 3-1 (a) Post-Consumer Recycled (PCR) plastics, and (b) Engineered Crumb Rubber (ECR) used in this project

3.3. Material Sampling

The aggregates were sampled from the contractor's asphalt plant in Columbia, MO on April 12, 2021. Each aggregate stockpile was sampled according to AASHTO R90-18 by making a mini-stockpile with the plant's front-end loader, as shown in Figure 3-2(a). The aggregates were sampled into five-gallon plastic buckets, as shown in Figure 3-2(b). The filled buckets were then transported to a storage warehouse. The bucket sized samples were split following AASHTO R76-16 through an alternating chute style splitter for further sample size reduction prior to drying. Dried aggregates were then batched according to the JMF proportions for lab mixing and compaction. Plant mix was sampled at the plant during production. The control mix was sampled on the night of August 5, 2021. There was no control mix compacted during the night of production. These buckets were put into storage until later reheat and lab compaction.

Each experimental mix had two nights of production. The first night was typically the driving lane, and the second night was the passing lane. Therefore, each night also had two mixes produced. The eastbound lanes were paved on August 19, and August 22. These are mixes 10ECR, and 50PE. The westbound lanes were paved on August 23, and August 24. These are mixes 25PE and 50PEL. The sampling occurred on the first night of production for each mix.

Most of the asphalt mixtures were sampled out of truck beds from a platform. However, a few of the samples were taken from small sampling piles deposited on the contractor's property if the sampling time was in close concurrence to a large QC/QA split. The ground sampling pads were created in a similar fashion to an aggregate sampling pad, i.e., a pile was made in a single dump, followed by a striking off of the top of the pile using a front-end loader bucket to create a flat surface to sample from. Regardless of sampling method, samples were pulled after at least 300 tons had been discharged through the silo. For each mix, seven five-gallon steel pails were filled with hot asphalt mix.

(a) (b)

Figure 3-2. (a) Aggregate stockpile at Capital Paving mix production plant, (b) Sampled aggregates

3.4. Material Handling During Production Night

All four experimental mixes were compacted both on the night of production and then again at a later date, to represent a reheat condition. This dual compaction effort was conducted in order to form a comparison of the added aging a mix undergoes when it is reheated for third party compaction and testing, and in support of MoDOT's BMD implementation in Missouri.

To accomplish compaction during night of production, the buckets of mix were loaded into a truck as soon as the sampling was completed. The university's lab is approximately 15 minutes from the asphalt plant. At the research lab, two of the pails were then split into asphalt pans according to the quartering method in AASHTO R47-19. The pans from the first bucket were immediately put into an oven set at the appropriate compaction temperature. At least three of the trays had stem thermometers placed in them to monitor the mix temperature during the reheating time. The trays from the second bucket were held out of the oven for an hour and then placed into an oven set at the mix's compaction temperature. This hold out was done in order to keep the later trays of mix from being held at a high temperature for too long while the first bucket's trays were being compacted.

Compaction commenced as soon as the thermometers indicated the mix had reached compaction temperature. Each mix had the following specimens compacted during the night of production: two gyratories to measure bulk specific gravity for air void confirmation, eight 62mm specimens and an uncompacted sample spread and separated for Gmm (theoretical maximum specific gravity) measurement. The Gmm was oven aged for the same time that it took for the other trays to reach compaction temperature. Four of the eight 62mm specimens were tested in the IDEAL-CT test, and the remaining four were tested in the Hamburg wheel track test (two-wheel paths).

The remaining pails were stored for additional testing, this time on the reheated mix, with pails reheated one at a time as needed. The pails were placed in an oven set to the mix compaction temperature. The temperature of the mix in the pail was monitored with a stem thermometer that was inserted into the mix from the top after the pail had been in the oven for several hours. Once the mix had reached approximately 100 ºC (220 ºF), it was split into asphalt trays following the same splitting procedure as before. The reheat procedure compacted the same number of specimens with the addition of two more Hamburg specimens for a total of three-wheel paths tested and two DCT gyratories for further lab characterization of the mix. To complete this larger number of compactions the work was completed over 3 days per mix.

Chapter 4

Testing and Analysis Methods

4.1. Overview

For this project, MoDOT specified that Balanced Mix Design be used, along with other demonstrative specifications to incentivize the contractor to achieve increased density and improved bonding of the overlay to the milled pavement surface. These can be found in MoDOT's Job Special Provisions (JSP) for the Stadium Blvd., route E/740 project, including NJSP-20-01, "Superpave Performance Testing and Increased Density," NJSP-18-08A, "Intelligent Compaction," and provisions for "Modified Bonded Asphaltic Concrete Pavement," which were all contained in the overarching project JSP for MoDOT job number 5S3318. BMD was recently introduced as a means of mixture design that is informed by mixture performance tests as opposed to only volumetrics, as is the case in the earlier Superpave mix design specification used in Missouri and around the U.S. Briefly, BMD can be implemented using one-of-three different approaches, including: (1) Volumetric Design with Performance Verification; (2) Performance-Modified Volumetric Design, and; (3) Performance-Designed Mixtures. At present, most agencies use the second approach, wherein a volumetric-based design is modified based on mixture performance test results. Usually, an agency outlines thresholds for two tests, one related to cracking and one to rutting to produce a "balanced" mixture.

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 32.0, 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 (~0.5") maximum rut depth requirement at 20,000 passes was imposed (at a test temperature of 50 ºC (122 ºF)). The tests are described briefly below. In addition to IDEAL-CT and Hamburg testing, two other tests were conducted on the reheated mixture samples: the Disc-shaped Compact Tension test (DC(T)), and the Rapid Rutting Test (RRT or also known as IDEAL-RT). The tests are described briefly below.

4.2. 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 ºF) 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 ºC (77 ºF). After conditioning, the specimens were centered between loading platens (see Figure 4-1(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. Figure 4-1(b) shows a sample of the software output, i.e., the load-displacement curve.

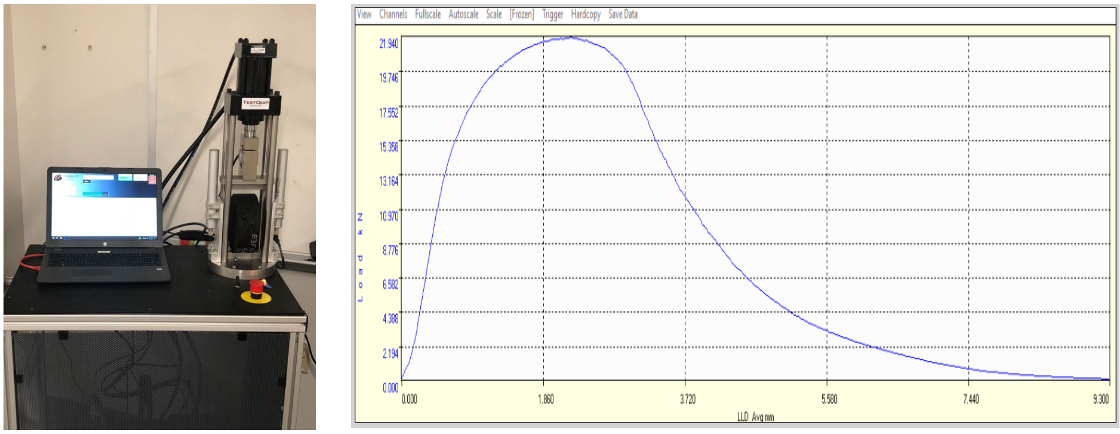
The cracking parameter for the IDEAL-CT test, called the CT-Index, is derived from the load-displacement curve, as described in Equation 1.

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

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 4-1. (a) The Test Quip IDEAL-CT apparatus at MAPIL, (b) Typical load-displacement curve from Test Quip software

4.3. 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 the steering becomes difficult and also the surface water flows through the ruts and causes hydroplaning.

Wheel load tracking (WLT) tests are the most common performance tests for measuring 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 (APA) (formerly known as Georgia-loaded wheel tester). The HWTT is performed in accordance to AASHTO T324 standard. A loaded steel wheel, weighing approximately 71.7 kg tracks over the samples placed in a water bath at 50ºC (122 ºF) (Figure 4-2). 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 4-2) was used in this study.

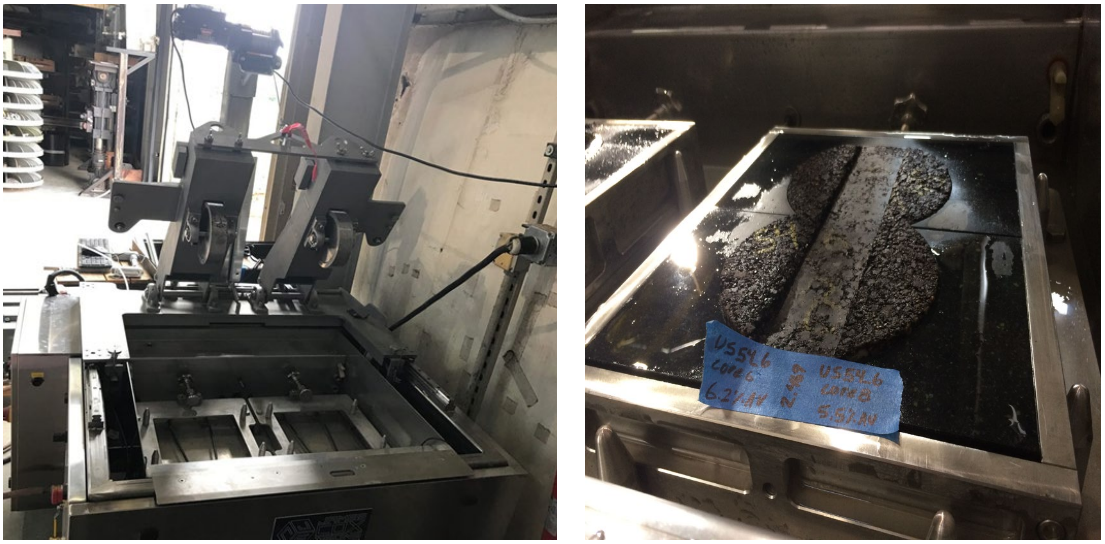


Figure 4-2. Hamburg Wheel Tracking Device: a) Test Device b) Mixtures after test

4.4. Rapid Rutting Test

The Rapid Rutting Test (RRT) was developed to rapidly determine asphalt mixture rutting resistance. Zhou and colleagues at the Texas Transportation Institute developed this test to be used for quality control of mixtures during production with respect to rutting resistance (Zhou, Hu, & Newcomb, 2020). Currently, most DOT's use loaded wheel testers (LWTs) such as HWTT to measure rutting resistance of the mixtures, but the LWTs are time-consuming and cannot be performed in a timely manner for a production plant chasing BMD targets. This test utilizes the same set-up as the IDEAL-CT test, but also implements a cradle at the bottom of the fixture to hold specimens in place, as shown in Figure 4-3. This cradle provides support to specimens forcing the formation of shear planes. The RRT is performed at 50°C under a constant loading rate of 50 mm/min until failure occurs, according to the ASTM working standard WK71466 (ASTM WK71466, 2020). This test uses a gyratory-compacted specimen of 150mm diameter and 62 mm thickness. The RT Index is computed using the shear strength of the specimen which, in turn, is calculated from the peak load obtained during the test and the specimen dimensions. Equations 2 and 3 show the computation of shear strength and RT-

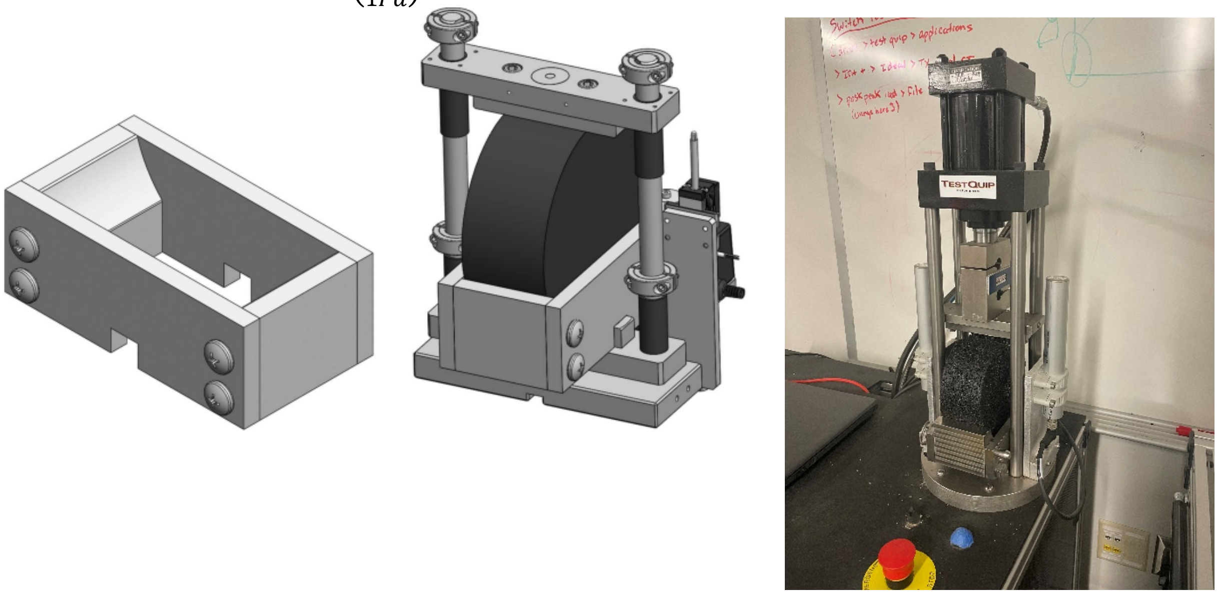
Index, respectively. A higher RT index value indicates higher rutting resistance. In this study a total of eight specimens were compacted and then tested to obtain an average RT index value for each of the four mixtures and in addition, the control mix was tested as well.

$$\tau_f = 0.356\left(\frac{P_{max}}{t * w}\right) \qquad [2]$$

where,

τ_f = Shear strength (Pa)
P_{max} = Maximum load (N)
t = Specimen thickness (m)
w = Width of upper loading strip (=0.0191 m)

$$RT_{index} = 6.618 * 10^{-5}\left(\frac{\tau_f}{1Pa}\right) \qquad [3]$$



(a)

(b)

Figure 4-3. (a) Rapid Rutting Test schematic from ASTM WK71466 (14) and (b) Lab testing apparatus

4.5. Disk-shaped Compact Tension Testing

The DC(T) test was developed to characterize the fracture behavior of asphalt concrete mixtures at low temperatures. The testing temperature is 10 ºC (50 ºF) warmer than the PG low temperature grade of the mixture, per ASTM D7313-13. The DC(T) test procedure includes conditioning of the fabricated specimen at the selected test temperature in a temperature-controlled chamber for a minimum of two hours. After the conditioning, the specimens are suspended on loading pins in DC(T) machine. A portable Test Quip DC(T) device was used in this project (see Figure 4-4(a)). The test is performed at a constant Crack Mouth Opening Displacement (CMOD) rate, which is controlled by a CMOD clip-on gage mounted at the crack mouth. The CMOD rate specified in ASTM D7313-13 is 0.017 mm/s (1 mm/min). To begin the testing sequence, a seating load no greater than 0.2 kN (typically about 0.1 kN) is applied to 'seat' the specimen. The test is completed when a crack has propagated and the post-peak load level is reduced to 0.1 kN. The fracture energy can be obtained by measuring the area under the load-CMOD curve and dividing it by the fractured area (ligament length times thickness). A typical load-CMOD curve is shown in Figure 4-4(b).

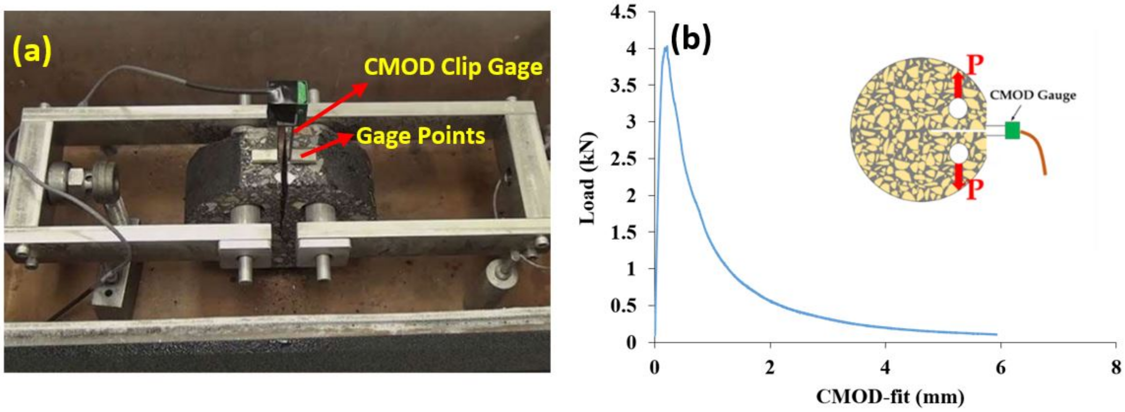


Figure 4-4. Disk-Shaped Compact Tension (DC(T)) test; (a) test loading fixture, and (b) Typical load versus crack opening displacement (CMOD) curve from DC(T) testing of asphalt mixtures

The fracture energy is computed as follows (Equation 4):

$$G_f = \frac{AREA}{B \cdot L} \qquad [4]$$

Where,

G_f = Fracture energy, in J/m^2
AREA = Area under Load-CMOD$_{FIT}$ curve, until the terminal load of 0.1 kN is reached
B = Specimen thickness, in m, generally 0.050 m (except for field cores)
L = Ligament length, usually around 0.083 m

The numerator of the equation represents the area under the Load-CMOD curve, which is the work required to create the fracture surface of size b*a. The area is generally computed using the quadrangle rule for numerical integration. The CMOD curve is generally the fitted CMOD, where a straight line is fit through the CMOD vs. time curve to enable data smoothing (ASTM D7313-07). The denominator of Eq. 3 represents the fractured area, i.e., B*L. Thus, fracture energy is computed as the work of fracture divided by the area fractured, which represents an average fracture energy density. Higher fracture energy values are associated with more crack resistant mixtures. Marasteanu et al. (2012) reported on the fracture energy thresholds on basis on various traffic levels as a part of an FHWA pooled fund study on low-temperature cracking (Marasteanu et al., 2012), which was later verified by Buttlar et al. (2019) (Buttlar, Rath, Majidifard, Dave, & Wang, 2019). The threshold for high traffic was 690 J/m^2, for moderate traffic was 460 J/m^2, and for low traffic was 400 J/m^2.

Chapter 5

Mixture Design

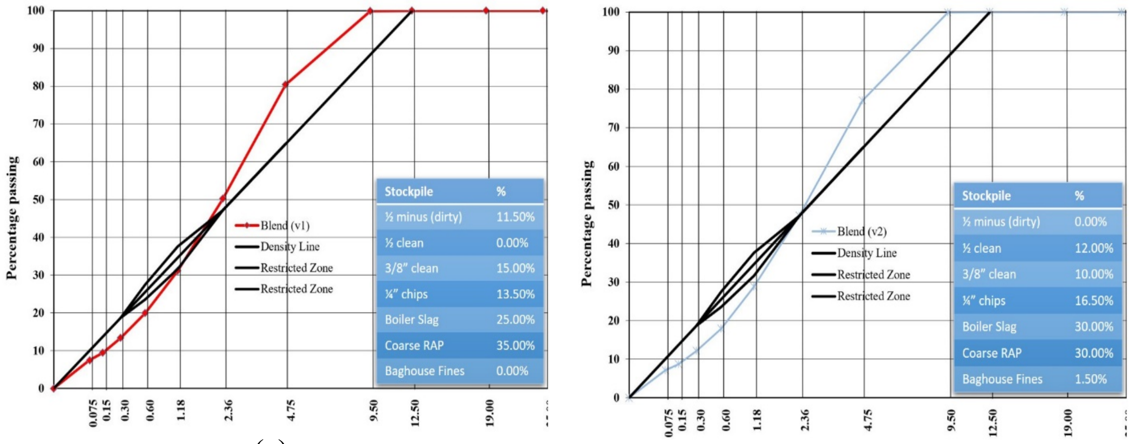
5.1. Overview

In this section, the steps used to meet the new BMD requirements are summarized. In addition, Hamburg-CT interaction plots are provided to attain a holistic view of mixture performance and to track the changes in the mixture performance as the different strategies were implemented. Various strategies were deployed to obtain mixtures with test scores the specified performance test thresholds for this project, which were:

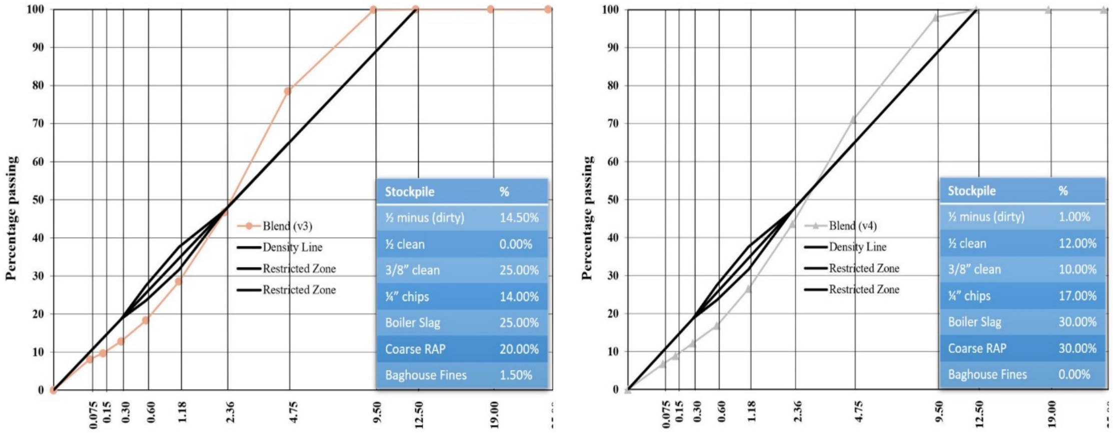
- 32.0 minimum for the CT-Index
- 12.5 mm maximum rut depth at 20,000 passes for Hamburg Wheel Track test (test temperature = 50 ºC (122 ºF))

5.2. BMD Optimization

During the course of the project, the initial aggregate gradation (provided by contractor for the control mix) was tweaked to obtain a gradation that worked better with the new, dry process recyclates, both in terms of CT-Index and Hamburg rut depth results. A summary of the aggregate gradations used during various mix design iterations are shown in Figure 5-1. The gradation for the control mix is shown in Figure 5-1 (d) (30% RAP). These four aggregate gradations are referred to as v1, v2, v3, and v4 during the design phase. In addition, the control section used a PG64-22V and was designed based on standard MoDOT Superpave mix design methodology, where a target of 4.0% air voids was followed, at 80 gyrations for a moderate traffic, urban arterial, which resulted in a virgin binder content of 4.0%. Furthermore, all the mixes included Evoflex CA-4 rejuvenator unless otherwise specified.



(a) (b)



Stockpile	%
½ minus (dirty)	14.50%
½ clean	0.00%
3/8" clean	25.00%
¼" chips	14.00%
Boiler Slag	25.00%
Coarse RAP	20.00%
Baghouse Fines	1.50%

Stockpile	%
½ minus (dirty)	1.00%
½ clean	12.00%
3/8" clean	10.00%
¼" chips	17.00%
Boiler Slag	30.00%
Coarse RAP	30.00%
Baghouse Fines	0.00%

(c) (d)

Figure 5-1. (a, b, c, d) Four different aggregate gradations used in the study during the BMD design process along with the stockpile percentages, referred to as v1, v2, v3, and v4 respectively. Note: v4 gradation is for the control mixture used in the remainder of the 7.2-mile (11.6 km) resurfacing project

5.2.1. Mix Naming Scheme in Design Phase

An appropriate naming scheme was implemented during the design phase devised from the combination of mix names and other important mix identifiers, as follows-

$$\{Mix\ Name\}\{Binder\ PG\ (High\ Temp.)\}\{Agg.Gradation\ \}\{Rejuvenator\}$$

The naming scheme was informed by details in Table 5-1. The following examples can be used to better understand the naming scheme-

- '25PE64v1': 25PE is the mix name, 64 is the binder PG (high temperature), and v1 is the gradation version;
- '10ECR58v4A': 10ECR is the mix name, 58 is the binder PG (high temperature), v4 is the aggregate gradation, and the letter 'A' signifies that the mix contains no Evoflex CA-4;
- '25PE58v4B': 25PE is the mix name, 58 is the binder PG (high temperature), v4 is the gradation version, and the letter 'B' signifies that the mix contains no Evoflex CA-4 but includes LOF anti-strip.

Table 5-1. Naming scheme index for mixtures during design phase

Mix Name (See Section 2.2)	Binder PG (High Temp.)	Aggregate Gradation Version (see Figure 5-1)	Presence of Rejuvenator	Presence of Anti-Strip
10ECR	58	v1	Mix names ending with 'A' signify absence of Evoflex CA-4 from design	Mix names ending with 'B' signify absence of Evoflex CA-4 and presence of LOF anti-strip
25PE		v2		
25PEL*	64	v3		
50PE		v4		

*25PEL mix (0.25% PE) was switched with a 50PEL mix (0.50% PE); see Section 5.3

5.2.2. Mix Design Iterations

Iteration group 1: Initial designs (35% RAP (v1 gradation), 4.3% PG64-22)

The v1 aggregate gradation had 35% RAP (see Figure 5-1(a)) with 3% Evoflex CA-4 rejuvenator (by weight of binder), and 4.3% PG64-22 binder (total binder content = 5.9%). The binder content was based on a Superpave design with air voids regressed to 3.5% at the design compaction level of 80 gyrations. The 10ECR mixture used this design binder content with an added 0.2% supplemental binder by weight of mix to compensate for the binder absorbed by rubber particles. On the other hand, the plastic mixes went through the standard Superpave mix design process for 3.5% air voids, resulting in 4.4% optimum virgin asphalt content. The CT-scores for the base (unmodified) mixture was 33.0, which was borderline considering the MoDOT threshold of 32.0. To minimize the amount of testing, only two mixes were tested with this gradation- 50PE64v1 and 10ECR64v1 mixes, as illustrated in the Hamburg-CT interaction plots in Figure 5-2(a). Addition of plastic and ECR stiffened up the mix and lowered the CT scores to 20.2 and 12.7 for the 50PE64v1 and the 10ECR64v1 mixes respectively, which are failing scores. It is worth mentioning that the rut depths for the 50PE64v1 and the 10ECR64v1 mixes were 2.2 mm and 3.1 mm at 20,000 passes.

Iteration group 2: Gradation change (30% RAP (v2 gradation), 4.6-4.7% PG64-22)

Following this, RAP content was lowered to 30% (v2 gradation, see Figure 5-1(b)) (retaining the full 3% Evoflex CA-4 dosage) with an intention to improve on CT scores. In addition, the 1/2” (12.7 mm) clean stockpile was used instead of the original higher fines stockpile, and 1.5% baghouse fines were added to the mix. The change in gradation led to an increase in virgin binder content to 4.6% of the PG64-22 for the base (unmodified) and GTR mixtures, and 4.7% for the plastic-modified mixtures. Note that GTR mixtures had an additional 0.2% supplemental binder. Even with decrease in the RAP%, the CT scores for the 10ECR64v2 (13.6), 25PEv2 mix (23.6), and the 50PE64v2 mix (12.0) did not cross the required threshold of 32.0. No Hamburg tests were conducted with this version of gradation, and hence this data has not been plotted. From a chronological viewpoint, the contractor (responsible for designing the control mix for the project) had already decided to lower the RAP content to 30%, and thus the research team followed suit with the experimental mixes in this strategy-iteration.

Iteration group 3: Gradation change (20% RAP (v3 gradation), 5.2% PG64-22)

In the following iteration, the RAP amount was further lowered to 20%(v3 gradation, see Figure 5-1(c)) (with 3% Evoflex CA-4), increasing the optimum virgin binder content to 5.2% of the PG64-22 for all the mixtures (GTR mixtures had additional 0.2% supplemental binder), with an aim of increasing the CT-Index values. Other aggregate stockpiles were adjusted to achieve the closest gradation curve to the initial version. With this version, the CT-Index scores improved for all the mixtures with 25PE64v3 (45.6) and 50PE64v3 (31.4) getting borderline CT scores, but the 25PEL64v3 (18.5) and 10ECR64v3 (20.3) mixes were still below the minimum CT value of 32. Once again, no Hamburg results were obtained for this iteration, and hence, data was not plotted on an interaction chart.

Iteration group 4: Base binder change (20% RAP (v3 gradation), 5.2% PG58-28)
These results prompted a change in the base binder from a PG64-22 to PG58-28. Notably, no change in the optimum virgin binder content was observed. ***With a softer base binder, the CT scores improved dramatically***, with all mixtures scoring above 55 in terms of CT Index. However, two-of-the-four mixtures failed to yield acceptable rutting results, with the 25PE58v3 mix rutting to 20.0mm at 16,000 passes, and the 10ECR58v3 mixture rutting 14.9 mm at 20,000 passes. The 50PE mix was also borderline with 12.0 mm rut depth at 20,000 passes. Only the 25PEL58v3 mix had an acceptable result of 10.7 mm rut depth at 20,000 passes. These results are plotted on Figure 5-2(b).

Iteration group 5: Gradation and binder content change (back to 30% RAP with 4.6-4.7% PG58-28)
At this point, the cracking scores were high which allowed the authors to increase the RAP% back to 30% with a goal to obtain more rut-resistant mixtures, and to re-align with the control mixture. As compared to the previous iteration that had 30% RAP, this gradation included both the ½” (12.7mm) stockpiles- dusty and clean, but no baghouse fines. The optimum virgin binder content was 4.6% for GTR mixes (0.2% supplemental binder was added while mixing) and 4.7% for the plastic mixes. With this iteration, the CT-scores were in range of 45-50, with rut depths (average of two-wheel paths) for two-of-four mixes still hovering near or below the borderline value. These results have been shown in Figure 5-2(c).

Iteration group 6: Preliminary recommendations
Due to a fast-approaching paving deadline for the project, recommendations were needed to be made at this stage of the project in order to begin finalizing change orders between the contractor and MoDOT involving experimental mix production. These recommendations can be seen in Figure 5-2(d). The 25PE58v4 and 10ECR58v4 mixtures were easily picked based on their best performance on rutting (though still borderline scores). For the other two mixtures (50PE and 25PEL), a decision had to be taken to either lean towards higher cracking resistance (Figure 5-2(b)) or sacrificing on cracking resistance to prioritize rutting resistance (Figure 5-2(c)). Since cracking is the main concern for MoDOT in this project, mixtures with excellent cracking resistance and acceptable rutting resistance were chosen (50PE58v3 and 25PEL58v3), as shown in Figure 5-2(d). In addition, the traffic level on the east side of the project is considerably lower than the west side, which involves mall traffic and an interchange with Interstate I-70. Thus, MoDOT was willing to accept the borderline Hamburg results at 20,000 passes as long as the 15,000 pass rut depths were found to be below 12.5mm.

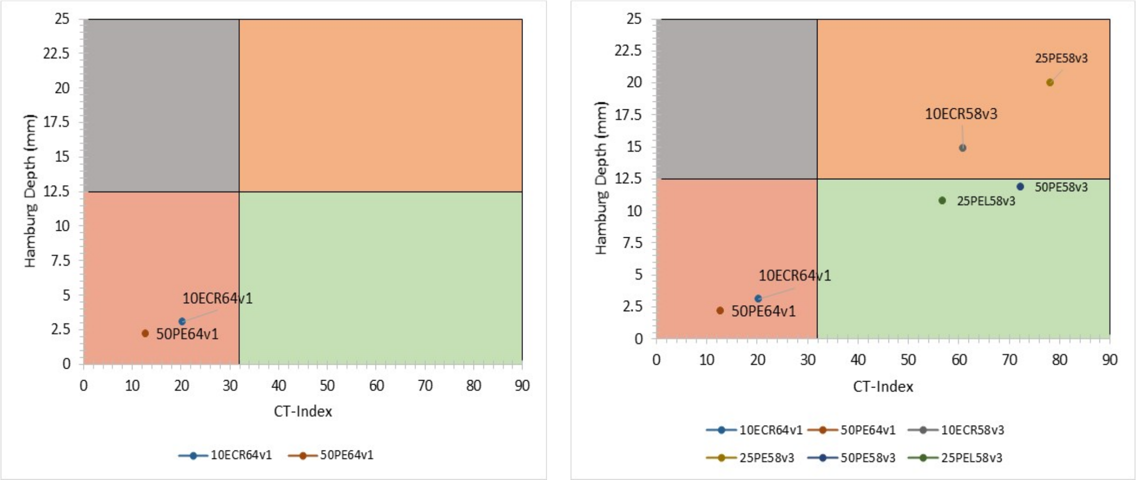
Iteration group 7: Additive optimization trials on preliminary recommended mixture designs (removal of Evoflex, and addition of anti-stripping agent)
Due to weather delays, additional time was granted to continue to optimize experimental mix designs. The next step was to find ways to increase the rutting resistance of the two recommended mixtures that were borderline (10ECR58v4 and 25PE58v4, had 12.5mm and 12.6mm rutting respectively). To achieve this, the Evoflex rejuvenator was replaced with 1.0% anti-strip by weight of binder. This followed feedback from the contractor, who found benefit in use of the antistrip agent in developing the control mix design under the BMD specification. Both of these iterations (removing Evoflex, and then adding anti-

strip) are shown in Figure 5-2(e) and Figure 5-2(f). Removal of Evoflex decreased the CT-index for all three plastic mixtures but increased it for the ECR mixture. At the same time, no significant movement in rut depths were observed for any of the mixtures. Addition of 1.0% anti-strip decreased CT-Index and increased rutting resistance for 25PE, 50PE, and 10ECR mixtures. For the 25PEL mixture, anti-strip had the opposite effect of increasing the CT-Index and decreasing rutting resistance. The result suggests the LOF anti-strip further softened the mix leading to the observed effect.

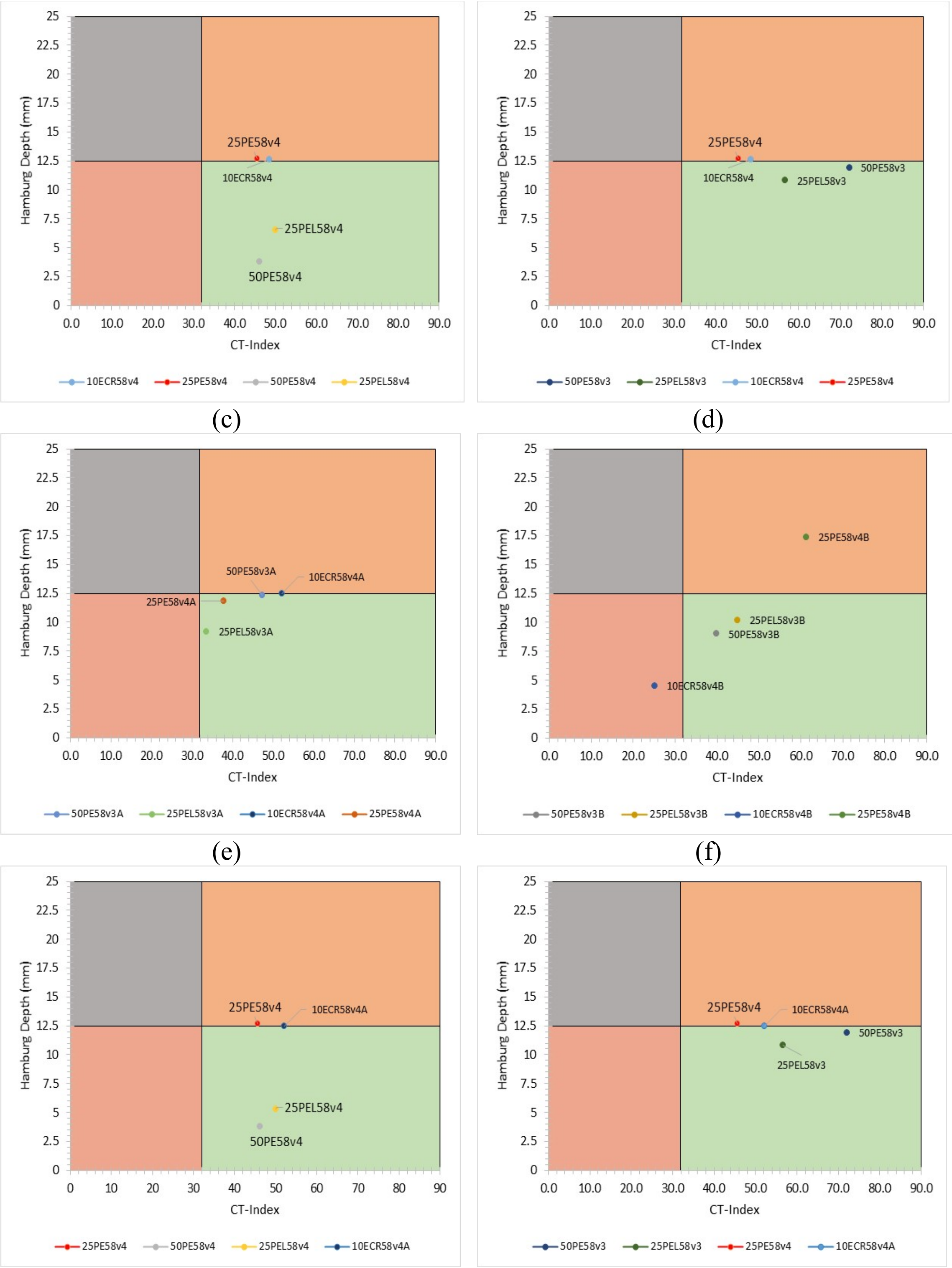
<u>Iteration group 8</u>: Final design team recommendations

In the end, two sets of recommendations were given, as outlined in Figure 5-2(g) and Figure 5-2(h). The first set of recommendations, shown in Figure 5-2(g) includes all mixtures with the fourth version of aggregate gradation (30% RAP and 30% slag, or v4 gradation) with PG58-28 binder (25PE58v4, 50PE58v4, and 25PEL58v4; see Figure 5-1(d)), where the 10ECR mix was recommended to be produced without Evoflex CA-4 in the binder (10ECR58v4A). The data suggested that that the 10ECR mixture performs better without the rejuvenator (and better without the anti-strip as well). The motivation for making this recommendation was the desire to match the contractor’s gradation in the control mixture with the experimental mixes.

The second set of recommendations were essentially the same as the preliminary recommendations except that the ECR mix is recommended without Evoflex CA-4 in the binder. A chemical incompatibility between Evoflex CA-4 and the chemical surfactant on the engineered crumb rubber particles are surmised to have produced the observed trends. Ultimately, a consensus was reached to use the mixes recommended in Figure 5h which maximized cracking scores at the expense of marginal Hamburg scores (25PE58v4, 50PE58v3, and 25PEL58v3, 10ECR58v4A). Again, the choice to design mixes with borderline Hamburg results can be viewed as reasonable because of the lower traffic on this portion of the route (the 15,000 pass results were several millimeters lower in rut depth, and thus more comfortably passing) and the desire to build as much crack resistance in the mix as possible to slow down the rate of reflective cracking, which was the primary distress leading to reduced life in the previous overlay cycle.



(a) (b)



(c) (d)

(e) (f)

(g) (h)

Figure 5-2. Hamburg-CT interaction plots for, (a) 1st iteration with PG64-22 binder and v1 gradation, (b) 3rd iteration with PG58-28 binder and v3 gradation, (c) 4th iteration with PG58-28 binder and v4 gradation, (d) Preliminary recommended designs, (e) Preliminary recommended designs without Evoflex CA-4 (represented by letter 'A' at the end of mix name), (f) Preliminary recommended designs minus

Evoflex CA-4 plus 1.0% LOF (anti-strip) (represented by letter 'B' at the end of mix name), (g & h) 1st and 2nd set of final recommended designs respectively

5.3. Final Designs

While these designs were submitted before 1st August 2021, the final project was constructed on 19th and 20th of August. Between the submission of the final recommended designs and the construction phase, the assembled data was reviewed by the involved agencies. Several key factors were discussed in the subsequent review that led to minor changes in the final mix designs that were placed on the project; as follows:

a. The use of a similar gradation for all mixtures was desirable for the ease of construction; a mix design with 30% RAP and PG58-28 binder (the v4 version aggregate) was chosen due to higher recycled content in the mix.

b. Unavailability of a co-reactant for Elvaloy™ RET at the time of the project: Elvaloy™ is used in conjunction with co-reactant and due to supply chain issues, the co-reactant was unavailable for the project. The research team conducted IDEAL-CT and Hamburg wheel track test on the 25PEL58v4 mix (30% RAP with PG58-28 binder with Elvaloy™) made without a co-reactant, and the results showed high cracking resistance (CT Index = 121) but insufficient rutting resistance (all replicates reached 20 mm passes before completing 20,000 passes).

c. Additional supply of PCR plastic made available: Dow was able to provide additional PCR plastic just prior to construction, which allowed the 25PEL58v4 mix to be stiffened by doubling the quantity of PCR plastic. The mix was modified with an additional quarter percent of PCR plastic, without the addition of Evoflex CA-4 (50PELv4A), resulting in acceptable BMD results. Figure 5-3 shows the Hamburg-CT interaction plot for the final mix designs that went into production (only mix names used). Note that all mixes used v4 gradation and PG58-28 binder. Further, 10ECR and 50PEL mix did not use Evoflex CA-4 and none of the mixtures used the anti-strip.

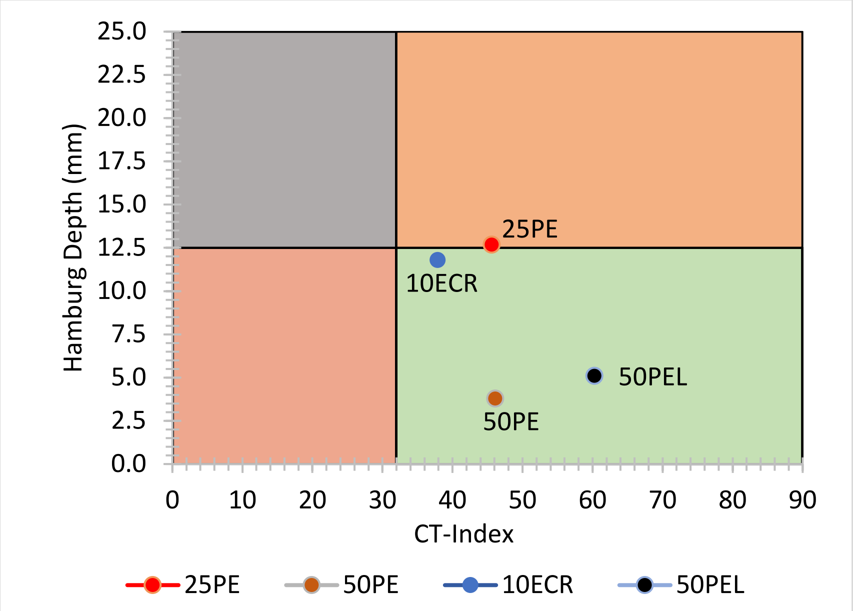


Figure 5-3. Interaction plot of final mix designs that went into production

The final layout for the demonstration project (with updated mixtures) is shown earlier in Figure 2-3 in Section 2.2. Details of the final mix designs are shown in Table 5-2.

Table 5-2. Mixture properties for final designs

Mix Name	AC %	Binder PG	Air Voids (%)	CT-Index	Hamburg Rut Depth @20,000 passes (mm)
10ECR	4.8	PG58-28	5.0	37.9	11.8
25PE	4.7	PG58-28	5.5	45.6	12.7
50PE	4.7	PG58-28	4.9	46.1	3.8
50PEL	4.7	PG58-28	5.0	60.3	5.1
Control*	4.0	PG64-22V	4.0	35.9	4.0

*Designed by Capital Paving; mixture performance tests conducted at Mizzou on compacted specimens provided by Capital paving

It is worth noting that the design air voids of the modified mixtures were around 5.0%. Initially, the Mizzou team began with an intention to design mixtures with regressed air voids, targeting 3.0-3.5%. During 'iteration group 4', when the design team was using 5.2% AC with 20% RAP, all the modified mixtures were between 3.0-3.5% air voids (note: the team was designing the 25PEL (0.25% PE with Elavloy^{TM}) instead of 50PEL (0.50% PE with Elavloy^{TM})). But, as noted, the mixtures were imbalanced due to high rutting values. Thus, the design team scaled back the virgin binder and increased the RAP content to 30% to obtain better balanced mixtures in terms of CT-index and rut depths. In addition, the team was incentivized to use 30% RAP in the modified mixtures as the control mix was using the same amount. Given that this project was to being undertaken utilizing the BMD methodology, the team, in consultation with MoDOT and Capital Paving, decided to just report the volumetrics and base the design completely on mixture performance tests.

Chapter 6

Mixture Production and Placement

6.1. Overview

This section focusses on mixture production, specifically on the lessons learned during the production phase. In addition, discussion on mat density is also included.

6.2. Lessons Learned

A unique facet of the Stadium Blvd. demonstration project was the use of dry process modification for both GTR and PCR plastics. Modern dry process methods, mostly used for GTR modification, entail addition of recyclates directly after heating of the aggregates and generally through a RAP collar or a similar entry point towards the bottom of the mixing drum to shield the material from the burner flame. The modern dry process RMA products are often pneumatically fed into the mixing drum using a fiber feeder type system through a flexible tube, as shown in Figure 6-1. Such a feeder system allows for a steady flow of GTR and can also be paired with the plant's operating system to be synced with the binder tank inputs. A similar method using the same feeder system was used in this project to introduce PCR plastics into the mix. The extensive experience using fiber feeder systems in producing dry process rubber modified mixtures proved to be critical during the plant production of the dry process PCR plastics modified mixtures.

The main difference in GTR and PCR plastics incorporation was their flow characteristics. While rubber particles were much finer and had a higher angle of repose due to particle roughness (GTR is angular, due to cryogenic fracturing or ambient grind processing), the LLDPE, PCR plastic feed stock used was in the form of small pellets, formed by extrusion and chopping. The pellets were visually smooth and clearly possessed a significantly lower angle of repose, which visually appeared to flow more readily through the feeder system originally been set up to feed GTR. The absence of significant particle contact friction initially led to difficulty in maintaining a proper flow of the plastic pellets into the mixing drum, overloading the drive motor. To resolve this issue, a temporary restrictor plate was inserted in final stage of the flow path (near the blower unit), which avoided overloading the feed system motor. Doubling the horsepower (hp) from 1 to 2 hp of the feeder drive on the weighing/metering side of the feeder unit also provided a factor of safety against motor overload and feeder unit shut down during the remainder of mix production.

It is worth noting that apart from these minor field adjustments, the rest of the project went smoothly and closely mirrored the equipment, procedures and results observed early in the project during the control mixture production and laydown stage. Very high in-place density was achieved during the project, aided by the very high temperatures present in late August, 2021, in mid-Missouri, as summarized in the next section.

(a)

(b)

(c)

Figure 6-1. (a) Feeder system used to incorporate rubber and plastic into asphalt mixture, (b) Top view of the feeder hopper with ground tire rubber (GTR), (c) Weighing/metering side of feeder unit with controls and data readout/output.

6.3. Field Density

All produced mixtures had no issues in achieving the required field density. Table 6-1 shows readings from the nuclear gauge and core density measurements for each of the sections in both the driving and passing lanes. To the best of the authors' knowledge, there was no significant difference in the roller passes between all the modified mixtures.

Table 6-1. Density measurements for placed mixtures

Section	Lane	Gauge Reading*	Core Density*
10ECR	Driving	95.0	95.8
	Passing	95.3#	95.6#
50PE	Driving	N/A	N/A
	Passing	94.4	94.9
25PE	Driving	95.5	94.6
	Passing	95.4	96.8
50PEL	Driving	N/A	95.6
	Passing	94.4	94.2

*Average of two values, unless otherwise specified

#Average of three values

N/A – Not Available

Chapter 7

Mixture Results

7.1. Overview

In this portion of the study, results from mixture testing are discussed. During this project, the modified mixtures (from the test sections) were tested during the night of production apart from being collected, reheated, and tested at a later date. This was done to support MoDOT's implementation of BMD method in Missouri.

It is important to note that the aggregate gradation during production differed slightly from design, as shown in Figure 7-1.

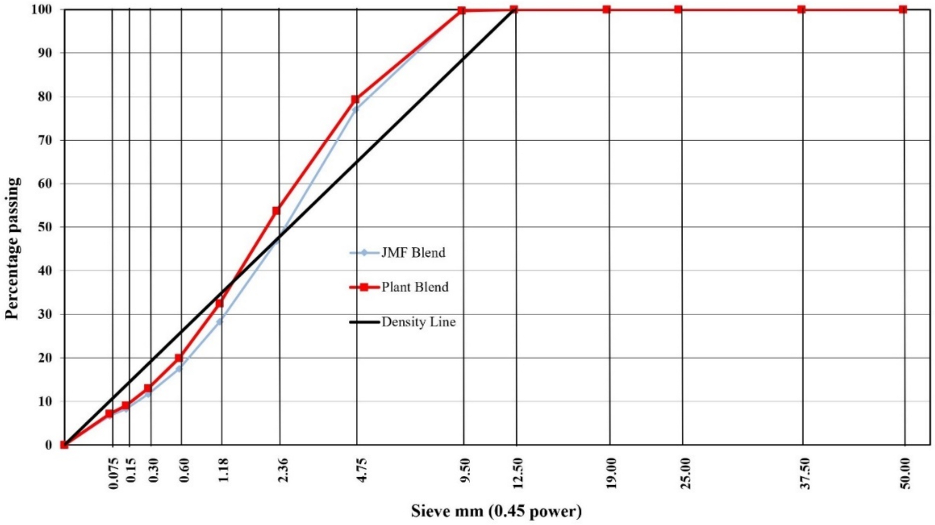
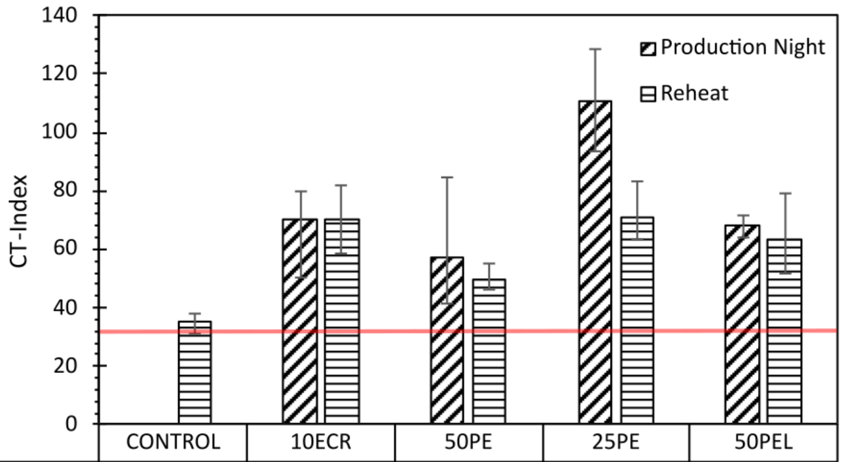


Figure 7-1. Variation in aggregate gradation during production compared to JMF

7.2. IDEAL-CT Results

In this project, the mixes were tested with and without reheating, meaning that a round of testing was performed on the night of production. This was in support of the BMD implementation initiative by MoDOT, wherein QC tests are expected to inform the production operation in real time. Additionally, there was common interest in understanding the effects of reheating on the mix performance tests, specifically with the use of these relatively new additives.

Figure 7-2 shows the CT index values for all the modified as well as the control mixture. As mentioned previously, the control mix included lower binder content compared to the modified mixtures. This is probably one of the factors that resulted in the higher CT-Index values of the modified mixtures. All the mixtures exceeded the CT-Index threshold of 32.0. Except the 25PE mix, all the mixtures showed statistically similar CT-Index values after reheating. The 25PE mix also had the highest CT-Index value among all the modified mixtures, perhaps because it had the least modification among all the modified mixtures (10% ECR by weight of virgin binder equated to about 0.5% of mix weight). Clearly, the modified mixes all significantly outperformed the control mix in terms of cracking resistance. This was expected due to lower binder content of the control mixture.



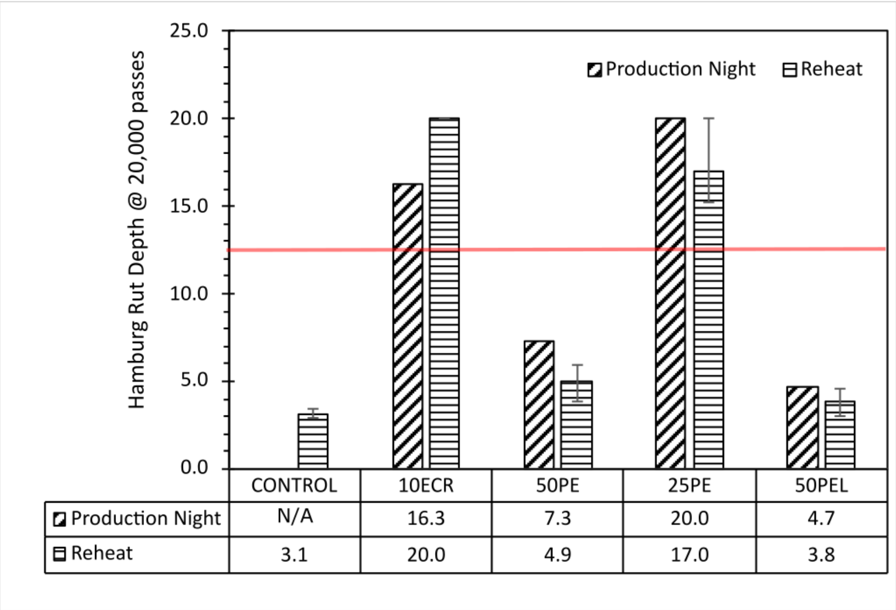
	CONTROL	10ECR	50PE	25PE	50PEL
▨ Production Night	N/A	70.5	57.4	110.6	68.5
⊟ Reheat	35.6	70.5	50.0	70.7	63.4

Figure 7-2. Performance of the as-produced asphalt mixtures in IDEAL-CT test (red line represents the threshold)

7.3. Hamburg Wheel Track Test Results

Figure 7-3 shows the Hamburg rut depth at 20,000 passes for all the mixtures including the control mix. Note that the rutting values from the production night are only from one wheel path (which is why there are no error bars). The 10ECR and 25PE mix failed the rutting threshold of 12.5 mm at 20,000 passes. The high rutting of the 25PE mix tracks with the fact that it has the least amount of modification and is close to a PG58-28 binder system (also resulting in a high CT-Index). All the modified mixtures except the 10ECR mix showed a decrease in rutting on reheating the mixtures. The unexpected trend of 10ECR (increase in rutting on reheating) could be due to testing a non-representative production sample. The 30% RAP used in the mixtures could be a possible source of variability. During laboratory testing, the rut depth for 10ECR mix was recorded to be 11.8mm at 20,000 passes, but the as-produced mixtures vary in overall gradation, as shown in Figure 7-1.

It should also be noted that none of the mixtures have shown any sign of rutting on the field till date. The portion of the project where the test sections were located (east) have a lower traffic level as compared to the western portion of the project, and more likely receive a 10,000 pass Hamburg traffic level. This explains why the mixes were optimized and adjusted in the field to address cracking resistance as a higher priority than rut resistance.



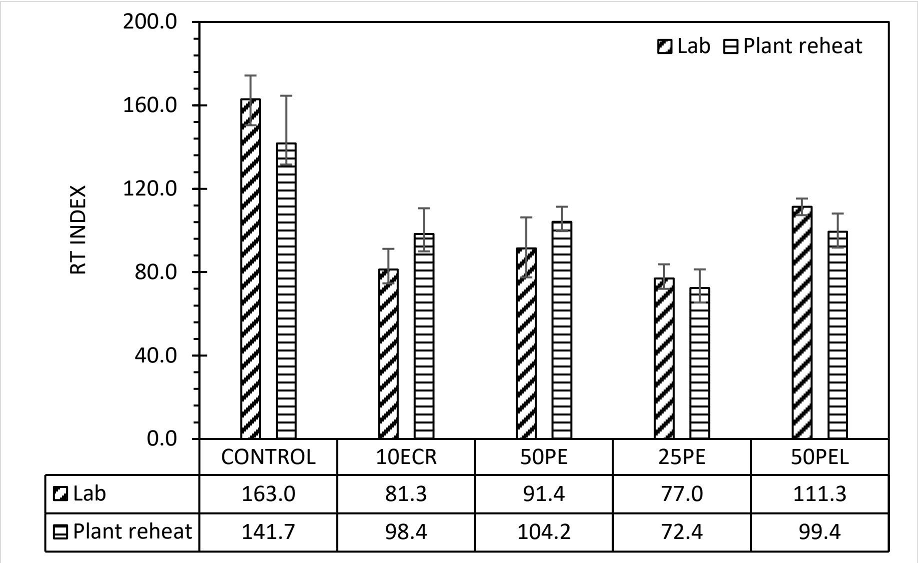
	CONTROL	10ECR	50PE	25PE	50PEL
▨ Production Night	N/A	16.3	7.3	20.0	4.7
▤ Reheat	3.1	20.0	4.9	17.0	3.8

Figure 7-3. Performance of the as-produced asphalt mixtures in Hamburg Wheel Track Test (red line represents the threshold)

7.4. IDEAL-RT or RRT Test Results

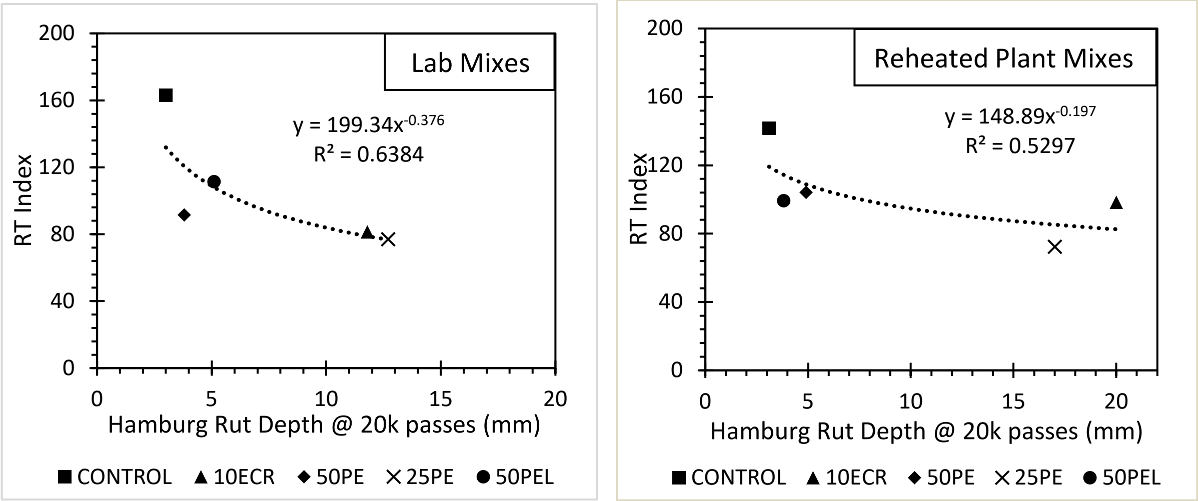
Figure 7-4 shows the RT index values that were obtained for both laboratory and reheated plant mixes. For lab mixtures, the control had the highest RT-Index followed by the mixes with 0.50% PE (50PE and 50PEL), and comparable values were obtained for the 10ECR mix and the 25PE mix. It is important to note here that the same ranking of the mixtures was observed from the HWTT results obtained for the production night mix as well. For the reheated plant mixtures, the ranking of the mixtures is similar for the lab mixtures except that the 50PE mix recorded the highest RT-Index among the modified mixtures (not the 50PEL). The 10ECR and 50PE mixtures exhibited an increase in the RT-Index value while other mixtures (control, 25PE, and 50PEL) showed a drop. One-way ANOVA was performed on the dataset and it was found that except the 25PE mix all the mixtures showed statistically significant difference between the RT-Index obtained from lab and reheated plant mixtures (95% confidence interval).

Given that the RRT is a new testing procedure with limited reporting in current literature, there are currently no thresholds associated with the RT-Index parameter that relate to pavement rutting. In any case, the obtained RT-Index data was compared to the HWTT rut depth results to investigate any correlation between those tests. Figure 7-5 illustrates the inverse correlation between RT index and Hamburg rut depth at 20,000 passes for both, lab and reheated plant mixtures. A power-law trendline was found to produce the best fit with the obtained dataset at an R^2 of 64% for the lab mixes (Figure 7-5(a)) and 53% for the plant mixtures (Figure 7-5(b)).



	CONTROL	10ECR	50PE	25PE	50PEL
▨ Lab	163.0	81.3	91.4	77.0	111.3
▤ Plant reheat	141.7	98.4	104.2	72.4	99.4

Figure 7-4. Performance of lab and reheated plant mixtures in Rapid Rutting Test



(a) (b)

Figure 7-5. Correlation between Hamburg rut depth and RT-Index for (a) lab and (b) reheated plant mixtures

7.5. DC(T) Test Results

Figure 7-6 shows the DC(T) fracture energy of all the modified as well as the control mixture. According to Marastaneu et al. (2012), expectedly, the control mix had the least fracture energy due to its lower binder content (Marasteanu et al., 2012). Amongst the modified mixtures, 10ECR mix exhibited the highest fracture energy, followed by 50PE, 25PE and 50PEL. The ECR has been known to impart additional fracture energy to asphalt specimens due to the crack pinning effect of rubber. Fracture energies of 25PE and 50PE mixtures were about the same and that is likely due to same low-temperature grade binder used in both of them. The 50PEL mixture, with the lowest fracture energy, could be showing the effects of adding Elvaloy^{TM} RET. Apart from the obvious chemical modification of the binder, the reaction process also included holding the binder at an elevated temperature for more than three hours (see Section 3.2 for details) which could have resulted in oxidative aging. These fracture energy values of the modified mixtures makes them appropriate for moderate traffic with a threshold of 460 J/m^2, with the 10ECR mix being on the borderline acceptable range for high traffic applications (and thus high project criticality) as well.

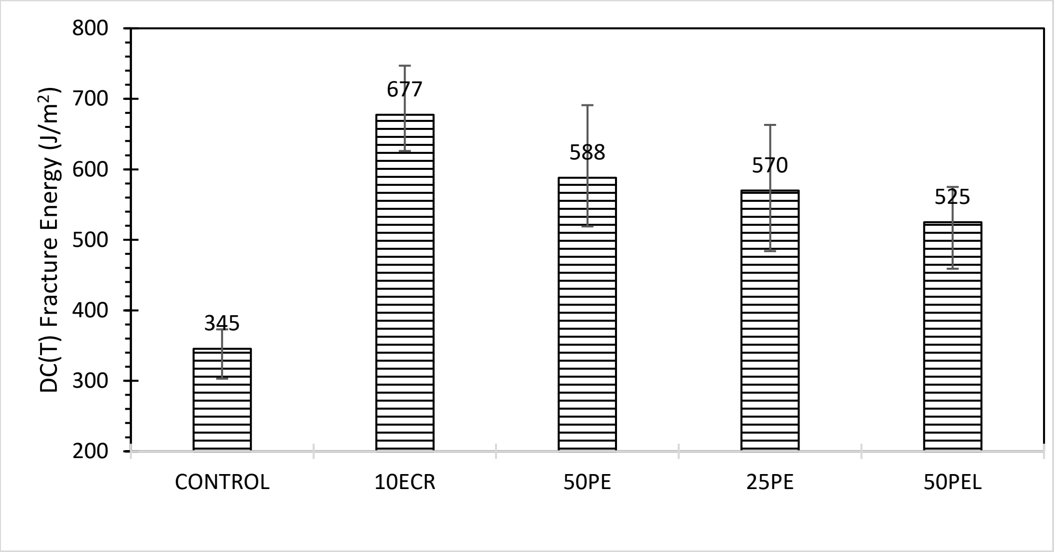


Figure 7-6. DC(T) test results

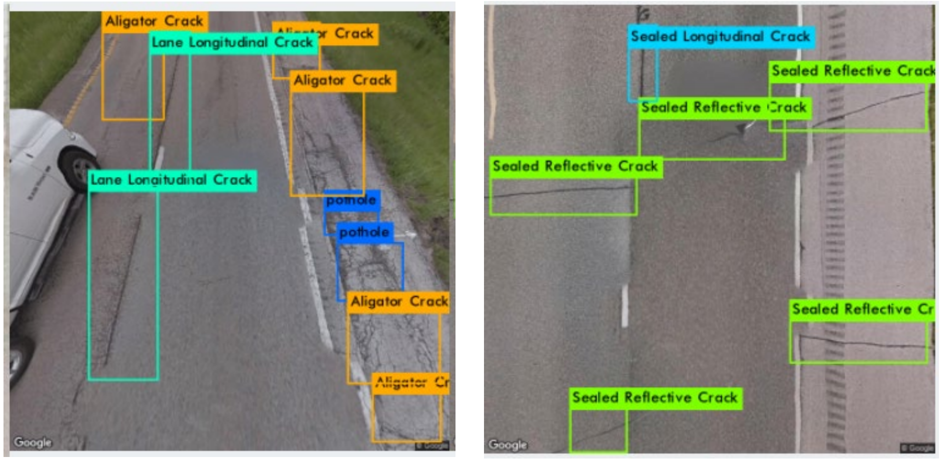
Chapter 8

Field Performance Evaluation

8.1. Smart Pavement Monitoring

Detailed field performance monitoring on the Stadium Blvd. demonstration project is being carried out using the Smart Pavement Monitoring algorithm developed at the University of Missouri-Columbia. Historically, pavement distress inspections have been performed using complex data collection vehicles, often combined with foot-on-ground surveys. In either approach, the process of distress detection can be considered as sub-optimal, as it inherently contains human bias, is very costly and inefficient, and can introduce safety risks for pavement monitoring personnel. An automated pavement evaluation software suite was developed by coding and integrating several machine learning and deep learning techniques for distress detection and pavement condition assessment. In the early stages of performance monitoring of the Stadium Blvd demonstration project, the software has been useful in detecting the onset of reflective cracks, as a relatively thin overlay (38 mm [1.5 inches]) was placed over an aged and deteriorated jointed concrete pavement. Extensive details about the development of the software has been reported elsewhere (Majidifard, Adu-Gyamfi, & Buttlar, 2020; Majidifard, Jin, Adu-Gyamfi, & Buttlar, 2020); however, a summary of the overarching software architecture and its key features are described now.

In order to develop the SPM software, multiple steps were performed. First 20,000 images were collected from different camera views including 360° views, Google Street view images, top-down camera views, etc. The images were annotated with 20 different critical distresses by pavement engineers. Finally, the models trained with the most recent deep learning object detection algorithm YOLO v5. After training and optimization, the developed machine learning (ML) models have been demonstrated as robust, flexible, cost-effective, and able to capture distresses from different camera views. Figure 8-1 demonstrates how the trained machine learning algorithms in the software locate and categorize pavement distresses in an automated fashion. A calibrated algorithm then converts the number and size of the bounding boxes to arrive at a consistent and accurate determination of distress types and extent. A second machine learning program then further categorizes the identified distresses in terms of the severity level. This dual-ML analysis approach was the key to arriving at accurate Type, Extent, and Severity assessments, which were not possible in previous AI-based automated pavement distress software packages. Model training by very experienced pavement experts represents a powerful strategy made possible through a machine learning based approach. The approach also produces repeatable, bias-free assessments. The efficiency of the approach opens the door for more frequent pavement assessments to be made, for instance year-over-year or even seasonal assessments to be made and plotted as deterioration curves, or viewed on a convenient data visualization platform. The ability to collect, aggregate, and analyze more data opens the door for better performance predictions, and moreover, more effective overall management of pavement networks.



Google, wide-view

Google, birds-eye view

Figure 8-1. Ability to detect pavement distresses from images with different viewing angles

8.2. Field Performance Results

In the first winter, it was mainly expected that reflective cracks may occur in the thin overlay placed over jointed PCC. A continuous stream of images of the pavement surface was recorded while driving on the sections using a simple, downward facing HD camera placed on a boom-type support mounted to a trailer hitch. The images were then segregated and marked with GPS coordinates using an in-house developed Python code. The GPS-tagged images were then run through the ML algorithm for identification of cracks, as shown in Figure 8-2. Table 8-1 shows the detected number of reflective cracks normalized to 100 m of section length. After the first winter, the reflective crack severity is low and the ride quality and overall appearance of the test sections is excellent.

According to the results in Table 8-1, the 50PEL section outperformed the other sections in terms of reflective cracking. This tracks with the laboratory performance of the 50 PEL mix, which contains recycled plastics in conjunction with a Reactive Elastomeric Terpolymer (RET) compatibilizer. Another important factor to consider is the underlying pavement condition. After the milling operations, it was observed that the milled surface of the western-most stretch (about 0.8 km or a half mile) of the 50PEL and ECR sections had remaining, existing asphalt overlay material instead of a milled concrete surface, as observed for the remainder of the section, as shown in Figure 8-3. This could explain the ranking of 10ECR section right below the 50PEL section, followed by 25PE and 50PE sections, as shown in Figure 8-4.

As mentioned in the previous section, the pavement has shown no signs of rutting. Interestingly, two days following the construction in August 2021, Columbia, MO experienced the highest air temperature recorded in 2021 of 98°F or 36.7°C, giving the pavement an early assessment on its rutting resistance, before field aging had occurred. Due to the combination of high temperatures, a thin overlay, a high tack coat rate, and moisture present due to rain events, minor blistering was noted in some locations of the control sections and test sections. However, these isolated distresses were deemed to be a system-level issue rather than a mix design or production issue, and were mostly concentrated in the control section.

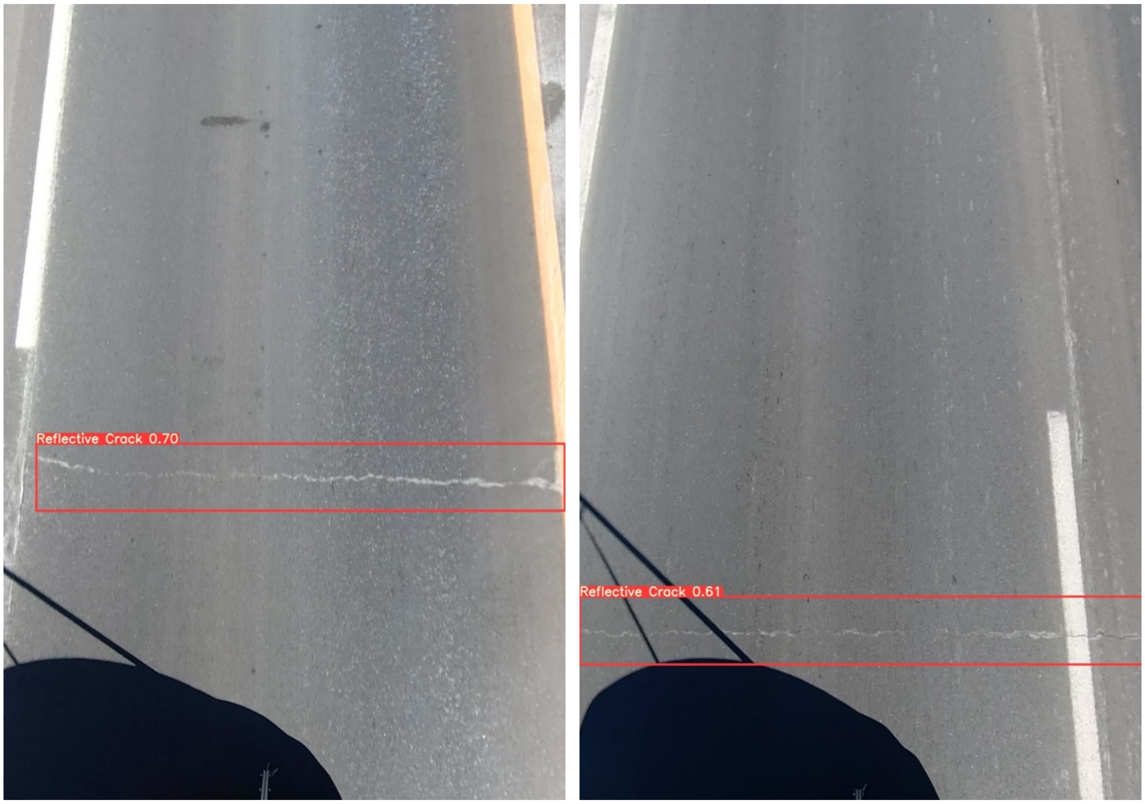


Figure 8-2. Examples of detected reflective cracks by the SPM software

Table 8-1. Measurement of reflective cracking in the pavement sections with modified mixtures

	Eastbound Driving Lane		**Westbound Driving Lane**		**Eastbound Passing Lane**		**Westbound Passing Lane**	
Mix	**10ECR**	**50PE**	**25PE**	**50PEL**	**10ECR**	**50PE**	**25PE**	**50PEL**
# of Reflective Cracks	53	28	58	13	62	25	42	12
Section Length (m)*	1650	540	1210	1250	1650	540	1210	1250
# of Reflective Cracks per 100m	3.21	5.19	4.79	1.04	3.76	4.63	3.47	0.96

*Excludes 50-100m of transition length on either side

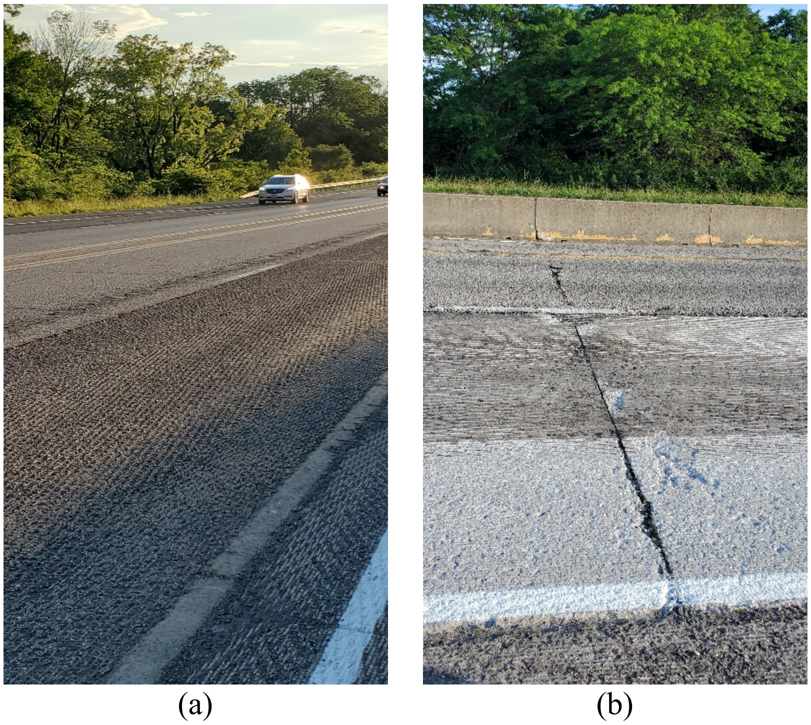

(a) (b)

Figure 8-3. (a) Example of underlying asphalt pavement on the western-most stretch of the 50PEL and 10ECR sections, (b) Example of underlying concrete sections on rest of the project

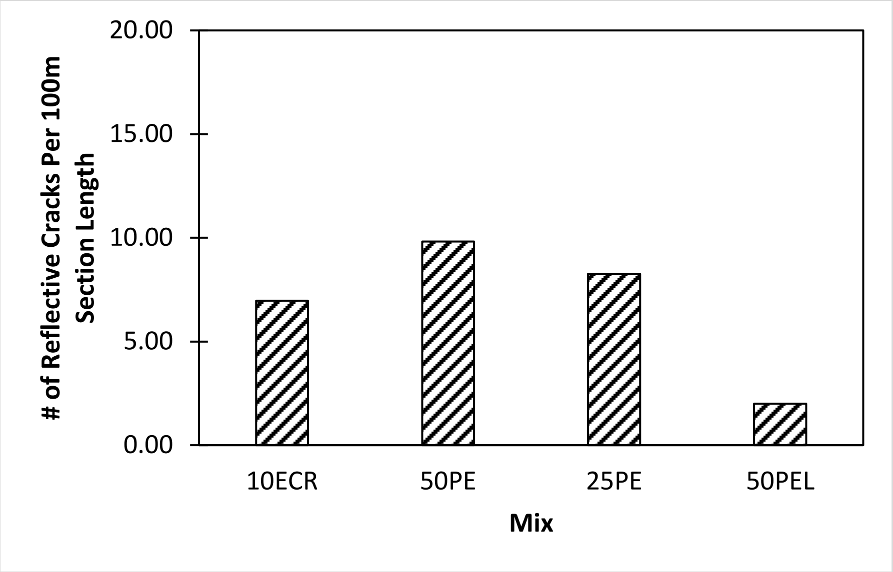


Figure 8-4. Ranking of the mixtures in terms of number of reflective cracks per 100m section length (Note: 20 cracks per 100 m of section translates to a crack every 5m or about 16 ft. (slab length is assumed to be about 15 ft.), which is roughly 100% reflective cracking rate)

Chapter 9

Summary, Conclusions and Recommendations

9.1. Summary and Conclusions

The Stadium Blvd. demonstration project provided an excellent opportunity to investigate new additives for use in developing innovative, recycled asphalt mixtures, i.e., post-consumer recycled plastic and engineered crumb rubber, both added by the contractor at the hot-mix asphalt production plant through a dry process. In addition, the project provided an opportunity for a real-world experience in implementing balanced mix design while promoting the use of modern, heterogeneous recycled asphalt mixtures. Other recyclates investigated in the project included reclaimed asphalt pavement (RAP), and slag, which was used to increase friction in the mix for its use on an urban arterial with stop-start traffic.

The results of the study allowed the following conclusions to be drawn:

- As an alternative to using a modified, virgin binder for Superpave mixtures in Missouri, mixture rutting and cracking performance test thresholds can be met by using a soft, unmodified binder in conjunction with either dry-process GTR or post-consumer recycled plastic or the use of a low dosage PMA with dry-process, post-consumer recycled plastic. This opens the door to increase the sustainability of asphalt mixtures by utilizing materials that are otherwise placed in landfills or utilized in less environmentally attractive end uses, such as energy production.
- Adding new recyclates to mixes that already contain other stiff, recycled materials such as RAP, make the design of crack-resistant mixtures even more challenging. This was apparent by the many iterations required to design mixtures that met MoDOT's current BMD specification. It appears that further progress in this direction will require increased availability of softer base binders and/or the use of rejuvenators.
- The most significant factor affecting the BMD mixture test results in this study was the choice of the virgin binder grade.
- The mixture with 0.25% LLDPE (by weight of mixture) and the mixture with 10% ECR (by weight of virgin binder) seemed to produce similar overall modification effects in the mixture. The mixture with 0.5% LLDPE (by weight of mixture) and the mixture with 0.50% LLDPE (by weight of mixture) plus Elvaloy™ RET polymer/compatibilizer also produced similar overall modification effects in the mixture, but at a higher degree of modification as compared to the aforementioned mixes.
- A few practical issues were encountered and addressed during the course of mix production, the most important of which dealt with the difference in the flow characteristics of plastics and GTR. The feeder system required modification to allow necessary and stable flow of PCR plastic pellets into the mixing drum.

- All modified mixtures except the 25PE mix showed minor effects (stiffening) from reheating on measured IDEAL-CT scores. On the other hand, all mixtures except the 10ECR mix showed an expected increase in rutting resistance with mixture reheating. It should be noted that the rutting results from the production night were limited for practical reasons and were reported for only one wheel path of testing, which could factor into the obtained results.
- It was interesting to note that even though the Hamburg results of the as-produced mixtures indicated the potential for rutting on 25PE and 10ECR sections, none of the placed sections have shown any signs of rutting, even after the sections endured the hottest day of 2021 in Columbia, MO, which occurred shortly after construction. The Hamburg is a torturous test and perhaps a relaxed specification, for e.g., rut depth at 10,000 passes should have been applied to the eastern portion of the Stadium Blvd. demonstration project, where lower traffic levels exists as compared to the western portion of the project, which collects interstate (I-70) traffic and higher truck traffic to the Columbia mall and surrounding businesses, including a quarry on the northernmost span of the rehabilitation project.
- Field evaluation showed that the 50PEL section outperformed all other sections, followed by 10ECR, 25PE and finally 50PE section. However, differing underlying conditions in the 50PEL section were noticed prior to construction; namely, the presence of additional asphalt overlays placed over the original jointed PCC pavement.
- The project demonstrated the advantages of a new, machine learning based pavement evaluation system, that allows monthly pavement evaluations to be performed with relative ease.
- Rapid Rutting Test results demonstrated that the calculated RT index values had an expected, inverse relationship with Hamburg rut depth. Both the tests tended to rank the mixtures in the same order or close to each other.
- In the DC(T) test, all modified mixtures exceeded the threshold required for a mix to be used in moderate traffic road, with the 10ECR mix being on the borderline of acceptance for high traffic application.

9.2. Recommendations

Based on the findings of this study, the following recommendations are suggested:

- The initial findings from this study show that both waste plastics and ground tire rubber modified asphalt mixtures perform well and can enhance mixture performance. More demonstration projects in different geographical locations and traffic conditions will be helpful in reinforcing the findings of this study and increase the use of these recyclates in asphalt mixtures making them more sustainable.
- Full-depth coring in the 50 PEL section is recommended to verify underlying pavement structural layering.
- Demonstration projects provide an opportunity to assist DOTs in their efforts to write and implement specifications. Recently, MoDOT implemented a dry process GTR specification after scrutinizing multiple demonstration projects for years. A similar process could be followed for waste plastics modification of asphalt mixtures as well. Some of the same modified volumetric calculation

procedures can be followed. Similar to including GTR as a second, soft material (in addition to asphalt), waste PE can be treated in a similar fashion in mixture volumetric calculations.

- In future projects, attempts should be made to use local waste streams of waste plastics and scrap tires in asphalt mixtures, thereby directly benefitting the local communities in the state.
- More research is needed on the use of mixed stream of waste plastics as opposed to using a singular type of waste plastic in asphalt mixtures, as was the case in this project and many other projects nationally that utilized waste plastics.
- This project allowed implementation of MoDOT's preliminary balanced mix design thresholds while using three recyclates in each mix design (rubber or plastic, plus slag, and RAP). More such projects would help MoDOT firmly establish their BMD thresholds and drive towards increased, responsible use of modern, heterogenous, sustainable asphalt mixtures.

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Appendix A

Literature Review

Post-Consumer Recycled (PCR) Plastics
The use of PCR plastics in asphalt mixtures has recently gained momentum in the US, partially as a result of China's 2018 National Sword policy that virtually eliminated their practice of accepting plastic waste (Willis et al., 2020). Preliminary research into the use of waste plastics as either an asphalt binder or mixture modifier have shown positive results in laboratory trials, but at this point very limited field data is available (Yin, Moraes, & Anand, 2020). To remedy this, various state and private agencies have supported or commissioned the construction of field demonstration projects featuring asphalt mixtures incorporating post-consumer recycled (PCR) plastics, including Missouri, Virginia, California, and Ohio.

There are several key aspects of the PCR plastics supply chain that will affect its cost and rate of incorporation into mainstream asphalt mixture paving. To begin with, there are many kinds of plastics and not all of them are preferable or even possible to use in asphalt (Grady, 2021). In fact, in most of the field projects to date, PE (polyethylene) or PE-rich blends have primarily been used. This is a wide class of polymers containing LDPE (low-density PE), LLDPE (linear low-density PE), and HDPE (High Density PE), and comprises a substantial portion of the plastic waste stream that is currently being recycled in very low proportions. As these products are used extensively for food and other packaging applications, they can be more difficult to sort and clean and may contain a variety of colors and are often layered together with other polymers or foils, leading to narrower recycling possibilities. This, however, suggests that with time, PE-rich, mixed PCR streams may prove to be an economically attractive recyclates for use in asphalt mixtures. PET (polyethylene terephthalate) is used in abundance in products such as beverage containers (plastic bottles); however, PET is not a good candidate for recycling in asphalt as it is a stiffer, higher-melting point thermoplastic that is already in high demand for recycling into various products, including drinking bottles made with recycled plastic content. Currently, most virgin polymer products are introduced as a binder modifier, i.e., incorporated using a wet process. Plastic, being lighter than asphalt binder and generally not very chemically compatible, has poor storage stability (F. Xu, Zhao, & Li, 2022). As a result, polymer modification generally involves chemical and/or mechanical engineering solutions to address storage stability, such as compatibilizing chemistries and the employment of storage tanks with agitators (continuous stirring).

To date, very few dry process PCR plastics projects have been undertaken in the US. The dry process (or the use of mixture additives) has some obvious economic and logistical advantages as compared to the wet process (binder modification). For instance, the issue of storage stability is avoided in the dry process. Three test sections containing dry process PCR plastic were used in a recent demonstration project on Stadium Blvd in Columbia, MO. The design of these dense-graded, Superpave mixtures following MoDOT's new BMD requirements was reported in Rath et al. (2022) (Punyaslok Rath et al., 2022). Building on this work, the sections that follow describe the lessons learned during the production and laydown of these mixes, along with the early field performance observations on the sections using an innovative, machine learning based pavement distress detection and quantification approach.

Ground Tire Rubber

Early research into adding GTR in asphalt binder suggested that GTR can enhance asphalt binder elasticity and promote crack resistance, while reducing the tendency towards rutting through increased binder viscosity (Way, 2012). Over time, two major methods were developed for the incorporation of GTR into asphalt mixtures: the wet process, which entailed modifying the asphalt binder with GTR before mixture production, and the original dry process, which entailed adding GTR to aggregates before mixture production (Buttlar & Rath, 2021). Both the processes had pros and cons but during the extensive trials that took place due to the FHWA mandate in the 1990s requiring states to increase the use of rubber-modified asphalt (RMA) mixtures, the wet process RMA mixtures showed better performance compared to original dry process RMA mixtures. Although the mandate never came to be implemented, a handful of states showed leadership in the use of RMA mixtures. California and Arizona, for instance, developed specifications around the wet process modification method for use in applications where a highly crack-resistant surface mixture was desired, such as for the resurfacing of deteriorated Portland cement concrete pavements to restore ride quality and other surface characteristics.

Over the past two decades, a number of states have begun experimenting with and building specifications around more refined dry process GTR products and improved plant production techniques. Modern dry process methods often use a chemically-engineered crumb rubber product, or ECR, and are much finer in size (minus 30 mesh) as compared to the earlier dry process products (P. Rath, Clark, Zuberer, & Buttlar, 2021). For a contractor, the dry process method is logistically easier to adopt as it requires minimum modification to an existing asphalt plant configuration. It is also less costly than the wet process approach. Over the past decade alone, more than 8 million tons of dry process RMA has been placed, sometimes placed side-by-side with polymer-modified asphalt mixtures serving as reference control sections. Currently, eight states are either working towards a specification to allow contractors to respond to bids with mixtures containing dry process RMA or already have a specification in place.

In the state of Missouri, two ECR demonstration projects were placed on interstates I-35 and I-44 in 2017 and 2019 respectively (P. Rath, Majidifard, Jahangiri, & Buttlar, 2019). Those sections focused on Stone Mastic Asphalt (SMA) mixtures and have demonstrated excellent performance to date. A more recent demonstration project was placed in Columbia, MO, this time with a dense-graded mixture containing dry process ECR used as an additive to meet MoDOT's new Balanced Mix Design (BMD) requirements. Details of the specific mix design trials and lessons learned can be found in Rath et al. (2022) (Punyaslok Rath et al., 2022).

Balanced Mix Design

BMD is defined as "asphalt mix design using performance tests on appropriately conditioned specimens that address multiple modes of distresses taking into consideration mix aging, traffic, climate, and location within the pavement structure (West, Rodenzo, Leiva, & Yin, 2018).” In essence, it’s an iterative mix design method which includes mixture performance tests selected based on local conditions, locally desired outcomes, and ideally (or at least, eventually), local knowledge of the relationship between performance test results and field performance. While volumetrics are still a part of the design method, depending on the framework of BMD adopted for a project, they are generally not the deciding factor in the final mixture design, unlike Superpave. Based on the concept of BMD, various strategies can be employed by the paving agency to improve the mixture designs and produce more durable asphalt pavements. A popular way of enhancing mixture durability is by adjusting its baseline constituents, such as shifting to softer base binder grades or incorporating modifiers such as ground tire rubber, rejuvenators, adjusting recycled asphalt pavement (RAP) sources and usage levels, and so on. As mentioned earlier, cracking has become an increasingly pervasive issue over the past few decades (Tran, Huber, Leiva, Pine, & Yin, 2019). Various researchers have shown the advantage of using a softer base-binder to address the cracking behavior of modern asphalt mixtures, especially when higher recycled content is used (Behnia, Dave, Ahmed, Buttlar, & Reis, 2011; Bonaquist, 2016; Willis et al., 2012). Furthermore, polymer or rubber modification has also been used in conjunction with a softer base binder to increase the binder useable temperature interval (UTI) and to provide additional protection against rutting and cracking (P. Rath, Love, Buttlar, & Reis, 2019; Timm et al., 2006; West et al., 2012). To this end, modern recycled mixtures have been successfully designed with BMD tools using a combination of softer binders, additional virgin binder, and various modifiers when relatively high recycling rates were targeted.