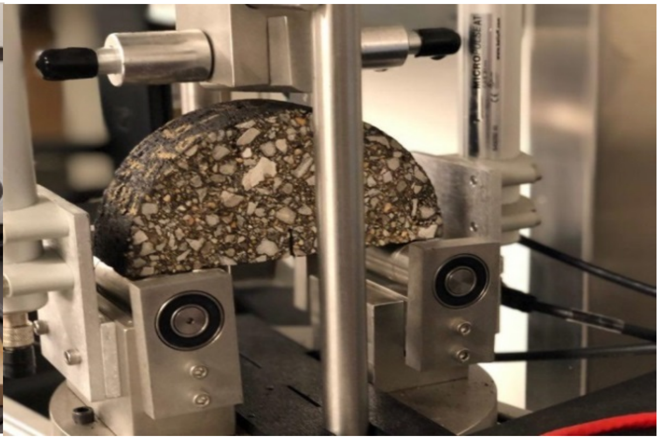
Understanding and Improving Heterogeneous, Modern Recycled Asphalt Mixes



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16. Abstract

A comprehensive research investigation was carried out to investigate the use of recycled materials in Superpave asphalt mixtures in Missouri. The investigation involved sampling of aggregates, binders, plant-produced mixtures, and field cores followed by a rigorous lab testing program. Lab testing included an extensive binder extraction and recovery (E & R) experiments, followed by a comprehensive suite of advanced binder tests. An attempt was made to shed light on effective strategies to iterate existing mix designs into more 'balanced mix designs' for modern, heterogeneous recycled mixtures in the Midwest. Different strategies were employed, such as the use of a softer virgin binder, the addition of a rejuvenator, and the employment of 5% to 20% of dry-process, engineered crumb rubber by weight of total binder. These mixes were subjected to a suite of cracking and rutting mixture performance tests to establish baseline performance, followed by four additional mix design iterations per mix (for a total of 10 investigated mixtures). The DC(T), I-FIT, IDEAL-CT, and Hamburg wheel tracking tests were used in the performance testing suite. Based on the results of the study, it was found that RAP, and particularly RAS, drive the need for the use of softer virgin binders to be used in modern, recycled asphalt mixtures in Missouri. Recommendations are provided with respect to the selection of softer virgin binder grades based on recycled material type and amount. Recommendations for balancing mixes with the use of rejuvenators and ground tire rubber are also provided.

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UNDERSTANDING AND IMPROVING HETEROGENEOUS, MODERN RECYCLED ASPHALT MIXES

Final Report

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List of Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
ABR	Asphalt Binder Replacement
AC	Asphalt Concrete
ANOVA	Analysis of Variance
ARAN	Automatic Road Analyzer
ASTM	American Society for Testing Materials
BBR	Bending Beam Rheometer
BMD	Balanced Mix Design
CMOD	Crack Mouth Opening Displacement
CRM	Crumb Rubber Modifier
DC(T)	Disc-Shaped Compact Tension Test
DOT	Department of Transportation
FI	Flexibility Index
FTIR	Fourier Transform Infrared
GTR	Ground Tire Rubber
HMA	Hot Mix Asphalt
HWTT	Hamburg Wheel Tracking Test
LAS	Linear Amplitude Sweep
LTPP	Long-Term Pavement Performance
IDEAL-CT	Indirect Tensile Asphalt Cracking Test
JMF	Job Mix Formula
MoDOT	Missouri Department of Transportation
MMDM	Mineral Matter Determination Methods
MSCR	Multiple Stress Creep Recovery
NAPA	National Asphalt Pavement Association
MAPA	Missouri Asphalt Pavement Association
NCAT	National Center for Asphalt Technology
NMAS	Nominal Maximum Aggregate Size
PAV	Pressure Aging Vessel
PMS	Pavement Management System
RAP	Recycled Asphalt Pavement
RAS	Recycled Asphalt Shingles
RTFO	Rolling Thin-Film Oven
SCB	Semi-Circular Bending Test
SGC	Superpave Gyratory Compactor
VMA	Voids in the mineral aggregate
WMA	Warm Mix Asphalt

EXECUTIVE SUMMARY

A comprehensive research investigation was carried out to investigate the use of recycled materials in Superpave asphalt mixtures in Missouri (MoDOT project TR201807). The investigation involved sampling of aggregates, binders, plant-produced mixtures, and field cores followed by a rigorous lab testing program. Lab testing included an extensive binder extraction and recovery (E & R) experiments, followed by a comprehensive suite of advanced binder tests.

An attempt was made to shed light on effective strategies to iterate existing mix designs into more ‘balanced mix designs’ for modern, heterogeneous recycled mixtures in the Midwest. Different strategies were employed, such as the use of a softer virgin binder, the addition of a rejuvenator, and the employment of 5% to 20% of dry-process, engineered crumb rubber by weight of total binder. These mixes were subjected to a suite of cracking and rutting mixture performance tests to establish baseline performance, followed by four additional mix design iterations per mix (for a total of 10 investigated mixtures). The DC(T), I-FIT, IDEAL-CT, and Hamburg wheel tracking tests were used in the performance testing suite.

A summary of the conclusions reached in the study include:

- For plant mixes, the highest resistance to rutting was observed for asphalt binders E & R from mixes containing RAS.
- The use of a rejuvenator actually increased the stiffness of the E & R asphalt binders. It is therefore believed that the rejuvenator increased the contribution or blending of recycled and virgin binders.
- Engineered crumb rubber (ECR) increased the E & R asphalt binder resistance to rutting by increasing the stiffness and elasticity.
- The use of softer virgin asphalt binders in recycled mixes containing high ABR facilitated the E & R process. It was noted that softer binders produced more accurate and less variable extracted AC percentages. The same results were observed for mixes containing Evoflex rejuvenator. The use of Evoflex in mixes containing recycled materials appeared to enhance the contribution of the recycled materials in these mixes, i.e., enhanced the interaction process between the binders from the recycled materials with the virgin asphalt binder.

- In the mixture performance balancing portion of the study, otherwise known as the ‘fix-the-mix’ experiments, the following conclusions were drawn:
    - The strategy of replacing the base binder with a softer virgin binder grade was generally effective in both investigated mixtures (US63_1 and US54_1).
    - In this study, the addition of a rejuvenator was not as effective as the other strategies investigated. However, the use of a rejuvenator served the purpose of helping achieve desirable volumetric properties in the mixtures, likely by increasing the lubricity/workability of the mixtures.
    - Engineered crumb rubber was introduced via a dry process in an attempt to further improve the cracking and rutting performance of the mixtures. The results showed that the DC(T) fracture energy test disagrees with the results obtained from the SCB (I-FIT) and IDEAL CT-index when GTR was introduced into the study mixtures. The use of rubber up to 20% increased the fracture energy of mixtures significantly (almost doubled), while the FI and CT-index scores were significantly reduced. This is somewhat counter-intuitive as field results suggest that rubber modification provides cracking resistance benefits to asphalt mixtures in the field, even under extreme environments and loading conditions. In terms of rutting, the addition of rubber increased the rutting resistance of the mixtures.

Evaluating BMD optimization as a whole, the use of a softer binder was the most effective strategy to optimize SCB(I-FIT) and IDEAL CT cracking test scores, while the incorporation of rubber along with a softer base binder and supplemental binder was the most effective method to maximize DC(T) fracture energy test results. In all cases, modern recycled mixtures appear to have a significant factor of safety against rutting, which suggests the increasing importance of softer virgin binder grades and effective rejuvenators and the importance of accessing these materials without greatly increasing asphalt mixture costs.

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

- For binder E & R, it is recommended to use the centrifuge MMDM if the filterless centrifuge device is available.

- The practice of recommending or requiring a softer virgin binder grade when recycled materials are used should be continued, even as BMD is rolled out. A simple table was developed to assist mix designers in this regard.
- When designing with very stiff recyclates, such as highly weathered RAP sources, RAS or waste plastic, it may be necessary to apply a weight factor to the stiffer recyclates. Current MoDOT specifications recommend that for mixes containing both RAP and RAS, the ABR should be computed as the ABR by RAP plus 2 times the ABR by RAS. A similar weight factor may be necessary as waste plastic mixtures are introduced. Recommendations for rejuvenator and GTR use were also provided.
- The use of GTR can increase mixture sustainability, while helping to meet performance test results. Depending on the cracking test selected, it may also be necessary to select a very soft binder and to increase binder content in the mix containing GTR, through the use of supplemental binder, increasing mixture VMA and/or regressing air void targets. For the dry-process GTR product studied herein, 0.1% supplemental binder is suggested by the manufacturer for each 5% of rubber used by weight of virgin binder.
- Attention should be paid to the availability of softer virgin binder supply in Missouri. As these recommendations are implemented, and as BMD is rolled out, the current supply of softer virgin binders may fall short of demand. A staged rollout of BMD may serve to provide a smooth transition.
- When designing at higher ABR levels and/or when using stiff recyclates, additional strategies may be required beyond virgin binder grade softening and rejuvenator use. These include:
    - Regressing air void targets below the typical 4% target associated with Superpave, to lower levels such as 3.5%, 3.0%, or perhaps even 2.5%.
    - Use of increased VMA targets.
    - Transforming older mix designs to meet newer BMD requirements will generally require building additional crack resistance into the mix. To save time, it is recommended to iterate mix designs initially by focusing on cracking

test results conducted with one or two test replicates, then introducing the Hamburg test and additional cracking test replicates only when a mix design is reached with a comfortable margin above the design cracking test requirement threshold.

- Experiment with different combinations and quantities of rejuvenators, anti-strip, and warm-mix additives.
- Failing to meet Hamburg requirements due to a mix that shows an inflection followed by a rapid increase in wheel track rut depth might require adjustments to improve moisture resistance, a better aggregate skeleton and/or a stiffer binder system (perhaps including more recycled material). A stripping inflection in the Hamburg test can result from a true stripping failure, plastic deformation in the mix or a combination of the two.

The movement towards increased sustainability in asphalt mixtures will require continued balancing of increased recycled material usage, mixture durability, and mixture economics. Major sacrifices in one or more of these three categories will not truly lead to long-term, sustainable solutions. Finally, this study highlights the significant challenges confronting the industry with respect to the need for even softer base binder supplies and a broad slate of effective rejuvenators, tailored to binders and aggregates with differing chemical characteristics.

1. INTRODUCTION

1.1. Background

The use of RAP in hot-mix asphalt (HMA) decreases the construction cost, reduces material transportation costs, and promotes sustainability. Aged binder in RAP is stiffer, which yields mixes with poor low temperature (LT) cracking and workability characteristics. To rectify these deficiencies, researchers and practitioners have tried methods such as the use of softer fresh bitumen, warm mix asphalt (WMA) additives, rejuvenators, and crumb rubber. On the other hand, hundreds-of-millions of scrap tires can be found stockpiles in the United States, leading to an ample supply of potentially recyclable ground tire rubber (GTR). Also, over ten million tons of tear-off roofing shingles are currently stockpiled, creating the potential for large-scale recycling of recycled asphalt shingles (RAS). Recycling these materials in asphalt pavements is a potentially sustainable solution and can often yield performance benefits if used correctly. However, a lack of scientific test results and effective tests, especially to evaluate new products and manufacturing processes, and a lack of clear quantification of costs vs. benefits impedes implementation by state transportation agencies and industry. There is a particular lack of literature and research experience with regards to newer ground tire rubber (GTR) asphalt products and their use in the Midwest. Adjustments to mix design procedures, particularly for those containing recycled asphalt shingles (RAS), also need to be studied. This project involved research collaboration between the University of Missouri Columbia, University of Missouri S&T, and the Missouri Department of Transportation (MoDOT), and the Missouri Asphalt Paving Association (MAPA). A laboratory and field investigation of modern asphalt rubber products, RAP, RAS, and rejuvenators available in the Midwest was conducted. Investigations included both asphalt binder and mixture performance characterization, including materials sampled from the field projects.

1.2. Research Motivation

According to the results of a previous, related project (Buttlar et al., 2019), recycled Superpave mixtures in Missouri were not falling in line with newer, balanced mix design performance test criteria. Almost across-the-board they were prone to cracking, but highly resistant to rutting. This was also observed during on-site coring visits and by reviewing data in MoDOT's pavement management system (as collected by ARAN pavement inspection vehicles). Therefore, an opportunity existed to investigate the steps needed to evaluate and transform previously designed Superpave mixtures in Missouri towards more balanced designs, i.e., those that strike a better balance between cracking and rutting performance. A robust collection of plant-sampled and field-cored materials also presented an opportunity to conduct an extensive binder extraction and recovery study, to provide additional clues towards the achievement of more balanced mixes with recycled materials. Towards these ends, several key research questions needed to be answered, including:

- How can asphalt mixture cracking performance be improved before resorting to changing aggregate structure and recycling content? What are the most effective strategies?

- Is there any correlation between the mixture and binder test results, and what deeper knowledge about mix balancing and optimization can be gained by examining both data sets?

- How do recycled binders interact with virgin binders? What role do rejuvenators play in this process?

- Can a simple set of best practice recommendations be developed to aid practitioners in balancing their current and future mix designs as MoDOT BMD specifications evolve and reach the full implementation stage?

1.3. Research

The work conducted herein was carried out under MoDOT research project number TR201811, “Understanding and Improving Heterogeneous, Modern Recycled Asphalt Mixes.” Six main tasks were conducted in this study, including:

- Literature review
- Experimental design
- Mixture testing focused on re-balancing recently placed MoDOT mixes
- Extraction, recover, and testing of binders from recently placed MoDOT mixes
- Data analysis and correlation
- Best practice recommendation development

The mixture tests conducted include:

- High temperature: Hamburg wheel tracking testing (submerged)
- Intermediate temperature: I-FIT Flexibility index testing (FI)
- Intermediate temperature: IDEAL cracking test index (CT)
- Low temperature fracture: DC(T) fracture energy (G_f)

Binder tests were performed at University of Missouri S&T on recovered binder from mixture cracking performance test samples collected from the MAPIL lab at the University of Missouri-Columbia, along with virgin binder collected from mix producers in a previous research project. The key steps involved in the binder portion of the study included:

- Extraction of asphalt binder from mix specimens
- Recovery of binder from binder-solvent solution
- Short-term aging of virgin asphalt binders
- Evaluation of rheological properties for virgin and recovered binders

Once mixture and binder testing were complete, correlations between binder and mixture properties were studied, and finally, best practice recommendations were developed by the research team.

1.4. Technology Transfer

In addition to the project quarterly and final reports, PowerPoint style presentation materials were assembled in preparation for presentations at technical meetings and/or webinar events. At the time of this writing, portions of the study materials have been reviewed at joint meetings held between the Missouri Department of Transportation and the Missouri Asphalt Pavement Association. A journal paper has been prepared (Majidifard et al., to be submitted), with others planned after the publication of this report. Preliminary results have been used in support of the fine tuning of newly developed BMD asphalt specifications in Missouri.

2. MATERIAL SAMPLING AND PROCESSING

2.1. Asphalt Mixtures Investigated

Based on the project proposal and further consultation with MoDOT, a total of 18 projects were selected for sampling and testing in this study. Wherever possible, existing sampled plant materials and cores from previous projects sponsored by MoDOT were utilized. These include samples produced during research projects TR201712 (Buttlar et al., 2019) and TR201811 (Buttlar et al., 2020),with the former project focusing on recycled asphalt mixtures and the latter focusing on balanced mix design and mixture performance testing. Selected materials from these studies were used to produce new recycled mixture formulations in an effort to transform the mixes toward higher performance, e.g., achieving cracking and rutting performance test scores akin to modern BMD specifications. Towards this end, an effort was made to select mixtures encompassing the following factors:

- **New** vs. **older** projects
- **Good** and **poor** performers
- **Range of** recycled **materials** and additives, i.e., RAP, RAS, GTR, Rejuvenator, Polymer
- **Geographic distribution** across Missouri, balanced against a **concentration** of a majority **of projects** around the center of the state to reduce sample transportation costs
- **Heavy sampling** (coring plus plant and paver sampling), to enable future testing and testing of reconstituted lab mixes, vs. **light sampling** for economy (coring only)

In previous studies, two levels of sampling were performed: Level 1 (heavy sampling) and Level 2 (light sampling). A total of 4 Level 1 projects were selected, along with 14 Level 2 projects, for a total of 16 projects (W. G. Buttlar, Meister, et al., 2019). These included a number of Long Term Pavement Performance (LTPP) Special Pavement Sections (SPS-10), which were constructed in the fall of 2016. These sections were placed on the southbound driving lanes of US54 just north of Osage Beach, MO. The asphalt contractor for the job was Magruder Paving, LLC, who utilized a drum-mix plant located near the intersection of Lakeside Rd. and US54, near Lakeland, MO, and incorporated aggregates from nearby quarries. While the focus of the

SPS-10 project was on warm-mix techniques, the project contained a robust collection of RAP, RAS, and rejuvenator combinations, as shown in Table 2-1.

After consultation with MoDOT, it was decided to focus all 16 projects on medium traffic volume facilities, which are dense-graded mixtures designed using Superpave principles. (Tables 2-2 and 2-3). Two-of-the-four Level 1 projects were part of the SPS-10 project in Osage Beach, while the other two were located on US63 near Moberly, MO, and US13 near Clinton, MO. The main recycling variable missing from the projects selected was GTR. It was therefore decided that the effects of GTR, virgin binder grade, and rejuvenator quantity would be investigated as means to balance selected Missouri Superpave mixes that were developed and placed in service prior to the current movement towards full BMD implementation.

Table 2-1. Summary of SPS-10 Sections Investigated (W. G. Buttlar, Meister, et al., 2019)

Test Section	APPROX. TONS	MIX DESIGN	AC	MOD1	MOD2
291001	500	SP125 16-83	PG64-22H		
291003	500	SP125 16-100	PG64-22H		
291002	500	SP125 16-93	PG64-22H	EVO M1	
291004	460	SP125 16-84	PG64-22H		
291008	480	SP125 16-99	PG64-22H	FLEX	
291005	290	SP125 16-91	PG58-28		
291007	680	SP125 16-89	PG58-28		
291009	970	SP125 16-98	PG58-28		
291010	360	SP125 16-95	PG46-34		
291006	400	SP125 16-94	PG58-28	PC2106	IPC70

Table 2-2. Summary of Level 1 Projects Selected (W. G. Buttlar, Meister, et al., 2019)

Section Short Label	Job No	County	Route /Dir	Location	Total %ABR	%ABR by RAP	%ABR by RAS	Misc.
MO13_1	J7P3010	Henry	MO 13 NB	S. of Clinton	16.6	16.6	0	1.5% Bag House Fines + 0.5% Mlife* T280
US54_6	J5P3131 mainline	Miller	US 54 NB	N. of Osage Beach	30.7	30.7	0	1% Mlife T280
US54_1	J5P3131 sect 10	Miller	US 54 SB	N. of Osage Beach	33	0	33	2.5% IPC-70 +3.5% PC 2106 + 1.5% Mlife T280
US63_1	J2P2213	Randolph	US 63 SB	S. of Moberly	35.2	35.2	0	0.5% IPC-70 +1.75% PC 2106 + 1.5% Mlife T280

*MORLIFE branded rejuvenator product

Table 2-3. Summary of Level 2 Projects Selected (W. G. Buttlar, Meister, et al., 2019)

Section Short Label	Job No	County	Route /Dir	Location	Total %ABR	%ABR by RAP	%ABR by RAS	Misc.
US63_2	J2P0773 SBL	Macon	US 63 SB	N of Macon, near LaPlata	29.9	19.9	10	1.5% Bag House Fines + 0.5% AD-here HP PLUS
US54_3	J5P3131 sect7	Miller	US 54	Osage Beach	33.1	17.9	15.2	1% Mlife* T280
US54_5	J5P3131 sect4	Miller	US 54	Osage Beach	0	0	0	1% Mlife T280
US54_4	J5P3131 sect5	Miller	US 54	Osage Beach	34.7	34.7	0	3% PC 2106, 1% MORLIFE T280
US54_2	J5P3131 sect8	Miller	US 54	Osage Beach	33.2	33.2	0	1% Mlife T280
US50_1	J5P0961	Moniteau/Morgan	US 50	Tipton	24.6	24.6	0	1% Lime
SPS10_1	J5P3131 Sect1	Miller	US 54 SB	N. of Osage Beach	23.6	23.6	0	1% Mlife T280
SPS10_2	J5P3131 Sect2	Miller	US 54 SB	N. of Osage Beach	24.5	24.5	0	1% Mlife T280
MO52_1	J5P0925	Morgan	MO 52	Versailles	33.5	0	33.5	1.5% BHF, 0.8%Adhere HP+
US54_7	J5P0769	Cole	US 54 WB	Brazito	0	0	0	0.25% LOF 65-00LS1
US54_8	J5D0600A	Cole	US 54	S of Jeff City	8.6	8.6	0	0.5% AD-here HP PLUS
SPS10_9	J5P3131 Sect9	Miller	US 54 SB	N. of Osage Beach	45.6	15.7	29.9	2% Mlife T280

*MORLIFE

Additional details regarding project location and core locations can be found in Buttlar et al. (2019). Five existing pavement sections constructed prior to 2016 were selected for coring and field performance history investigation., as indicated by the shaded cells in Table 2-4, shown alongside selected plant sampled mixtures introduced earlier. Table 2-6 presents five additional mixtures sampled during the recently completed balanced mix design study (Buttlar et al., 2020), which were included for evaluation in the current study based upon their diversity in recycled material type and contents, including one virgin mix.

Table 2-4. Summary of Plant Mixtures Collected with Level 2, Regular Sampling Protocol (Buttlar et al., 2019)

	Cons. Year	Section	ABR[9] %		Total P_b[10] %	Virgin Binder	Modifier(s)	NMAS (mm)
			%RAP	%RAS				
1	2016	MO13_1 (17-17-0)	24	0	5.7	PG64-22 H[11]	Type 1[1]:0.5%	9.5
2	2016	US63_1 (35-35-0)	35	0	5.1	PG58-28	Type 2[2]:0.5% + Type 3[3]:1.75%	12.5
3	2016	US54_6 (31-31-0)	31	0	5.1	PG58-28	Type 1:1%	12.5
4	2016	US54_1 (33-0-33)	0	33	5.2	PG58-28	Type 4[4]:2.5% + Type 5[5]:3.5% + Type 1:1.5%	12.5
5	2011	US50_1 (25-25-0)	25	0	4.5	PG64-22	Type 6[6]:1.5% + Type 7[7]:1%	12.5
6	2010	MO52_1 (34-0-34)	0	34	4.8	PG64-22	Type 6: 1.5%, Type 7:0.8%	12.5
7	2008	US63_2 (30-20-10)	20	10	5.6	PG64-22	Type 6: 1.5% + Type 7: 0.5%	12.5
8	2016	US54_2 (33-33-0)	33	0	5.3	PG58-28	Type 1: 1%	12.5
9	2016	US54_3 (33-18-15)	18	15	5.2	PG58-28	Type 1: 1%	12.5
10	2016	US54_4 (35-35-0)	35	0	4.8	PG64-22 H	Type 5:3% + Type 1:1%	12.5
11	2016	US54_5 (0-0-0)	0	0	5.4	PG64-22 H	Type 1: 1%	12.5
12	2003	US54_7 (0-0-0)	0	0	6.2	PG64-22	Type 8[8]: 0.25%	12.5
13	2006	US 54_8 (9-9-0)	9	0	5.6	PG70-22	Type 7: 0.5%	12.5
14	2016	SPS10-1 (24-24-0)	24	0	5.2	PG64-22 H	Type 1:1%	12.5
15	2016	SPS10-2 (25-25-0)	25	0	5	PG64-22 H	Type 1:1%	12.5
16	2016	SPS10-3 (25-25-0)	25	0	5	PG64-22H	Type 1:1% + Type 2: 0.5%	9.5
17	2016	SPS10-6 (17-0-17)	0	17	5.4	PG58-28	Type 1: 1%	9.5
18	2016	SPS10-9 (46-16-30)	16	30	5.3	PG46-34	Type 1: 2%	12.5

1. Type 1. Anti-stripping agent ('Morelife T280')
2. Type 2. Warm-mix additive (‘Evotherm’)
3. Type 3. Rejuvenator additive (‘EvoFlex CA’)
4. Type 4. Anti-stripping agent (‘IPC-70’)
5. Type 5. Warm-mix additive (‘PC 2106’)
6. Type 6. Bag house fines
7. Type 7. Anti-stripping agent (‘AD-here HP Plus’)
8. Type 8. Anti-stripping agent (‘LOF 65-00LS1’)
9. ABR = Asphalt binder replacement
10. By total mass of binder, including neat and recycled
11. Heavy traffic designation (from MSCR test)

Table 2-5. Summary of Plant Mixtures Collected with Level 1, Heavy Sampling Protocol

No.	Cons. Year	Section	ABR[9] %		Total P_b[10] %	Virgin Binder	Modifier(s)	NMAS (mm)
			%RAP	%RAS				
1	2016	MO13_1 (17-17-0)	17	0	5.7	PG64-22 H[11]	Type 1[1]:0.5%	9.5
2	2016	US63_1 (35-35-0)	35	0	5.1	PG58-28	Type 2[2]:0.5% + Type 3[3]:1.75%	12.5
3	2016	US54_6 (31-31-0)	31	0	5.1	PG58-28	Type 1:1%	12.5
4	2016	US54_1 (33-0-33)	0	33	5.2	PG58-28	Type 4[4]:2.5% + Type 5[5]:3.5% + Type 1:1.5%	12.5

1. Type 1. Anti-stripping agent ('Morelife T280')
2. Type 2. Warm-mix additive (‘Evotherm’)
3. Type 3. Rejuvenator additive (‘EvoFlex CA’)
4. Type 4. Anti-stripping agent (‘IPC-70’)
5. Type 5. Warm-mix additive (‘PC 2106’)
7. Type 7. Anti-stripping agent (‘AD-here HP Plus’)
8. Type 8. Anti-stripping agent (‘LOF 65-00LS1’)
9. ABR = Asphalt binder replacement
10. By total mass of binder, including neat and recycled
11. Heavy traffic designation (from MSCR test)

Table 2-6. Summary of Field Cores Collected for BMD Project (Buttlar et al., 2020)

Route	Cons. Year	Section	Virgin Binder grade	Total Asphalt Content (%)	ABR (%)	ABR (%) by RAP	ABR (%) by RAS	NMAS (mm)
0	2014	MO 151	PG64-22	4.7	30.6	15.9	14.7	12.5
1	2011	US 36 E	PG64-22	5.1	24.7	24.7	0	12.5
2	2010	US 54 E	PG70-22	5.7	11.8	11.8	0	12.5
3	2005	MO 94	PG64-22	5.6	0	0	0	12.5
4	2015	MO 6 W	PG58-28	5.9	29.6	29.6	0	4.75
5	2013	US 61 N	PG64-22H	5.3	29.6	29.6	0	9.5

2.2. Selection of Mixtures for 'Fix-the-Mix' Study Task

For the detailed BMD mixture adjustment study conducted herein ('fix-the-mix' study), two baseline mixture designs from sampled field sections were chosen. The first section sampled was placed on the southbound lanes of US Route 63 in Randolph County near Moberly, MO, and is hereby referred to as US63_1. The second section was a mainline mix placed adjacent to recently installed Long-Term Pavement Performance (LTPP) test sections on US route 54 in Camden and Miller Counties near Eldon, MO. This test section is hereby referred to as US54_6.

The guiding principles used in the fix-the-mix research task included:

- A baseline asphalt mixture design was adopted, which followed the Superpave volumetric design principles used in Missouri
- Keeping the aggregate gradation/system intact, various modifications were applied to the mixture designs to achieve a superior and/or more balanced mix in terms of rutting and cracking behavior
- Multiple cracking tests were employed (DC(T), I-FIT, and IDEAL), while only a single rutting test (Hamburg was used)
- The modifications included replacing the base binder with a softer grade binder, adding a rejuvenator to the base mix, and/or adding various percentages of recycled ground tire rubber (GTR) to the mix via the dry-process method. The use of GTR was motivated by a recent study, which provided new insights regarding the toughening mechanisms resulting in properly designed GTR mixes, such as macro-scale crack pinning.

- The goal of the study was not to pursue an exhaustive, full-factorial exploration of additive dosage rates, various combinations, etc., rather; a systematic approach towards achieving a more balanced mix design in the fewest possible iterations was employed, akin to the exercise a contractor might pursue when implementing BMD for the first time
- When dry-process GTR was used, supplemental binder was also automatically used following the manufacturer's recommendation, i.e., for each 5% of GTR by weight of binder used, an additional 0.1% of supplemental virgin binder was added to the mix
- Performance test thresholds were based on recommendations provided in (Buttlar et al., 2020)
- Mixes were adjusted in an attempt to strike a better balance between recommended DC(T) and HWTT cracking thresholds and then the same mixture iterations were tested in the IFIT and IDEAL cracking tests so that differences in strategies for maximizing scores in the various cracking tests could be studied
- Although out of the scope of the current study, mixes could be re-optimized using the IFIT and/or IDEAL tests to set cracking test thresholds based on the findings of this study

The following sections introduce the performance tests adopted in this project and then detail the mix designs used in this study.

2.3. Mix Designs Used in the 'Fix-the-Mix' Study Task

The first MoDOT mix investigated (US 63_1) was a 12.5mm NMAS dense-graded mixture, using four aggregate sources: two coarse aggregate sources collected from Burlington and Cedar Valley, MO, respectively, a manufactured sand collected from Cedar Valley, MO, and finally a RAP source with 4.5% asphalt content, creating an asphalt binder replacement (ABR) level of 33.3%. The mix used a base binder graded as Superpave PG58-28 as supplied from the Philips 66 refinery in Kansas City, MO. The base mix design contained Evotherm J12 (0.5% by weight of binder) and Evoflex CA (1.75% by weight of binder). The mixtures in this study were prepared using a standard bucket mixer, where aggregates and binder were heated in a forced-draft oven before being mixed. Evoflex and Evotherm additives were stirred into the binder before mixing with aggregates. Figure 2-1 provides a snap-shop of selected materials used in this study task. Figure 2-2 and Table 2-7 provide gradation information for the US 63_1 mixture.

Figure 2-1. Laboratory Materials Including Virgin Aggregates, RAP, Virgin Binder, Rejuvenators, Additives and Ground-Tire Rubber

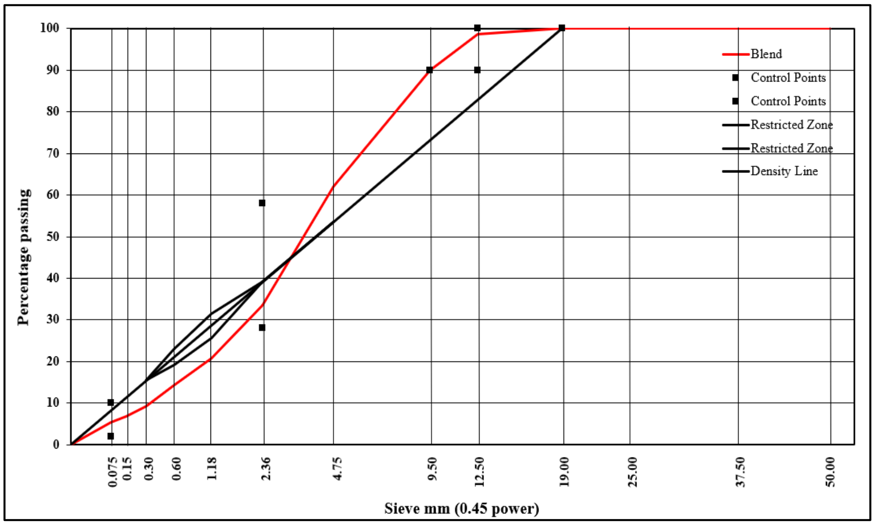


Figure 2-2. Gradation of US63_1 Superpave Mixture

Table 2-7. Stockpile Gradations (% passing) and Blending Proportions for Mix US63_1

Sieve Size or Number	Sieve Size (mm)	Stockpile 1 3/4" (35% of blend)	Stockpile 2 3/8" (18% of blend)	Stockpile 3 MAN SAND (7% of blend)	Stockpile 4 RAP (40% of blend)	US 63_1 final blend
2 inches	50.00	100.00	100.00	100.00	100.00	100.00
1 1/2 inches	37.50	100.0	100.0	100.0	100.0	100.0
1 inch	25.00	100.0	100.0	100.0	100.0	100.0
3/4 inch	19.00	100.0	100.0	100.0	100.0	100.0
1/2 inch	12.50	96.0	100.0	100.0	100.0	98.6
3/8 inch	9.50	81.2	100.0	100.0	91.1	89.9
No. 4	4.75	37.1	92.5	99.5	63.4	62.0
No. 8	2.36	11.3	33.6	96.8	42.1	33.6
No. 16	1.18	5.3	5.4	75.7	31.6	20.8
No. 30	0.60	4.1	2.8	40.2	24.2	14.4
No. 50	0.30	3.4	2.4	15.4	16.4	9.3
No. 100	0.15	2.9	2.1	6.0	12.6	6.9
No. 200	0.075	2.5	1.9	3.6	10.2	5.5

Mixtures were produced following the reported job-mix formulas and then subjected to the performance testing suite to establish baseline performance properties. Based on the results, which generally indicated an imbalance between cracking test scores (too low) and rutting test results (passing with a margin of safety), various fix-the-mix steps were systematically attempted, as outlined in Table 2-8. Again, a non-exhaustive approach was taken to arrive at a more balanced design in the fewest number of iterations possible, followed by a discussion of what appeared to be the most effective adjustments to transform existing non-BMD mix designs to be more balanced according to typical, modern BMD targets.

Table 2-8. Iterations of Mixture Modifications Applied to US63_1 Mixes

Type	Softer binder	Rubber	Rejuvenator
US 63_1_C (Control)	PG 58-28 (no change)	0	1.75% Evoflex 0.5% Evotherm
US 63_1_46_R	PG 46-34	0	1.75% Evoflex 0.5% Evotherm
US 63_1_46	PG 46-34	0%	No
US 63_1_46_E10	PG 46-34	10%	No
US 63_1_46_E20	PG 46-34	20%	No

Volumetrics for all mix iterations based on this blend are shown in Table 2-9. All mixtures were compacted to 80 gyrations in the Superpave Gyratory Compactor (SGC). As part of driving towards more balanced mixes, the traditional Superpave method of designing at 4% air voids design was relaxed, as modern BMD principles do not typically require strict adherence to a 4% air void target. Also, for comparison purposes, only one factor was altered between experimental trials. For instance, when a softer binder was used, other factors such as binder content were kept constant. In terms of ingredient compatibility, none of the mixtures appeared to have a problem except in the trial labeled as US63_1_46, wherein a softer binder was used without the use of warm mix additives. The final air void level after 80 gyrations for mix US63_1_46 was 5.6%, which was significantly higher than the reference MoDOT mix originally designed at 4% air voids. The reference mix was in fact found to possess an average of 4.4% voids for the plant materials sampled and produced in this study. This finding clearly indicated the positive effect of warm mix additives in terms of the compactability of modern, recycled asphalt mixtures. It is hypothesized that a combination of factors, including recycled binder softening/reincorporation as a fully liquid phase, lubricity characteristics imparted by the WMA additive, and/or a net reduction in mastic stiffness at mixing and compaction temperatures were likely driving the observed improvements in recycled mix compaction.

Table 2-9. Details for US63_1_C Mix Iterations Compacted to 4.0±0.5% Air Voids

Mix Name	US 63_1_C	US63_1_46	US63_1_46_R	US63_1_46_E10	US63_1_46_E10
Binder Used	PG 58-28	PG 46-34	PG 46-34	PG 46-34	PG 46-34
Total Binder %	5.1	5.1	5.1	5.3	5.5
Virgin Binder %	3.4	3.4	3.4	3.6	3.8
ABR %	33.3	33.3	33.3	32.1	30.9
Gmm	2.455	2.460	2.458	2.438	2.425
Va %	4.4	5.6	4.4	4.5	3.9
Va % for performance tests	7	6.9	6.9	6.8	6.7
VMA	14.1	16.5	15.4	16.2	16.2
VFA	72	65.8	71.6	72.2	75.3

The other mix design (US54_6) was also a 12.5 NMAS dense-graded mixture, placed as an LTPP research section on US 54 in Camden County, near Eldon, MO. The mix used four stockpiles consisting of: coarse aggregates having NMAS levels of ¾" and ½" (with 8 and 7% chert respectively), collected from Gasconade, Missouri; manufactured sand collected from the vicinity of Osage River and finally; a RAP source with 5.1% asphalt leading to an asphalt binder replacement (ABR) level of about 30%. Mix gradation details are provided in Figure 2-3 and Table 2-10. The mix incorporated the same base binder as the first mix (PG58-28 collected from the Philips 66 refinery in Kansas City, MO).

Table 2-11 shows the modifications applied to the baseline mix to eventually achieve the required BMD test thresholds. Three variables were selected to be altered during this phase of the study- the use of a softer binder grade (PG46-34), the addition of rejuvenator (3% Evoflex CA), and the addition of dry-process rubber (levels of 5% and 20% GTR by weight of virgin binder were used). For the mixes with GTR, supplemental binder was added according to the manufacturer's recommendation (0.1% supplemental virgin binder was added for the 5% GTR mix, while 0.4% supplemental binder was used for the 20% GTR mix). An engineered crumb rubber (ECR) product was used in the current study, which has been used as a modifier in several hundreds-of-thousands of tons of SMA and dense-graded mixtures placed since 2016 on the Illinois Tollway, as described in (W. G. Buttlar, Jahangiri, et al., 2020). The variables were strategically chosen after examining the baseline performance of the control (unmodified) US 54_6 mix.

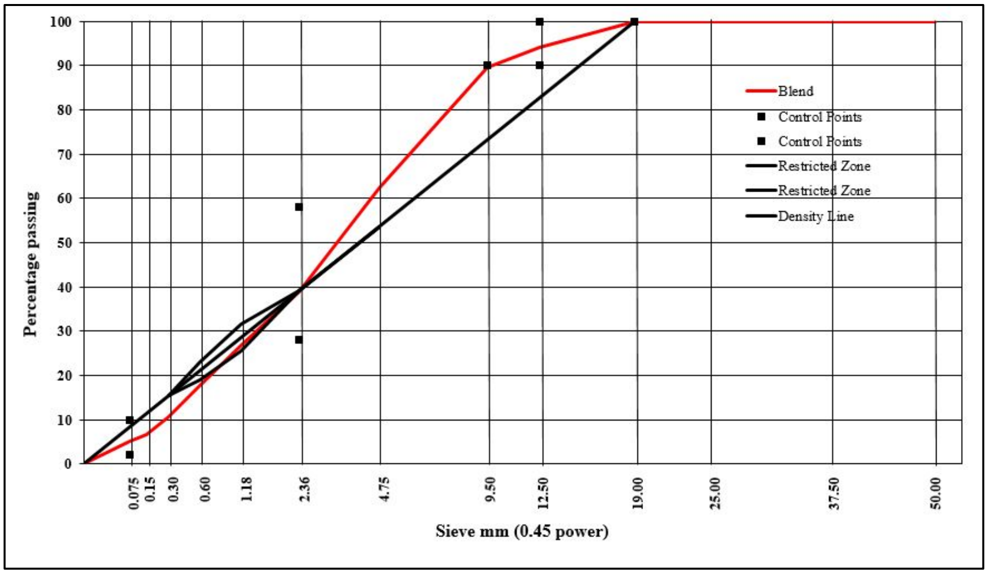


Figure 2-3.Gradation of US54_6 Mixture

Table 2-10. Stockpile Gradations (% passing) and Blending Proportions for Mix US54_6

Sieve Size or Number	**Sieve Size (mm)**	**Stockpile 1 3/4" (14% of blend)**	**Stockpile 2 3/8" (29% of blend)**	**Stockpile 3 MAN SAND (25% of blend)**	**Stockpile 4 RAP (32% of blend)**	**US 54_6 Final Blend**
2 inches	50.00	100.00	100.00	100.00	100.00	100.00
1 1/2 inches	37.50	100.00	100.00	100.00	100.00	100.00
1 inch	25.00	100.00	100.00	100.00	100.00	100.00
3/4 inch	19.00	100.0	100.00	100.00	100.00	100.00
1/2 inch	12.50	58.0	100.00	100.00	100.00	94.12
3/8 inch	9.50	28.0	99.9	100.00	99.00	89.57
No. 4	4.75	5.0	38.9	100.00	79.00	62.26
No. 8	2.36	4.3	3.2	80.00	54.00	38.81
No. 16	1.18	4.0	2.6	49.00	41.00	26.68
No. 30	0.60	3.2	2.4	27.00	31.00	17.81
No. 50	0.30	3.0	2.2	13.00	20.00	10.71
No. 100	0.15	2.5	1.9	4.00	15.00	6.70
No. 200	0.075	2.2	1.5	2.0	12.00	5.08

Table 2-11. Iterations of Modifications Applied to US54_6 Mixes (32% ABR by RAP)

Type	Softer binder	Rubber	Rejuvenator
US 54_6_C	PG 58-28 (no change)	0	
US 54_6_46	PG 46-34	0	No
US 54_6_46_E5	PG 46-34	5%	No
US 54_6_R	PG 58-28	0	3% Evoflex
US 54_6_46_E20	PG 46-34	20%	No

The volumetric properties of the US54_6 mixture trials are shown in Table 2-12. For this mix, the iteration with 5% dry GTR had issues with compaction and exhibited high air voids (6.8%) at 80 gyrations. A possible reason for poor compaction could be insufficient space for rubber particles to fit in the aggregate skeleton of the dense-graded mix. It was surprising to see that the compaction issues were resolved in 20% dry GTR mix, perhaps due to the enhanced lubricity provided by the additional supplemental binder accompanying the higher amount of rubber used and the engineered chemical coating on the surface of the ECR rubber particles, which include a compaction aid according to the manufacturer. Experience has shown that, unlike gap-graded mixtures such as stone-mastic asphalt (SMA), adjustments are sometimes needed in the process of adding GTR to an existing mix design in order to provide room for the swollen GTR particles. These adjustments generally involve moving the blended gradation away from the maximum density line on the finer side of the gradation (sand-sized particle range and finer).

Table 2-12. Details for US54_6 Mix Iterations Compacted to 4.0+0.5% Air Voids

Mix	US54_6_C	US 54_6_R	US 54_6_46	US 54_6_46_E5	US 54_6_46_E20
Binder Used	PG 58-28	PG 58-28	PG 46-34	PG 46-34	PG 46-34
Total Binder %	5.1	5.1	5.1	5.2	5.5
Virgin Binder %	3.6	3.6	3.6	3.7	4.0
ABR (%)	29.4	29.4	29.4	28.8	27.3
Gmm	2.468	2.474	2.477	2.481	2.446
Va %	4.6	4.5	5.2	6.8	3.8
Va % for performance tests	7.2	7.1	7.4	7.0	6.5
VMA (14<)	15.2	15.0	15.5	16.7	15.3
VFA (65-78)	70.0	70.0	66.6	59.9	75.3

2.4. Mixing and Compaction

All samples were fabricated and tested at the MAPIL Lab at UMC. Plant mixtures were sampled and stored in the lab in sealed, 5-gallon steel pails and reheated until the mix was workable. Next, the material was reduced to a gyratory sample following the quartering method described in AASHTO R47 (AASHTO, 2008). Compaction temperatures were set according to the Job Mix Formula (JMF) supplied by the contractor.

Lab mixes were produced from the collected aggregates and binders following the contractor supplied JMF. Prior to mixing, aggregates were dried overnight and then batched. The mixing process was carried out in a bucket-style lab mixer (Figure 2-4), and mixtures were then short-term aged in the oven for 2 hours before compaction, at the compaction temperature. For rubber-modified mixtures, GTR was incorporated into the binder before mixing with aggregates. Following manufacture recommendations, binder and GTR were heated to 170°C then blended in a high-shear mixer at 3500 rpm for 30 minutes. The GTR-modified binder was then added to aggregates heated to 190°C, and bucket-mixed. The plant and lab mixture specimens were compacted in a Superpave Gyratory Compactor (SGC) and then fabricated into mixture performance test specimens.

Figure 2-4. Bucket Lab Mixer (left), Gyratory Compactor (Right)

2.5. Sample Size

In this research, DC(T) and HWTT specimens were fabricated from both plant- and lab-produced mixtures. To perform the HWTT test, a 62 mm height cylindrical sample with 150mm diameter was produced in a gyratory compactor according AASHTO T 324. For the DC(T), a gyratory specimen of 150 mm diameter and 140 mm height was produced and, according to ASTM D7313, subsequently cut into two 50 mm thick slices. Two loading holes of 25 mm diameter and a notch of approximately 62 mm in length were fabricated into DC(T) specimens. Figure 2-5 illustrates the sample fabrication process used for DC(T) specimens. A minimum of three replicates were used in DC(T) testing, while a minimum of four replicates were used for HWTT testing.

Figure 2-5. DC(T) Fabrication Process

2.6. Materials for Binder Studies

Sixty field sample "cores" were collected from different routes in two batches: the first batch had 38 samples (Figure 2-6) and the second batch had 22 samples (Figure 2-7). More details about the first and second batch samples are presented in Table 2-13 and Table 2-14, respectively. For field samples taken from routes constructed in 2016, the cores were sampled within two weeks after the pavement construction process in 2016. Therefore, the E & R asphalt binders from those mixes were considered as short-term aged binders. The asphalt binders E & R from the other field samples were treated as long-term aged binders. The long-term aged field samples in the first batch were collected in 2016. The field samples in the second batch were gathered in 2019. These mixes contained different asphalt binder replacement (ABR) percentages by recycled materials (RAP and/or RAS) and different additives. Some mixes contained neither RAP nor RAS (e.g. US 54-5, US 54-7, and MO 94). After testing the compacted samples at the University of Missouri-Columbia (Mizzou), the samples were collected and brought to the asphalt lab at Missouri University of Science and Technology (Missouri S&T).

Twelve plant mixes were designed following Superpave and mixed in a drum-mix plant. The plant is located near the intersection of Lakeside Rd. and US 54, near Lakeland in Missouri. The asphalt contractor was Magruder Paving, LLC. The plant mixes were sampled from behind the paver. These mixes were reheated and compacted using Pine GB1 Superpave gyratory in Mizzou. After testing the compacted samples in Mizzou, the samples were collected and brought to the asphalt lab at Missouri S&T, Figure 2 8. These mixes contained either RAP or RAS. More details about these mixes are illustrated in Table 2 14. The E & R asphalt binders from the plant mixes were treated as short-term aged binders.

Different lab mixes were designed following Superpave using the same original asphalt binders used in the US 54-6 and US 63-1 plant mixes (PG 58-28) or using a softer one (PG 46-34). Moreover, different additives and engineered crumb rubber (ECR) percentages were used in the lab mixes. More details about these mixes are shown in Table 2 15. The E & R asphalt binders from the lab mixes were analyzed as short-term aged binders.

The field, plant, and lab mix codes represent the route name (e.g. MO 13), section number (e.g. 1), core/coding system (e.g. HP13), virgin asphalt binder high PG temperature (e.g. PG 64 H), and ABR percentages achieved by RAP-RAS combinations (e.g., 17-0 represents 17% RAP and 0% RAS).

Figure 2-6. First Batch of Field Mix Cores

Figure 2-7. Second Batch of Field, Plant, and Lab Mixes

Table 2-13. Details for First Round of Field Mix Sampling

#	Code	Job No.	County	Route /Dir	Locat-ion	Air Voids (%)	Virgin asphalt PG	Plan PG	Virgin AC[a] (%)	Total AC (%)	ABR by RAP (%)	ABR by RAS (%)	NMAS[b] (mm)	Year Built[c]	Additives
1	MO 13-1-5-PG 64H (17-0)	J7P3010	Henry	MO 13 NB	S. of Clinton	6.8	64-22H	70-22	4.4	5.7	17	0	9.5	2016	Morelife T280 0.5%
2	MO 13-1-7-PG 64H (17-0)					6.6									
3	MO 13-1-11-PG 64H (17-0)														
4	US 54-6-9-PG 58 (31-0)	J5P3131 mainline	Miller	US 54 NB	N. of Osage Beach	5.6	58-28	70-22	3.6	5.1	31	0	12.5	2016	Morelife T280 1%
5	US 54-6-7-PG 58 (31-0)														
6	US 54-6-2-PG 58 (31-0)														
7	US 54-1-2a-PG 58 (0-33)	J5P3131 sect 10	Miller	US 54 SB	N. of Osage Beach	3.0	58-28		3.6	5.2	0	33	12.5	2016	IPC70 2.5%, PC2106 3.5%, Morelife T280 1.5%
8	US 54-1-3a-PG 58 (0-33)														
9	US 54-1-4-PG 58 (0-33)														
10	US 63-1-9-PG 58 (35-0)	J2P2213	Randolph	US 63 SB	S. of Moberly	7.0	58-28	70-22	3.4	5.1	35	0	12.5	2016	Evotherm 0.5%, Evoflex CA 1.75%
11	US 63-1-5-PG 58 (35-0)														
12	US 63-1-2-PG 58 (35-0)														
13	US 63-2-5-PG 64 (20-10)	J2P0773 SBL	Macon	US 63 SB	N of Macon, near LaPlata	9.8	64-22		4.1	5.6	20	10	12.5	2008	Baghouse fines 1.5%, AD-here HP plus 0.5%
14	US 63-2-2-PG 64 (20-10)					7									
15	US 63-2-11-PG 64 (20-10)														
16	US 54-3-8a-	J5P3131	Miller	US	Osage	6.4	58-28		3.6	5.2	18	15	12.5	2016	Morelife

	PG 58 (18-15)	sect7		54	Beach										T280 1%
17	US 54-3-6a-PG 58 (18-15)					6.2									
18	US 54-3-2-PG 58 (18-15)														
19	US 54-5-5a-PG 64H (0-0)	J5P3131 sect4	Miller	US 54	Osage Beach	4.6	64-22H	64-22	5.4	5.4	0	0	12.5	2016	Morelife T280 1%
20	US 54-5-9a-PG 64H (0-0)					4.4									
21	US 54-4-1a-PG 64H (35-0)	J5P3131 sect5	Miller	US 54	Osage Beach	4.7	64-22H		3.2	4.8	35	0	12.5	2016	PC2106 3%, Morelife T280 1%
22	US 54-4-4a-PG 64H (35-0)					4.8									
23	US 54-4-7-PG 64H (35-0)														
24	US 54-2-7a-PG 58 (33-0)	J5P3131 sect8	Miller	US 54	Osage Beach	4	58-28		3.6	5.3	33	0	12.5	2016	Morelife T280 1%
25	US 54-2-6-PG 58 (33-0)					3.9									
26	US 54-2-3-PG 58 (33-0)														
27	US 50-1-9-PG 64 (25-0)	J5P0961	Moniteau /Morgan	US 50	Tipton	10	64-22		3.8	5	25	0	12.5	2011	BHF 1.5%, AD-here HP plus 1%
28	US 50-1-4-PG 64 (25-0)														
29	US 50-1-2-PG 64 (25-0)														
30	MO 52-1-6-PG 64 (0-34)	J5P0925	Morgan	MO 52	Ver-sailles	7.9	64-22		3.7	4.8	0	34	12.5	2010	BHF 1.5%, AD-here HP plus 0.8%
31	MO 52-1-3-PG 64 (0-34)														
32	MO 52-1-9-PG 64 (0-34)														
33	US 54-7-7-PG 64 (0-0)	J5P0769	Cole	US 54 WB	Brazito	3.7	64-22		6.2	6.2	0	0	12.5	2003	LOF 65-00LS1 0.25%
34	US 54-7-2-PG 64 (0-0)					5									

35	US 54-7-4-PG 64 (0-0)														
36	US 54-8-6-PG 70 (9-0)	J5D0600 A	Cole	US 54	S. of Jeff City	4.4	70-22		5.1	5.6	9	0	12.5	2006	AD-here HP plus 0.5%
37	US 54-8-4-PG 70 (9-0)					2.3									
38	US 54-8-3-PG 70 (9-0)														

[a] AC: Asphalt Content, [b] NMAS: Nominal Maximum Aggregate Size, and [c] Const.: Construction.
Morelife T280, AD-here HP Plus, LOF 65-00LS1, and IPC-70: anti-stripping agents.
Evotherm and PC 2106: warm-mix additives.
Evoflex CA: rejuvenator additive.

Table 2-14. Details for Second Round Field Mix Sampling

No.	Code	Route/Dir	Virgin asphalt PG	Contract PG	Total AC (%)	ABR by RAP (%)	ABR by RAS (%)	NMAS (mm)	Date of most recently overlay
1	MO 151-7-PG 64 (16-15)	MO 151	64-22	64-22	4.7	16	15	12.5	2010
2	MO 151-5a-PG 64 (16-15)								
3	MO 151-10a-PG 64 (16-15)								
4	MO 151-2a-PG 64 (16-15)								
5	MO 151-11-PG 64 (16-15)								
6	US 61 N-9a-PG 64H (30-0)	US 61 N	64-22H	64-22H	5.3	30	0	9.5	2013
7	US 61 N-3a-PG 64H (30-0)								
8	US 61 N-6a-PG 64H (30-0)								
9	US 54-12a-PG 70 (12-0)	US 54 E	70-22	70-22	5.7	12	0	12.5	2010
10	US 54-6a-PG 70 (12-0)								
11	US 54-2a-PG 70 (12-0)								
12	MO 6-4a-PG 58 (30-0)	MO 6 W	58-28	64-22	5.9	30	0	4.75	2015
13	MO 6-5a-PG 58 (30-0)								
14	MO 6-10a-PG 58 (30-0)								

15	MO 6-11a-PG 58 (30-0)								
16	MO 6-8a-PG 58 (30-0)								
17	MO 94-9a-PG 64 (0-0)	MO 94	64-22	64-22	5.6	0	0	12.5	2005
18	MO 94-12a-PG 64 (0-0)								
19	MO 94-6a-PG 64 (0-0)								
20	US 36-10a-PG 64 (25-0)	US 36 E	64-22	64-22	5.1	25	0	12.5	2011
21	US 36-13a-PG 64 (25-0)								
22	US 36-12a-PG 64 (25-0)								

Table 2-15. Plant-sampled Mix Details

No.	Code	Job No.	County	Route/ Dir	Location	Virgin asphalt PG	Plan PG	Virgin AC (%)	Total AC (%)	ABR by RAP (%)	ABR by RAS (%)	NMAS (mm)	Const. Year	Additives
1	MO 13-1-HP13-PG 64 H (17-0)	J7P3010	Henry	MO 13 NB	S. of Clinton	64-22H	70-22	4.4	5.7	17	0	9.5	2016	Morelife T280 0.5%
2	MO 13-1-HP16- PG 64 H (17-0)													
3	MO 13-1-HP14- PG 64 H (17-0)													
4	US 54-6-HP3-PG 58 (31-0)	J5P3131 mainline	Miller	US 54 NB	N. of Osage Beach	58-28	70-22	3.6	5.1	31	0	12.5	2016	Morelife T280 1%
5	US 54-6-DP4A-PG 58 (31-0)													
6	US54-6-DP4B-PG 58 (31-0)													
7	US 54-1-1DCTP1B-PG 58 (0-33)	J5P3131 sect 10	Miller	US 54 SB	N. of Osage Beach	58-28		3.6	5.2	0	33	12.5	2016	IPC70 2.5%, PC2106 3.5%, Morelife T280 1.5%
8	US 54-1-1DCTP2B-PG 58 (0-33)													
9	US 54-1-1DCTP1A-PG 58 (0-33)													
10	US 63-1-HP8-PG 58 (35-0)	J2P2213	Randolph	US 63 SB	S. of Moberly	58-28	70-22	3.4	5.1	35	0	12.5	2016	Evotherm 0.5%, Evoflex CA 1.75%
11	US 63-1-HP9-PG 58 (35-0)													
12	US 63-1-DP3A-PG 58 (35-0)													

Table 2-16. Simulated Lab Asphalt (‘Fix-the-Mix’) Details

No.	Code	Code Abbreviated	Virgin AC (%)	Total AC (%)	Virgin Asphalt PG	ABR by RAP (%)	ABR by RAS (%)	ECR[a] (%)	Additives
US 54-6 Lab Mixes									
1	US 54-6-H9-H10-PG 58 (31-0)	US 54-6	3.6	5.1	58-28	31	0	0	
2	US 54-6-H1-PG 58 (31-0)								
3	US 54-6-D2a-PG 58 (31-0)								
4	US 54-6-D1a-PG 58-R (31-0)	US 54-6-R							3% Evoflex
5	US 54-6-H5-H6-PG 58-R (31-0)								
6	US 54-6-D1a-PG 46 (31-0)	US 54-6-PG 46			46-34				
7	US 54-6-H3-H10-PG 46 (31-0)								
8	US 54-6-H3-PG 46-E5 (31-0)	US 54-6-PG 46-E5	3.7	5.2				5	
9	US 54-6-D2b-PG 46-E5 (31-0)								
10	US 54-6-H7-H8-PG 46-E5 (31-0)								
11	US 54-6-H4-PG 46-E20 (31-0)	US 54-6-PG 46-E20	4	5.5				20	
12	US 54-6-H1-PG 46-E20 (31-0)								
US 63-1 Lab Mixes									
13	US 63-1-H4-PG 58-R (35-0)	US 63-1-R	3.4	5.1	58-28	35	0		3.75% Evoflex, 0.5% Evotherm
14	US 63-1-D1b-PG 58-R (35-0)								
15	US 63-1-H2-PG 58-R (35-0)								
16	US 63-1-D2a-PG 46 (35-0)	US 63-1-PG 46			46-34				
17	US 63-1-H6-PG 46 (35-0)								
18	US 63-1-D1b-PG 46 (35-0)								
19	US 63-1-D2b-PG 46-R (35-0)	US 63-1-PG 46-R							3.75% Evoflex, 0.5% Evotherm
20	US 63-1-H3-PG 46-R (35-0)								
21	US 63-1-D2a-PG 46-R (35-0)								
22	US 63-1-H2-PG 46-E10 (35-0)	US 63-1-PG 46-E10	3.6	5.3				10	
23	US 63-1-H5-PG 46-E10 (35-0)								
24	US 63-1-D2b-PG 46-E20 (35-0)	US 63-1-PG 46-E20	3.8	5.5				20	
25	US 63-1-Gmb3-PG 46-E20 (35-0)								

[a] ECR: Engineered Crumb Rubber

3. BINDER RECOVERY AND PERFORMANCE TESTING

3.1. Extraction of Asphalt Binders from Asphaltic Mixes

A meticulous approach was taken towards establishing sound binder extraction and recovery procedures consistent with MoDOT central materials lab procedures. To this end, the co-PI and graduate students from Missouri S&T spent a number of days visiting and training with MoDOT wherever common equipment was possessed. Based on this training, the centrifuge extraction process of asphalt binders from mixes was performed according to ASTM D2172 / D2172M-17e1 (ASTM D2172, 2017), which is hereafter referred to as "**method A**". Trichloroethylene (TCE) solvent was used to extract the asphalt binder from the mixes, with attention to safe handling procedures appropriate for this aggressive, chlorinated solvent. A centrifuge extractor model H1460 obtained from Ploog Engineering Co., Inc. (Crown Point, IN, USA) was used. This device is shown in Figure 3-1-a. An approximately 100 ml representative sample was taken from the effluent (extracted asphalt binder, TCE, and mineral matter) and placed into an ignition dish to estimate the amount of mineral matter in the effluent using the ashing method (ASTM D2172, 2017). To ensure a precise extracted percentage of asphalt binder, at least two replicates were tested. The amount of the mineral matter was removed from the remaining effluent using a filterless centrifuge obtained from Ploog Engineering Co., Inc. (Figure 3-1-b), and quantified. The mineral matter obtained following the referenced ashing and centrifuge procedures are presented in Figure 3-1-c and Figure 3-1-d, respectively. Thus, the extracted percentage of asphalt binder was calculated using the ashing and centrifuge mineral matter determination methods, or MMDMs.

3.2. Recovery of Asphalt Binder from Binder-Solvent Solution

Asphalt binders were recovered from the asphalt binder-solvent solutions, after mineral matter removal, using a rotavap. This device, presented in Figure 3-1-e, was obtained from Cole-Parmer Instrument Co. (Vernon Hills, IL, USA). The procedures for implementing this experiment are illustrated in ASTM D5404 / D5404M-12(2017) (ASTM D5404/D5404M-12, 2017).

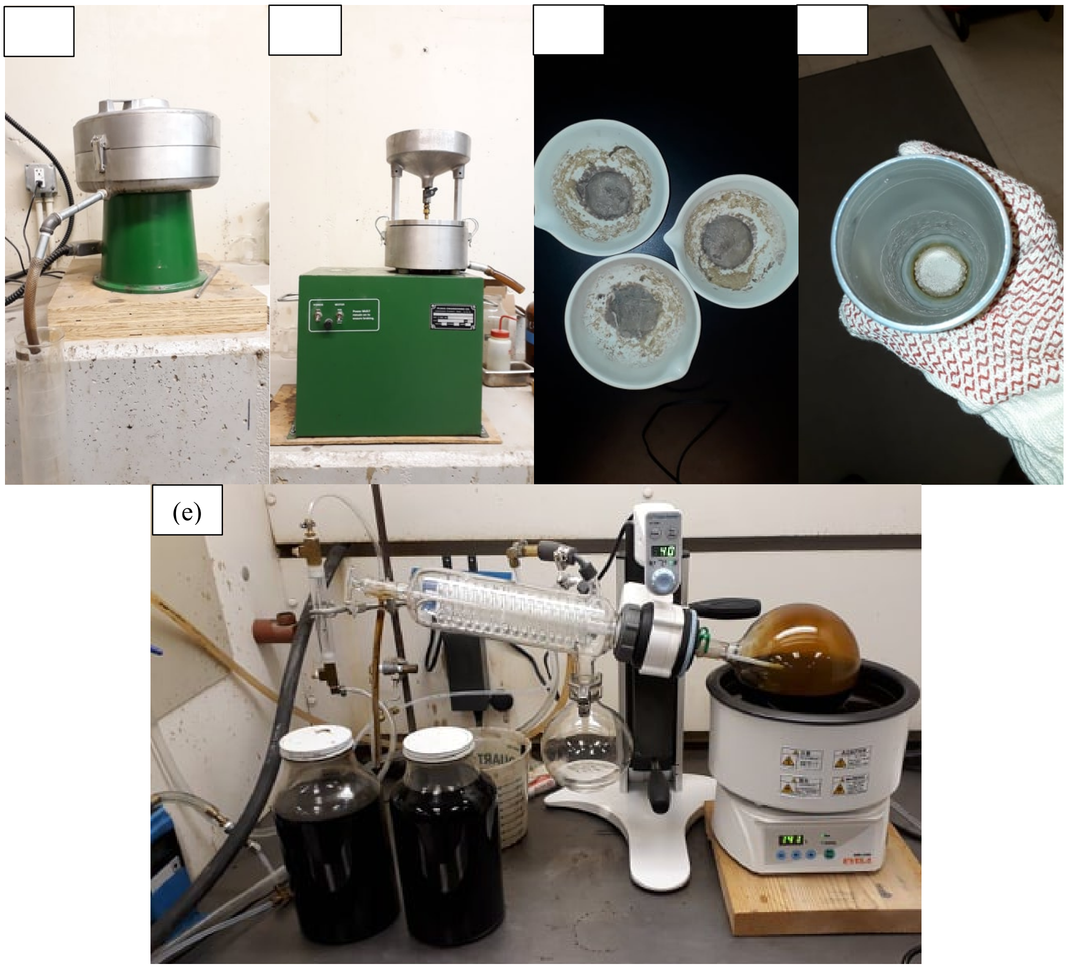


Figure 3-1. Extraction and Recovery Processes; (a) Centrifuge Extractor, (b) Filterless Centrifuge, (c) Ashing Dishes Containing Mineral Matter, (d) Centrifuge Metal Cup Containing Mineral Matter, and (e) Rotavap

3.3. Short-Term Aging for Virgin Asphalt Binders

Short-term aging was carried out according to ASTM D2872-19 (ASTM D2872, 2012) for the virgin asphalt binders. Testing was implemented using the RTFO device obtained from James Cox & Sons Inc. (Colfax, CA, USA).

3.4. Evaluating the Virgin and Extracted & Recovered Asphalt Binders' Rheological Properties

A Dynamic Shear Rheometer (DSR), Anton Paar MCR 302, was used following ASTM D7175-15 (AASHTO-T-315, 2019) to characterize the rheological properties for virgin, short-term aged virgin, and E & R asphalt binders. For short-term aged virgin and E & R asphalt binders, treated as short-term aged binders, samples with a thickness of 1 mm and 25 mm in diameter were analyzed. For the E & R asphalt binders treated as long-term aged binders, samples with 2-mm thickness and an 8-mm diameter were analyzed. For the AASHTO binder's grading system, AASHTO M332 (AASHTO-M-332, 2020) specification was used. This specification recommends using the multiple stress creep recovery (MSCR) test for evaluating the high PG temperature.

The aged virgin and E & R asphalt binders were analyzed by the DSR using temperature sweep and frequency sweep testing. For the plant, lab, and field mixes constructed & collected in 2016, the E & R asphalt binders were treated as RTFO aged asphalt binders. For the other field mixes, constructed before 2016, the E & R asphalt binders were analyzed assuming roughly a similar long-term aging state as would be obtained when testing pressure aging vessel (PAV) aged asphalt binders.

The temperature sweep test was implemented twice for each asphalt binder using two different samples and the average results were analyzed. Different temperatures were selected in the temperature sweep testing based on asphalt binder aging state (RTFO or PAV). For RTFO samples, different PG high temperature grade (rutting) test temperatures were selected beginning with the high PG temperature of the virgin asphalt binder or contract PG and ending with 94°C and tested at 6°C increments. For asphalt binders failing before 94°C, testing was terminated. Some E & R asphalt binders would have surpassed the 94°C high temperature grade requirements; however, due to typical DSR limitations, further elevation of testing temperature was not possible. For PAV samples, the intermediate fatigue cracking test temperatures were selected beginning with 10°C and ending with 34°C, across 3°C intervals.

For the frequency sweep testing, three temperatures were used based on the asphalt binder type (RTFO or PAV) through different frequencies (100 to 0.1 rad/sec). For the RTFO samples, different temperatures were selected inside a range of 52, 58, 64, and 70°C temperatures. For PAV samples, a range of 16, 19, 22, and 25°C temperatures were selected. The master curves, Cole-Cole plots, and black diagrams for the aged virgin and E & R asphalt binders were derived from the frequency sweep testing and analyzed at 60°C and 22°C for RTFO and PAV samples, respectively. Due to time and material limitations, low temperature binder testing was not performed as part of this study.

The MSCR test was implemented following ASTM D7405-20 to evaluate the resistance of the RTFO-aged virgin and E & R binders, treated as RTFO-aged binders, to rutting. This was achieved by calculating the percentage of recovery (%R) and non-recoverable creep compliance (J_{nr}) at the high PG temperatures of the virgin binders or a reference temperature (60°C) by applying ten creep cycles at two different levels of stresses (0.1 and 3.2 kPa). For each creep cycle, the loading time was 1 sec and the unloading time (recovery) was 9 sec.

The linear amplitude sweep (LAS) test was used to further characterize fatigue cracking resistance following AASHTO TP 101-14 (AASHTO TP 101, 2014). This test was applied for asphalt binders E & R from field mixes constructed before 2016, treated as PAV samples. The selected reference temperature was 22°C. The test was conducted by applying two stages on 8-mm diameter and 2-mm thickness samples. The first stage was a frequency sweep test, which was applied to evaluate the damage analysis by applying a 0.1% strain load over a frequency range between 0.2 and 30 Hz. The second stage included the amplitude sweep test that was conducted at a constant frequency of 10 Hz in a strain-control mode. A linearly increased strain load was applied from zero to 30% over 3100 loading cycles (10 cycles per second). The number of load repetitions to failure (N_f) for binders was calculated based on the measurements of the LAS test. The N_f parameter represents fatigue damage resistance (literally, the # of cycles to fatigue failure in the test), where higher N_f values reflect higher resistance to fatigue cracking damage. The N_f was calculated according to the strain levels suggested for strong (thicker, newer, stiffer) and weak (thinner, older, more flexible) flexible pavement structures, i.e., 2.5 and 5% strain, respectively.

4. MIXTURE PERFORMANCE TESTS

4.1. DC(T) Fracture Test

The DC(T) test was developed to characterize the fracture behavior of asphalt concrete mixtures at low temperatures (W. G. Buttlar, Rath, et al., 2019). The testing temperature is 10°C warmer than the PG low temperature grade of the mixture, per (ASTM D7313-13). Thermal cracking in asphalt pavements can be considered as occurring in pure tensile opening or fracture Mode I, as the cracks propagate perpendicular to the direction of the thermal-induced stresses in the pavement, i.e., transverse to the direction of traffic. The fracture energy is computed as follows:

$$G_f = \frac{AREA}{B \cdot L} \tag{1}$$

where, G_f denotes fracture energy in J/m^2, AREA is the area under Load-CMOD$_{FIT}$ curve, until the terminal load of 0.1 kN is reached. B is specimen thickness in m, generally, 0.050 m (2 inch) (except for field cores) and L is ligament length, usually around 0.083 m. The DC(T) test procedure used in this study 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 the DC(T) machine.

A portable Test Quip DC(T) device was used, which is housed at MAPIL. 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). Marasteanu et al. (2007, 2012) recommended thresholds for DC(T) fracture energy based on traffic level as 400, 460, and 690 J/m2 for low, medium, high traffic levels respectively (M. O. Marasteanu et al., 2012; Mihai O. Marasteanu et al., 2007). For this project, a threshold of 460 J/m^2 was adopted as the threshold for the medium-level traffic specified in the problem statement. Additional DC(T) threshold recommendations across a range of mix types as used in Missouri and for SMA and dense-graded mixtures in Illinois can be found in (W. G. Buttlar, Urra-Contreras, et al., 2020) and (W. Buttlar et al., n.d.), respectfully.

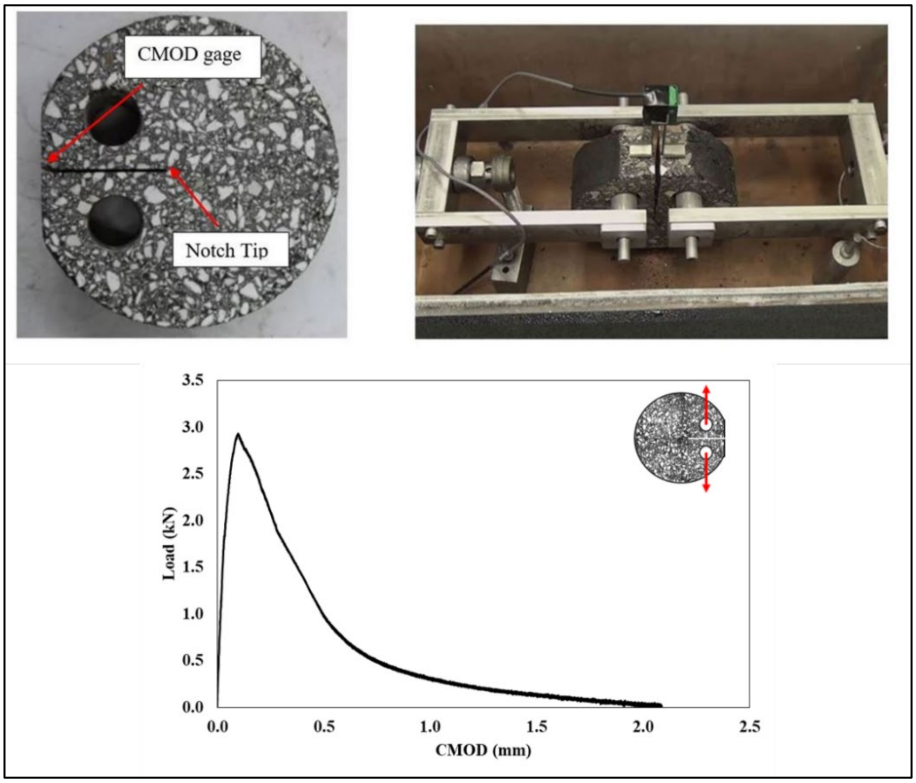


Figure 4-1. DC(T) Specimen (Top-Left), DC(T) Loading Fixture (Top-Right), and Typical Load-CMOD Curve from DC(T) Testing of Asphalt Mixtures (Bottom)

4.2. Semi Circular Bending, I-FIT Test

The flexibility index (FI) from the I-FIT test is an empirical index parameter that is computed as the total fracture energy divided by the absolute value of the slope of the post-peak softening curve multiplied by a scaling factor (Eq. 4).

$$FI = \frac{G_f}{|m|}(0.01) \tag{4}$$

where G_f is computed in a similar manner as to the DC(T) test, and m represents the slope of the post-peak softening curve. The FI was originally proposed as a means to identify brittle mixtures prone to premature cracking and was specifically developed to be sensitive to recycled material content (AASHTO TP124-16). There are countless ways to estimate the slope of a curve resulting from a material test, and this became a challenge for test standardization early in the development of the I-FIT. At present, to address this source of variability, the slope parameter can be determined using a software program available from the Illinois Center for Transportation or can be programmed into a spreadsheet or MATLAB. A MATLAB code was developed by researchers in the MAPIL lab.

To fabricate samples, a notch is cut along the axis of symmetry of a semi-circular bend specimen to a depth of 15±1 mm (0.6 inch). Test specimens are then conditioned in the environmental chamber at 25ºC for 2 hr ± 10 min. After a contact load of 0.1 kN is reached, the test is carried out at a rate of 50 mm/min. The test is considered to be complete when the load drops below 0.1 kN.

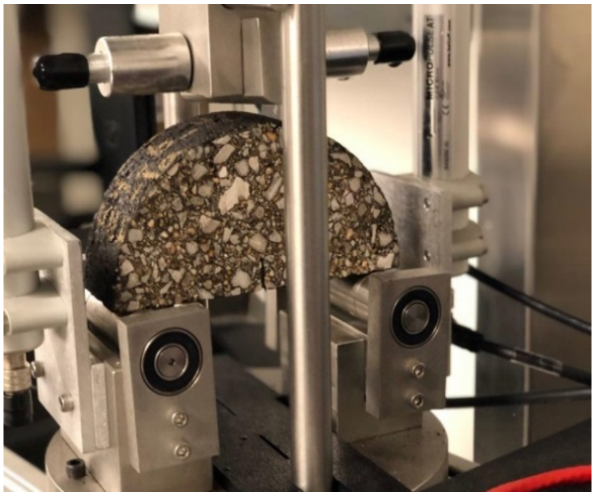


Figure 4-2. SCB I-FIT apparatus in MAPIL lab

4.3. IDEAL-CT Test

The IDEAL-CT test was developed to characterize the cracking potential of asphalt concrete mixes at an intermediate (room) temperature. The test set-up is similar to the traditional indirect tensile strength test and performed at 25°C under a constant loading rate of 50 mm/min until failure occurs (ASTM D8225, 2019). The test is gaining popularity in practice due to its basic sample preparation and testing requirements, as specimens do not require gluing, notching, drilling or additional cutting. A sample thickness of 62 mm (2.5 inches) is recommended for mixes with nominal maximum aggregate size (NMAS) blend gradations of less than 25 mm (ASTM D8225), or 1 inch, and for specimens compacted to a 7±0.5% air void level. The test procedure requires conditioning the mixture specimens in a temperature-controlled chamber for a minimum of 2 hours at 25 ℃. The Test Quip I-FIT test apparatus at MAPIL is equipped with a second loading fixture and ram, which was used for the IDEAL CT testing conducted herein. A seating load of 0.1 kN was applied in order to make appropriate contact between the loading heads and the sample. The sample was then loaded in ram displacement control mode (e.g., constant load-line deflection, or LLD), while the loading level was measured via an electronic load cell.

The cracking parameter for the IDEAL-CT is derived from the load vs. displacement curve. The larger the CT-index, the better cracking resistance of the mixture. A minimum of CT-index=65 is proposed by (Zhou, 2018) while the recommended CT for Superpave mixes is 105. The CT index equation is as follows.

$$CT_{index} = \frac{G_f}{|m_{75}|} \times \left(\frac{l_{75}}{D}\right) \times \left(\frac{t}{62}\right) \tag{5}$$

where,

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

$|m_{75}|$ = Slope parameter (absolute value of the slope after reduction to 75% of peak load)

l_{75} = Vertical displacement after reduction to 75% of peak load (mm)

D = Specimen diameter (mm)

t = Specimen thickness (mm)

4.4. Hamburg Wheel Track Test (HWTT)

In order to evaluate the rutting performance of the mixtures, the HWTT was conducted in accordance to the AASHTO-T324 standard (AASHTO-T324, 2017). In this test, a loaded steel wheel weighing approximately 71.7 kg tracks over the samples submerged in a water bath held constant at 50ºC. The vertical deformation imparted to the specimen is recorded at 220 points along the length of wheel loading. The test is stopped when either the specimen rut depth reaches 20 mm (0.79 inch) or the number of wheel passes reaches 20,000. A Cooper Hamburg device was used in this study, shown in Figure 4-3. For this study, a rut depth threshold of 12.5 mm (0.5 inch) at 20,000 passes was adopted (Larrain, 2015; Buttlar et al., 2020).

Figure 4-3. Hamburg Wheel Track Machine (Left), Asphalt Specimen Inside Hamburg Machine after Testing (right)

4.5. Hamburg-DC(T) Performance Space Diagram

Figure 4-4 presents a convenient x-y plotting form known as the ‘performance-space diagram,’ or more specifically in this case, the Hamburg-DC(T) plot. This plot allows the simultaneous evaluation of rutting and cracking behavior (W. G. Buttlar et al., 2016). Some useful trends that can often be observed when viewing data in this form are:

- The best overall performing mixtures will appear in the upper-right corner of the diagram (low rutting depth, high fracture energy). These can be considered as high ‘total energy’ mixtures, i.e., rut and crack (or damage) resistant. These are high toughness mixtures, and the best candidates for surfacing materials especially in demanding climates and for high traffic volumes.
- Mix variables that increase net total energy in the mix and thus ‘move’ mixtures in the direction of the upper-right corner of the plot include:
    - Higher quality binder (low temperature susceptibility, higher Useful Temperature Range, or UTI), degree of polymer modification;
    - Higher quality aggregate (stronger, more angular, better bond with asphalt);
    - The presence of crack interceptors or rut mitigators, such as fibers, rubber particles, and even RAS (but only if properly used).

Other salient features of the plot include:

- Binders with different grades but similar UTI tend to move a mixture along a 'binder tradeoff axis, or roughly speaking, diagonal lines moving in the upwards-left or downwards-right directions, for stiffening and softening, respectively;
- Pure stiffening components, such as RAP, tend to move points upwards and to the left;
- Pure softening components, such as rejuvenators, tend to move points downwards and to the right;
- Binders with higher UTI, where the grade bump is on the high temperature grade, tend to move points mainly upwards, but also slightly to the right due to the benefits of polymer in stretching and maintaining load transfer across forming cracks;
- Binders with higher UTI, where the grade bump is on the low temperature grade, tend to move points mainly to the right, but also slightly upwards, again, due to the benefits of polymer in stretching across crack faces as they form, and;
- Data points that appear in the undesirable middle-to-lower-left portion of the plot are sometimes those that contain RAP and insufficient binder bumping, and possibly poor bond, where the RAP tended to cause lower DC(T) values, and the nature of the RAP-virgin material combination led to a moisture-susceptible mix with high Hamburg rut depth value.

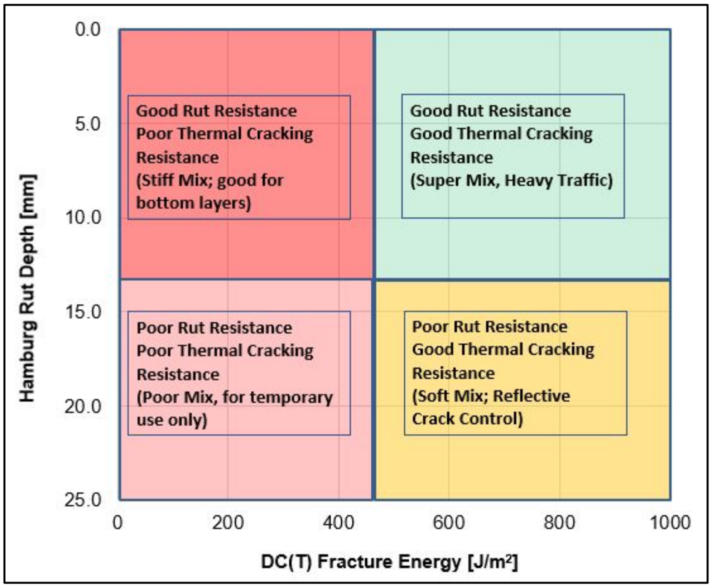


Figure 4-4. Concept of Hamburg-DC(T) Plot

5. BINDER TESTING RESULTS

5.1. Relating Asphalt Binders Extracted & Recovered from the Plant Mixes to the Corresponding RTFO-Aged Virgin Asphalt Binders

In this section, the E & R asphalt binders obtained from the twelve plant mixes received by the Missouri S&T research team from the MU team Table 2-14 are compared to the corresponding RTFO-aged virgin asphalt binders. The asphalt binders E & R from the plant mixes were treated as RTFO-aged virgin asphalt binders. First, a comparison of binder content yielded from the E & R procedure as compared to the expected value (from the mix design) are presented, followed by an analysis of results obtained from the standard binder testing suite used in this investigation. A full presentation of test results and analysis for all of the mixture investigated are provided in Appendix A.2.

5.1.1. Extraction of Asphalt Binders from Plant Mixes

The extracted asphalt content (AC) percentages using the ashing, centrifuge, and average ashing and centrifuge MMDMs are illustrated in Figure 5-1. Only two samples had the same reference (or ‘actual’) and extracted AC% (experimentally measured) using ashing MMDM as illustrated in Figure 5-1-a. Moreover, around 60% of the samples had extracted AC% values lower than the reference percentages. This illustrates that the ashing MMDM underestimated the extracted AC%. By contrast, by using the centrifuge MMDM, Figure 5-1-b, one-third of the samples had an extracted AC% with the same values of the actual AC%. To increase the accuracy of the extracted AC% calculation, the total mineral matter quantity inside the effluent was estimated using the average ashing & centrifuge MMDMs as presented in Figure 5-1-c.

A one-way analysis of variance (ANOVA) was calculated using JMP Pro software to compare the means of the different extracted AC% using different MMDMs and the mean of the reported AC%. Table 5-1 illustrates the ANOVA results. There is no significant difference between the means of the actual or extracted AC% using the ashing, centrifuge, or the average of ashing & centrifuge MMDMs. This was illustrated by the Prob > F “p-value” because it was greater than the significance level α (0.05).

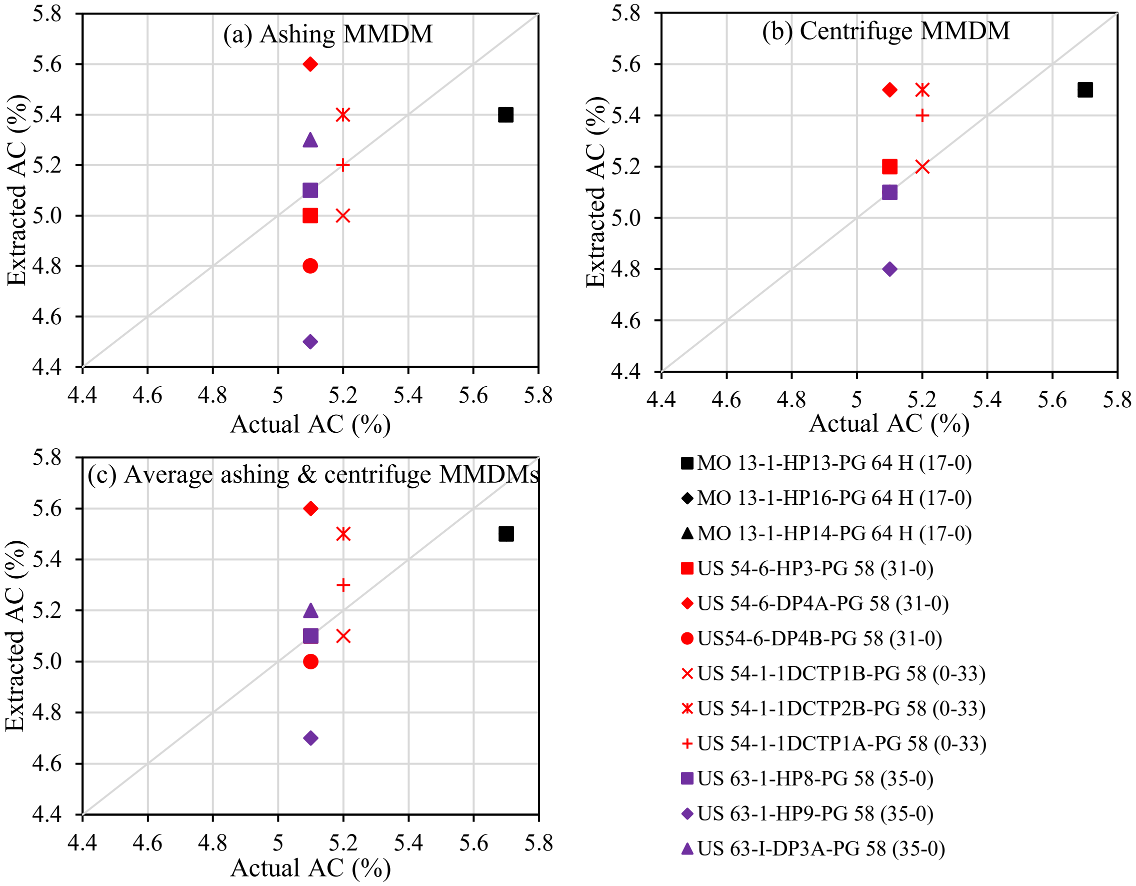


Figure 5-1. Reference (Actual) vs Extracted AC% using Different MMDMs for Plant Mixes Containing RAP or RAS

Table 5-1. ANOVA Results for Actual and Extracted AC% for the Plant Mixes

Source	DF*	Sum of Squares	Mean Square	F Ratio	Prob > F
Method	3	0.089	0.030	0.406	0.749
Error	44	3.211	0.073		
C. Total	47	3.300			

*degrees of freedom

Figure 5-2 shows the extracted AC per actual AC percentages for plant asphaltic mixes using different MMDMs. For around 75% of the plant mixes, the extracted AC% using the centrifuge MMDM was slightly higher than the extracted AC% using the ashing MMDM. By using average ashing and centrifuge MMDMs, the extracted AC per actual AC percentages were found between 91 and 109% for mixes containing RAP, and between 98 and 105% for mixes containing RAS. Consequently, the extracted AC percentages from mixes containing RAS were found to be more accurate than the extracted AC percentages from mixes containing RAP.

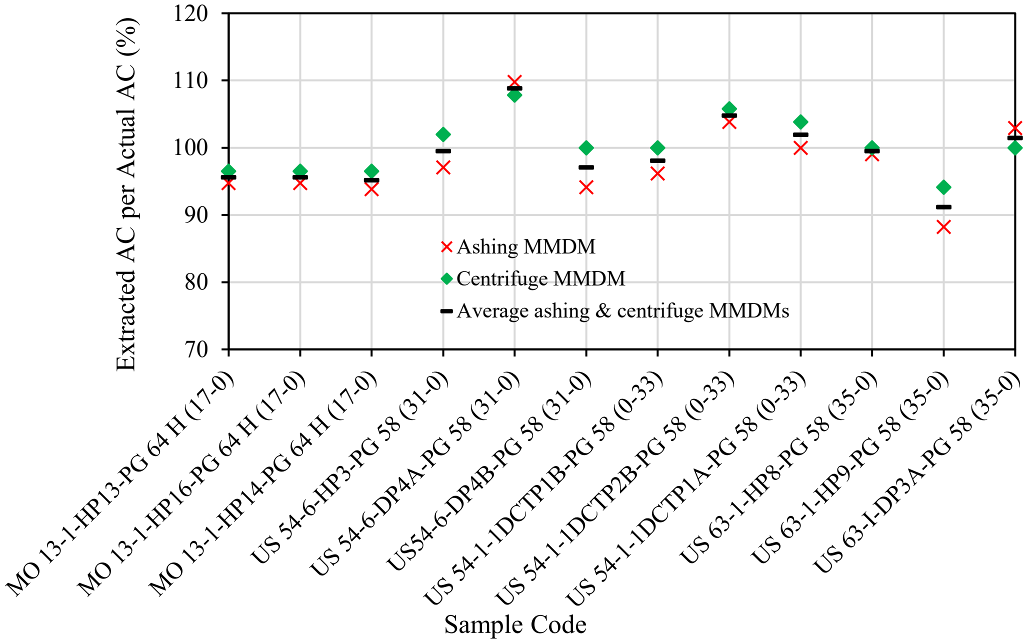


Figure 5-2. Extracted AC vs. Actual AC % for Plant Asphaltic Mixes using Different MMDMs

5.1.2. Analysis of the Asphalt Binders Before and After the Extraction and Recovery Processes

Table 5-2 illustrates the high PG temperature for the E & R asphalt binders and the corresponding RTFO-aged virgin asphalt binders. As explained in Chapter 3, 94°C was the maximum DSR temperature setting available. Using 17% ABR by RAP changed the asphalt binder high PG temperature from 64 heavy traffic (H) to 64 extremely heavy traffic (E). Moreover, using 31% or 35% ABR by RAP increased the asphalt binder high PG temperature from 58 to 76°C. For asphalt binder E & R from plant samples containing 33% ABR by RAS, the resulting high PG temperature exceeded 94°C. This occurred due to the high stiffness of the polymer-modified, air-blown asphalt binder present in the shingles, which was undoubtedly further stiffened during the service life of the roofing shingle.

To compare the effect of RAP or RAS on the E & R asphalt binder properties, asphalt binders E & R from mixes US 54-6 and US 54-1 were compared. These mixes had the same virgin asphalt binder and similar percentages of recycled materials: 31% ABR by RAP for US 54-6 and 33% ABR by RAS for US 54-1. However, the high PG temperature for the E & R asphalt binders from US 54-6 mixes increased three grades from 58 to 76°C and the high PG temperature for the E &

R asphalt binders from US 54-1 mixes increased more than six grades from 58 to more than 94°C. *This illustrates the E & R asphalt binders from mixes containing RAS was significantly stiffer than the E & R asphalt binders from mixes containing RAP.*

Table 5-2. High PG Temperature for the E & R Asphalt Binders from the Plant Mixes and the Corresponding RTFO Aged Virgin Asphalt Binders

Plant Sample Code	RTFO Aged Virgin Asphalt Binders			E & R Asphalt Binders		
	High PG / Continuous Grade Temperature	|G*|/sinδ (kPa)[a]	$J_{nr}3.2$ (kPa^{-1}) & $J_{nr\ diff}$ (%)[a]	High PG / Continuous Grade Temperature	|G*|/sinδ (kPa)[a]	$J_{nr}3.2$ (kPa^{-1}) & J_{nrdiff} (%)[a]
MO 13-1-HP13-PG 64 H (17-0)	64H / 72.61	6.09	$J_{nr}3.2$ = 1.36 & $J_{nr\ diff}$ = 33.58	64E / 88.92	39.94	$J_{nr}3.2$ = 0.08 & $J_{nr\ diff}$ = 14.32
MO 13-1-HP16- PG 64 H (17-0)				64E / 91.36	50.54	$J_{nr}3.2$ = 0.05 & $J_{nr\ diff}$ = 13.17
MO 13-1-HP14- PG 64 H (17-0)				64E / 87.88	36.44	$J_{nr}3.2$ = 0.09 & $J_{nr\ diff}$ = 14.32
US 54-6-HP3-PG 58 (31-0)	58 / 62.46	3.96	$J_{nr}3.2$ = 2.85 & $J_{nr\ diff}$ = 13.36	76 / 76.57	2.39	$J_{nr}3.2$ = 4.60 & $J_{nr\ diff}$ = 16.83
US 54-6-DP4A-PG 58 (31-0)				76 / 77.58	2.68	$J_{nr}3.2$ = 3.81 & $J_{nr\ diff}$ = 16.55
US54-6-DP4B-PG 58 (31-0)				76 / 77.94	2.71	$J_{nr}3.2$ = 3.95 & $J_{nr\ diff}$ = 14.72
US 54-1-1DCTP1B-PG 58 (0-33)				94[b]	14.33	$J_{nr}3.2$ = 0.64 & $J_{nr\ diff}$ = 27.63[c]
US 54-1-1DCTP2B-PG 58 (0-33)					10.98	$J_{nr}3.2$ = 0.77 & $J_{nr\ diff}$ = 31.36[c]
US 54-1-1DCTP1A-PG 58 (0-33)					8.55	$J_{nr}3.2$ = 1.08 & $J_{nr\ diff}$ = 33.35[c]
US 63-1-HP8-PG 58 (35-0)	58 / 58.52	2.43	$J_{nr}3.2$ = 4.39 & $J_{nr\ diff}$ = 16.33	76 / 78.08	2.74	$J_{nr}3.2$ = 3.68 & $J_{nr\ diff}$ = 26.96
US 63-1-HP9- PG 58 (35-0)				76 / 79.06	3.17	$J_{nr}3.2$ = 3.13 & $J_{nr\ diff}$ = 26.80
US 63-1-DP3A- PG 58 (35-0)				76 / 77.92	2.76	$J_{nr}3.2$ =3.67 & $J_{nr\ diff}$ = 28.49

[a] measured at the high PG temperature.
[b] the succeeded high PG temperature exceeded 94°C; however, the binder evaluation was ended at this temperature.
[c] measured at 94°C.

Figure 5-3 illustrates the rutting parameter (|G*|/sinδ) measured at different temperatures using the temperature sweep test for E & R asphalt binders from the plant mixes and the corresponding RTFO-aged virgin asphalt binders. Replicated measurements were implemented to ensure the repeatability of the result. The coefficient of variation (COV) in the rutting parameter values for the asphalt binders E & R from samples containing RAS is between 16 and 22%, which was higher than the values for samples containing RAP (5 to 15% COV). As the temperature increased, the difference between the rutting parameter for the E & R asphalt binders decreased. It is worthwhile to note that adding RAP or RAS to the mixes increased the stiffness of the E & R asphalt binders as compared to the corresponding RTFO-aged virgin asphalt binders. This was easily detected by the increase in the Superpave binder rutting parameter.

From Figure 5-3-b and Figure 5-3-c, US 54 and US 63-1 samples contained virgin asphalt binders with a PG 58-28. However, the US 63-1 PG 58 virgin binder was found to be softer than the US 54 PG 58 virgin binder, at least in terms of its lower rutting parameter score at the same temperature. In addition, increasing the ABR by RAP from 31% for US 54-6 PG 58 samples to 35% for US 63-1 PG 58 samples increased the stiffness of the E & R asphalt binders. Comparing the E & R asphalt binders in Figure 5-3-b & Figure 5-3-c with Figure 5-3-a, by decreasing the ABR percentage by RAP, from 31% or 35% to 17%, and increasing the high PG temperature for the virgin asphalt binder, from PG 58 to PG 64 H, the stiffness of the E & R asphalt binders increased significantly. Therefore, the use of virgin binders with increasingly high PG temperature grades in Missouri asphalt mixes plays a crucial role in increasing the stiffness of the E & R asphalt binders when used with the investigated recycled materials. Using RAS in mixes significantly altered the asphalt binder properties after the recovery process, both in terms of high overall binder stiffening and also in terms of the stiffness versus temperature profile. By comparing the asphalt binders E & R from samples containing 33% ABR by RAS, presented in Figure 5-3-d, and samples having 31% ABR by RAP, presented in Figure 5-3-b*, asphalt binders E & R from mixes including RAS showed a much stiffer behavior – roughly 70 times stiffer at 52^{o}C*.

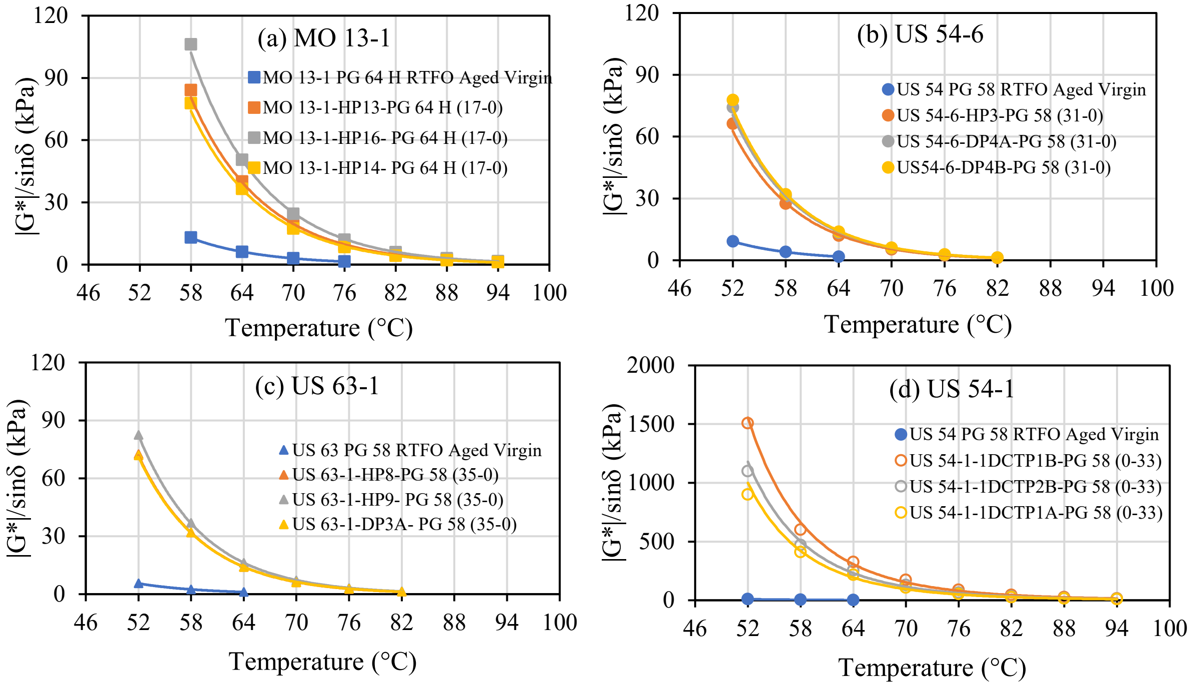


Figure 5-3. Temperature Sweep Test Results for the E & R Asphalt binders from the Plant Mixes and the Corresponding RTFO Aged Virgin Asphalt Binders

Figure 5-4 presents the rutting parameter ratio, which was calculated at the high PG temperature of the virgin asphalt binders. It was calculated by dividing the |G*|/sinδ for the E & R asphalt binders from the plant mixes per the same parameter for the corresponding RTFO aged virgin asphalt binders. Columns with the same pattern fill indicate samples with the same virgin asphalt binder. For samples containing RAS, the rutting parameter ratio reached the highest values (between 103 and 151). For asphalt binders E & R from samples containing RAP, the rutting parameter ratio was between 6 and 15. Although the US 63-1 PG 58 virgin asphalt binder was softer than the US 54 PG 58 virgin asphalt binder, US 63-1 E & R asphalt binders had a higher rutting parameter ratio because it contained a higher ABR by RAP (35%). The asphalt binders E & R from the MO 13-1 samples containing 17% ABR percentage by RAP and a stiff asphalt binder (PG 64-22H) had approximately the same rutting parameter ratio of the asphalt binders E & R from US 54-6 samples containing 31% ABR percentage by RAP and a soft asphalt binder (PG 58-28). This reflects that the grade of the virgin asphalt binder in combination with the percentage of the recycled materials controlled the grade of the E & R asphalt binders. The US 54-1 mixes containing 33% ABR by RAS and US 54-6 mixes containing 31% ABR by RAP had the same virgin asphalt binder (PG 58-28); however, asphalt binders E & R from US 54-1 samples were stiffer than the E & R from US 54-6 samples. This illustrates the effect of the air-blown asphalt component existing in the RAS on significantly increasing the stiffness of the E & R asphalt binders.

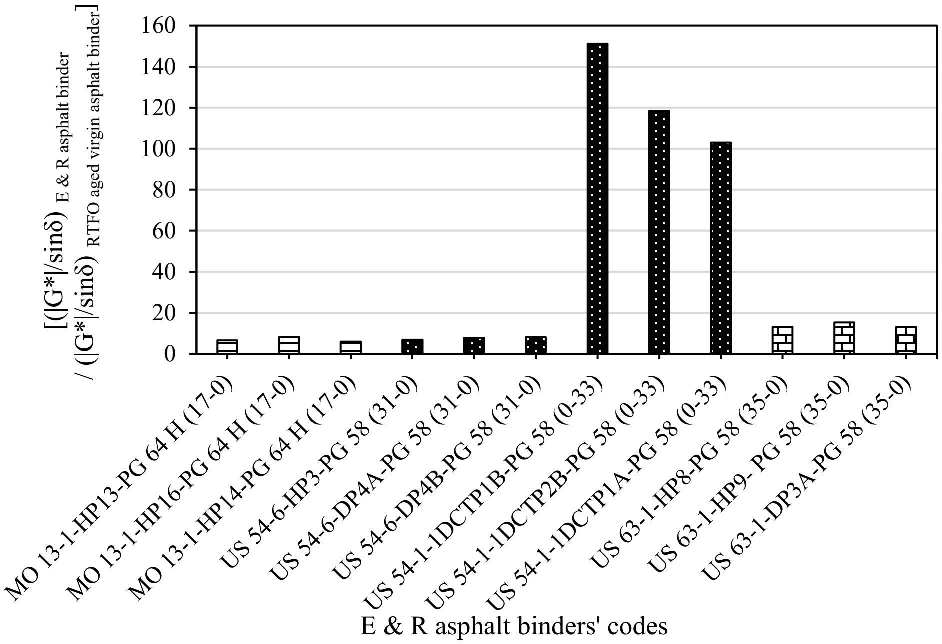


Figure 5-4. Rutting Parameter Ratio, Measured at the High PG Temperature of the Virgin Asphalt Binders, for the E & R Asphalt Binders from the Plant Mixes and the Corresponding RTFO-aged Virgin Asphalt Binders

The rutting parameter derived from master curves for the E & R asphalt binders from the plant mixes and the corresponding RTFO-aged virgin asphalt binders at 60°C is presented in Figure 5-5. For the RTFO-aged virgin asphalt binders, the MO 13-1 PG 64 H showed the highest stiffness as compared to other RTFO-aged virgin asphalt binders through different frequencies. This difference had predominantly appeared at the lower frequencies more than the higher frequencies. For the samples containing RAP, all the E & R asphalt binders showed a higher stiffness as compared to the corresponding RTFO-aged virgin asphalt binders. The highest rutting parameter values were obtained for asphalt binders E & R from samples containing 33% ABR percentage by RAS (US 54-1). The difference in binder stiffnesses for these materials as evidenced by the spread between curves is quite drastic, considering that a log-log plot was used to display the data. One log cycle decade represents a 10x change in binder stiffness.

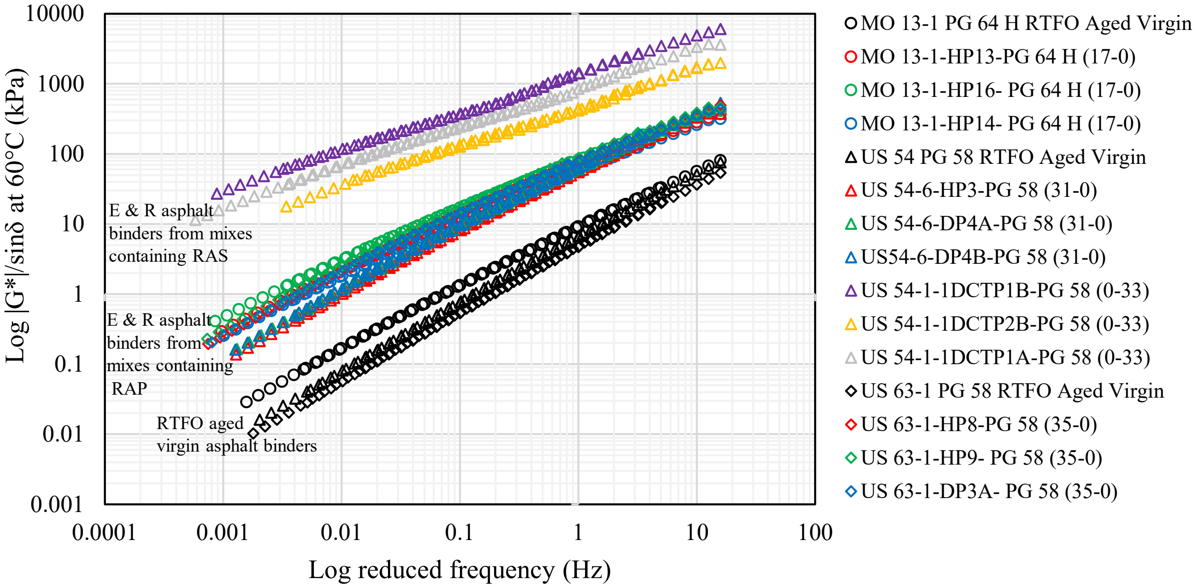


Figure 5-5. Master Curve for the E & R Asphalt Binders from the Plant Mixes and the Corresponding RTFO Aged Virgin Asphalt Binders Measured at 60°C

The Cole-Cole plots analyzed at 60°C for the RTFO-aged virgin and the E & R asphalt binders from MO 13-1, US 54, and US 63-1 plant mixes are presented in Figure 5-6-a, Figure 5-6-b, and Figure 5-6-c, respectively. These plots are used to illustrate the relation between loss (G″) and storage (G′) moduli (Airey, 1997; Ashish et al., 2017). 'Loss' represents the purely viscous portion of the response, while 'Storage' refers to the elastic portion. For the E & R asphalt binders, a downward shift towards the G′ axis and to the right-hand side of the curve can be observed. This indicated an increase in the elastic behavior (Deef-Allah et al., 2019) of the E & R asphalt binders.

Figure 5-6-d, Figure 5-6-e, and Figure 5-6-f show the black diagrams measured at 60°C for the RTFO aged virgin and the E & R asphalt binders from MO 13-1, US 54, and US 63-1 plant mixes, respectively. These diagrams show the relationship between the |G*| and δ. A shift towards higher |G*| values and increasing elasticity (lower δ values) was observed for RAP, and especially, RAS mixtures. The maximum shift was observed for asphalt binders E & R from US 54-1 (containing 33% ABR percentage by RAS) and US 63-1 (containing 35% ABR percentage by RAP). These enhancements in stiffness and elasticity are useful in terms of their effect on rutting resistance, but may provide significant trade-offs in terms of decreased cracking resistance.

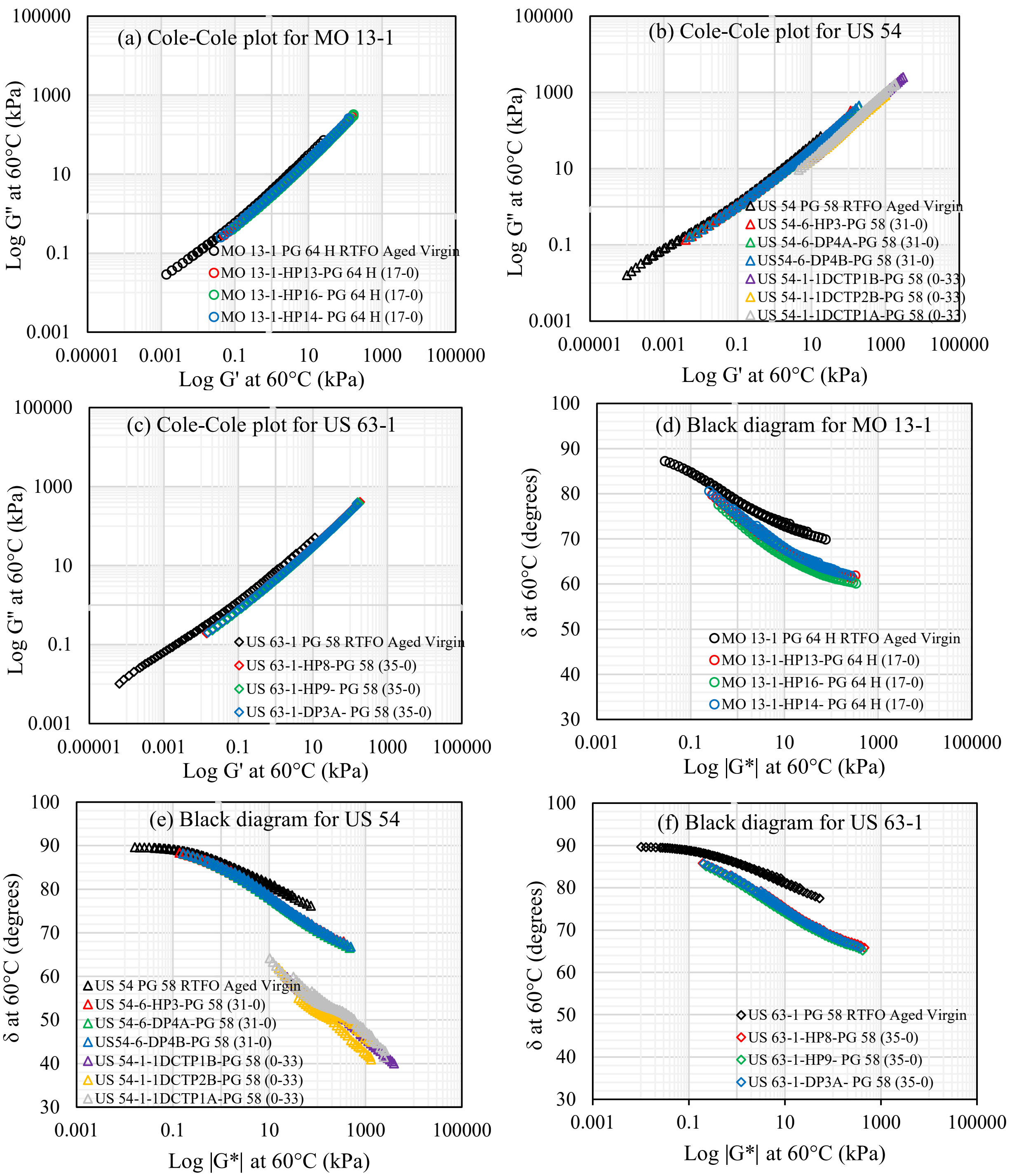
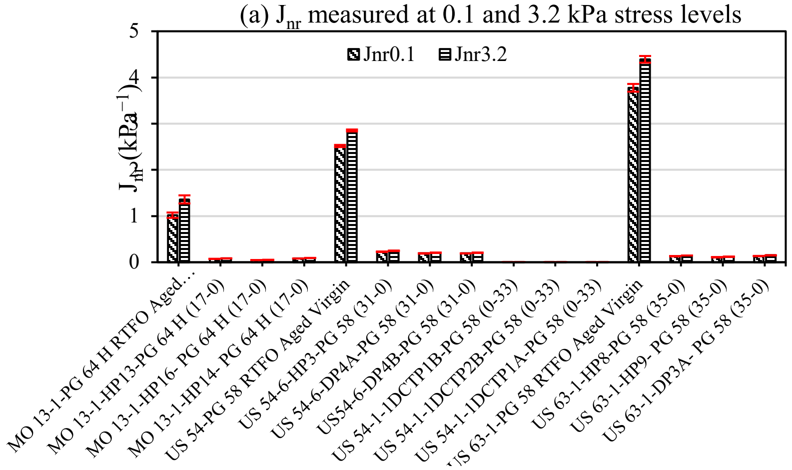


Figure 5-6. Cole-Cole plots and Black Diagrams Analyzed at 60°C for the E & R Asphalt Binders from the Plant Mixes and the Corresponding RTFO Aged Virgin Asphalt Binders

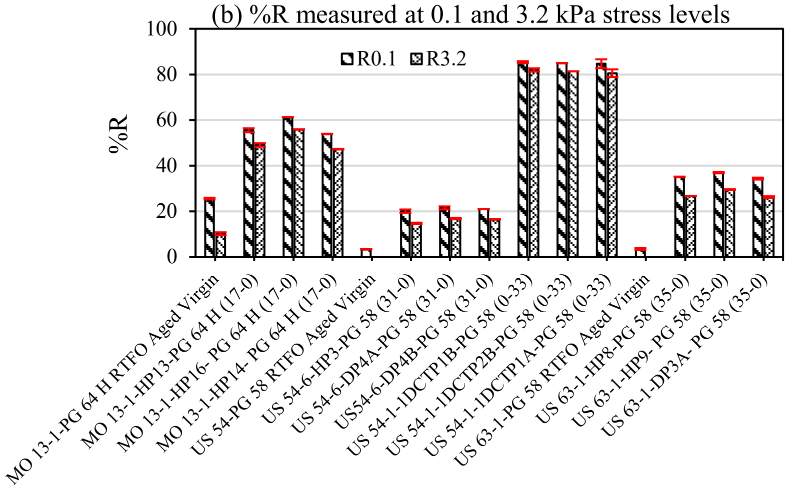
Figure 5-7 presents the MSCR test results for the E & R asphalt binders from the plant mixes and the corresponding RTFO-aged virgin asphalt binders measured at 0.1 and 3.2 kPa stress levels and the high PG temperatures of the virgin asphalt binders. Replicated measurements were implemented to ensure the repeatability of this test. Figure 5-7-a shows the J_{nr} at 0.1 and 3.2 kPa stress levels (J_{nr}0.1 and J_{nr}3.2). COV values with less than 6.43, 2.81, and 11.11% were found for the RTFO-aged virgin binders, E & R binders from mixes containing RAP, and E & R binders from mixes containing RAS, respectively. The MO 13-1 PG 64H RTFO aged virgin asphalt binder had the lowest J_{nr} value as compared to the other two RTFO aged virgin asphalt binders due to its very high stiffness. As expected, the J_{nr} values decreased for all E & R asphalt binders as compared to the corresponding RTFO-aged virgin binders. This was related to the increase in the stiffness of these E & R asphalt binders resulting from the aged asphalt binders present in the RAP and the stiff, aged air-blown asphalt present in the mixes containing RAS. The increase in the stiffness was demonstrated through increases in $|G^*|$, $|G^*|/\sin\delta$, the rutting parameter, and the PG high temperature grade. The lowest J_{nr} values were obtained for the asphalt binders E & R from mixes containing RAS (US 54-1), indicating the presence of a stiff, elastic binder. Figure 5-7-b shows the %R at 0.1 and 3.2 kPa stress levels (R0.1 and R3.2). COV values with less than 10.99, 3.53, and 2.28% were obtained for the RTFO aged virgin binders, E & R binders from mixes containing RAP, and E & R binders from mixes containing RAS, respectively. For the RTFO-aged virgin asphalt binders, the highest %R values were obtained for MO 13-1 PG 64 H. Moreover, both US 54 PG 58 and US 63-1 PG 58 RTFO aged virgin asphalt binders had a zero R3.2. However, the E & R asphalt binders showed an enhancement in the %R values. The highest %R values were obtained for the asphalt binders E & R from mixes containing RAS (US 54-1). The increase in the %R values for the E & R asphalt binders was related to the enhancement in the elasticity values (lower δ and higher G' values).

To compare the RTFO-aged virgin asphalt binders to those associated with the E & R samples, the percentage increase in %R and the percentage decrease in J_{nr} are illustrated in Figure 5-7-c, for binders tested at the 0.1 kPa stress level. The R3.2 values for the RTFO-aged virgin asphalt binders were both equal to zero. For most samples, the percentage decrease in the $J_{nr0.1}$ value was nearly 100%. The highest percentage of decrease in the $J_{nr0.1}$ was obtained for asphalt binder E & R from samples containing RAS. Furthermore, the percentage of increase in the R0.1 reached the highest values for asphalt binders E & R from US 54-1 mixes containing 33% ABR by RAS. This was related to the stiffness and elastic behavior of the air-blown asphalt component in the RAS. Also as expected, increasing the ABR by RAP boosted the percent increase in R0.1.

(a) J_{nr} measured at 0.1 and 3.2 kPa stress levels



(b) %R measured at 0.1 and 3.2 kPa stress levels



(c) Percentages of increase in %R & decrease in J_{nr} at 0.1 kPa stress level

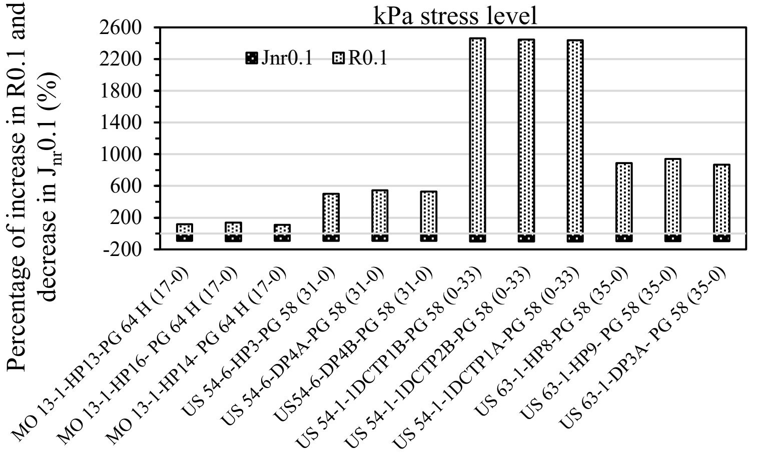


Figure 5-7. MSCR Test Results for E & R Asphalt Binders from the Plant Mixes and the Corresponding RTFO Aged Virgin Asphalt Binders Measured at the High PG Temperature of the Virgin Asphalt Binders

5.2. Summary of Other Binder Tests Performed

Following the general flow of testing presented in Section 5.1, binder testing on E&R binders from other plant-produced and field-cored sections were also performed. For brevity, a full summary of these results can be found in Appendix A.2. The key findings of these results can be summarized as:

- RAS, while adding significant overall stiffness to the binder system, does not always yield the highest stiffness values at a particular testing temperature (for instance, at the PG intermediate binder testing temperature, which is used for fatigue cracking assessment). Thus, it is important to conduct a full binder characterization, and to conduct tests on the mixture.
- A fraction of rubber particles can be captured in at least two different places in the E&R apparatus. Thus, binder test results on E&R binders from mixtures containing GTR are not expected to be fully representative of the stiffening and strengthening effect of rubber in asphalt. This also reinforces the importance of mixture testing.
- The use of rejuvenators (Evoflex, for instance) tended to **increase** the stiffness of the E & R asphalt binders, perhaps counterintuitively. This was likely due to the increased blending or incorporation of the recycled materials with the virgin binder. This increased ‘interaction process’ between the binder from recycled material (RAP/RAS) and the virgin asphalt binder might therefore be expected to cause a decrease or mixed results in mixture cracking test scores, especially those that are heavily weighted towards stiffness rather than strength or total fracture energy. Such is the case with the I-FIT and IDEAL tests. Thus, contractors may not be incentivized to use rejuvenators when these tests are specified.
- The virgin binders used in the investigated mixtures graded out as either PG 58-XX or PG 70-XX (the latter was in fact PG 64-22H, MSCR graded binder).
  - Recycled mixtures produced with the PG 58-XX did much better in terms of binder cracking test scores, while those produced with the stiffer PG70-XX binder had better rutting scores.

- The resulting PG high temperature grade of the E&R binders, which contain virgin binder plus stiffening contributions from RAP, RAS and/or GTR depending on the section investigated varied over a wide range (Figure 5-8). This range included: PG 70-XX, PG 76-XX, PG 82-XX, PG 88-XX, and even PG 94-XX). In comparison, the Missouri climate is PG 64-XX, and factoring in traffic intensity for state roads utilizing Superpave mixes, the plan or target PG grade should be in the range of PG 70-XX to PG 76-XX.

- Of the E&R samples investigated (there are 23 samples plotted in Figure 5-8 that are not virgin binder reference samples), 10 graded out at PG 70-XX and 5 graded out at PG 76-XX, for a total of 15-out-of-23 samples (about two-thirds) grading out in the desired target range. The other 8 samples graded between one and three grades higher than PG 76-XX.

- It is suspected (and moreover, desired) that the trend of about one-third of Missouri mixes having over-stiffened binder systems may lessen in the near future as the full roll-out of BMD proceeds across the state. If working as intended, the new mixture cracking test requirements should help correct the imbalance in these mixtures, i.e., stiff/brittle mixtures displaying field cracking and very low Hamburg rut depths.

- Improved binder and mixture cracking test scores in the future will result from the use of: (1) softer base (virgin) binders; (2) increased virgin binder content (possibly resulting from lower design voids and/or higher mixture VMA); (3) the use of certain rejuvenators (at certain concentration levels), considering that the use of rejuvenators can either soften or stiffen the resulting binder system depending on a number of variables; (4) the proper use of additives such as GTR or waste plastic, but ***only when combined*** with other stiffness-reducing strategies (such as with the use of a softer base binder); and/or the use of lower recycled material quantities and less stiff recyclates (such as less aged RAP sources).

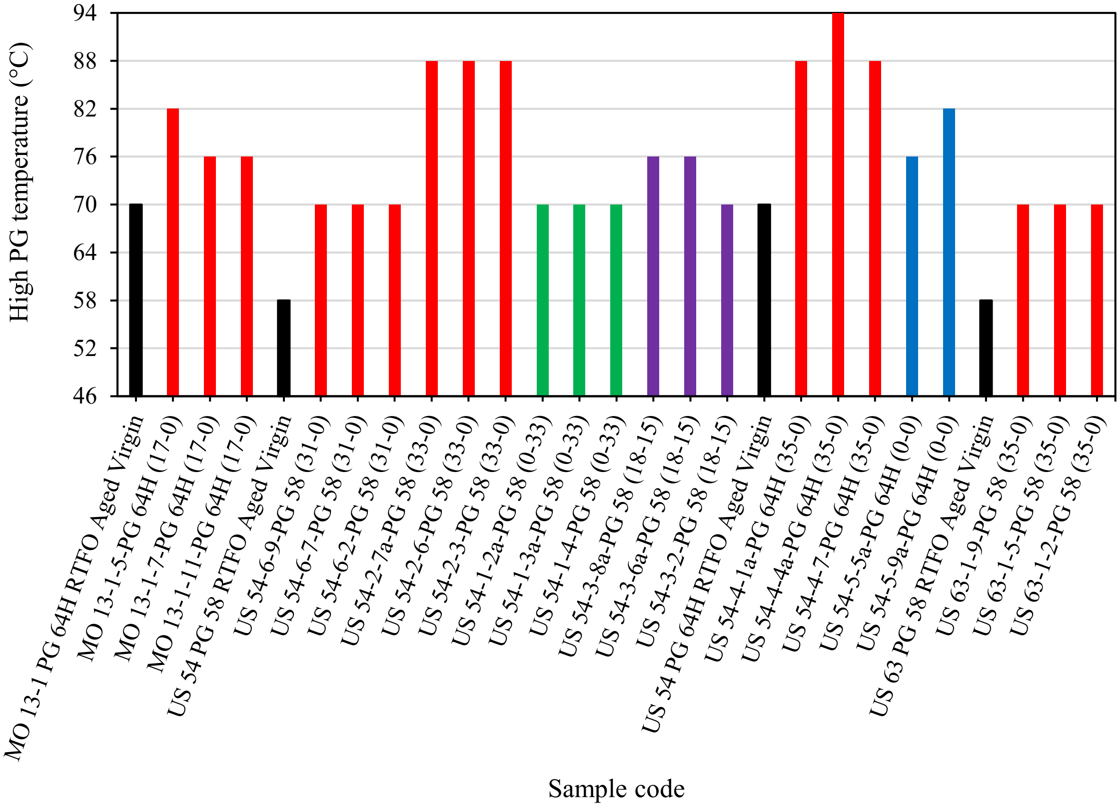


Figure 5-8. The High PG Temperatures for the RTFO Aged Virgin and E & R Asphalt Binders from Different Field Mixes, Constructed in 2016

6. MIXTURE TESTING RESULTS

6.1. DC(T) Results for Lab Mixtures in the Fix-the-Mix Study Task

Figure 6-1 shows the DC(T) fracture energy for the five iterations undertaken for the US63_1 mix. This study adopted a fixed test temperature of -12°C, based on the mid-Missouri climatic conditions which usually call for a PGXX-22 plan binder grade (where XX varies depending on design traffic and geographic location in Missouri). Results show that the control mix (no additional modifications) had very low fracture energy compared to the lowest recommended threshold for mainline mixes in Missouri: 400 J/m^2 for lower traffic volume roads (W. G. Buttlar, Urra-Contreras, et al., 2020), and 500 J/m^2 for moderate traffic volume routes. The roads investigated herein are borderline between the low/moderate traffic volume level categories (W. G. Buttlar, Urra-Contreras, et al., 2020). The lower fracture energy could be attributed to the absence of bumping (softening) of the virgin binder grade considering the high ABR level of the mixture. Thus, a softer binder grade was used as a first step to improve/balance performance. The softer binder grade mix, with and without rejuvenator, performed better in fracture energy but was still below the lowest desired threshold of 400 J/m^2.

For the next iteration, 10% dry-process ground tire rubber was added to the mix along with the softer binder. The modification proved to be beneficial with a fracture energy increase of about 80 J/m^2. For the final iteration, 20% rubber with softer binder grade led to a fracture energy increase of close to 150 J/m^2 as compared to the control mixture, pushing it just beyond the 400 J/m^2 threshold for low traffic routes in Missouri.

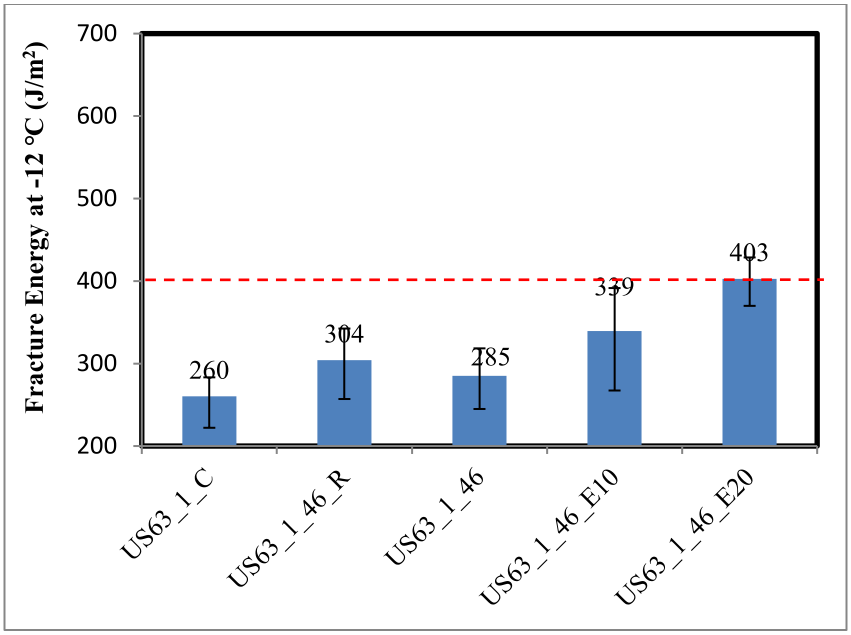


Figure 6-1. DC(T) Fracture Energy Test Results for US63_1 Mixtures

Figure 6-2 shows the fracture energy results obtained from DC(T) testing at -12 ℃ for the US54_6 mix iterations. The control mix, which had 29.4% ABR, resulted in average fracture energy of 378 J/m^2, failing to reach the threshold of 400 J/m^2. Adding 3% Evoflex CA to the mix (US54_6_58_R) did not appreciably alter the fracture energy in this mix. Similar tendencies were reported in binder testing (Chapter 5). This somewhat unexpected result might be due to the specific chemical interactions and blending between the binder, RAP, and rejuvenator in this mix – resulting in slightly lower fracture energy as compared to the control mix. Next, a softer binder system (PG46-34) was incorporated into the mixture, which led to an improvement in fracture energy. Compared to the control mix, the DC(T) fracture energy increased by 53 J/m^2. This placed the second trials between the low and moderate traffic level fracture energy thresholds of 400 and 500 J/m^2, respectively. Thus, additional trials were carried out to strive towards further improvements. While retaining the softer virgin binder grade, dry-process GTR was added to the mixture, at levels of 5% and 20% by weight of the base binder, respectively, in iterations 4 and 5. The incorporation of 5% rubber by weight of binder (US54_6_46_E5) increased mixture fracture energy to 483 J/m^2. In the final iteration, using 20% GTR, a significant boost in fracture energy to a level 567 J/m^2 was observed, which finally surpassed the fracture energy threshold of 500 J/m^2 recommended for medium traffic level road facilities in Missouri. The combination of mix adjustments significantly boosted thermal cracking resistance to a level of about 50% higher than the original control mix.

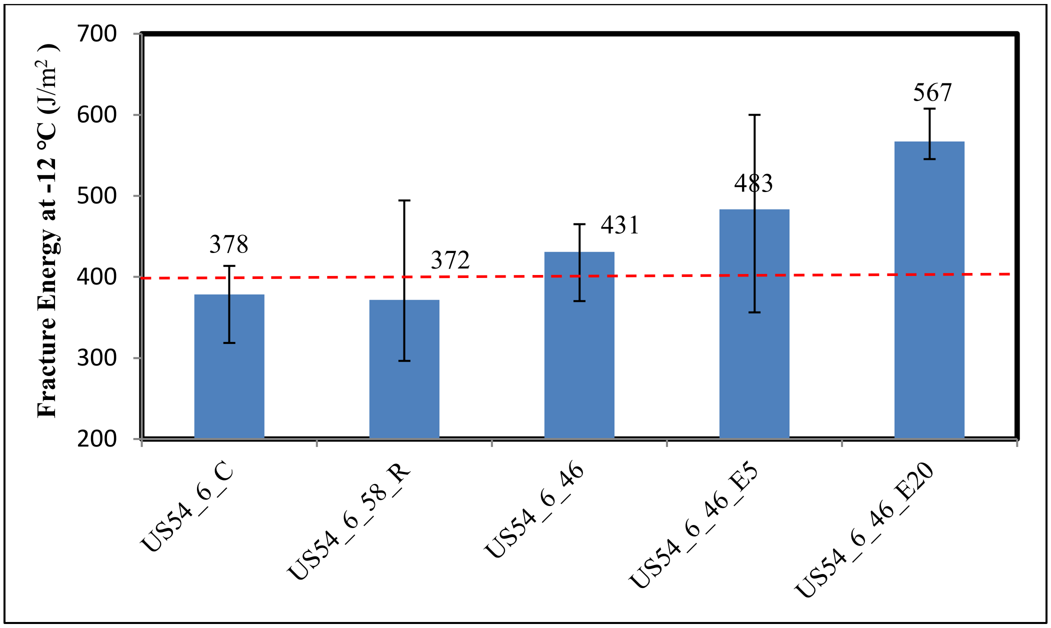


Figure 6-2. DC(T) Fracture Energy Test Results for US54_6 Mixtures

6.2. I-FIT Results for Lab Mixtures

The results of SCB (I-FIT) tests performed on the five mixture iterations for the two study mix types are shown in Figure 6-3. Using a softer binder improved the FI value significantly in the US54_6 mixture, while it did not significantly affect the US63_1 mixture. In both mixtures, the rejuvenator did not help to improve the cracking performance as gauged by the FI. When crumb rubber was added to the mixture with a softer binder, the FI score decreased significantly. This was in contrast to DC(T) fracture results, where the addition of dry-process GTR and supplementary binder increased the fracture energy quite significantly in some cases.

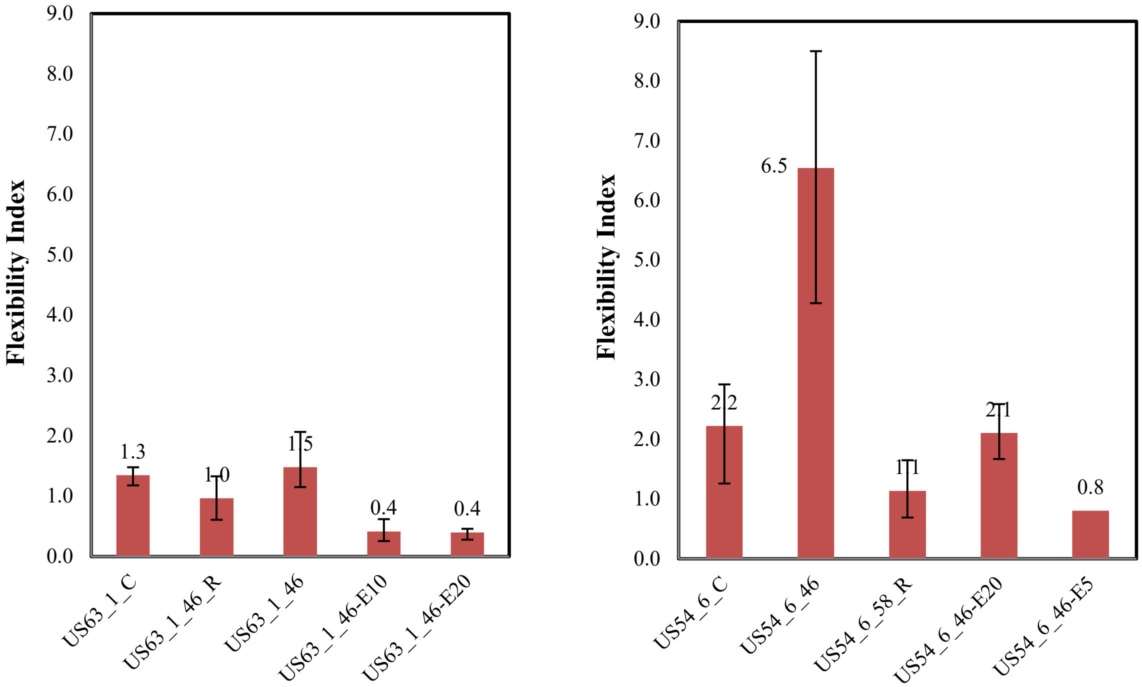


Figure 6-3. Flexibility Index Results for US63_1 and US54_6 Mixtures

6.3. IDEAL CT Results for Lab Mixtures

Figure 6-4 represents IDEAL CT results for the tested mixtures. The use of a softer binder and rejuvenator in the US63 mixture did not improve the IDEAL CT index. The consistency of this result between all 3 cracking tests appears to suggest the presence of a relatively weak aggregate structure in this mixture. However, the softer binder plus rejuvenator had a positive effect on the CT index for the US54 mixture. However, the use of crumb rubber along with supplemental binder significantly reduced the IDEAL CT values measured for both mixtures, consistent with the trend observed in the SCB (I-FIT) results. The disagreement of IDEAL CT and FI with DC(T) FE test for the rubber modified mixtures is stark and certainly deserves more investigation in future studies. The intermediate cracking test results are somewhat counter-intuitive as field results suggest that rubber modification provides cracking resistance benefits to asphalt mixtures in the field, even under extreme environments and loading conditions (Davison et al., 2000; Nazzal et al., 2016). For now, it can be reasonably concluded that the different test modes, test temperatures and loading rates used in the three cracking tests underlie the differences observed in cracking index trends observed with the mix alterations investigated herein.

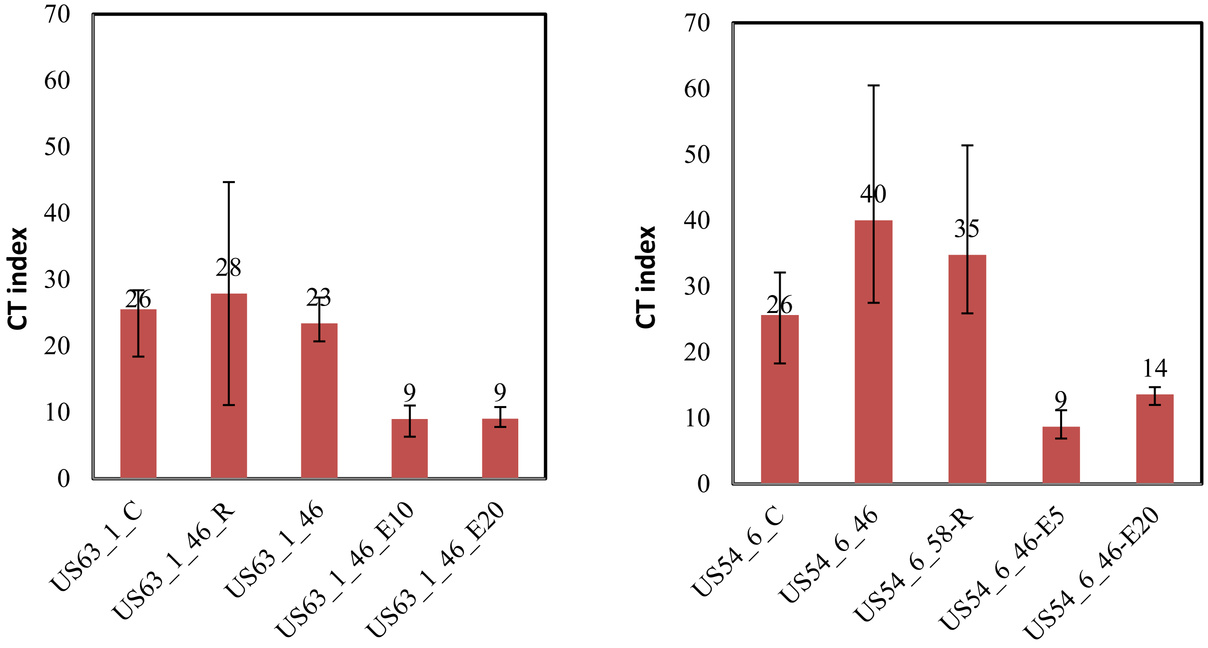


Figure 6-4. IDEAL CT Index Results for US63_1 and US54_6 Mixtures

6.4. Hamburg Results for Lab Mixtures

The rutting resistance of the baseline control mixtures was excellent, providing a large factor of safety and motivation for the mixture iterations described in the preceding sections (aimed at ‘softening’ the mix and other strategies to increase crack resistance). The results of the mixture iterations are shown in Figure 6-5. Replacing the base binder with the softer binder grade increased the max rut depths measured, as expected, but well within recommended tolerances (W. G. Buttlar, Urra-Contreras, et al., 2020). Notably, the addition of rubber not only increased the fracture energy but also helped in increasing the rut resistance (GTR mixes possessed the lowest HWTT rut depths).

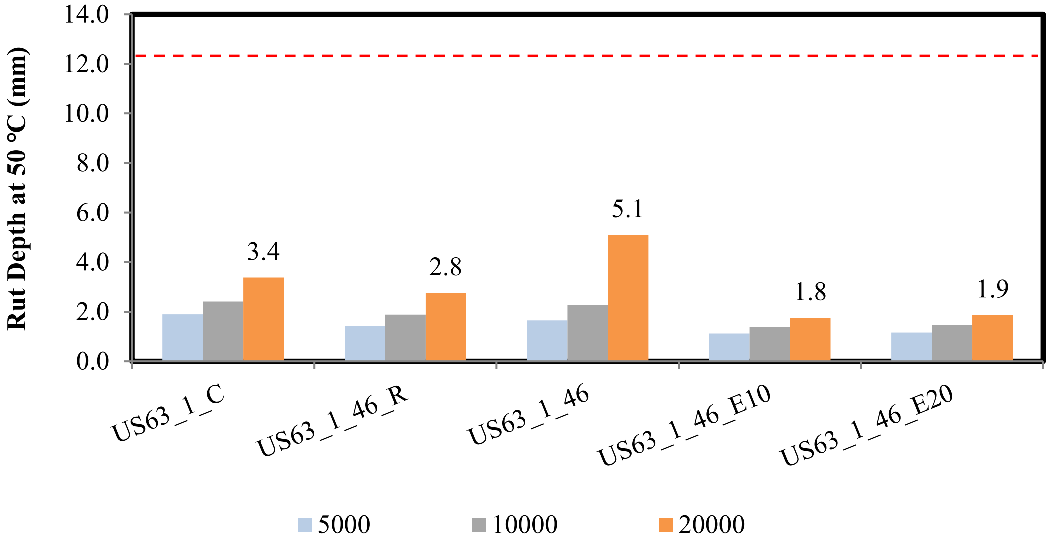


Figure 6-5. Hamburg Wheel Track Test Results for US63_1 Mixtures

Figure 6-6 shows the HWTT results for the US54_6 mix trials. As shown in this figure, all of the trials could easily meet the maximum rut depth criterion (12.5 mm), with minimal rutting potential even at 20,000 passes. Once again, replacing the base binder with a softer grade binder slightly increased the permanent deformation compared to the control mix, as expected. The addition of ground tire rubber also produced the best performing mixtures in terms of rutting resistance, as evidenced by the last two iterations of the mixture. However, unlike DC(T) fracture energy, which benefitted from the higher GTR level of 20%, in terms of rutting resistance, the 5% GTR mixes slightly outperformed the 20% GTR mixes. However, since all of the GTR test results were below 2 mm of rutting after 20,000 passes, all can be considered as very low rut potential mix designs.

Although outside of the scope of the current study, the results, especially those for the GTR mixes, suggest that an additional factor of safety against rutting exists in the investigated mixtures. However, in locations such as Missouri, it is not currently practical to obtain binders softer than the PG 46-34 grade investigated in this study. Thus, as modern, recycled asphalt mixtures continue to evolve in the evolving circular economy, asphalt technologists must address the trends towards stiffer materials present in RAP stockpiles, less ductile base binder materials, higher presence of fines in recycled materials, and the challenge of incorporating waste plastic as another candidate recycling ingredient. In other words, how can we make sustainable mix design – sustainable?

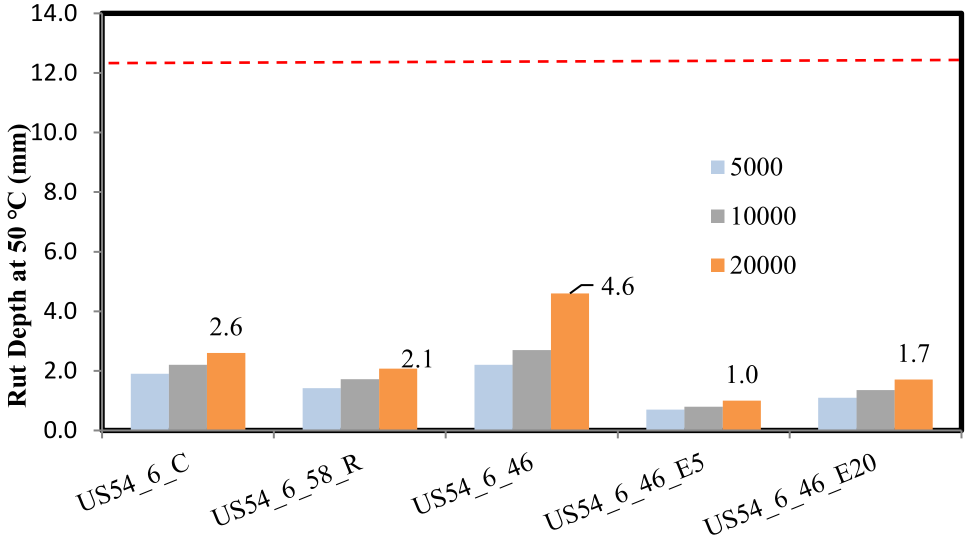


Figure 6-6. Hamburg Wheel Track Test Results for US54_6 Mixtures

6.5. Performance-Space Diagram for Lab Mixtures

As mentioned in the previous section, plotting in Hamburg-DC(T) space allows simultaneous comparison of the overall performance of the mix. Results from the US63_1 mixtures are shown in Figure 6-7. As expected, all the mixes fall in the red section of the plot, indicating inadequate thermal cracking performance for the requirements of this project. While the employed strategies did push the mix in the right direction (shown with green arrow), none of the modifications were enough to push it over the set thermal cracking threshold.

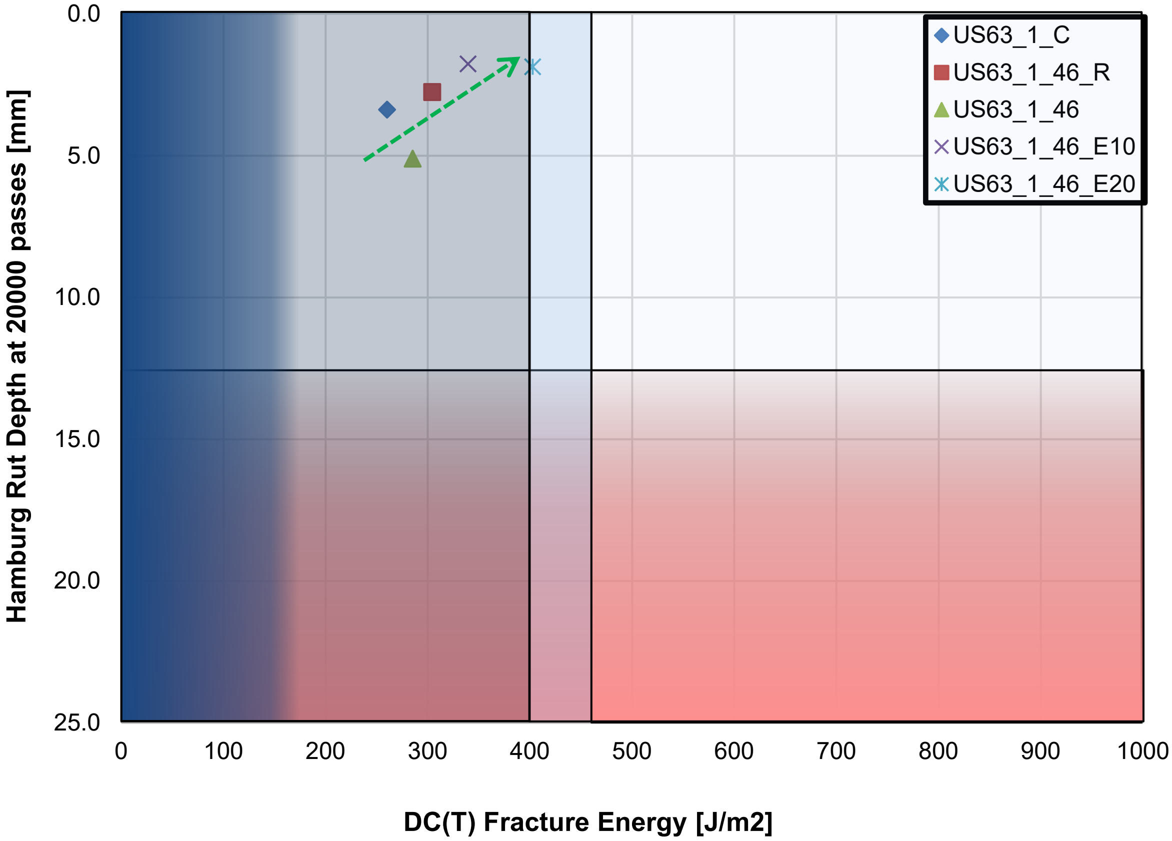


Figure 6-7. Hamburg-DC(T) Performance Space Diagram for US63_1 Mixture

Although the addition of rubber helped to improve the mix in terms of thermal cracking and rutting, the mixture was still very prone to thermal cracking with the fracture energy barely crossing the lowest threshold of 400 J/m^2. This could be due to the poor quality of aggregates used in this mix. Thus, another local mix design was adopted to be modified following BMD principles. This failed mix iteration, however, showed the immense potential of ground tire rubber in resisting thermal cracking and improving rut resistance of the asphalt mixture.

Figure 6-8 shows the DC(T) and Hamburg results for US54_6 mixture iterations. As seen from the plot, the addition of rejuvenator and then replacing the base binder with softer binder pushed the mixture towards better fracture energy but sacrificed rut resistance (shown with blue arrow). However, the addition of rubber in conjunction with softer grade binder replenished the rut resistance of the mix and added thermal cracking resistance, allowing the mix to cross the set threshold (shown with green arrow).

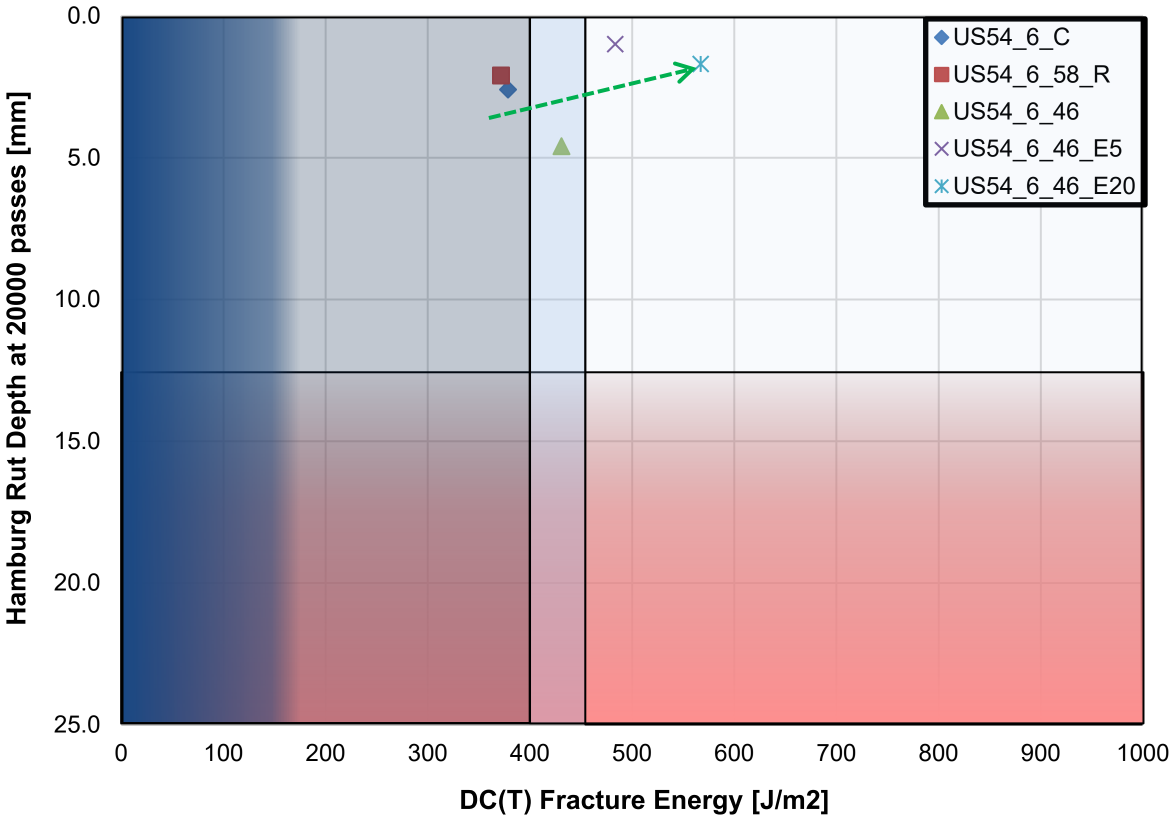


Figure 6-8. Hamburg-DC(T) Performance Space Diagram for US54_6 Mixture

In summary, as shown in the previous sections, the 1st mix iteration, US63_1, could not pass the thermal cracking threshold adopted for this study. Thus, a 2nd mix iteration, US54_6, was tried, and various modification strategies were tried in line with the concepts of BMD. Finally, by using softer grade binder and rubber in conjunction, the thermal and rutting thresholds were achieved.

7. COMPARISON OF E & R BINDER AND MIXTURE TESTING RESULTS

7.1. High-Temperature Results

7.1.1. Mixes Constructed and Sampled in 2016

Figure 7-1 presents Hamburg wheel tracking results for mixtures constructed in 2016 first reported by Buttlar et al. (2019), plotted along with the PGHT grade of the virgin binders used. Hamburg results for the US54_4 and US54_2 mixes indicated the lowest rut depth. The recycled material percentage used in these mixes was relatively high, and for comparison, note that the MO13_1 mix had a lower RAP level and exhibited a higher rut depth. The US63_1 section was among the highest in rut depth. Although it had a similar RAP content as US54_4 and US54_2, it utilized a softer virgin binder. From a BMD perspective, viewing rut depths alone is not sufficient to determine if a mix is well-balanced. Very low Hamburg rut depths (for instance, below 3 mm) often come at the expense of lower cracking test scores for dense-graded mixtures (and therefore unbalanced mixes).

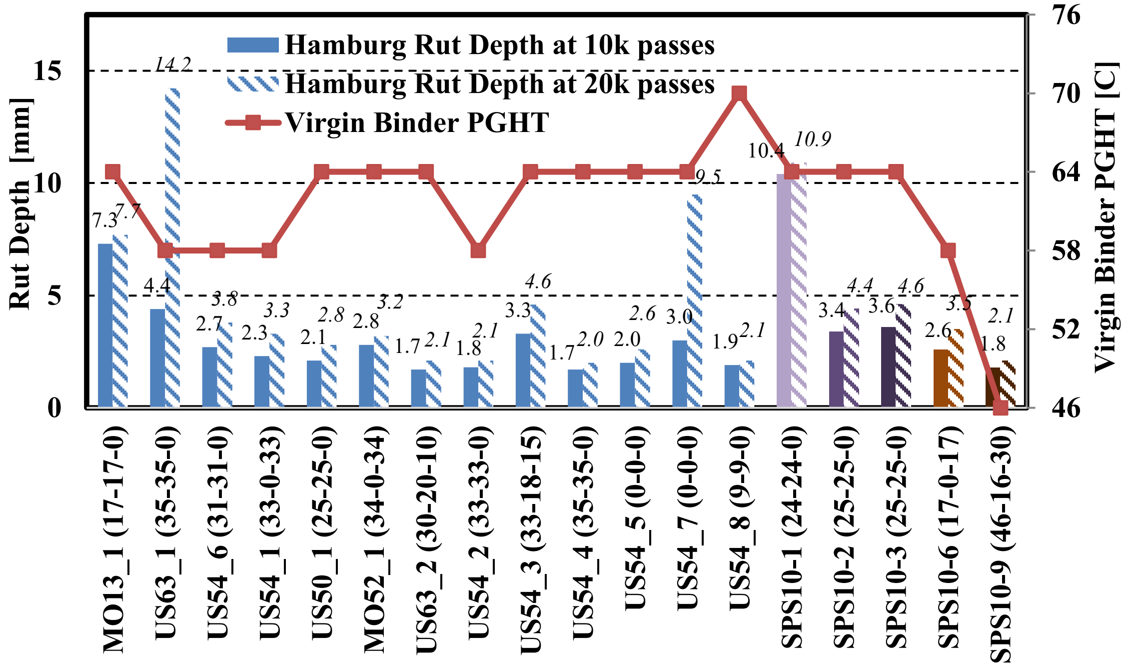


Figure 7-1. Hamburg Rut Depths (at 10k & 20k passes) for Sections Constructed in 2016

The temperature sweep test results for the E & R asphalt binders from field mixes constructed in 2016 are presented in Figure 7-2. The US54_4 and US54_2 binders had the highest Superpave rutting parameter scores, which agreed with Hamburg mix test results. Some difference in high temperature scoring occurred when comparing predominantly RAS vs. predominantly RAP mixes. As mentioned earlier in the report, the binders found in RAS used in Missouri are stiffer than the binders found in Missouri RAP. However, for E & R binders obtained from mixes containing RAS, the resistance to rutting was measured to be lower than binders E & R from mixes containing RAP. This is assumed to have occurred due to the lack of full interaction between the binders included in the RAS and the virgin asphalt binders. The binder data presented in Figure 7-3 and Figure 7-4 reinforced this observation.

Figure 7-5 shows the MSCR test results for the binders E & R from field mixes constructed in 2016. The binders E & R from the US54_5, US54_4, and US54_2 showed the highest percent recovery (elastic behavior). Additionally, the US54_4 and US54_2 binders presented the lowest J_{nr} values (permanent deformation). Again, this ranking is in agreement with the mix testing results.

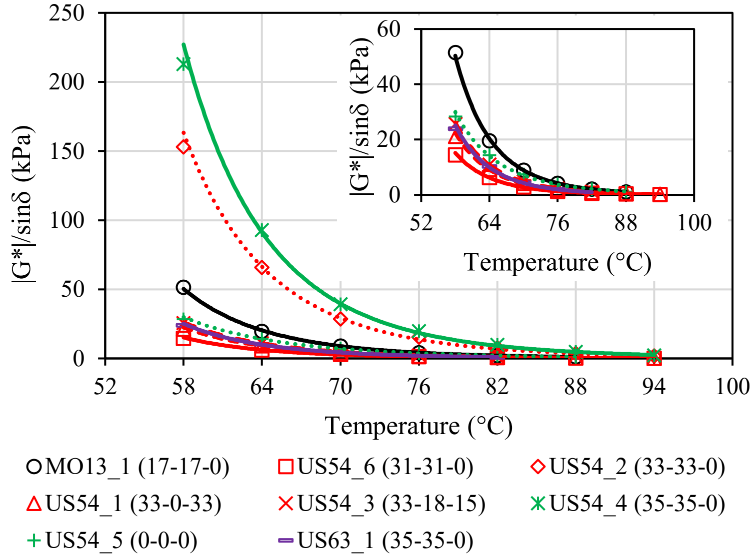


Figure 7-2. Temperature Sweep Test Results for E & R Binders from Field Mixes Constructed in 2016

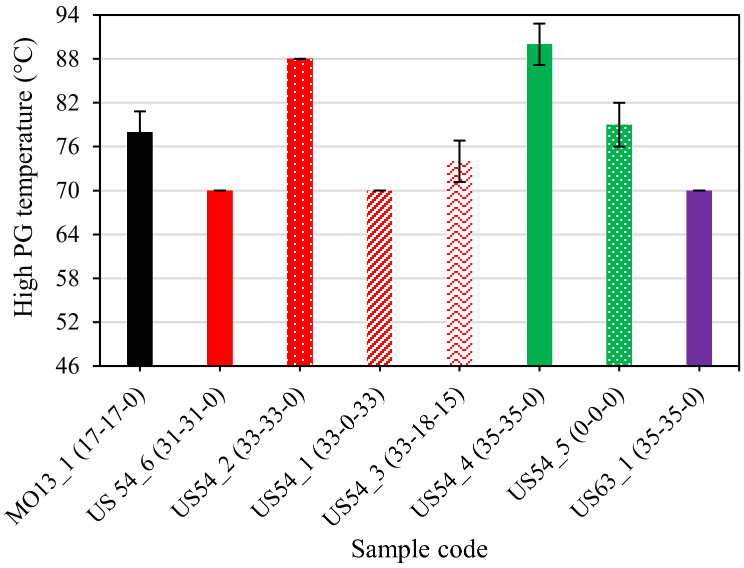


Figure 7-3. High PG Temperature for E & R Binders from Field Mixes Constructed in 2016

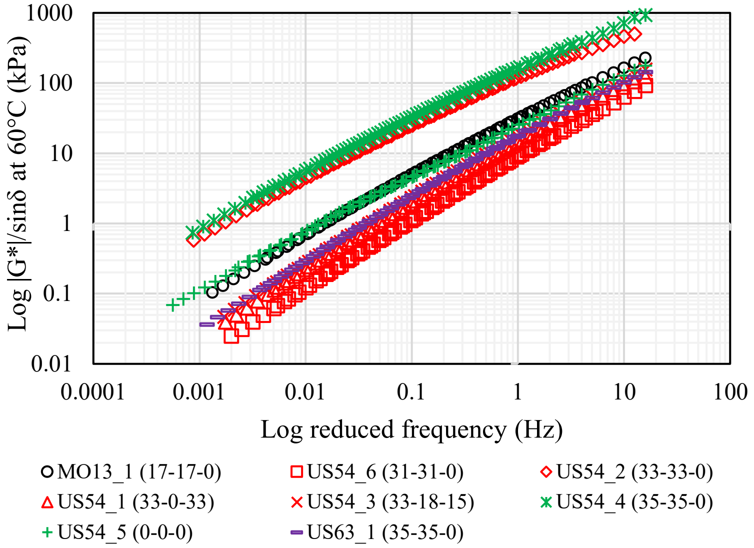


Figure 7-4. Master Curve Measured at 60°C for E & R Binders from Field Mixes Constructed in 2016

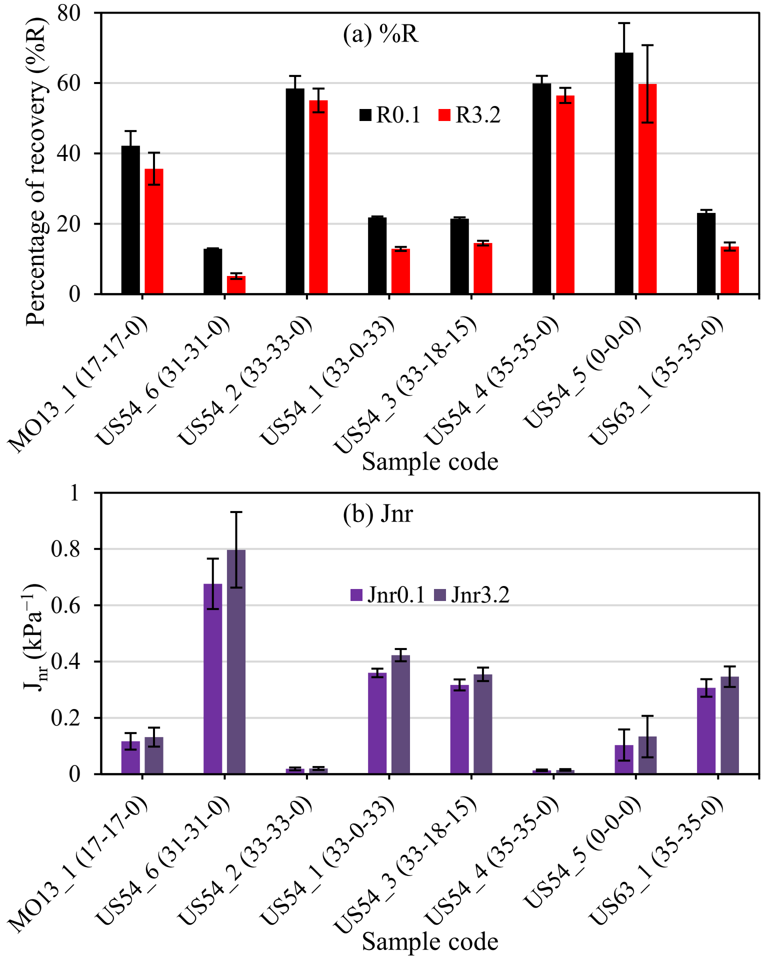


Figure 7-5. MSCR Test Results Measured at 60°C for E & R Binders from Field Mixes Constructed in 2016

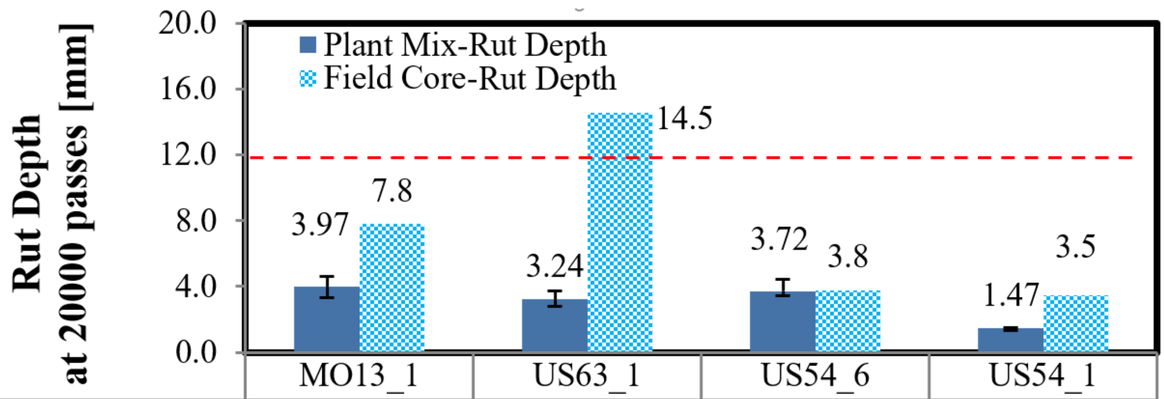
7.1.2. Field and Plant Mixes Constructed in 2016 and their E & R Asphalt Binders

For the plant mixes presented in Figure 7-6, the lowest resistance to rutting was observed for the MO13_1 mix. As reported by Buttlar et al. (2019), this likely occurred due to the nature of the aggregates and their interaction with the binder system. By contrast, the worst resistance to rutting illustrated in Figure 7-7 to 10 was noted for binders E & R from the US54_6 mix. While on one hand the MO13_1 mix contained a lower percentage of recycled materials than US56_6; on the other hand, it contained a stiffer virgin asphalt binder. Thus, the MO13_1 E & R binders showed higher resistance to rutting than the US 54_6 E & R binders. The asphalt binder included in the US63_1 mix was softer than the binder included in the US54_6 mix. However, the US 63_1 mix contained a higher percentage of recycled materials than the US 54_6 mix. Therefore, the binder E & R from the US54_6 showed the lowest rutting resistance.

The US54_6 and US63_1 plant mixes showed similar resistance to rutting (Figure 7-6). In contrast, the asphalt binders E & R from these two mixes exhibited different binder rutting scores (Figure 7-7, Figure 7-8, Figure 7-9, Figure 7-10). The binders E & R from the US63_1 was stiffer than the binders E & R from the US54_6 mixes. The virgin asphalt binder included in the US63_1 mix was softer than the virgin binder used in the US54_6 mixes. However, the US63_1 contained a higher ABR percentage by RAP than the US54_6 by 4%.

The US54_1 plant mix (containing RAS) showed the highest resistance to rutting as illustrated in Figure 7-6. The same observations were noted for the E & R asphalt binder from the temperature sweep test results in Figure 7-7. The high PG temperature for the binder E & R from this mix exceeded 94°C (Figure 7-8). This E & R binder showed the highest rutting parameter at different frequencies and the highest %R in Figure 7-9 and 10-a, respectively. The J_{nr} values for this binder at 0.1 and 3.2 stress levels reached approximately zero, as illustrated in Figure 7-10b, indicating very high stiffness and elasticity.

For the field mixes and the corresponding E & R asphalt binders, a lower rutting resistance was noted as compared to those of the plant mixes. It is hypothesized that more interaction processes occurred between the virgin and recycled binders in the plant mixes. After sampling the plant mixes from behind the paver, the reheating process before the compaction process in the lab appeared to have caused more interaction to occur. The interaction process for the US54_1 field mix did not appear to be sufficient to achieve full interaction between the virgin and RAS binders. Thus, binders E & R from the mixes containing RAP showed higher stiffness. For the US54_1 plant mix, a fuller interaction process appeared to have been achieved, as evidenced by the higher stiffness measured for those E & R binders as compared to the binders E & R from the mixes containing RAP.



	MO13_1	US63_1	US54_6	US54_1
Plant Mix-Rut Depth	3.97	3.24	3.72	1.47
Field Core-Rut Depth	7.8	14.5	3.8	3.5
Neat Binder PGHT	64	58	58	58
Total ABR	17	35	31	33
ABR by RAP	17	35	31	0
ABR by RAS	0	0	0	33

Figure 7-6. Comparing HWTT Rut Depth of Field Cores and Plant Mixes from 2016 Sampling

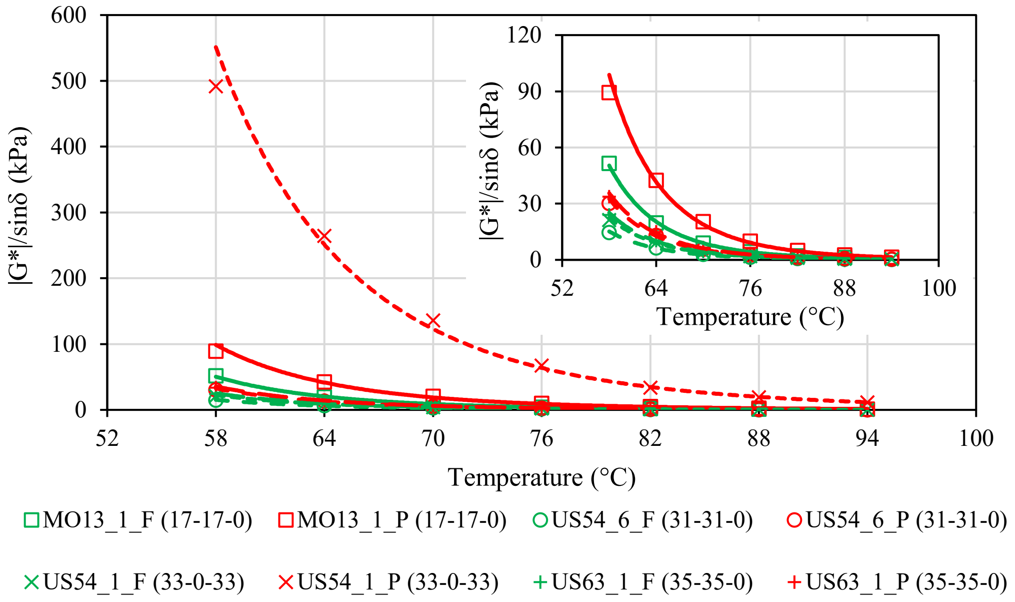


Figure 7-7. Temperature Sweep Test Results for E & R Binders from 2016 Field and Plant Mixes

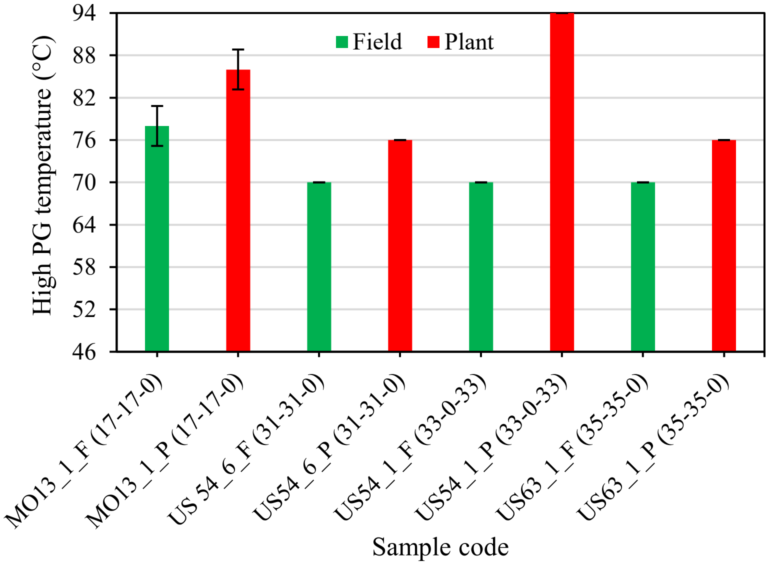


Figure 7-8. High PG Temperature for E & R Binders from Field and Plant Mixes Constructed in 2016

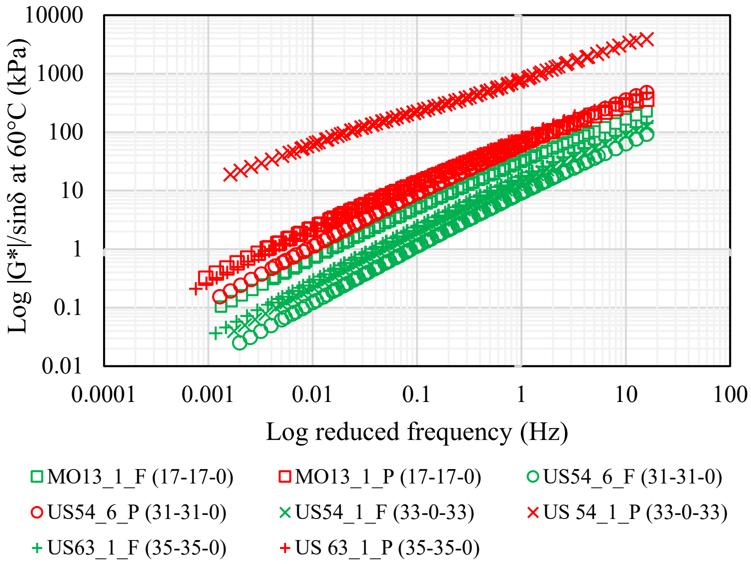


Figure 7-9. Master Curve Measured at 60°C for E & R Binders from Field and Plant Mixes Constructed in 2016

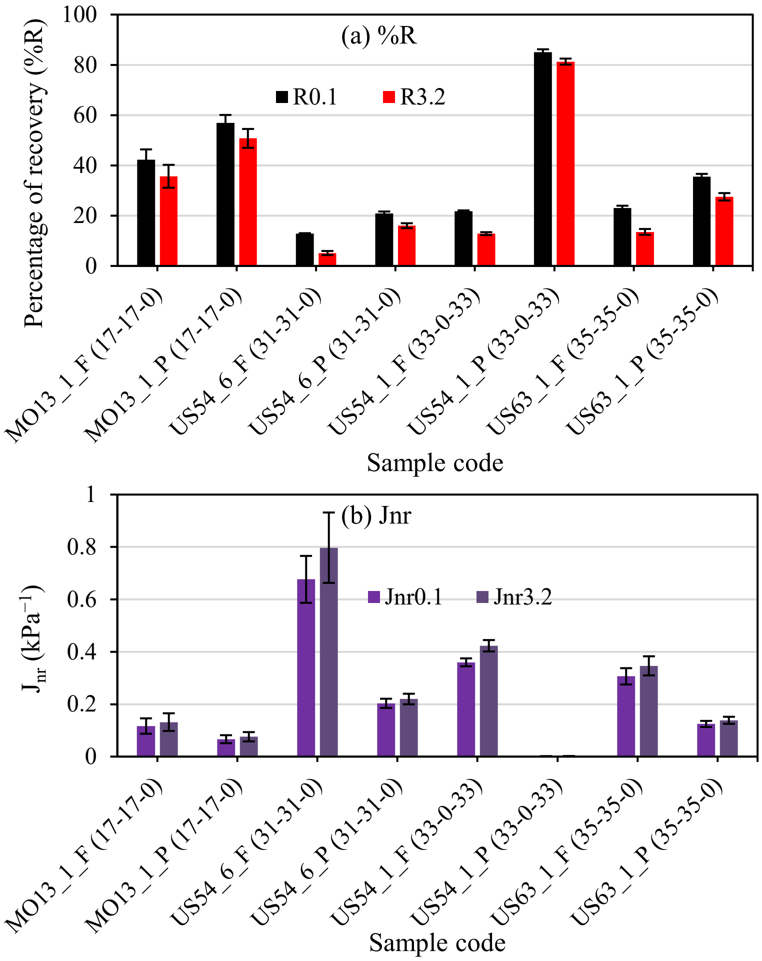


Figure 7-10. MSCR Test Results Measured at 60°C for E & R Binders from Field and Plant Mixes Constructed in 2016

7.1.3. Lab Mixes and Their E & R Asphalt Binders

The Hamburg wheel track test results for the US54_6 and US63_1 lab mixes are presented in Figure 7-11. The mixes containing engineered crumb rubber (ECR) showed the highest resistance to rutting. The binders E & R from these mixes had the highest Superpave rutting parameter presented in Figure 7-12. Furthermore, these binders presented the highest %R and the lowest J_{nr} values (Figure 7-13 and Figure 7-14), indicating high stiffness and elasticity in the rubber-modified binder system. The use of a softer virgin asphalt binder base grade decreased the resistance to rutting for both the mixes and the corresponding E & R asphalt binders, as expected. Adding Evoflex to the US54_6_C and US63_2_46 mixes actually increased the rutting resistance in the mix, where similar results were noted for the corresponding E & R asphalt binders. This result suggests that the Evoflex rejuvenator increased the recycled materials' contribution inside the mixes, or stated otherwise, increased the interaction process between the virgin and recycled binders and, in turn, increased the rutting resistance.

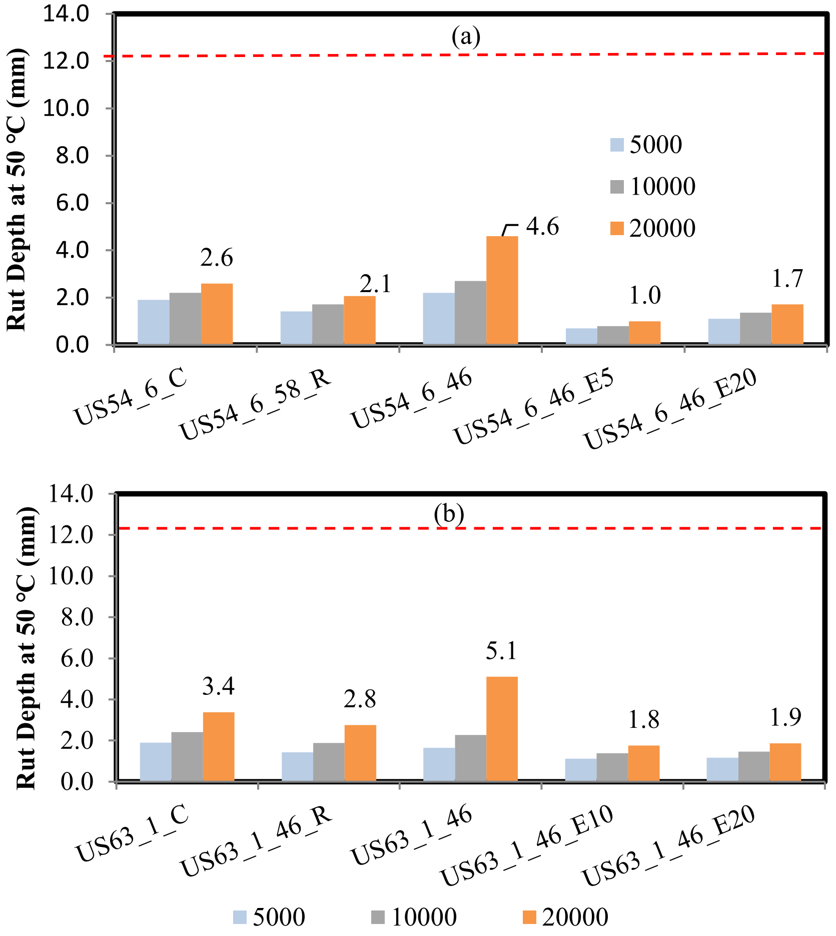


Figure 7-11. Hamburg Wheel Track Test Results for (a) US54_6 and (b) US63_1 Mixes

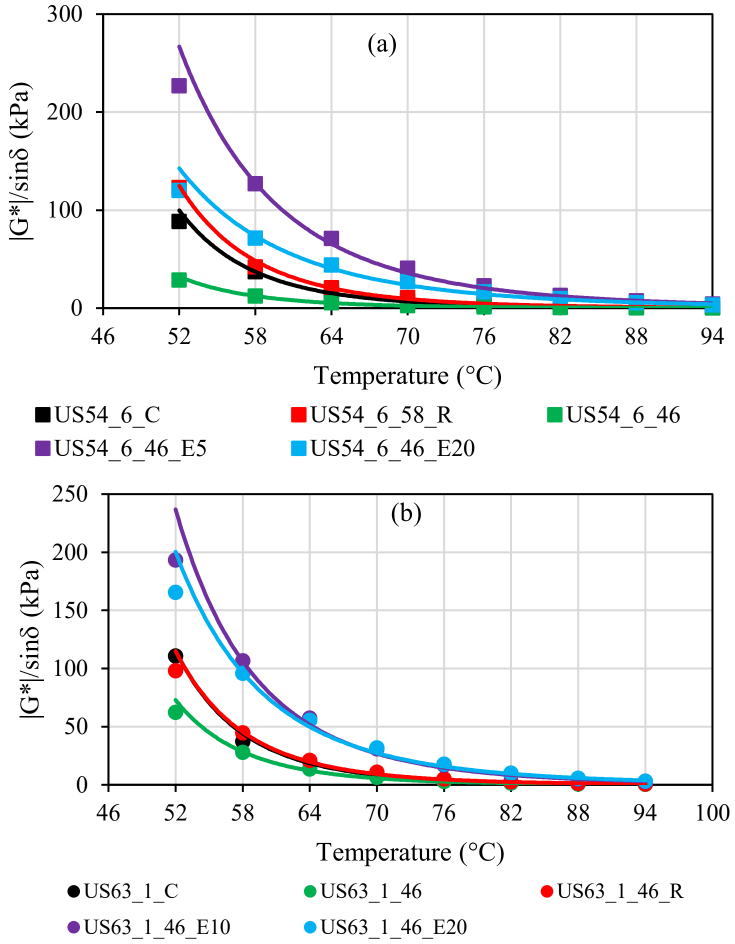


Figure 7-12. Temperature Sweep Test Results for E & R Binders from (a) US54_6 and (b) US63_1 lab Mixes

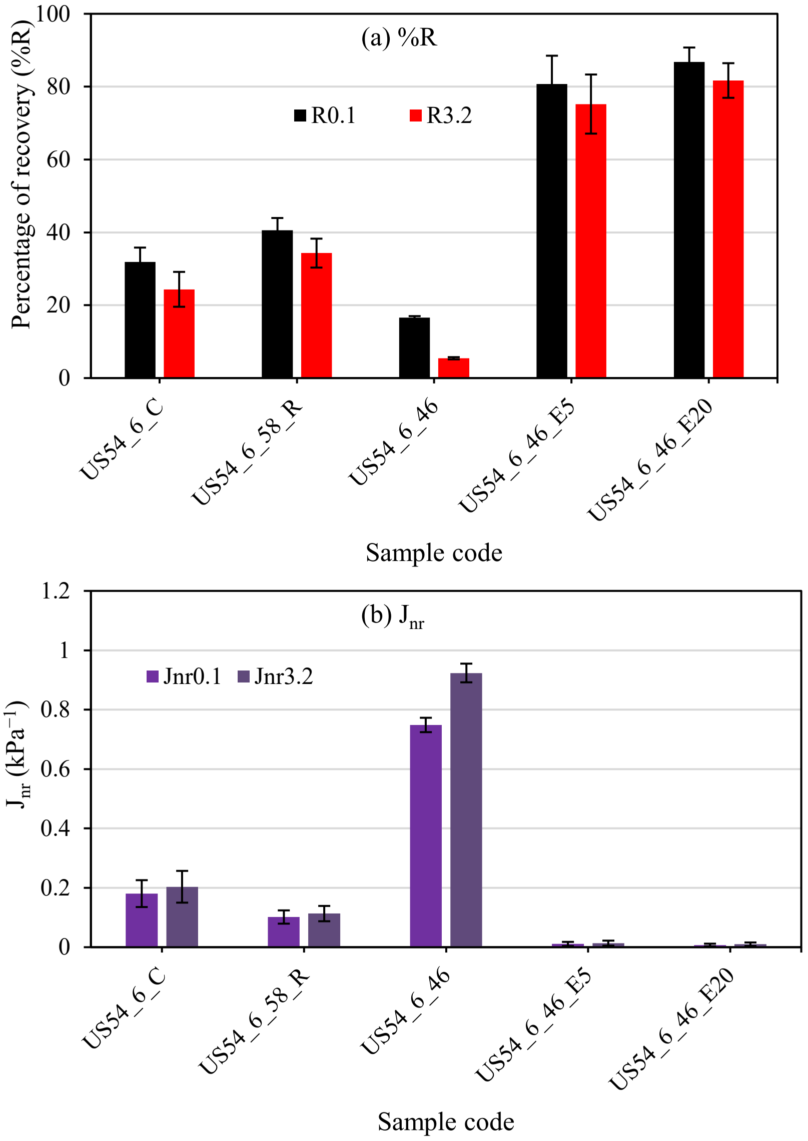


Figure 7-13. MSCR Test Results Measured at 60°C for E & R Binders from US54_6 lab Mixes

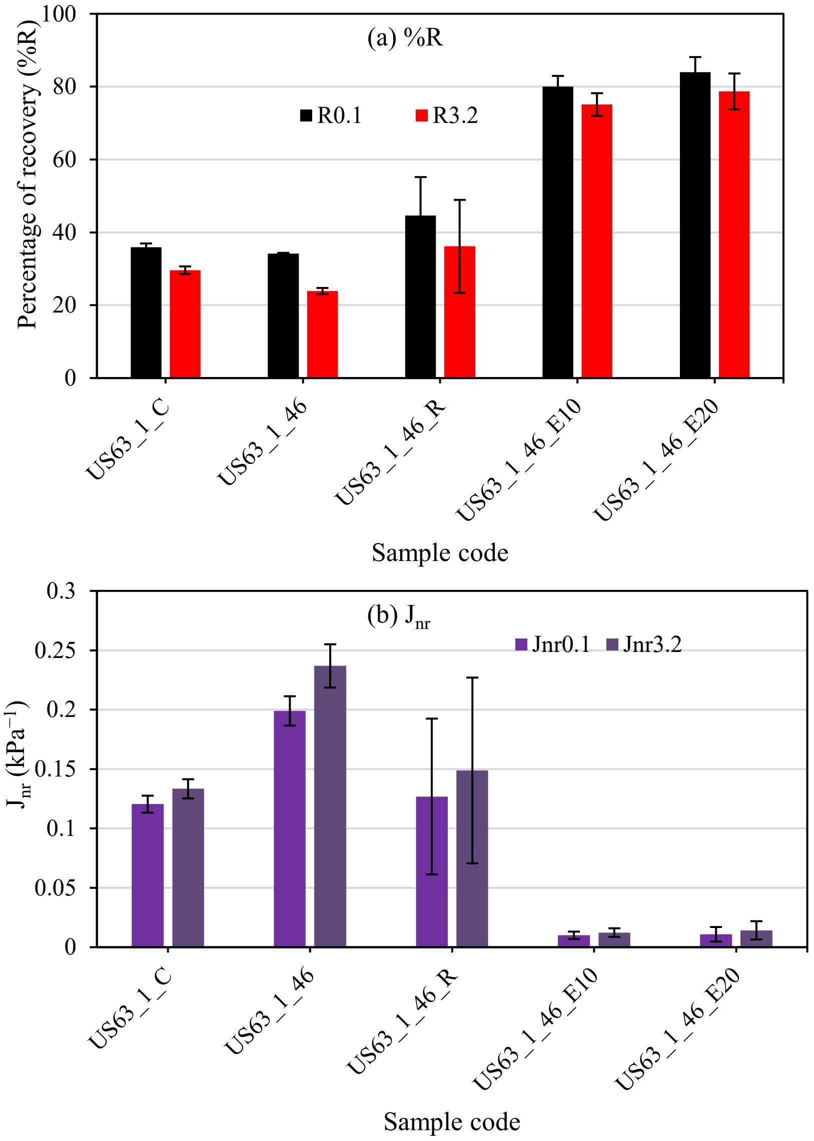
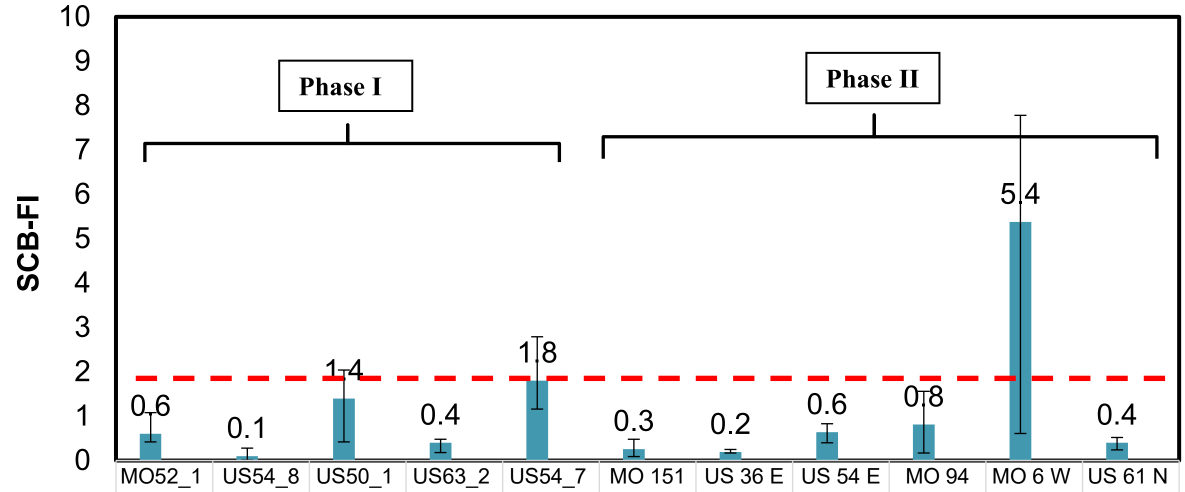


Figure 7-14. MSCR Test Results Measured at 60°C for E & R Binders from US63_1 lab Mixes

7.2. Intermediate-Temperature Results

In this section, the fatigue resistance results for the long-term aged field mixes and their corresponding E & R asphalt binders were discussed. The mixes termed as Phase I were cored in 2016, while Phase II coring occurred in 2019. Figure 7-15 illustrates the I-FIT mix cracking test results obtained for these materials, where the MO 6 W mixes (field-aged about 5 years at the time of sampling) showed the highest FI scored. In contrast, the lowest FI scores were recorded for the US54_8, US 36 E, and MO 151 mixes. The MO 151 mix contained 16 and 15% ABR percentages by RAP and RAS, respectively, and was 9 years old at the time of coring. The US 36 E section contained 25% ABR by RAP and was 8 years old. The US 54_8 mix contained 9% ABR by RAP; however, it was 10 years old and contained a stiff virgin asphalt binder (PG 70-22). Some mixes were older than the MO 151 section, namely, MO 94 and US 54_7. However, these older sections scored in the I-FIT as having higher resistance to fatigue cracking, likely due to the absence of recycled materials.



	MO52_1	US54_8	US50_1	US63_2	US54_7	MO 151	US 36 E	US 54 E	MO 94	MO 6 W	US 61 N
■ DC(T) FE	0.6	0.1	1.4	0.4	1.8	0.3	0.2	0.6	0.8	5.4	0.4
COV [%]	45.5	99.6	45.0	27.7	33.5	76.8	21.1	33.8	91.9	61.5	29.2

Figure 7-15. I-FIT SCB FI and Coefficient of Variability for Long-term Aged Field Sections

The temperature sweep test results for the E & R asphalt binders from the long-term aged binders are presented in Figure 7-16. The highest resistance to fatigue cracking was noted for the binders E & R from the MO 6 mix. This agrees with the mix testing results. However, the lowest resistance to fatigue cracking was recorded for binders E & R from the MO 151 and US 54 E mixes. The MO 151 mix contained both RAP and RAS with a total ABR percentage of 31% and it was 9 years old during the sampling process. The US 54 E was 9 years old and it contained one of the lowest ABR percentages by RAP (12%), but a stiff virgin asphalt binder (PG 70-22) was used. Therefore, both the mix and binder testing results agree that the MO 151 samples had low resistance to fatigue cracking. This suggests that PG 64-22 binder contains polymer and therefore possesses a low temperature susceptivity, it may not be the best choice for use in mixes containing recycled materials. As a virgin binder blending component, it is too stiff for use with recycled mixes in Missouri.

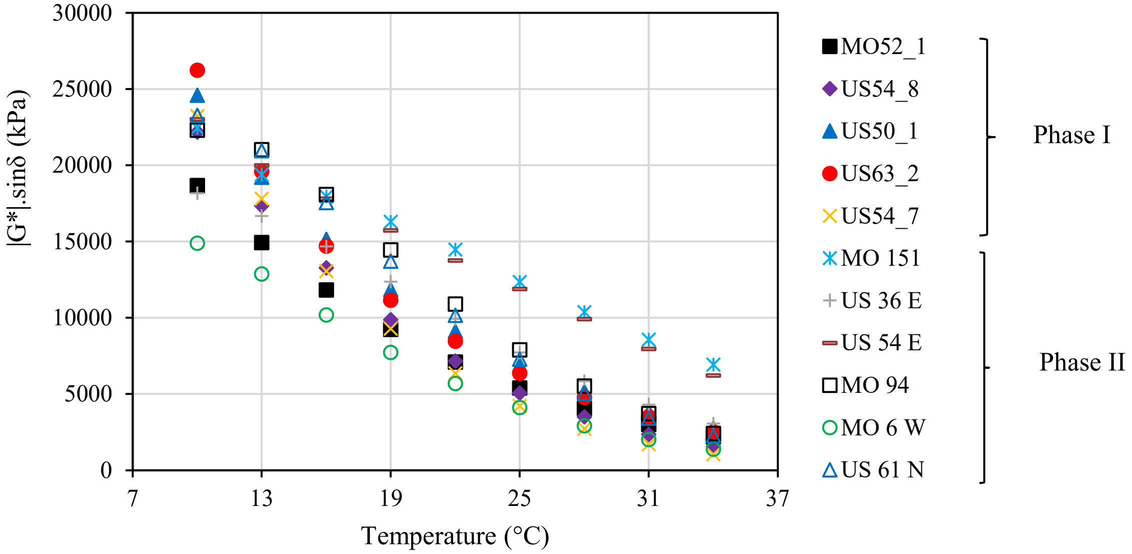


Figure 7-16.Temperature Sweep Test Results for E & R Binders from Long-term Aged Field Mixes

The Superpave fatigue cracking parameter measured at 22°C for the E & R binders is presented in Figure 7-17. The highest parameter values were recorded for the MO 151 and US 54 E binders indicating the worst fatigue cracking resistance. By contrast, the lowest parameter value was noted for the MO 6 binders representing the highest resistance to fatigue cracking. The same observations can be noted from Figure 7-18 that shows the intermediate PG temperature for the E & R asphalt binders. The MO 151 and US 54 E binders had the highest intermediate PG temperatures that reflected the worst fatigue cracking resistance. The intermediate temperature for some binders E & R from both MO 151 and US 54 E mixes exceeded 34°C. Contrarily, the MO 6 binders showed the lowest intermediate PG temperature, which indicated the highest fatigue cracking resistance. The same results were observed from the master curve in Figure 7-19.

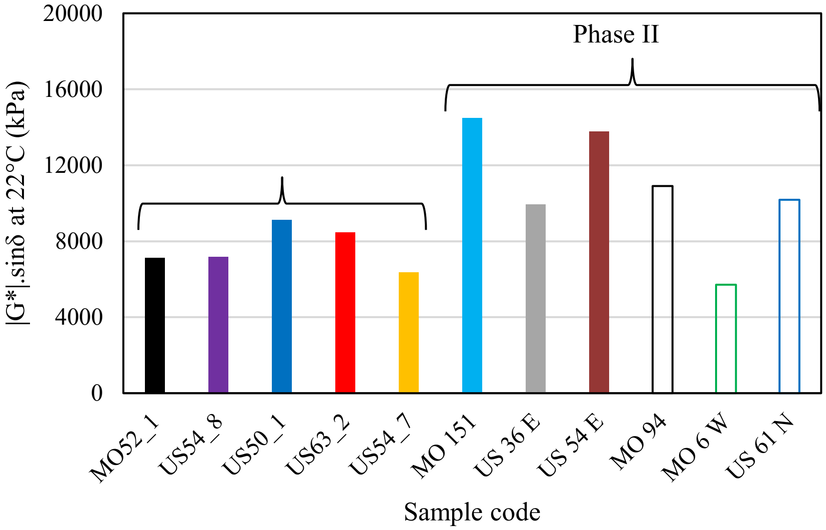


Figure 7-17. Superpave Fatigue Cracking Parameter Measured at 22°C for E & R Binders from Long-term Aged Field Mixes

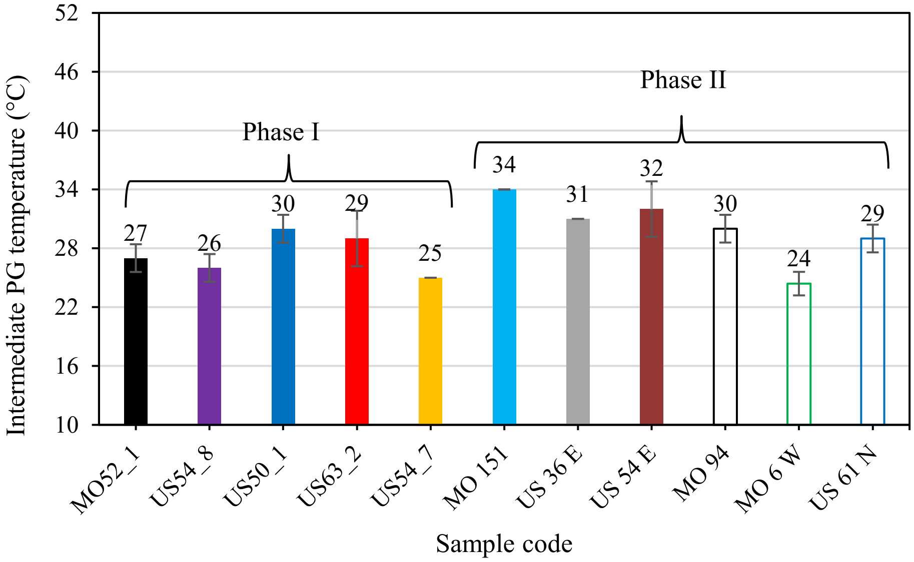


Figure 7-18. Intermediate PG Temperature for the E & R Binders from Long-term Aged Field Mixes

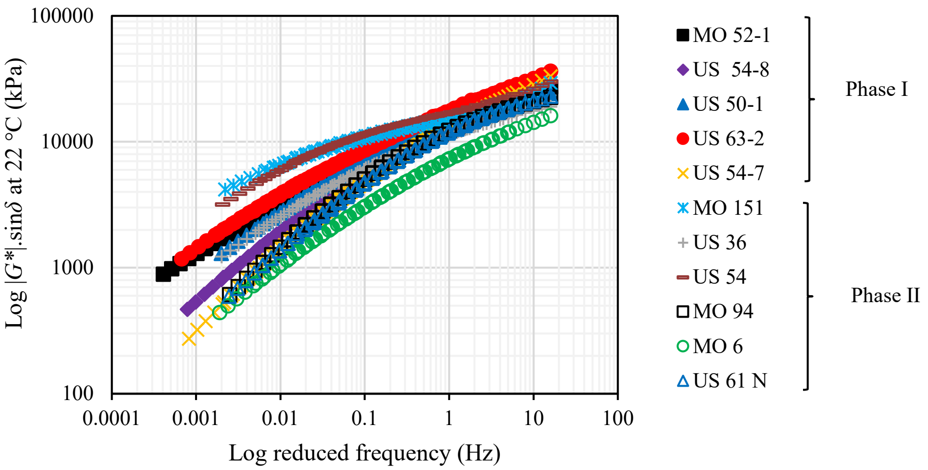


Figure 7-19. Master Curve Measured at 22°C for the E & R Binders from Long-term Aged Field Mixes

Figure 7-20 illustrates the Nf values measured at 2.5 & 5% strain levels and 22°C reference temperature for the E & R asphalt binders from the long-term aged field mixes. The highest Nf values were noted for the binders E & R from the MO 6 mix. The lowest Nf values were recorded for the US 54 E E & R binders. Some E & R binders from the MO 151 and US 54 E mixes showed zero Nf values, which represent very poor fatigue cracking resistance. The mix and binder testing results agreed that the MO 6 section had the highest fatigue cracking resistance. The MO 151 showed the lowest fatigue cracking resistance at 5% strain and had a low I-FIT score of 0.3.

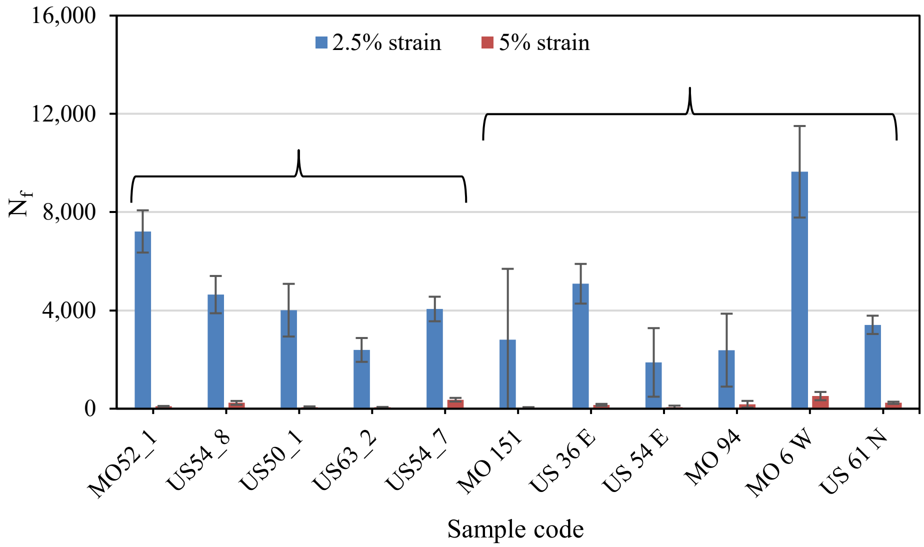


Figure 7-20. N_f at 2.5 and 5% Strain and 22°C for Binder from Long-term Aged Field Mixes

A series of figures were developed to investigate the correlation between binder and mixture fatigue cracking tests at intermediate temperatures. Figure 7-21 shows that the best correlation was obtained for the higher strain level binder fatigue test as compared to the FI scores from the I-FIT mix cracking test. Because the I-FIT is a cracking test driven to failure (a crack is driven across the notched, semi-circular bend specimen), it can be viewed as a high strain test. Thus, its higher correlation to the binder fatigue test performed at higher strain (5%) is an intuitive result.

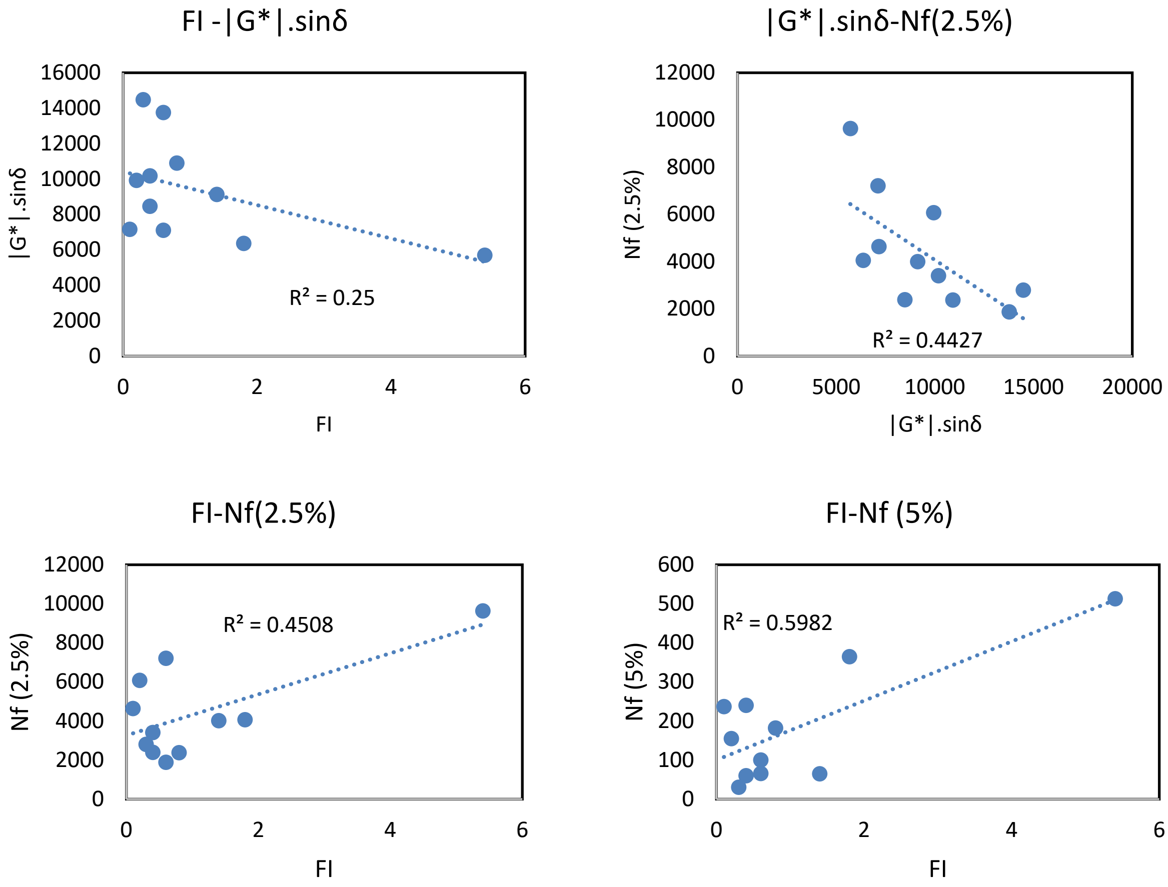


Figure 7-21. Correlation of Binder N_f at Intermediate Temperature with I-FIT FI

Figure 7-22 and Figure 7-23 illustrate a mix-by-mix comparison of binder and mixture cracking test results. In Figure 7-22, a good but not perfectly correlated relationship between mixture FI (blue bars) and binder stiffness (red dots) can be observed. Figure 7-23, which compares binder fatigue test results to mixture FI, yielded a similar result.

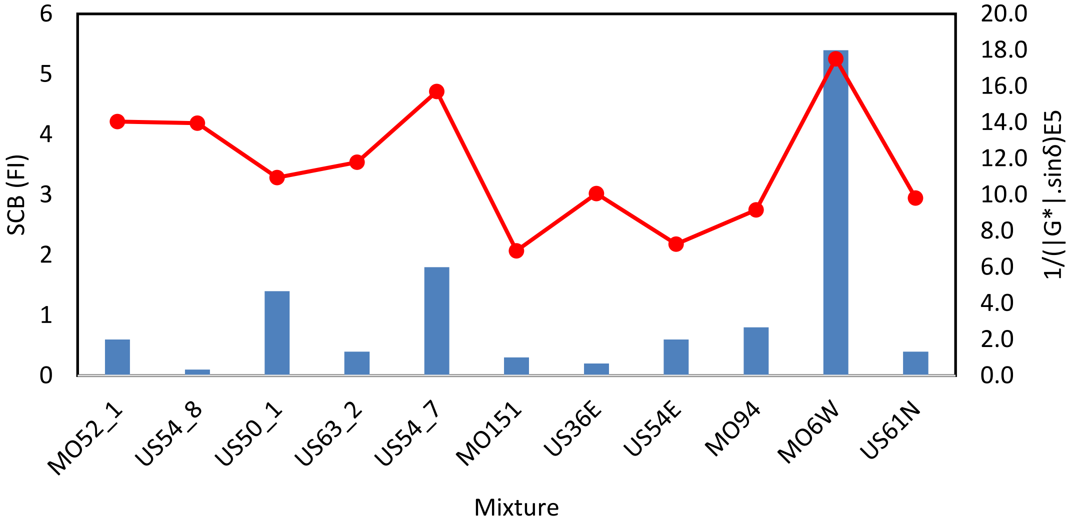


Figure 7-22. Correlation of the Inverse of Binder |G*|sinδ at Intermediate Temperature with Mix FI for Field Aged Sections

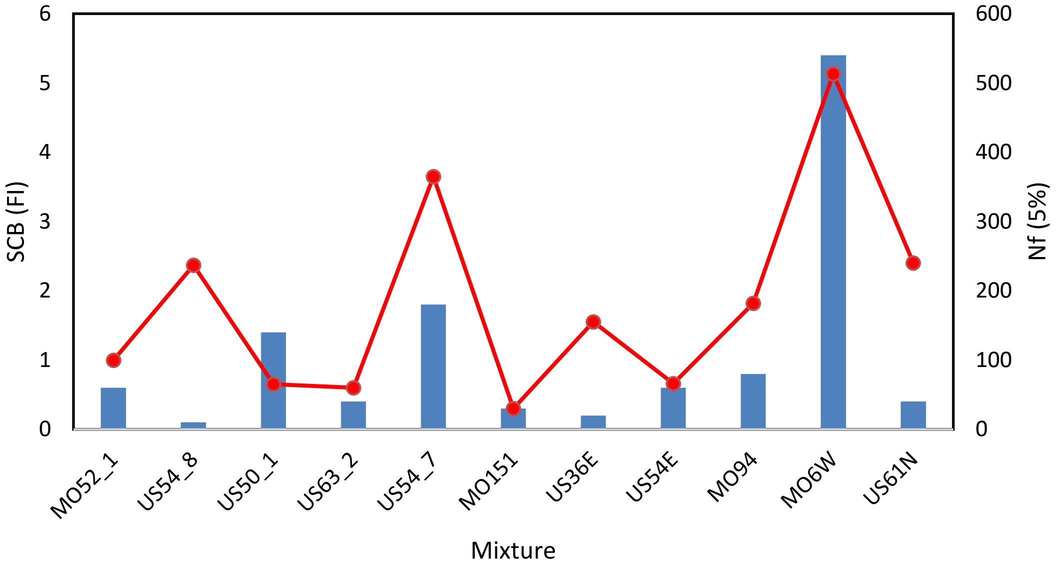


Figure 7-23. Correlation of N_f (5%) Parameter at Intermediate Temperature with FI for Field Aged Sections

It is concluded from these plots, and moreover from the collective data presented throughout this chapter that:

- Binder testing and mixture testing each have their place in asphalt mixture design, control, and forensic research
    - Binder testing showed utility in evaluating the degree of binder interaction in various sample types (lab, field/plant, field/core)
    - Mixture testing showed the benefits of considering aggregate effects, such as its effect on rut resistance and moisture resistance
- RAS possesses a high melting point and a different binder system as compared to virgin and RAP binders. This leads to some differences in ranking of binder test scores on E&R binder material as compared to mix scores.
- Reasonable correlation exists between certain binder intermediate test results and mixture FI, particularly binder fatigue N_f (at 5% strain) and mixture FI scores ($r^2 \approx 0.6$). This suggests that prior to starting mix design trials, binder testing of proposed virgin and recycled binder components could be used as a screening tool prior to conducting more time-consuming mix design trials.

8. DEVELOPMENT OF BEST PRACTICES FOR DESIGNING ASPHALT MIXTURES WITH MODERN RECYCLED MATERIALS

8.1. Evaluation of Current Practices for Binder Grade Selection in Missouri

Table 8-1 provides a summary of the target or plan grade of binder for various mixtures investigated, along with the virgin binder grade selected by the contractor and resulting in-situ binder grade determined from E&R binders. For newer projects cored shortly after construction, the E&R binder grade is considered to be in a short-term aging condition, and termed RTFO in Table 8-1. Results from older, cored projects were considered to be in a long-term aged condition and labeled as PAV.

Table 8-1 Summary of ABR Levels, Binder Grades, and Comparison to New Recommendations for Investigated Mixtures Subjected to Binder testing on E&R Samples

Code	Virgin asphalt PG	Contract PG	ABR by RAP (%)	ABR by RAS (%)	Extracted Binder Type*	Extracted Binder High PG temp.	Comments
US 54_8-6-PG 70 (9-0)	70-22	70-22	9	0	PAV	n.a.	Appropriate virgin binder selected
US 54_8-4-PG 70 (9-0)							
US 54_8-3-PG 70 (9-0)							
US 54-12a-PG 70 (12-0)	70-22	70-22	12	0	PAV	n.a.	Appropriate virgin binder selected
US 54-6a-PG 70 (12-0)							
US 54-2a-PG 70 (12-0)							
MO 13-1-5-PG 64H (17-0)	64-22H	70-22	17	0	RTFO	82	Softer virgin binder suggested
MO 13-1-7-PG 64H (17-0)						76	
MO 13-1-11-PG 64H (17-0)							
US 50-1-9-PG 64 (25-0)	64-22	64-22	25	0	PAV	n.a.	Softer virgin binder suggested
US 50-1-4-PG 64 (25-0)							
US 50-1-2-PG 64 (25-0)							
US 36-10a-PG 64 (25-0)	64-22	64-22	25	0	PAV	n.a.	Softer virgin binder suggested
US 36-13a-PG 64 (25-0)							
US 36-12a-PG 64 (25-0)							
US 61 N-9a-PG 64H (30-0)	64-22H	64-22H	30	0	PAV	n.a.	
US 61 N-3a-PG 64H (30-0)							
US 61 N-6a-PG 64H (30-0)							
MO 6-4a-PG 58 (30-0)	58-28	64-22	30	0	PAV	n.a.	Appropriate virgin binder selected
MO 6-5a-PG 58 (30-0)							
MO 6-10a-PG 58 (30-0)							
MO 6-11a-PG 58 (30-0)							
MO 6-8a-PG 58 (30-0)							
US 54_6-9-PG 58 (31-0)	58-28	70-22	31	0	RTFO	70	
US 54_6-7-PG 58 (31-0)							
US 54_6-2-PG 58 (31-0)							
US 54_2-7a-PG 58 (33-0)	58-28	70-22**	33	0	RTFO	88	Appropriate virgin binder selected (However, stiff E&R binder resulted)
US 54_2-6-PG 58 (33-0)							
US 54_2-3-PG 58 (33-0)							
US 63_1-9-PG 58 (35-0)	58-28	70-22	35	0	RTFO	70	Appropriate virgin binder selected
US 63_1-5-PG 58 (35-0)							
US 63_1-2-PG 58 (35-0)							
US 54_4-1a-PG 64H (35-0)	64-22H	70-22**	35	0	RTFO	70	Softer virgin binder suggested
US 54_4-4a-PG 64H (35-0)							
US 54_4-7-PG 64H (35-0)							
US 54_1-2a-PG 58 (0-33)	58-28	70-22**	0	33	RTFO	70	Softer virgin binder suggested (due to high % RAS)
US 54_1-3a-PG 58 (0-33)							
US 54_1-4-PG 58 (0-33)							
MO 52-1-6-PG 64 (0-34)	64-22	64-22**	0	34	PAV	n.a.	Softer virgin binder suggested (due to high % RAS)
MO 52-1-3-PG 64 (0-34)							
MO 52-1-9-PG 64 (0-34)							
US 63_2-5-PG 64 (20-10)	64-22	70-22**	20	10	PAV	n.a.	Softer virgin binder suggested (due to high total ABR which includes RAS)
US 63_2-2-PG 64 (20-10)							
US 63_2-11-PG 64 (20-10)							
US 54_3-8a-PG 58 (18-15)	58-28	70-22**	18	15	RTFO	76	Softer virgin binder suggested (due to high total ABR which includes RAS)
US 54_3-6a-PG 58 (18-15)							
US 54_3-2-PG 58 (18-15)						70	

MO 151-7-PG 64 (16-15)	64-22	64-22	16	15	PAV	n.a.	Softer virgin binder suggested (due to high total ABR which includes RAS), two grades softer
MO 151-5a-PG 64 (16-15)							
MO 151-10a-PG 64 (16-15)							
MO 151-2a-PG 64 (16-15)							
MO 151-11-PG 64 (16-15)							
MO 13-1-HP13-PG 64 H (17-0)	64-22H	70-22	17	0	RTFO	88	Softer virgin binder suggested
MO 13-1-HP16- PG 64 H (17-0)							
MO 13-1-HP14- PG 64 H (17-0)						82	
US 54-6-HP3-PG 58 (31-0)	58-28	70-22	31	0	RTFO	76	Appropriate virgin binder selected (However, stiff E&R binder resulted)
US 54-6-DP4A-PG 58 (31-0)							
US54-6-DP4B-PG 58 (31-0)							
US 63_1-HP8-PG 58 (35-0)	58-28	70-22	35	0	RTFO	76	Appropriate virgin binder selected (However, stiff E&R binder resulted)
US 63_1-HP9- PG 58 (35-0)							
US 63_1-DP3A- PG 58 (35-0)							
US 54_1-1DCTP1B-PG 58 (0-33)	58-28	64-22**	0	33	RTFO	> 94	Softer virgin binder suggested (due to high total ABR, all by RAS), at least two grades softer
US 54_1-1DCTP2B-PG 58 (0-33)							
US 54_1-1DCTP1A-PG 58 (0-33)							

* Based upon the construction and sampling years.
** Assumed contract grade

8.2. Best Practice Recommendations for Binder Selection, Use of Rejuvenators and Rubber

The following recommendations for binder selection, use of rejuvenators and ground tire rubber were prepared based on the mixture and binder performance test results in this project and other recently completed, related studies. Additional recommendations to aid the mix designer are provided in Section 8.3. Recommendations are based on total asphalt binder replacement (ABR) in the mix, which is generally achieved with RAP or RAS in current practice. However, other recyclates, such as waste plastic, may provide additional sources of binder replacement in the near future. When designing with a softer binder, best results will be obtained when selecting a binder that is one grade softer on both the low and high temperature grade. This will create a full grade bump down across all temperature ranges, i.e., moving from a PG 64-22 to PG 58-28, or in the MSCR grading system, moving from a PG 64H-22 to PG 58H-28. The next best choice would be to use a binder that has been bumped downward in terms of the low temperature grade, for instance, from PG 64-22 to PG 64-28. However, this will only drop the intermediate temperature performance by one-half grade (3 °C), which may limit the improvement observed in the mixture cracking test, which is run at an intermediate temperature. It may also require a more expensive binder, such as a polymer modified binder.

Based on the research conducted herein, a rejuvenator is recommended whenever designing with recycled materials, especially for ABR levels above 15%. This will increase binder interactivity between the virgin and recycled binder sources. Based on manufacturer's recommendations, higher ABR levels will naturally require higher dosages of rejuvenator.

Table 8-2 Recommended Starting Points for Binder Selection, Use of Rejuvenators and GTR for Designing Recycled Mixtures in Missouri

Recycling Content in terms of Asphalt Binder Replacement	Recommendations
0 to 14.9%	***No grade bump*** Rejuvenator recommended 5-10 % GTR optionally
15.0 to 29.9%	***One grade bump softer*** Rejuvenator required 10-20% GTR optionally
30% or greater	***Two grade bumps softer*** Rejuvenator required 10-20% GTR optionally

In addition, when designing with very stiff recycles, such as highly weathered RAP sources, RAS or waste plastic, it may be necessary to apply a weight factor to the stiffer recyclates. The MSSHC suggests that for mixes containing both RAP and RAS, the ABR should be computed as the ABR by RAP plus 2 times the ABR by RAS. A similar weight factor may be necessary for waste plastic. Finally, as shown in this report, the use of GTR can increase mixture sustainability, while helping to meet performance test results. Depending on the cracking test selected, it may also be necessary to select a very soft binder and to increase binder content in the mix containing GTR, through the use of supplemental binder, increasing mixture VMA and/or regressing air void targets. For the dry-process GTR product studied herein, 0.1% supplemental binder is suggested by the manufacturer for each 5% of rubber used by weight of virgin binder.

8.3. Other Best Practice Recommendations for Designing Recycled Mixes

Additional recommendations for designing asphalt mixtures containing recycled materials were prepared based on the binder and mixture test results obtained in this project and other recently completed studies.

8.3.1 Other Binder-Related Considerations for Designing with Recycled Materials

It is recommended to conduct extraction and recovery experiments for each mix containing recycled materials to check the contract grade in the job mix formula (JMF). This is being recommended because the high-performance grade (PG) temperature for the majority of the extracted and recovered (E & R) binders was greater than the high PG temperature of the contract grade by at least one grade (6°C per grade). The interaction process is the key point for achieving the compatibility between the virgin and recycled binders. Characterizing the E & R asphalt binders not only depended upon choosing the appropriate virgin asphalt binder grades, selecting the percentage of the recycled materials, and following the Missouri standard specifications for highway construction (MSSHC) but also on achieving the interaction process between the recycled materials and virgin asphalt binders. For the same mix, changing the interaction process changed the high PG temperature of the E & R binders (e.g. field and plant samples in Table 8-1). The E & R binders from the plant mixes showed higher PG temperatures than the high PG temperatures of the binders E & R from the field mixes.

It is recommended to use a rejuvenator in all mixes containing recycled materials. One of the challenges in using recycled materials in asphalt mixes is the compatibility process between the virgin binder and the binders included in the recycled materials. This appeared with changing the interaction process: the plant samples were collected and reheated in the lab causing more interaction processes to occur between the virgin and recycled binders. It was found that using Evoflex rejuvenator enhanced the interaction process between the virgin and recycled binders. This additive was viewed as increasing the RAP/RAS contribution (blending) in the mixes. Thus, the interaction process between the virgin and recycled binders increased by increasing the solubility of the recycled materials.

More clarifications are needed in the MSSHC regarding using both RAP and RAS in the asphalt mixes. In the MSSHC, it was mentioned that for mixes containing both RAP and RAS, the percent effective virgin binder replacement or asphalt binder replacement (ABR) by RAP plus 2 times the ABR by RAS should be less than or equal to 40%. However, in another portion of the MSSHC, it was recommended that the ABR by RAP and RAS (not doubled) should be less than or equal to 40%, which is not identical. Also, according to the MSSHC, PG 64-22 asphalt binder may be used in mixes containing recycled materials under specific considerations. Consequently, it is not recommended to use asphalt binders with a PG higher than (64-22). Using asphalt binders with high PG temperature of 70 was found in this study to reduce the fatigue resistance in mixture and binder tests. Recommendations for mixes containing waste plastic will also need to be developed in future research studies.

8.3.2 Other Mixture-Related Considerations for Designing with Recycled Materials

In the emerging era of BMD, additional best practices are expected to evolve with respect to designing mixes with recycled materials to meet BMD requirements while minimizing design iterations, minimizing cost, and maximizing mixture sustainability. Based on this study, the following best practice recommendations are suggested:

- When designing at higher ABR levels and/or when using stiff recyclates, additional strategies may be required beyond virgin binder grade softening and rejuvenator use. These include:
    - Regressing air void targets below the typical 4% target associated with Superpave, to lower levels such as 3.5%, 3.0%, or perhaps even 2.5%. Care must be exercised in using very low design void targets, as rutting or flushing potential may be increased. Rutting potential should be controlled, however, by meeting Hamburg requirements.
    - Use of increased VMA targets.
- When conducting mix design iterations in practice, avoid using a full factorial experimental design approach, i.e., a strategy where a number of factors are considered simultaneously and where the complete slate of mixture tests are conducted. Rather:
    - Pre-screen binder selection using the techniques suggested in the previous section.
    - Transforming older mix designs to meet newer BMD requirements will generally

  require building additional crack resistance into the mix. It is therefore recommended to iterate the mixes initially by focusing on cracking test results conducted with one or two test replicates, then introducing the Hamburg test and additional cracking test replicates only when a mix design is reached with a comfortable margin above the design cracking test requirement threshold.

- Experiment with different combinations and quantities of rejuvenators, anti-strip, and warm-mix additives. Additional considerations along these lines include:
  - Be aware that some manufacturers of these additives have developed products designed to accomplish more than one objective, such as warm-mix plus anti-strip.
  - Not every anti-strip additive will work well with every binder and/or aggregate source. If stripping is detected in the Hamburg test, consult the manufacturer to consider using a different product (with a different underlying chemistry). Several trials may be necessary.
  - Bear in mind that a stripping inflection in the Hamburg test can result from a true stripping failure, plastic deformation in the mix or a combination of the two. Thus, failing to meet Hamburg requirements due to a mix that shows an inflection followed by a rapid increase in wheel track rut depth might require adjustments to improve moisture resistance, a better aggregate skeleton and/or a stiffer binder system (perhaps including more recycled material).

9. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

9.1 Summary

A comprehensive research investigation was carried out to investigate the use of recycled materials in Superpave asphalt mixtures in Missouri, leading to best practice recommendations geared towards the achievement of passing mixes as modern, balanced mix design requirements are rolled out in Missouri. The investigation involved sampling of aggregates, binders, plant-produced mixtures, and field cores followed by a rigorous lab testing program. Lab testing included extensive binder extraction and recovery experiments, followed by a comprehensive suite of advanced binder tests.

An attempt was made to shed light on effective strategies to iterate existing mix designs into more ‘balanced mix designs’ for modern, heterogeneous recycled mixtures in the Midwest. Different strategies were employed, such as the use of a softer virgin binder, the addition of a rejuvenator, and the employment of 5% to 20% of dry-process, engineered crumb rubber by weight of total binder. Two dense-graded asphalt mixtures designed and placed on Missouri roadways prior to the use of BMD were adopted as the baseline mix designs. These mixes were subjected to a suite of cracking and rutting mixture performance tests to establish baseline performance, followed by four mix design iterations per mix (for a total of 10 investigated mixtures). The DC(T), I-FIT, IDEAL-CT, and Hamburg wheel tracking tests were used in the performance testing suite.

9.2 Conclusions

Based on the results and analysis reported herein, the following conclusions were drawn:

- For plant mixes, the highest resistance to rutting was observed for asphalt binders E & R from mixes containing RAS. For mixes containing the same PG virgin binder, the E & R asphalt binders from mixes containing RAS were stiffer than the E & R asphalt binders from mixes containing RAP. This demonstrated the effect of the air-blown asphalt component in the RAS on increasing the stiffness and elasticity of the E & R asphalt binders.
- The use of a rejuvenator actually increased the stiffness of the E & R asphalt binders. It is therefore believed that the rejuvenator increased the contribution or blending of recycled and virgin binders.

- The asphalt binders E & R from mixes containing a virgin asphalt binder with a high PG temperature of 70°C and 12% ABR by RAP showed reduced fatigue cracking resistance.
- From the standpoint of binder testing, the use of RAS enhanced the resistance of the E & R asphalt binders to fatigue cracking as compared to binders E & R from mixes containing RAP. The asphalt binders E & R from mixes containing 34% ABR by RAS showed higher fatigue cracking resistance than asphalt binders E & R from mixes containing 25% ABR by RAP.
- For plant mixes, the asphalt binders E & R from mixes containing 33% ABR by RAS were measured to possess a high PG temperature grade of more than 94°C, while the binders E & R from mixes containing 31% ABR by RAP had a high PG temperature grade of 76°C. This was related to the effect of the aged air-blown asphalt binders included in the RAS.
- However, for field mixes, the E & R asphalt binders from mixes containing either 31% ABR by RAP or 33% ABR by RAS had the same high PG temperature (70°C). Consequently, the asphalt binders E & R from the plant mixes showed higher PG temperatures than the binders E & R from the field mixes. This increase was approximately one to two grades (6°C per grade) for mixes containing RAP and more than four grades for mixes containing RAS. Thus, the re-heating step implemented for the plant mixes caused more contribution of the binders included in the recycled materials especially for the binders existing in the RAS. This contribution increased the interaction process between the virgin and recycled material binders.

- Engineered crumb rubber (ECR) increased the E & R asphalt binder resistance to rutting by increasing the stiffness and elasticity. However, during the E & R process, some rubber was present in the recovered aggregate, and in the fines captured during the centrifuge stage. Thus, the binder testing results are not expected to be fully representative of the ECR binder system.

- The ashing MMDM was very sensitive and required a highly skilled operator. It underestimated the extracted AC percentages if the 100-ml representative sample contained a high amount of mineral matter. However, the centrifuge MMDM accurately determined the total mineral matter in the extracted effluent.

- The use of softer virgin asphalt binders in recycled mixes containing high ABR facilitated the E & R process. It was noted that softer binders produced more accurate and less variable extracted AC percentages. The same results were observed for mixes containing Evoflex rejuvenator. The use of Evoflex in mixes containing recycled materials appeared to enhance the contribution of the recycled materials in these mixes, i.e., enhanced the interaction process between the binders from the recycled materials with the virgin asphalt binder.
- In the 'fix-the-mix' portion of the study, the following conclusions were drawn:
    - The strategy of replacing the base binder with a softer virgin binder grade was generally effective in both investigated mixtures (US63_1 and US54_1). According to performance test results, it was concluded that the US63 aggregate structure was relatively weak. Therefore, the use of a softer binder was not as effective as compared to the US54_1 section, where all three cracking tests showed a positive effect when a softer based binder was used. The softer base binder led to higher HWTT rut depths, but still far from the maximum threshold of 12.5 mm even for the highest traffic designs entailing 20,000 wheel track passes.
    - In this study, the addition of a rejuvenator was not as effective as the other strategies investigated. However, the use of a rejuvenator served the purpose of helping achieve desirable volumetric properties in the mixtures, likely by increasing the lubricity/workability of the mixtures. According to the results, when the rejuvenator was eliminated from the mixture, it did not meet the volumetric properties (4% voids at Ndesign). This suggests the value of using a rejuvenator when designing high-RAP mixtures.
    - Engineered crumb rubber was introduced via a dry-process in an attempt to further improve the cracking and rutting performance of the mixtures. The results showed that the DC(T) fracture energy test disagrees with the results obtained from the SCB (I-FIT) and IDEAL CT-index when GTR was introduced into the study mixtures. The use of rubber up to 20% increased the fracture energy of mixtures significantly (almost doubled), while the FI and

CT-index scores were significantly reduced. This is somewhat counter-intuitive as field results suggest that rubber modification provides cracking resistance benefits to asphalt mixtures in the field, even under extreme environments and loading conditions. In terms of rutting, the addition of rubber increased the rutting resistance of the mixtures.

Evaluating BMD optimization as a whole, the use of a softer binder was the most effective strategy to optimize SCB(I-FIT) and IDEAL CT cracking test scores, while the incorporation of rubber along with a softer base binder and supplemental binder was the most effective method to maximize DC(T) fracture energy test results. In all cases, modern recycled mixtures appear to have a significant factor of safety against rutting, which suggests the increasing importance of softer virgin binder grades and effective rejuvenators and the importance of accessing these materials without greatly increasing asphalt mixture costs.

9.3 Recommendations

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

- For binder E & R, it is recommended to use the centrifuge MMDM if the filterless centrifuge device is available.
- The practice of recommending or requiring a softer virgin binder grade when recycled materials are used should be continued, even as BMD is rolled out. Table 8-1 was developed, which sets recommended thresholds for virgin binder grade softening based on research observations.
- When designing with very stiff recyclates, such as highly weathered RAP sources, RAS or waste plastic, it may be necessary to apply a weight factor to the stiffer recyclates. The MSSHC suggests that for mixes containing both RAP and RAS, the ABR should be computed as the ABR by RAP plus 2 times the ABR by RAS. A similar weight factor may be necessary for waste plastic. Recommendations for rejuvenator and GTR use were also provided in Table 8-1.
- The use of GTR can increase mixture sustainability, while helping to meet performance test results. Depending on the cracking test selected, it may also be necessary to select a very soft binder and to increase binder content in the mix

containing GTR, through the use of supplemental binder, increasing mixture VMA and/or regressing air void targets. For the dry-process GTR product studied herein, 0.1% supplemental binder is suggested by the manufacturer for each 5% of rubber used by weight of virgin binder.

- Attention should be paid to the availability of softer virgin binder supply in Missouri. As these recommendations are implemented, and as BMD is rolled out, the current supply of softer virgin binders may fall short of demand. A staged rollout of BMD may serve to provide a smooth transition.
- When designing at higher ABR levels and/or when using stiff recyclates, additional strategies may be required beyond virgin binder grade softening and rejuvenator use. These include:
  - Regressing air void targets below the typical 4% target associated with Superpave, to lower levels such as 3.5%, 3.0%, or perhaps even 2.5%. Care must be exercised in using very low design void targets, as rutting or flushing potential may be increased. Rutting potential should be controlled, however, by meeting Hamburg requirements.
  - Use of increased VMA targets.
  - When conducting mix design iterations in practice, avoid using a full factorial experimental design approach, i.e., a strategy where a number of factors are considered simultaneously and where the complete slate of mixture tests are conducted. Transforming older mix designs to meet newer BMD requirements will generally require building additional crack resistance into the mix. It is therefore recommended to iterate the mixes initially by focusing on cracking test results conducted with one or two test replicates, then introducing the Hamburg test and additional cracking test replicates only when a mix design is reached with a comfortable margin above the design cracking test requirement threshold.
- Experiment with different combinations and quantities of rejuvenators, anti-strip, and warm-mix additives. Additional considerations along these lines include:

    - Be aware that some manufacturers of these additives have developed products designed to accomplish more than one objective, such as warm-mix plus anti-strip.
    - Not every anti-strip additive will work well with every binder and/or aggregate source. If stripping is detected in the Hamburg test, consult the manufacturer to consider using a different product (with a different underlying chemistry). Several trials may be necessary.
- Failing to meet Hamburg requirements due to a mix that shows an inflection followed by a rapid increase in wheel track rut depth might require adjustments to improve moisture resistance, a better aggregate skeleton and/or a stiffer binder system (perhaps including more recycled material). A stripping inflection in the Hamburg test can result from a true stripping failure, plastic deformation in the mix or a combination of the two.

The movement towards increased sustainability in asphalt mixtures will require continued balancing of increased recycled material usage, mixture durability, and mixture economics. Major sacrifices in one or more of these three categories will not truly lead to long-term, sustainable solutions. Finally, this study highlights the significant challenges confronting the industry with respect to the need for even softer base binder supplies and a broad slate of effective rejuvenators, tailored to binders and aggregates with differing chemical characteristics.

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APPENDIX

A.1. Literature review (binder)

Recycling of asphalt pavements has started during the 1970s with the oil embargo and the dramatic rise in the prices of crude oil, which lead to a drop in the asphalt supply levels. During that time, agencies and contractors examined asphalt mixes containing 80% reclaimed asphalt pavement (RAP) (Copeland, 2011; Newcomb et al., 2016; West & Willis, 2014). Between the 1980s and 1990s, recycled asphalt shingles (RAS) were used in the asphaltic mixes (Newcomb et al., 2016; West & Willis, 2014). The use of RAP or RAS in the asphalt mixes reduces the demand for natural resources, reduces the emissions during the production process, and decreases the quantities of materials dumped in landfills (M. Z. Alavi et al., 2017; West et al., 2009).

Using RAS in the pavement industry is increasing in the U.S. due to the valuable constituents that make them more appropriate to be used with asphaltic mixtures. RAS contains oxidized air-blown asphalt binder percentage ranging from 19 to 36% by weight, granules "ceramic-coated or sand-sized natural aggregate" from 20 to 38% by weight, mineral filler/stabilizer (limestone, dolomite, silica) from 8 to 40%, and fibers "fiberglass or cellulose backing" 2 to 20% by weight (Rubino, 2010; Willis & Turner, 2016). The fibers were observed during making sieve analysis for the aggregate after the extraction process for mixes containing RAS as indicated in Figure A-1.

Figure A-1. Fibers Existing with the Aggregate after the Extraction Process of Asphalt Binders from Mixes Containing RAS

These fiber backings constitute the basic structure of shingles. They are saturated with air-blown asphalt. Both sides of the backings are covered with this kind of asphalt cement. Usually RAS asphalt binder content is five times more than what is obtained from RAP (Alvergue, 2014); however, the properties of both binders are different (Z. Alavi et al., 2015). The top side of the shingles is covered with granules (crushed rocks coated with ceramic metal oxides) to protect shingles from the sun rays. The bottom side is covered with fine sand to prevent the agglomeration of shingles during the transportation process. RAS contains valuable materials that are very essential to the asphaltic mixtures. Shingles are preferred to be grounded to 100% passing the 3/8-inch sieve according to the Missouri Department of Transportation (MoDOT) specifications. Shingles shall be used in mixtures containing asphalt binder PG 64-22. However, when the ratio of virgin effective binder to total binder is between 60 and 70% in the mixture, the grade of the virgin binder may be PG 58-28 or PG 52-28 instead of PG 64-22 (Zhou, Button, et al., 2012).

In 2002, the MoDOT received its first request regarding using the post-consumer RAS in the asphaltic mixture in Saint Louis. Missouri allows using of RAS in asphalt pavements within a percentage of less than or equal to 7% (West & Willis, 2014). MoDOT implemented a demonstration project in December 2004 to assess using RAS in the pavement; this project was constructed in 2005 on Route 61/67 in Saint Louis County, Missouri. MoDOT allowed using of RAS in the asphalt mixtures through a provisional specification in 2006 followed by a formal specification in 2008 (West & Willis, 2014). In 2009, the MoDOT used 53,000 tons of RAS and 50,000 tons of RAP in the pavement industry. This saves $20 million in resurfacing projects during that year. Adding RAS to asphalt mixtures as an asphalt alternative source increased by 80% from 2009 to 2012 (Willis & Turner, 2016). The percentage of RAS in the asphalt mixture is typically five percent by the weight of the mix. Using RAS with a percentage of five percent in the hot mix asphalt (HMA) would lead to a cost savings between $1.00 and $2.80 per ton according to the National Asphalt Pavement Association estimations (Davis, n.d.). Based on a technical report implemented in 2013, assuming a cost of $600 per ton for virgin asphalt binder, using 5% RAS in the asphaltic mixture could save $4 to $7 per ton of HMA (Zhou, Li, et al., 2012). MoDOT uses RAS percentage from two to five percent in the mix or no more than 20% effective virgin binder replacement (Davis, n.d.). Generally, in Missouri, up to 7% RAS (tear-off) is accepted to be used with PG 64-22 asphalt binder (Salari, 2012; Zhou, Button, et al., 2012).

Exploring the effect of the recycled materials (e.g. RAP, RAS, or both) on the performance of the extracted & recovered (E & R) asphalt binders' performance is the main idea followed in this report. Different methods can be used to extract asphalt binders from the asphaltic mixes. However, the centrifuge extraction method is the most common method used to extract asphalt binders from mixes using solvents (Rodezno & Grant, 2018) because of its simplicity and use at room temperature (Mehta et al., 2012; Mikhailenko et al., 2020). This method can be used if the characterizing of the E & R asphalt binder is necessary. However, one of the main drawbacks of this method is leaving around 4% of the total binder with the aggregate (Mehta et al., 2012; Rodezno & Grant, 2018; Stroup-Gardiner & Nelson, 2000). The solvent used dissolves the asphalt binder; however, during the extraction process, some mineral matter (dust) is captured within the dissolved asphalt binder. The mineral matter can be removed using a filterless centrifuge. After removing the mineral matter from the extracted solvent, the asphalt binders are recovered using a distillation process that could be achieved by a rotary evaporator "rotavap". This recovery process was used since the 1970s (Collins-Garcia et al., 2000); however, the overheating process in the rotavap would result in increasing the stiffness of the recovered asphalt binders. Furthermore, any remaining solvent in the recovered asphalt binders could result in decreasing the asphalt binders' stiffness. It was observed that even 0.5% of the solvent remaining in the recovered asphalt binders could result in a 50% decrease in the viscosity value (AbuHassan et al., 2019).

Rodezno and Julian (Rodezno & Grant, 2018) investigated the effect of different extraction methods (centrifuge, ignition, asphalt analyzer "automated", and reflux) on the behavior of the E & R asphalt binders. Eight mixes were analyzed; those mixes either contained a virgin asphalt binder or contained recycled materials (RAP, RAS, or both). The testing program was achieved with the collaboration of different laboratories in Wisconsin to evaluate the within-lab and between-lab variability. For the centrifuge extraction method, an average difference between the actual and extracted asphalt binder was found to be 0.21% for mixes containing a virgin binder and may reach to 0.38% for mixes containing a high percentage of recycled materials (recycled binder percentage of 30-35%). The within-lab and between-lab variability were not affected using recycled materials in asphaltic mixes. Ignition and asphalt analyzer extraction methods had the highest accuracy since the average differences between the actual and extracted asphalt binder's percentages were 0.05 and 0.17%, respectively. However, the ignition method cannot be used when the characterization of the extracted asphalt binder is necessary. Unfortunately, the asphalt analyzer apparatus is not available in our lab. Regardless of the extraction method and type of solvent [toluene, trichloroethylene (TCE), and n-propyl bromide], there was no significant difference in the performance grade (PG) characterization of the E & R asphalt binders (Rodezno & Grant, 2018). However, another research showed that there was a difference in the properties' characterization of the E & R asphalt binders using the three aforementioned types of solvents (AbuHassan et al., 2019)

The main issue of using RAS in asphaltic mixes is the high stiffness of its asphalt component. This asphalt is an oxidized air-blown type, which is stiffer than the ordinary asphalt binder (Alvergue, 2014). The percentage of asphaltene increases while the percentages of oil and resin constituents decrease linearly with time during the air-blowing process of an asphalt flux (Kleinschmidt & Snoke, 1958). The asphalt flux is "the residuum of atmospheric and vacuum distillation processes used by petroleum refineries" (Health, 2001). The air blowing process causes an increase in the stiffness of the asphalt by increasing the softening point and decreasing the ductility and penetration (Health, 2001; Kleinschmidt & Snoke, 1958). The resulting air-blown asphalt would be more viscous and less temperature-susceptible (Health, 2001). Moreover, the oxidation effect in the tear-off shingles caused a stiffer property for the E & R asphalt as compared to the asphalt E & R from manufactured waste shingles (Alvergue, 2014; Zhou et al., 2013). It was found that the average high PG temperature for asphalt E & R from manufactured waste and tear-off shingles is 130 and 178°C, respectively (Willis & Turner, 2016; Zhou et al., 2013).

The properties of RAP binders cannot be categorized regionally since they varied for different stockpiles in Massachusetts and varied from one season to another (Austerman et al., 2020). Generally, researchers have reported the high PG temperature for the asphalt binders E & R from RAP to be between 76 and 94°C (M. Z. Alavi et al., 2017; Austerman et al., 2020; Daniel et al., 2010; Ma et al., 2020). Alavi et al. (M. Z. Alavi et al., 2017)collected three RAP sources from three plants in California and evaluated the properties of the E & R asphalt binders. The high PG temperatures for the E & R RAP binders were between 82 and 88°C, while the low PG temperature was around −4°C. This illustrates that the asphalt binders E & R from RAP are aged. It was found that the E & R asphalt binders from mixes containing no or low percentages of recycled materials (recycled binder percentage of 5-20%) had a PG 64-28 (Rodezno & Grant, 2018). However, the virgin asphalt binder used in these mixes had a PG 58-28, which illustrates an increase in the high PG temperature of the E & R asphalt binders by one grade (6°C). Adding a higher percentage of recycled materials would lead to stiffer E & R asphalt binders. For mixes having high percentages of RAP (recycled binder percentage of 30-35%), the E & R asphalt binders had a PG 70-22. For mixes having the same high percentages (recycled binder percentage of 30-35%) by using RAP and RAS, the E & R asphalt binders showed more increase in the high PG temperature that reached a value of 76°C. This illustrates that using both RAP and RAS can significantly alter the properties of the E & R asphalt binders (Rodezno & Grant, 2018). Sadek et al. (Sadek et al., 2020) compared the rheological properties of the asphalt binders E & R from the plant- and lab-produced mixes containing RAP at high, intermediate, and low temperatures using multiple stress creep recovery (MSCR), linear amplitude sweep (LAS), and bending beam rheometer testing, respectively. It was reported that the properties were different at the high and intermediate temperatures. Mullapudi et al. (Mullapudi et al., 2019) have mixed different proportions of extracted and recovered RAP binders with virgin asphalt binders. The authors (Mullapudi et al., 2019) found that the oxygenated functional groups' indices, IS=O and IC=O, increased with increasing RAP binders' percentages. Increasing the RAP binder's percentage in the mix had increased the asphalt binders' rutting resistance by increasing the complex shear modulus (|G*|), high PG temperature, recovery percentages (%R), and decreased the phase angle (δ) and the non-recoverable creep compliance (Jnr).

The oxidative functional groups [e.g. sulfoxide (S=O) and carbonyl (C=O)] in asphalt binders' Fourier Transform Infrared (FTIR) spectra can reflect the aging condition. Poulikakos et al. (Poulikakos et al., 2019) proved that increasing the aging process of asphalt binders led to a higher intensity of these functional groups. The rolling thin film oven (RTFO) aging process in the lab at 163°C underrates the chemical aging as compared to binders E & R from the HMA. The authors (Poulikakos et al., 2019) recommended using the sulfoxide index to represent short-term aging. A good correlation was observed between the mechanical and the chemical properties, IS=O & IC=O (Mullapudi et al., 2019).

Piérard et al. (Piérard et al., 2010) investigated the effect of the extraction process on the asphalt binder content. Styrene-butadiene-styrene or ethyl vinyl acetate modified asphalt binders were extracted from fresh, short-term aged, and compacted mixtures prepared in the laboratory. Two asphalt binder and aggregate types were used. Different solvents like toluene, dichloromethane, and TCE were used to extract binders. The average extracted content of asphalt binder, regardless of the solvent, was 6.3 ± 0.2% that is considered a relative decrease of around

5% compared to the initial binder content (6.6%). The FTIR results showed that the asphalt binder content decrease was not related to the decreases in the polymer content since the intensity of the released polymer's peaks were similar for the modified binder used in the preparation of mixtures and the recovered one. Toluene and TCE are preferable to dichloromethane. No appreciable effect of the aggregate type and/or the compaction process was noted on the percentage of the extracted binder. Moreover, the percentage of the extracted binder from short-term aged mixtures depended mainly on the type of the asphalt binder and the selected solvent. The recovery process of asphalt binder from asphalt binder and solvent combinations is very sensitive. The recovery process should be terminated when no traces of solvents (e.g. TCE) are observed. These residues even with small amounts could affect the recovered asphalt binder's rheological properties. Nösler et al. (Nösler et al., 2008) had found a decrease in the ring and ball softening point by 6°C because of the presence of TCE in the recovered binder by a percentage of 0.9% by weight. On the other hand, the over-cooking recovery process is also not preferred since this will produce an asphalt binder that is excessively aged (Li et al., 2014; Zhou, Li, et al., 2012).

Sirin and Tia (Sirin & Tia, 2003) evaluated the effect of the extraction process using reflux on the extracted percentage of asphalt binder from field and lab asphalt mixtures containing crumb rubber modifier (CRM). Mixtures modified with CRM had an actual asphalt binder content of 6.34% and a CRM percentage of 0.76%, which was a total of asphalt and CRM content of 7.1% by the weight of the mix. Conventional mixtures with only an asphalt binder percentage of 6.34% were evaluated. The authors have concluded that the extracted asphalt binder percentage was lower than the actual one either for the mixtures modified with CRM or the conventional ones (without CRM modification). For the mixes modified with CRM, an average asphalt binder and CRM percentage (not extracted) was found to be 0.86%. For conventional mixes, an average asphalt binder not extracted percentage of 0.25% was obtained. Thus, the average percentage of CRM that remained in the reflux was 0.61% (0.86-0.25%) out from a CRM percentage of 0.76% by the weight of the mixture. This illustrates that existence of recycled materials like CRM in the asphalt mixes would make the extraction process of the asphalt binders from these mixes more difficult.

A.2. Binder test and results

A.2.1. Characterizing the Asphalt Binders Extracted and Recovered from the Field Mixes

Constructed before 2016

In this section, the asphalt binders E & R from the US 63-2, US 50-1, US 54-8, MO 52-1, and US 54-7 field mixes, presented in, and the field mixes presented in Table 2- are compared. These binders were treated as PAV aged binders. Unfortunately, the virgin binders used in these mixes were not available to be compared with the E & R asphalt binders.

A.2.1.2. Properties of Asphalt Binders E & R from Field Mixes Constructed before 2016

The temperature sweep test results for the E & R binders from field mixes containing RAP and RAS are illustrated in Figure A-2. Both US 63-2 and MO 151 mixes contained asphalt binders with the same PG (64-22). Moreover, US 63-2 and MO 151 mixes were 8 and 9 years old, respectively. Thus, the asphalt binders E & R from the MO151 mixes showed lower resistance to fatigue cracking than the US 63-2 E & R binders. This was reflected from the trendlines in Figure A-2-b because the MO 151 binders had slopes lower than the slope of the trendlines in Figure A-2-a for the US 63-2 binders. The same results were noted in Figure A-3 by comparing the fatigue cracking parameters (|G*|.sinδ) for the E & R asphalt binders at 22°C. Another reason was the higher percentage of recycled materials included in the MO 151 mixes.

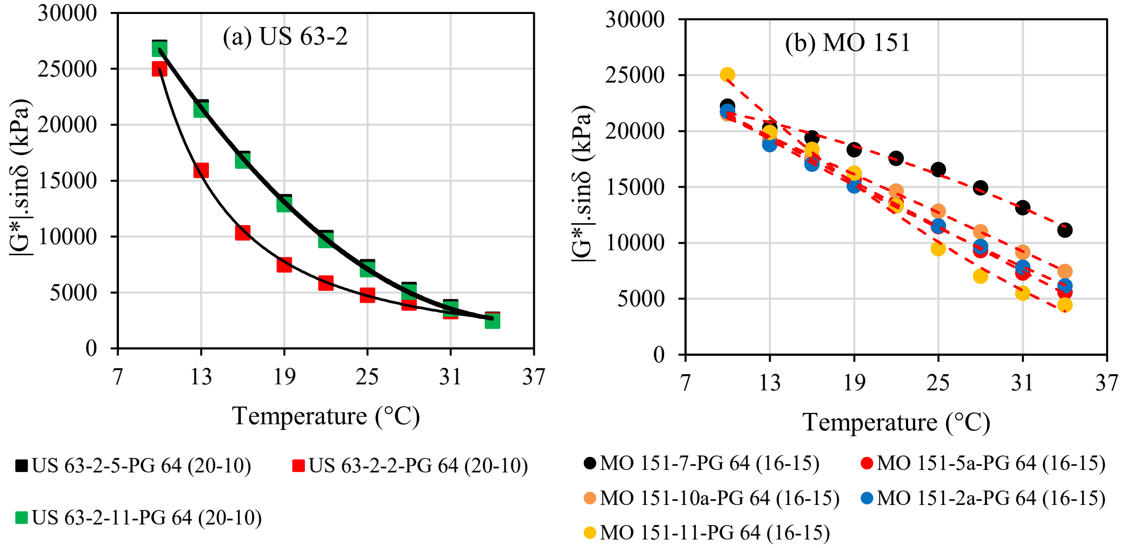


Figure A-2. Temperature Sweep Test Results for the E & R Asphalt Binders from US 63-2 and MO 151 Field Mixes, Constructed before 2016, Containing RAP and RAS

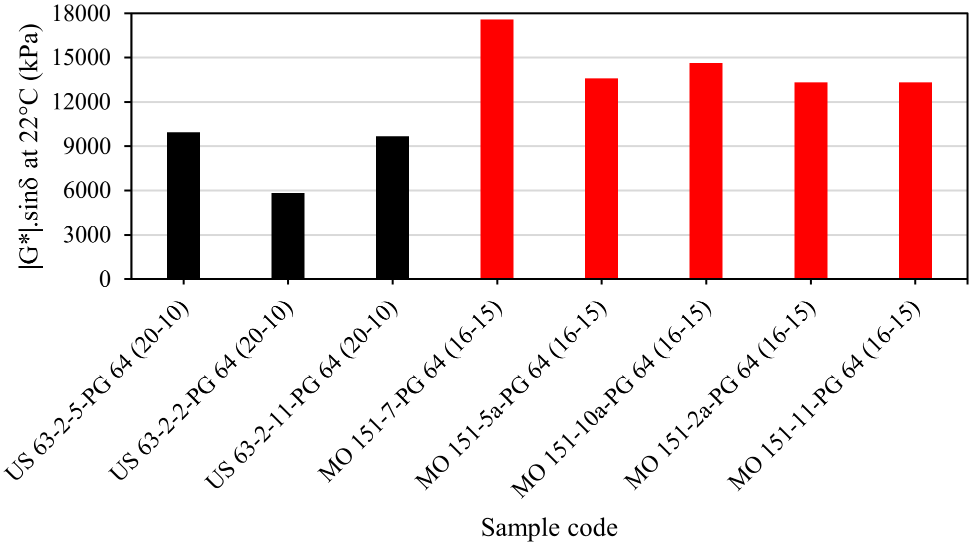


Figure A-3. Fatigue Cracking Parameter for the E & R Asphalt Binders from US 63-2 and MO 151 Field Mixes, Constructed before 2016, Containing RAP and RAS Measured at 22°C

Figure A-4 shows the master curve, fatigue cracking parameter measured at different frequencies (100 to 0.1 rad/sec) and reference temperature (22°C), for the E & R asphalt binders from US 63 and MO 151 field mixes. The extracted asphalt binders from MO 151 showed higher stiffness as compared to binders E & R from US 63-2 mixes at low frequencies. At high frequencies, no significant difference was observed.

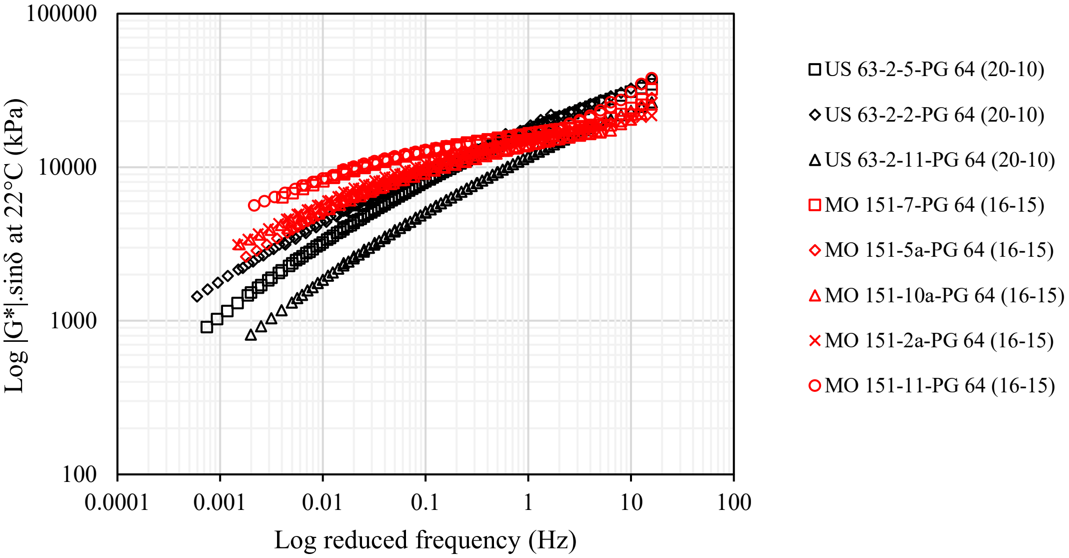


Figure A-4. Master Curve for the E & R Asphalt Binders from US 63-2 and MO 151 Field Mixes, Constructed before 2016, Containing RAP and RAS Measured at 22°C

The temperature sweep results for asphalt binders E & R from field mixes containing RAP only are presented in Figure A-5. The mixes contained different asphalt binders and different RAP percentages. By analyzing the fatigue cracking parameter at a reference temperature (22°C), presented in Figure A-6, it can be concluded that asphalt binders E & R from MO 6 mixes had the highest resistance to fatigue cracking. These binders showed the lowest |G*|.sinδ values in Figure A-5 and Figure A-6. The MO 6 mixes contained the highest ABR percentage by RAP (30%), but they had a soft asphalt binder (PG 58-28) and were 4 years old during the sampling process. Although both MO 6 and US 61N mixes have the same ABR (30% RAP), the asphalt binders E & R from the US 61N mixes showed lower resistance to fatigue cracking as compared to binders E & R from MO 6 mixes. This occurred because the US 61N mixes were older than the MO 6 mixes by 2 years and contained a stiffer virgin asphalt binder (PG 64-22H). The same results can be observed from the master curve in Figure A-7: asphalt binders E & R from US 61N mixes showed higher |G*|.sinδ values as compared to binders E & R from MO 6 mixes.

The worst resistance to fatigue cracking at 22°C was recorded to the asphalt binders E& R from US 54-12a and US 54-6a mixes. Both mixes were 9 years old during the sampling process and they included a stiff asphalt binder (PG 70-22); however, the mixes included 12% ABR percentage by RAP. This illustrates that using asphalt binders having a high PG temperature of 70 or higher is not recommended in the case of using recycled materials. The master curve, Figure A-7, shows the same results because the asphalt binders E & R from US 54 mixes showed the highest fatigue cracking parameter values.

The US 50-1 and US 36 mixes contained virgin asphalt binders with the same PG (64-22) and had the same ABR percentage by RAP. The US 36 mixes were older than the US 50-1 mixes by 3 years. Thus, the trendlines for these binders, presented in Figure A-5-c and Figure A-5-d, were different especially at the lowest temperature (10°C). However, the asphalt binders E & R from these mixes had approximately the same |G*|.sinδ values measure at 22°C, Figure A-6. The same results were observed in the master curve, Figure A-7.

Asphalt binders E & R from US 54-8 mixes showed better resistance to fatigue cracking than the asphalt binders E & R from the US 36 mixes. However, the US 54-8 mixes were older than the US 36 mixes by 2 years. Moreover, US 54-8 mixes contained a stiffer virgin asphalt binder as compared to the asphalt binders included in the US 36 mixes. This was related to the higher percentage of RAP included in the US 36 mixes. The US 36 mixes contained ABR percentage by RAP two and a half times greater than the ABR percentage by RAP included in the US 54-8 mixes. The same observations were deduced from the master curve in Figure A-7.

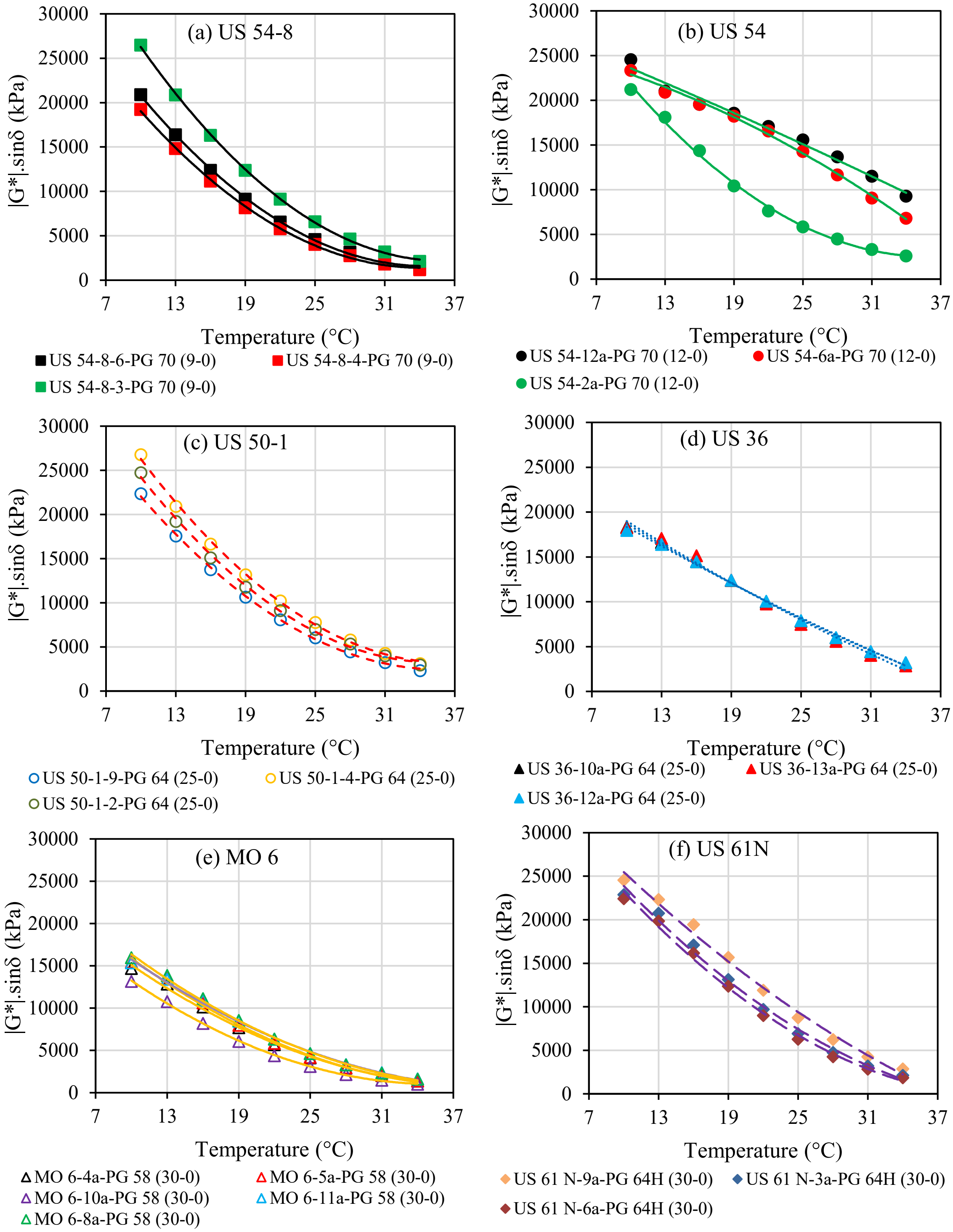


Figure A-5. Temperature Sweep Test Results for the E & R Asphalt Binders from Field Mixes, Constructed before 2016, Containing Different Percentages of RAP

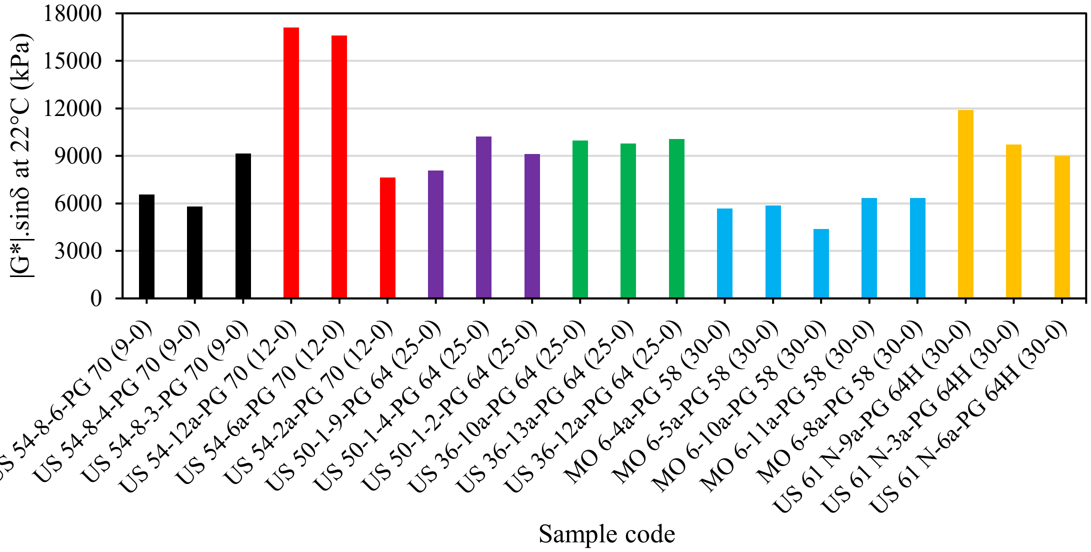


Figure A-6. Fatigue Cracking Parameter for the E & R Asphalt Binders from Field Mixes, Constructed before 2016, Containing Different Percentages of RAP and Measured at 22°C

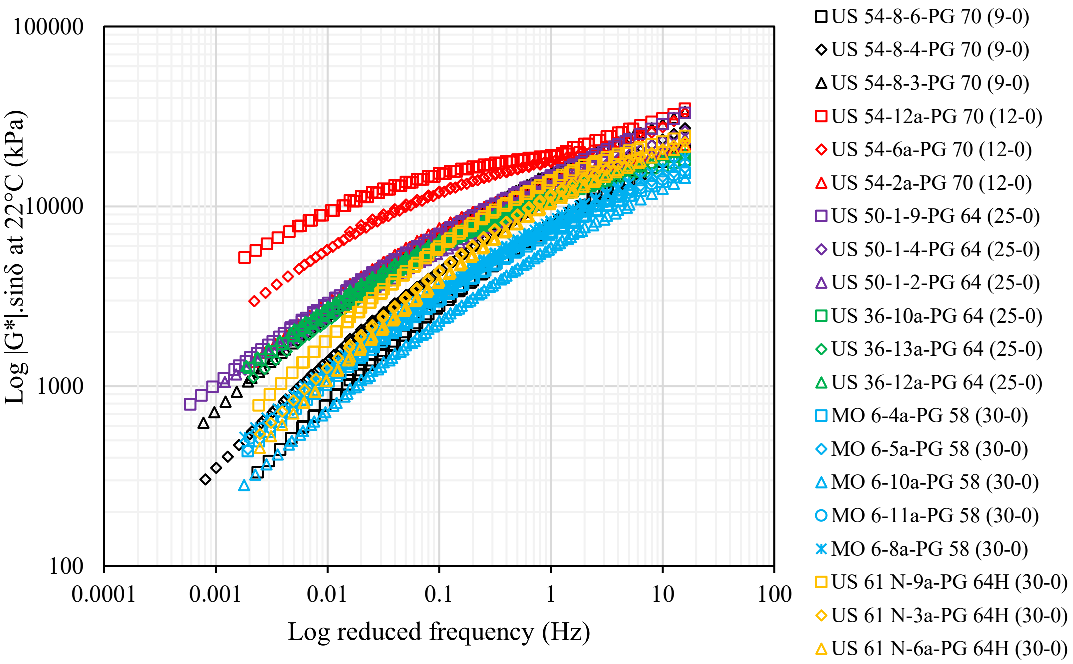


Figure A-7. Master Curve for the E & R Asphalt Binders from Field Mixes, Constructed before 2016, Containing Different Percentages of RAP and Measured at 22°C

Figure A-8 shows the temperature sweep results for the E & R asphalt binders from mixes containing 34% ABR percentage by RAS and virgin asphalt binder PG 64-22. These mixes were 6 years old during the sampling process. The fatigue cracking parameter for these binders measured at 22°C is presented in Figure A-9. The master curve for the E & R binders is shown in Figure A-10. These results were similar to the results of the E & R asphalt binders from US 54-8 mixes containing 9% ABR by RAP, a stiffer asphalt binder (PG 70-22), and were 10 years old during the sampling process.

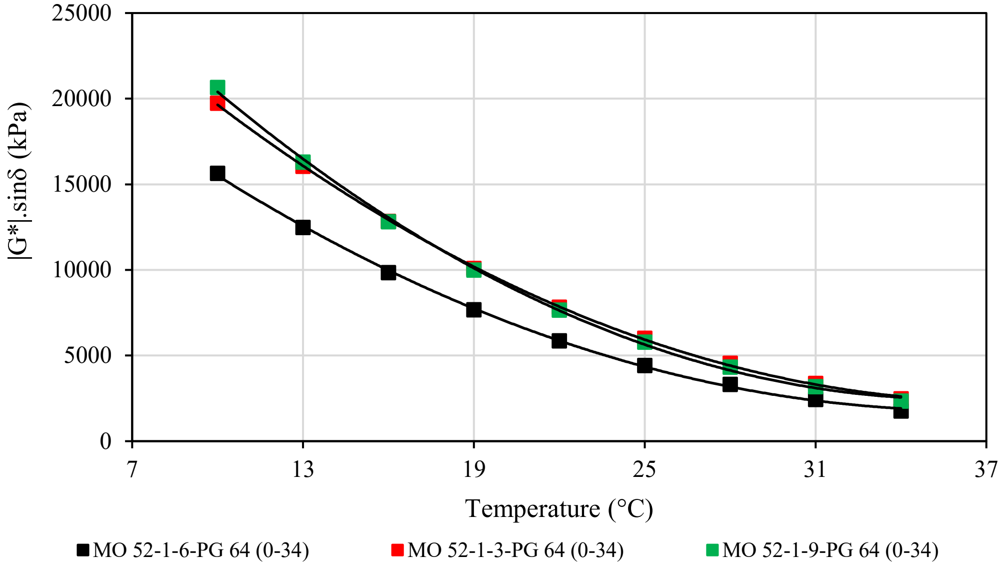


Figure A-8. Temperature Sweep Test Results for the E & R Asphalt Binders from MO 52-1 Field Mixes, Constructed before 2016, Containing 34% ABR Percentage by RAS

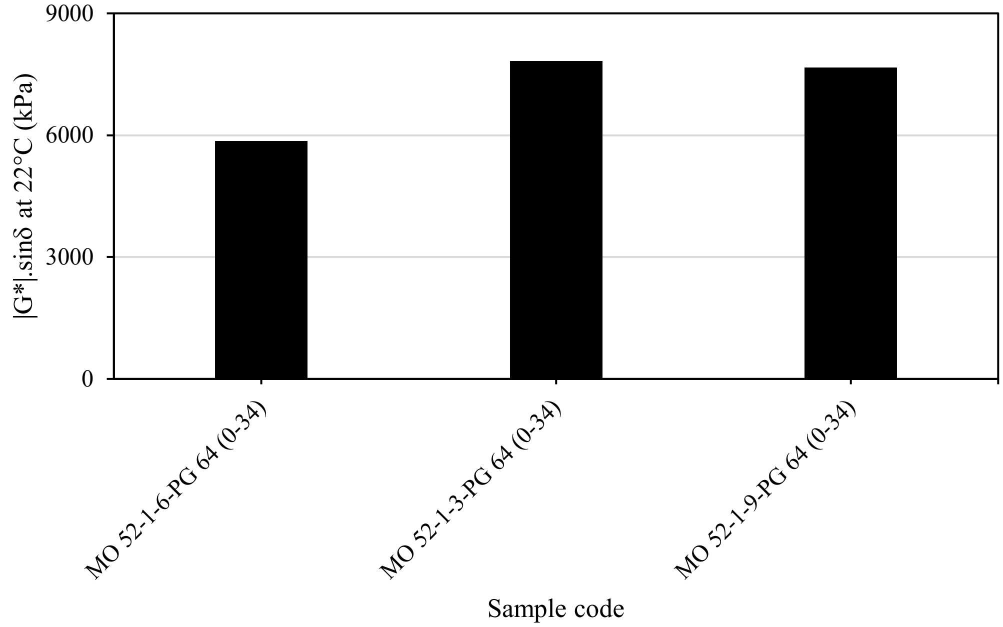


Figure A-9. Fatigue Cracking Parameter for the E & R Asphalt Binders from Field Mixes, Constructed before 2016, Containing 34% ABR Percentage by RAS and Measured at 22°C

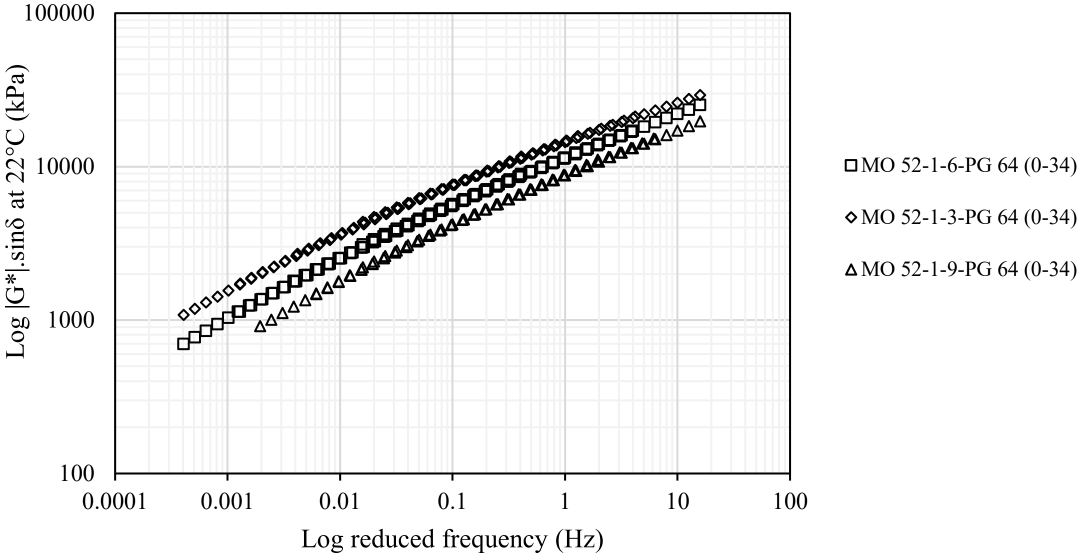


Figure A-10. Master Curve for the E & R Asphalt Binders from Field Mixes, Constructed before 2016, Containing 34% ABR Percentage by RAS and Measured at 22°C

Figure A-11 shows the temperature sweep test results for the asphalt binders E & R from US 54-7 and MO 94 mixes containing neither RAP nor RAS. The US 54-7 and MO 94 mixes were 13 and 14 years old during the sampling process. Thus, the E & R asphalt binders from US 54-7 mixes showed higher fatigue cracking resistance than the asphalt binders E & R from MO 94 mixes. The same results were noted in Figure A-12 and Figure A-13 by comparing the fatigue cracking parameter for the E & R binders from these mixes at 22°C. A similar rank in cracking performance was also noted in mixture testing. In addition, the US 54-7 mix, in general, displayed the best cracking performance of all field cores evaluated in a previous study (Buttlar et al., 2019).

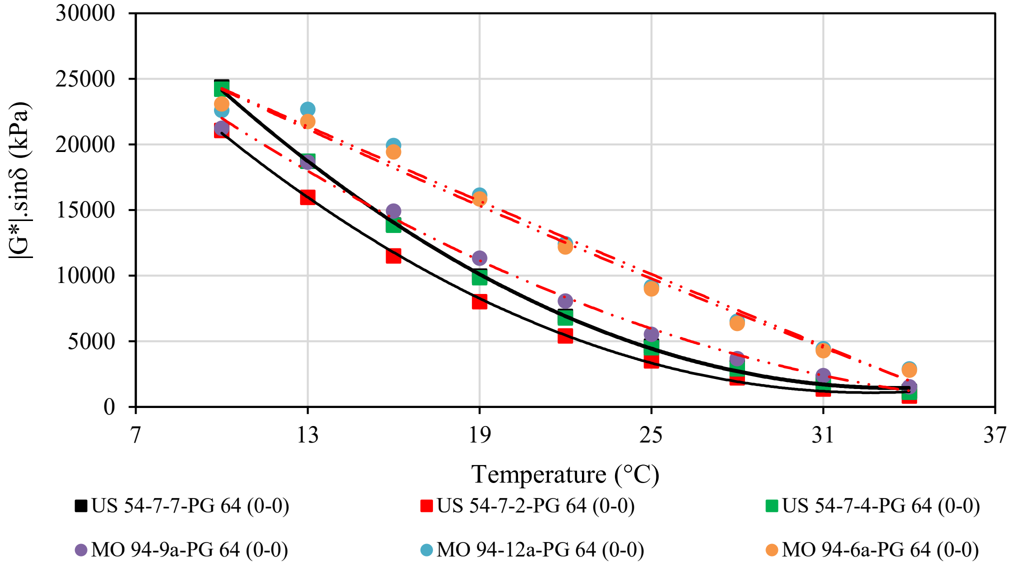


Figure A-11. Temperature Sweep Test Results for the E & R Asphalt Binders from US 54-7 and MO 94 Field Mixes, Constructed before 2016, Containing Neither RAP nor RAS

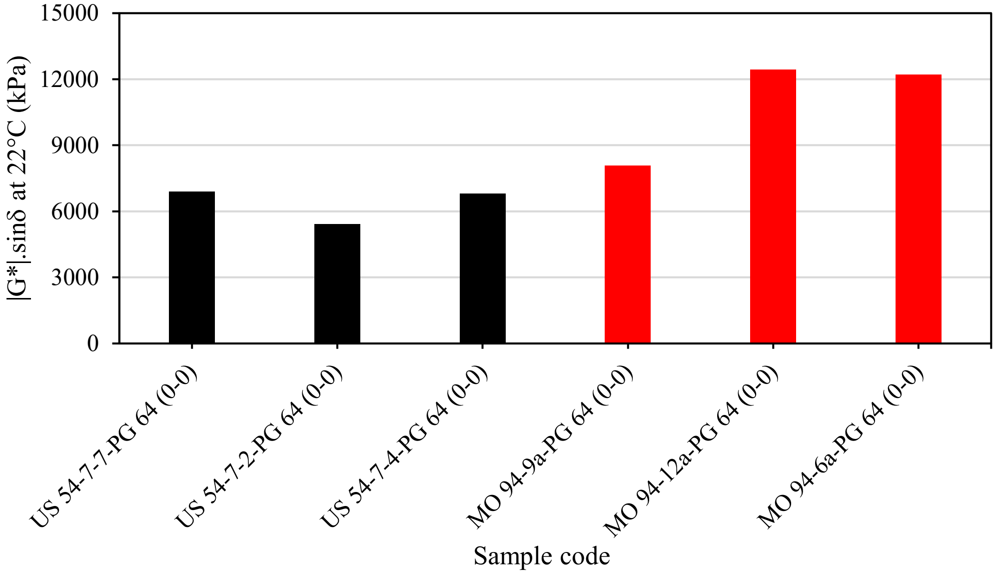


Figure A-12. Fatigue Cracking Parameter for the E & R Asphalt Binders from US 54-7 and

MO 94 Field Mixes, Constructed before 2016, Containing neither RAP nor RAS Measured at 22°C

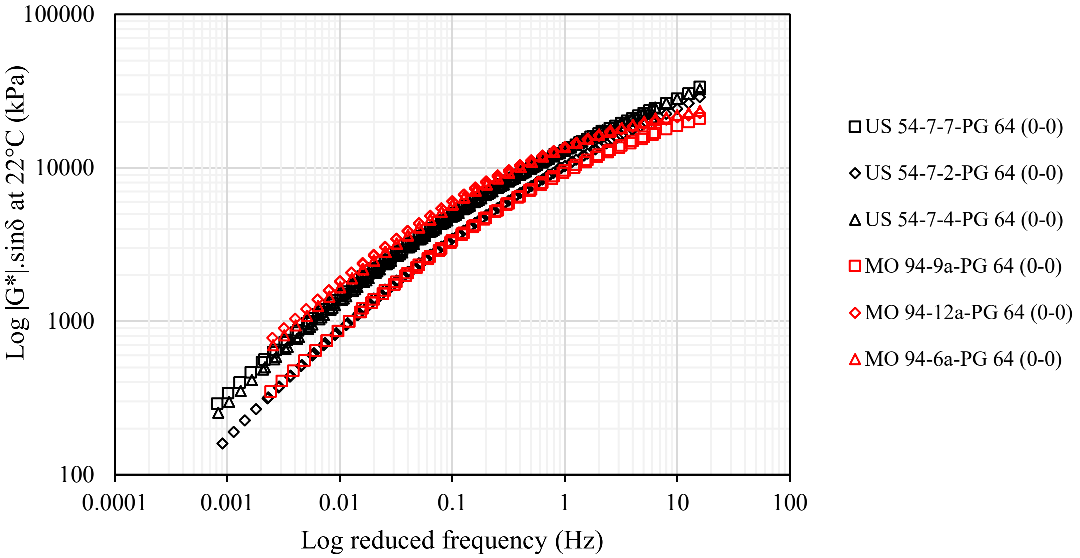


Figure A-13. Master Curve for the E & R Asphalt Binders from US 54-7 and MO 94 Field Mixes, Constructed before 2016, Containing neither RAP nor RAS and Measured at 22°C

To compare the E & R binders from field mixes constructed before 2016, Figure A-14-a illustrates the intermediate PG temperatures for the E & R binders from mixes containing no recycled materials and PG 64-22 virgin asphalt binders. The US 54-7 and MO 94 mixes were 13 and 14 years old during the sampling process. Therefore, the asphalt binders E & R from the US 54-7 mixes presented higher resistance to fatigue cracking than the binders E & R from the MO 94 mixes. This was affirmed by lower intermediate (Figure A-14-a) PG temperatures and a higher number of load repetitions to failure (N_f) at 2.5 and 5% strain levels and 22°C temperature, Figure A-14-b.

Figure A-15 presents the intermediate PG temperatures and the N_f values (measured at 2.5 and 5% strain levels and 22°C temperature) for the asphalt binders E & R from mixes containing different ABR percentages by RAP and different virgin asphalt binders. By comparing Figure A-15-a and Figure A-15-b, it was concluded that E & R asphalt binders from different mixes can have the same intermediate PG temperature; however, the N_f values could be significantly different (e.g. binders E & R from the US 54-8 and MO 6 mixes). The lowest resistance for fatigue cracking (the highest intermediate PG temperature and the lowest N_f values) was recorded for asphalt binders E & R from the US 54 mixes. These mixes were 9 years old during the sampling process, contained 12% ABR percentage by RAP, and included PG 70-22 asphalt binder. The asphalt binder E & R from US 54-12a-PG 70 (12-0) shows a zero N_f value, which represents a failure for this sample to resist fatigue cracking at 22°C. This failure is shown in Figure A-16. The asphalt binders E & R from US 54-8 mixes showed higher resistance to fatigue cracking than the binders E & R from the US 54 mixes. This occurred because the US 54-8 mixes contained lower ABR percentage by RAP than the US 54 mixes; however, the US 54-8 mixes were older than US 54 mixes by 1 year. The highest resistance to fatigue cracking was recorded for asphalt binders E & R from the MO 6 mixes. These mixes were 4 years old during the sampling process and contained PG 58-28 virgin asphalt binder; however, they had a high percentage of recycled materials (30% ABR percentage by RAP). The US 61N and MO 6 mixes had the same ABR percentage by RAP (30%). However, the values for the N_f, at 2.5% strain level, for the asphalt binders E & R from the US 61N mixes decreased by 75% as compared to the values for the binders E & R from the MO 6 mixes. This returned to the high stiffness of the virgin asphalt binder included in the US 61 N mixes (PG 64-22H); however, the MO 6 mixes contained a softer asphalt binder (PG 58-28). Moreover, the MO 6 mixes were newer than US 61 N mixes by 2 years during the sampling process. The US 36 mixes were older than the US 61 N mixes by 2 years; however, the binders E & R from the US 36 mixes showed a higher resistance to fatigue cracking than binders E & R from the US 61 N mixes. This was related to the low ABR percentage by RAP included in the US 36 mixes, which was 25%. Moreover, they contained a softer asphalt binder (PG 64-22).

The asphalt binders E & R from mixes containing no recycled materials, Figure A-14, showed non-zero N_f values. However, these mixes were greater than or equal to 13 years old during the sampling process. Thus, these mixes were nearing the end of a typical asphalt overlay life. However, incorporating stiffer asphalt binders and/or using RAP, Figure A-15, deteriorated the resistance to fatigue cracking significantly. This was noted for asphalt binder E & R from US 54-12a-PG 70 (12-0) mix, which had zero N_f values at 2.5 and 5% strain levels.

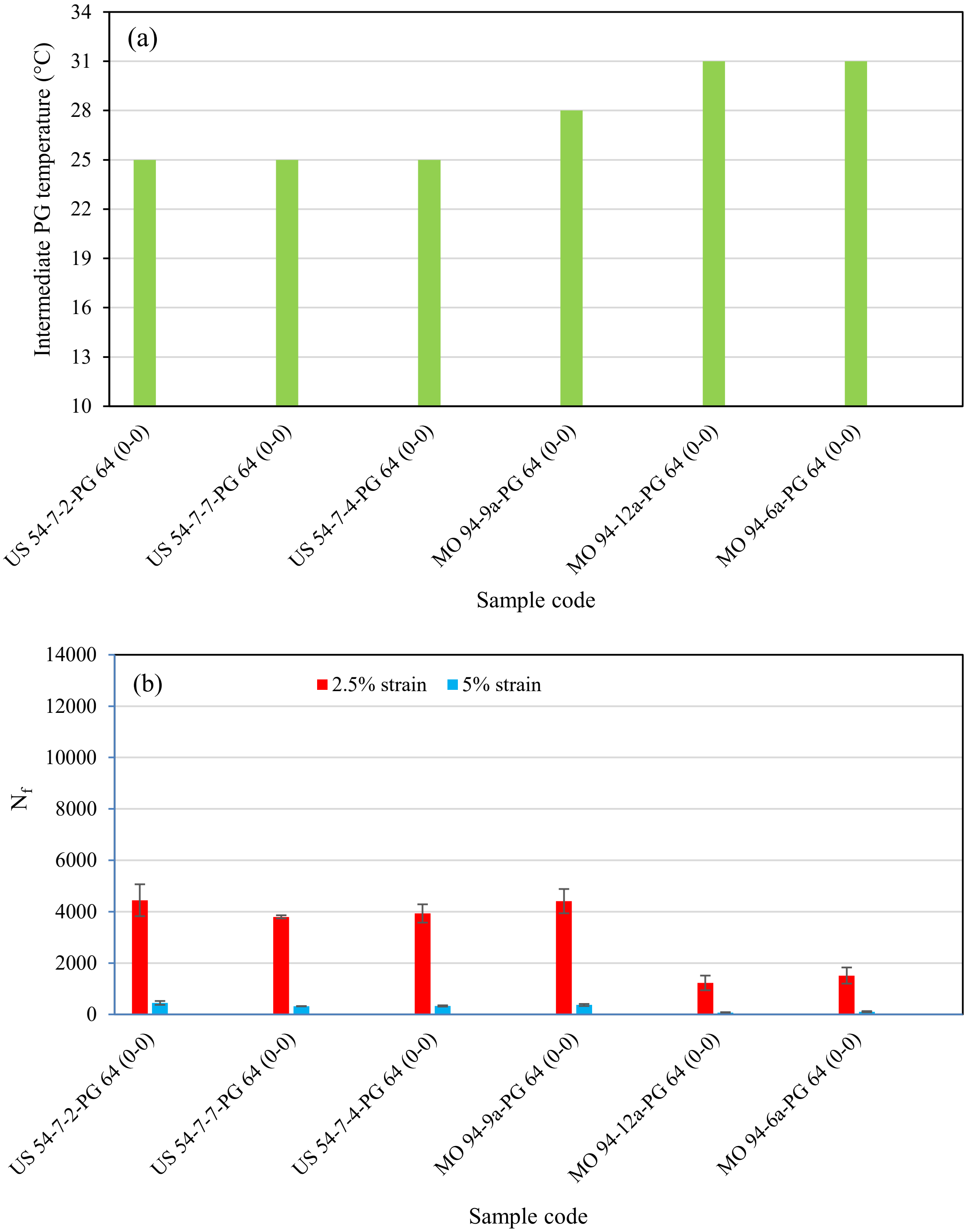


Figure A-14. (a) Intermediate PG Temperatures in °C and (b) N_f at 2.5 and 5% Strain and 22°C Temperature for Asphalt Binders E & R from Field Mixes, Constructed before 2016, Containing no Recycled Materials

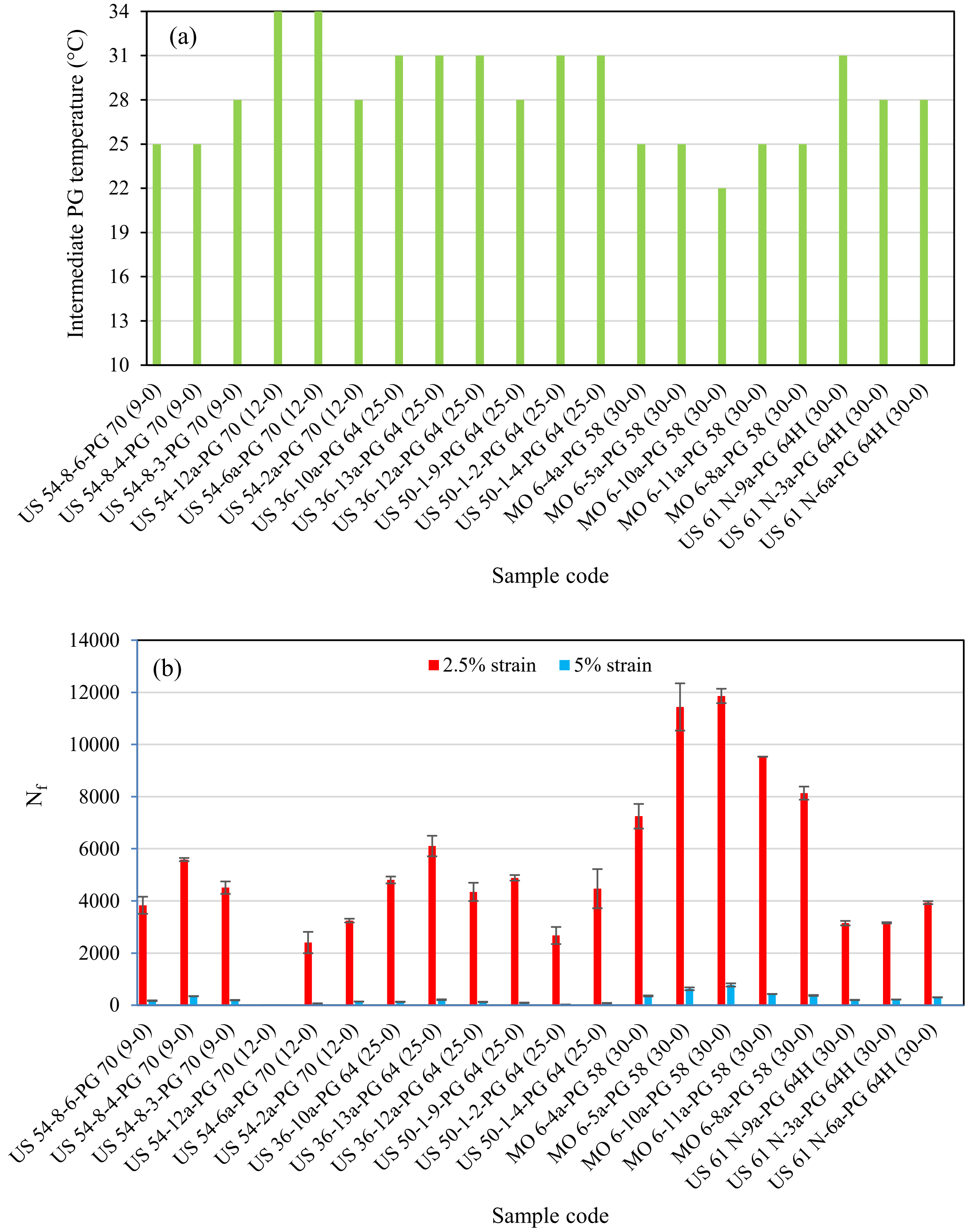


Figure A-15. (a) Intermediate PG Temperatures in °C and (b) N_f at 2.5 and 5% Strain and 22°C Temperature for Asphalt Binders E & R from Field Mixes, Constructed before 2016, Containing Different ABR Percentages by RAP

Note: The asphalt binders E & R from the US 54-12a-PG 70 (12-0) and US 54-6a-PG 70 (12-0) mixes had intermediate PG temperature greater than 34°C.

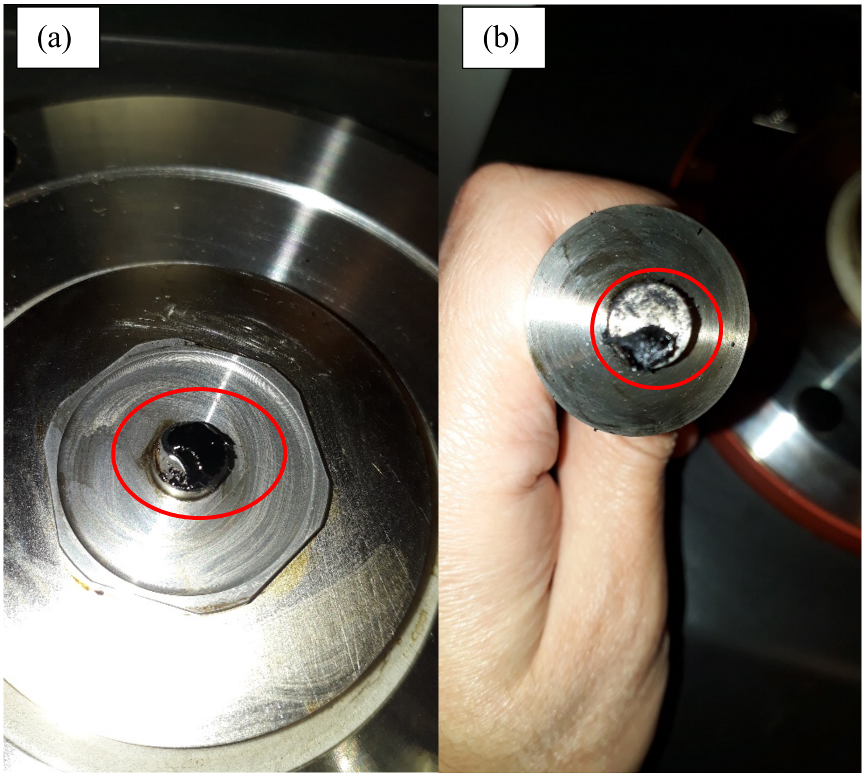


Figure A-16. Fatigue Failure for Asphalt Binder E & R from the US 54-12a-PG 70 (12-0) Mix at 22°C; (a) Sample Failure at the DSR Lower Plate and (b) Sample Failure at the DSR Upper Plate

Figure A-17 illustrates the intermediate PG temperatures and Nf values, measured at 2.5 and 5% strain levels and 22°C temperature, for the asphalt binders E & R from mixes containing 34% ABR percentage by RAS. The MO 52-1and US 50-1 mixes had asphalt binders with the same PG (64-22). The MO 52-1 mixes were older than US 50-1 mixes by 1 year. Moreover, the MO 52-1 mixes had a higher percentage of recycled materials, 34% ABR by RAS, than the percentage included in the US 50-1 mixes (25% ABR by RAP). However, the asphalt binders E & R from mixes containing RAS showed higher resistance to fatigue cracking than binders E & R from mixes containing RAP. This reflects that using RAS in the asphaltic mixes enhanced the resistance of the E & R asphalt binders to fatigue cracking as compared to binders E & R from mixes containing RAP. This is a somewhat counter-intuitive result, as RAS was shown before to greatly increase binder stiffness. On the other hand, RAS binders may be very different than typical paving-grade binders in that they are generally air-blown, may contain polymers, and some amount of fibers may be present even after E&R is performed.

Figure A-18 shows the intermediate PG temperatures and N_f values, measured at 2.5 and 5% strain levels and 22°C temperature, for the asphalt binders E & R from mixes containing different ABR percentages by RAP-RAS. The mixes were greater than or equal to 8 years old during the sampling process. Thus, the N_f values for binders E & R from some MO 151 mixes were zero.

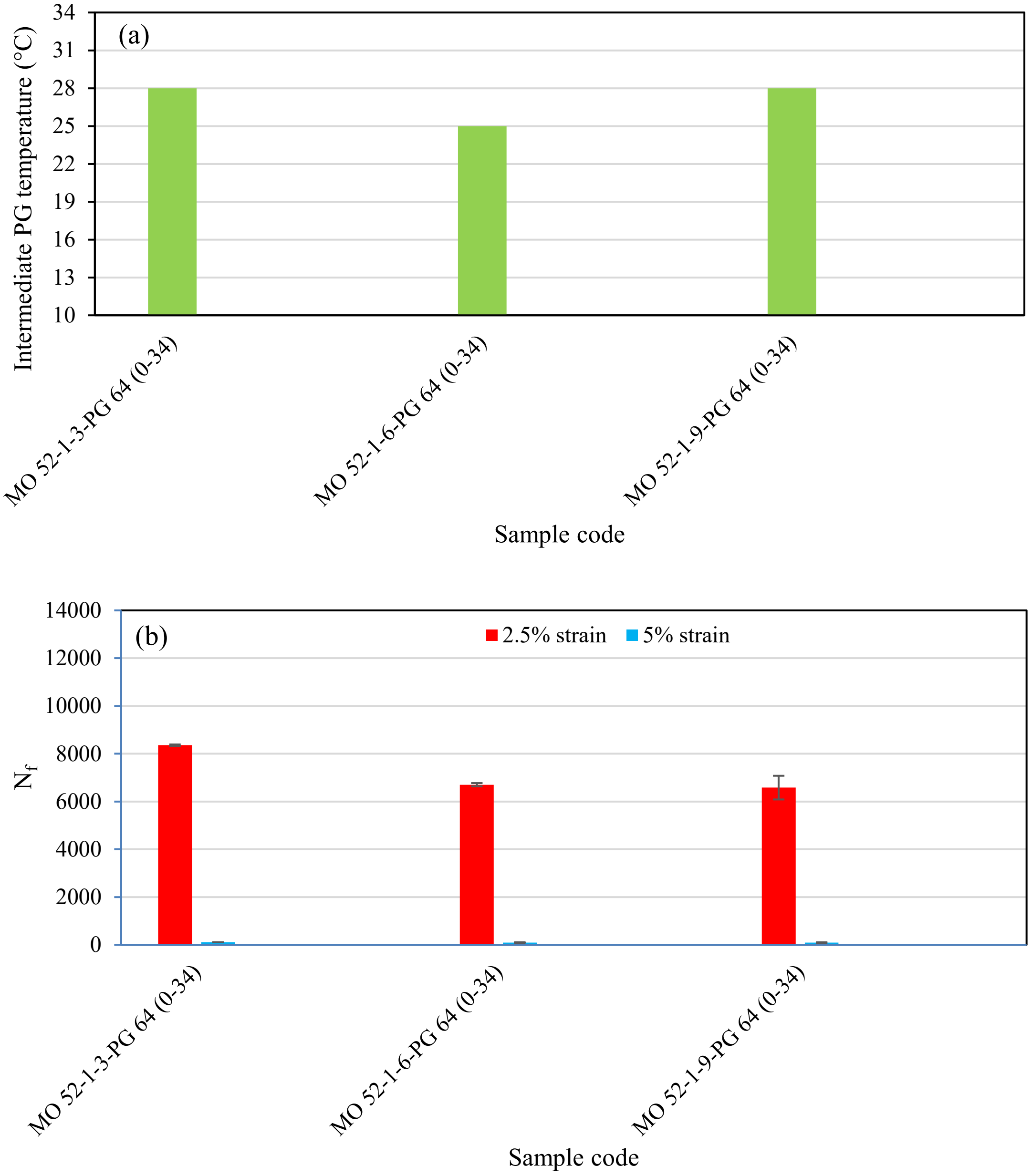
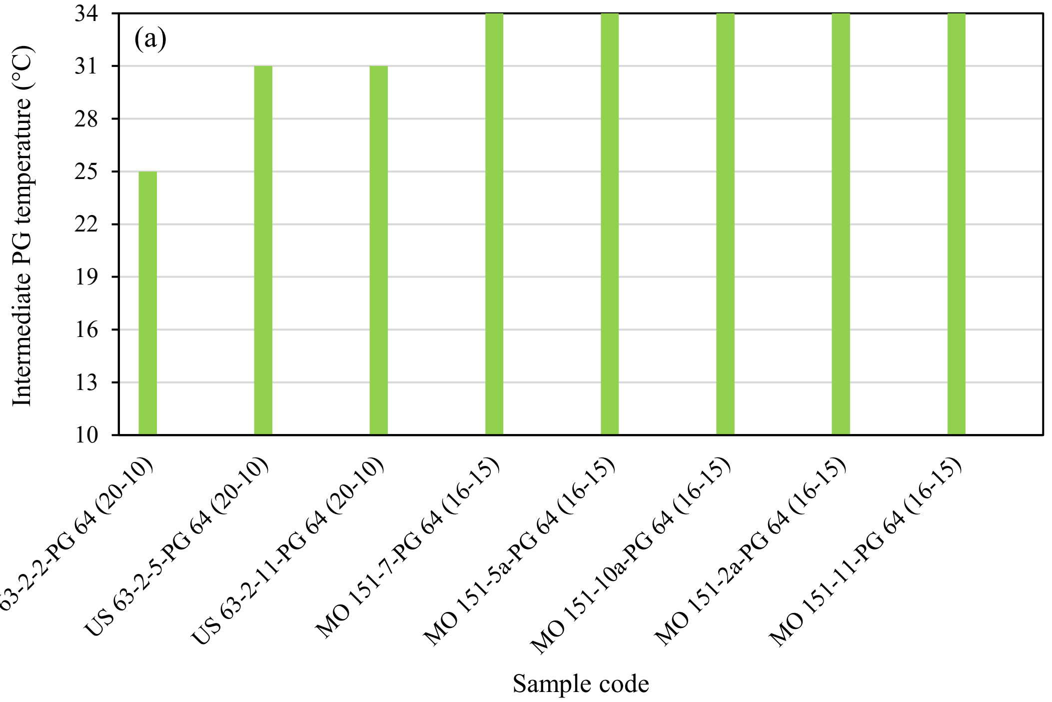


Figure A-17. (a) Intermediate PG Temperatures in °C and (b) N_f at 2.5 and 5% Strain and 22°C Temperature for Asphalt Binders E & R from Field Mixes, Constructed before 2016, Containing 34% ABR Percentage by RAS



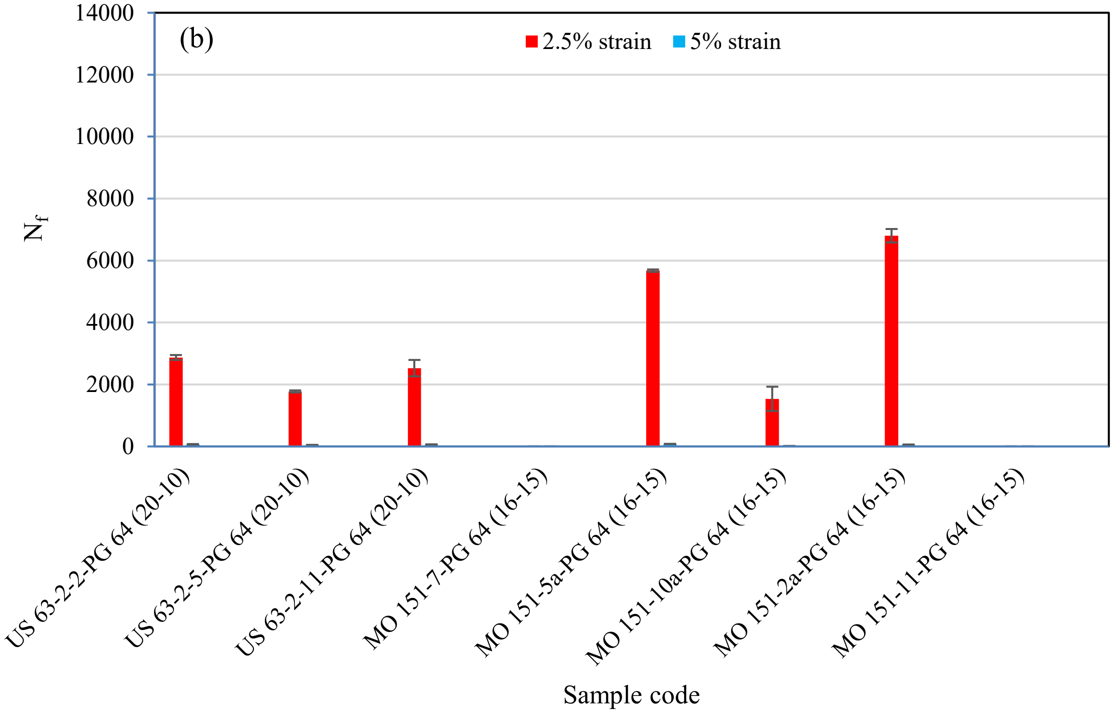


Figure A-18. (a) Intermediate PG Temperatures in °C and (b) N$_f$ at 2.5 and 5% Strain and 22°C Temperature for Asphalt Binders E & R from Field Mixes, Constructed before 2016, Containing Different ABR Percentages by RAP-RAS

Note: The intermediate PG temperature exceeded 34°C for asphalt binders E & R from the MO 151-7-PG 64 (16-15), MO 151-5a-PG 64 (16-15), MO 151-10a-PG 64 (16-15), and MO 151-2a-PG 64 (16-15) mixes.

A.2.2. Relating Asphalt Binders Extracted and Recovered from Field, Plant, and Lab Mixes to the Corresponding RTFO Aged Virgin Asphalt Binders

In this section, the asphalt binders E & R from the US 54-6 and US 63-1 field, plant, and lab mixes were compared to the RTFO aged virgin asphalt binders. The field and plant mixes contained 31 and 35% ABR percentages by RAP. The asphalt binders E & R from the field mixes were treated as RTFO aged asphalt binders because the samples were collected within two weeks after the construction process in 2016. Moreover, the asphalt binders E & R from the lab and plant mixes were analyzed as RTFO aged asphalt binders. For lab mixes containing Engineered Crumb Rubber (ECR), a type of dry-process ground tire rubber (GTR), it was observed that part of the rubber particles remained with the aggregate, the second part of the particles dissolved in the asphalt binder, and the third part was extracted with the effluent. Figure A-19 illustrates the ECR particles that remained with the aggregate and extracted with the effluent. A fraction of the recovered ECR rubber particles were first observed in the recovered aggregates. A second fraction of the rubber particles were present in the E&R asphalt binder, which enhances binder stiffness, elasticity, and strength. A third fraction was observed in the metal cup along with the mineral matter collected in the filterless centrifuge process. Thus, it is difficult to properly assess GTR effects on binders in a forensic manner, as not all of the binder ends up in the E&R binder sample. This reinforces the importance of mixture testing, particularly testing that can be readily done on field-produced samples.

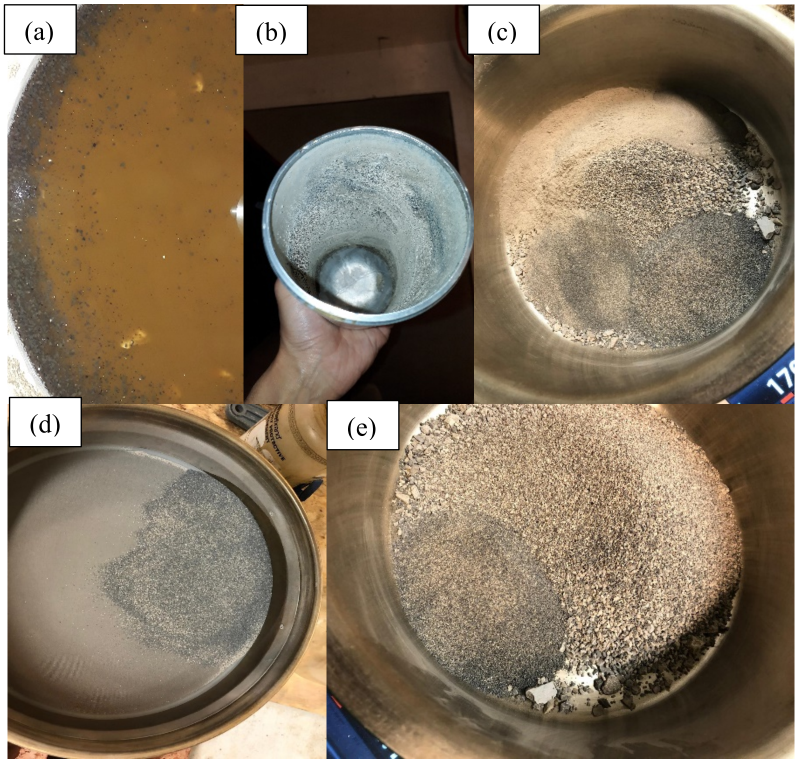


Figure A-19. The Extracted Rubber Particles; (a) Particles Suspended with the TCE in the Extractor Bowl, (b) Particles with the Mineral Matter in the Metal Cup after the Filterless Centrifuge Process, and (c, d, and e) Particles Remaining with the Aggregate

A.2.2.1. Extraction of the Asphalt Binders from Field, Plant, and Lab Mixes

The actual and extracted AC% are presented in Figure A-20 for the US 54-6 field, plant, and lab mixes using different MMDMs. The actual AC for field, plant, and lab mixes was 5.1%; however, some lab mixes had actual AC% of 5.2 and 5.5%. The extracted AC percentages using ashing MMDM, presented in Figure A-20-a, were between 4.4 and 6%. The centrifuge MMDM, Figure A-20-b, presents more accurate extracted AC percentages that were between 4.8 and 5.6%. Figure A-20-c shows the extracted AC percentages by calculating the mineral matter using both ashing and centrifuge MMDMs. The ashing MMDM underestimated the extracted AC% for US 54-6 mixes. Thus, most of the extracted AC percentages in Figure A-20-a and Figure A-20-c were lower than the actual AC percentages.

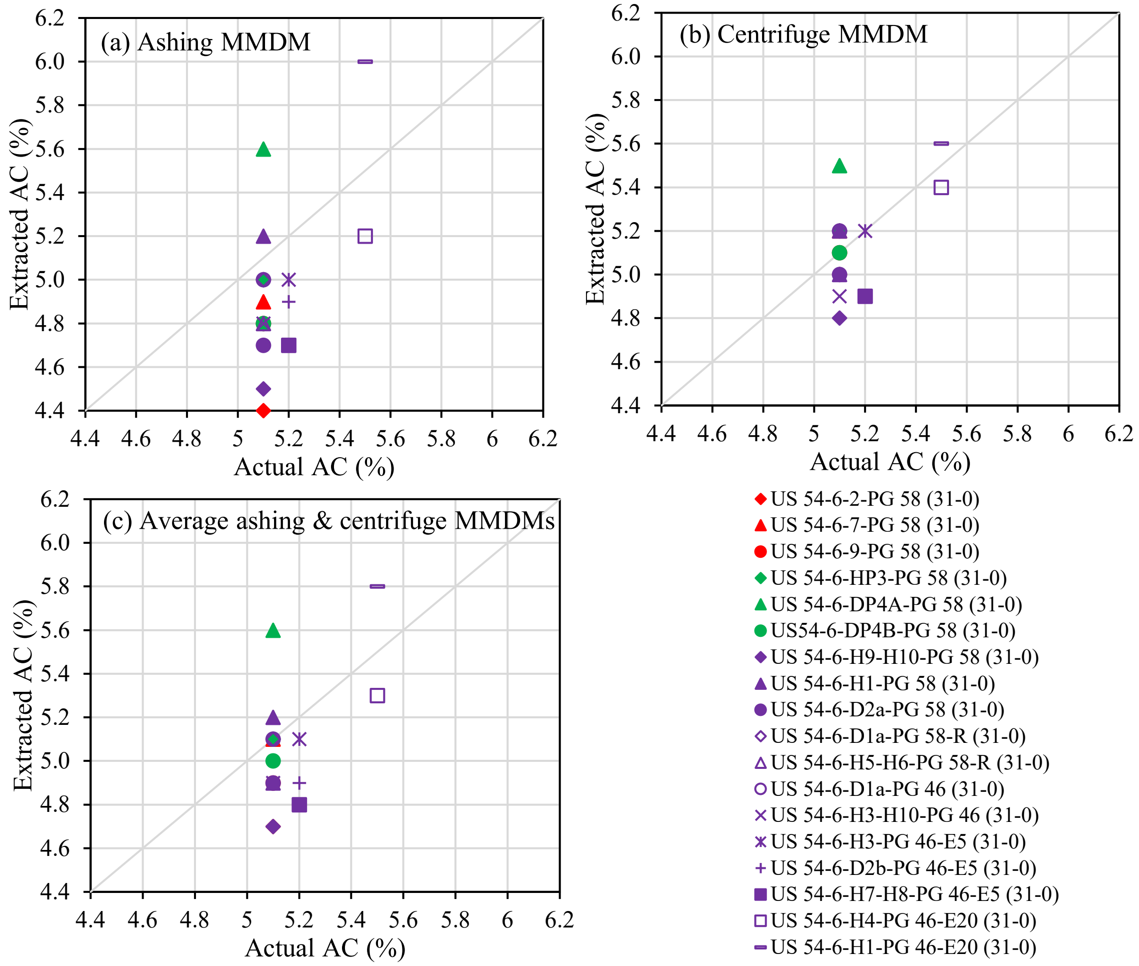


Figure A-20. Actual vs Extracted AC% using Different MMDMs for the US 54-6 Field, Plant, and Lab Mixes

The actual AC vs extracted AC percentages for the US 63-1 field, plant, and lab mixes are illustrated in Figure A-21. The actual AC for field, plant, and lab mixes was 5.1%; however, some lab mixes had actual AC% of 5.3 and 5.5%. Using ashing or centrifuge MMDM, presented in Figure A-21-a or Figure A-21-b, overestimated the extracted AC% as compared to the actual percentages. The extracted AC percentages using the ashing MMDM were between 4.5 and 6%. The centrifuge MMDM presented more accurate extracted AC percentages, which had values between 4.7 and 5.8%. Using both ashing and centrifuge MMDM, illustrated in Figure A-21-c, resulted in extracted AC percentages between 4.6 and 5.9%.

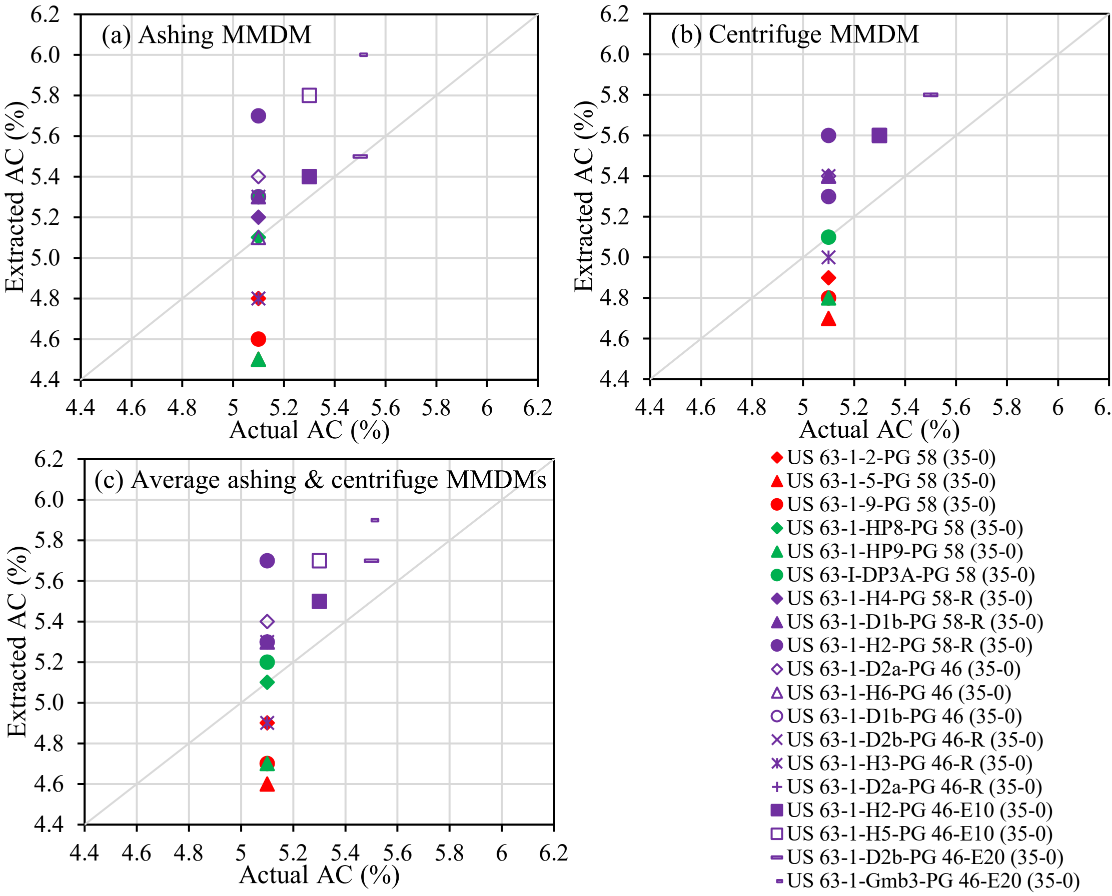


Figure A-21. Actual vs Extracted AC% using Different MMDMs for the US 63-1 Field, Plant, and Lab Mixes

To better understand the effect of the MMDMs on the extracted AC percentages, the means of the extracted AC% using different MMDMs were compared with the mean of the actual AC%. The ANOVA results are shown in Table A -. The p-value (Prob > F) is 0.3833, which was greater than the 0.05 significance level. Thus, no significant difference was found between the means of the extracted AC% using different MMDMs as compared to the mean of the actual AC%.

Table A -1. ANOVA Results for the Actual and Extracted AC% for the US 54-6 and US 63-1 Field, Plant, and Lab Mixes

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Method	3	0.294	0.098	1.025	0.383
Error	144	13.774	0.096		
C. Total	147	14.068			

Figure A-22 presents the extracted AC per actual AC percentages for the US 54-6 field, plant, and lab mixes using different MMDMs. The extracted AC per actual AC percentages were found between 85 and 110%. The centrifuge MMDM showed higher extracted AC% as compared to the ashing MMDM. Moreover, the highest extracted AC per actual AC percentages were found for US 54-6 plant mixes.

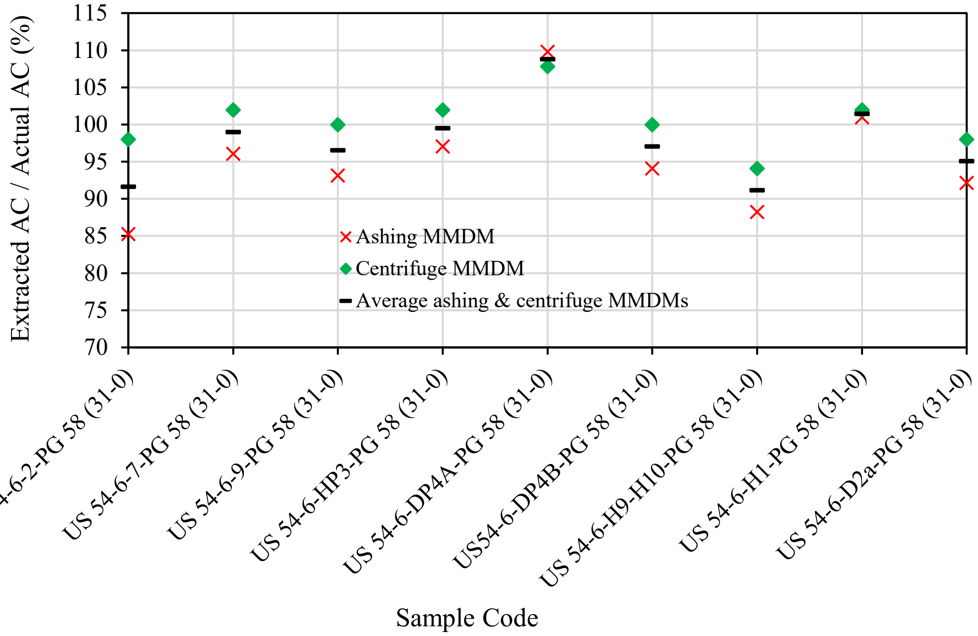


Figure A-22. Extracted AC per Actual AC% for US 54-6 Field, Plant, and Lab Asphaltic Mixes using Different MMDMs

Figure A-23 presents the extracted AC per actual AC percentages for US 54-6 lab mixes using different MMDMs. The extracted AC per actual AC percentages were found between 88 and 110%. The centrifuge MMDM showed higher extracted AC% as compared to the ashing MMDM for most samples. Adding 3% Evoflex increased the extracted AC per actual AC percentages, which reflects the role of Evoflex in enhancing the contribution of the recycled materials in the mixes. This contribution increased the interaction process between the recycled materials' binders and the virgin asphalt binder. The same results were observed by using a softer virgin asphalt binder (PG 46-34): less variations were observed for the extracted AC per actual AC percentages using different MMDMs.

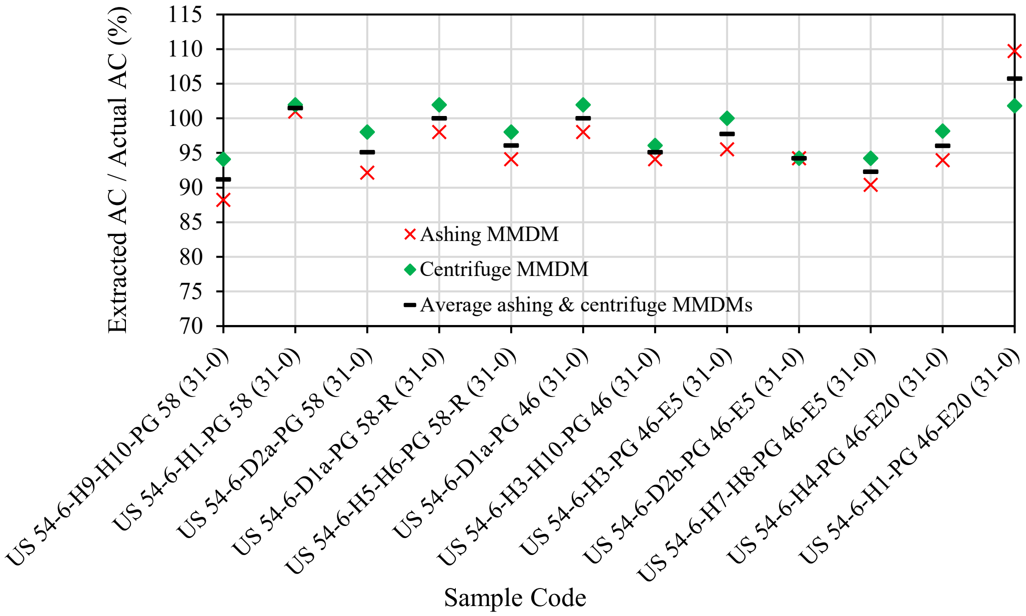


Figure A-23. Extracted AC per Actual AC% for US 54-6 Lab Asphaltic Mixes using Different MMDMs

Figure A-24 shows the extracted AC per actual AC percentages for the US 63-1 field, plant, and lab mixes using different MMDMs. The extracted AC per actual AC percentages were found between 88 and 112%. The centrifuge MMDM showed higher extracted AC% as compared to the ashing MMDM for most samples. Moreover, the highest extracted AC per actual AC percentages were found for plant and lab mixes.

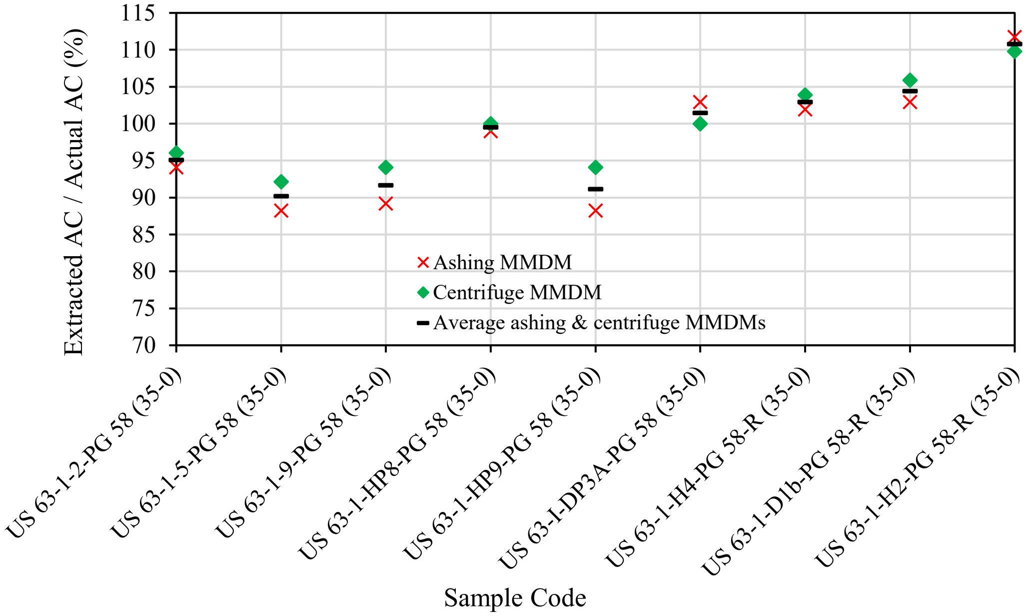


Figure A-24. Extracted AC per Actual AC% for US 63-1 Field, Plant, and Lab Asphaltic Mixes using Different MMDMs

Figure A-25 presents the extracted AC per actual AC percentages for US 63-1 lab mixes using different MMDMs. The extracted AC per actual AC percentages were found between 95 and 112%. The centrifuge MMDM showed higher extracted AC% as compared to the ashing MMDM for most samples.

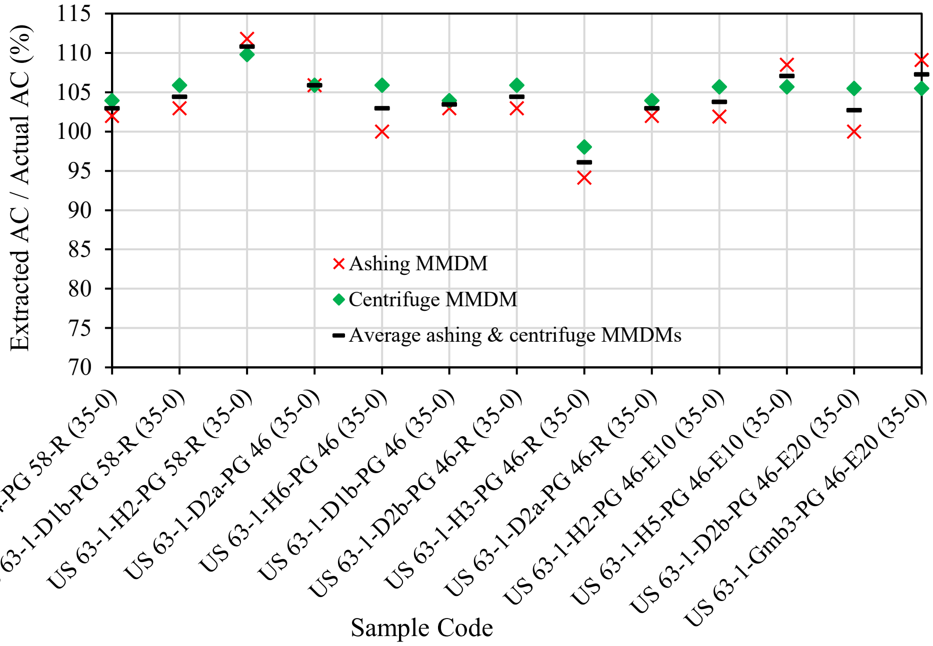


Figure A-25. Extracted AC per Actual AC % for US 63-1 Lab Asphaltic mixes using Different MMDMs

A.2.2.2. Properties of the RTFO Aged Virgin and Extracted and Recovered Asphalt Binders from the Field, Plant, and Lab Mixes

The MSCR test results, measured at 0.1 and 3.2 kPa stress levels and 60°C temperature, are illustrated in Figure A-26 for RTFO aged virgin and E & R asphalt binders from US 54-6 and US 63-1 field, plant, and lab mixes. Both US 54 and US 63-1 asphalt binders had the same PG (PG 58-28); however, the US 54 was stiffer than the US 63 asphalt binder. The US 54 binder showed lower J_{nr} and higher %R values than the US 63 binder. The E & R asphalt binders had higher %R and lower J_{nr} values than values for the corresponding RTFO aged virgin binders due to the stiffness effect of the asphalt binder component existed in the RAP. Furthermore, asphalt binders E & R from US 63-1 mixes revealed lower J_{nr} and higher %R values as compared to asphalt binders

E & R from US 54-6 mixes. This occurred because the US 63-1 mixes contained 4% ABR percentage by RAP higher than the US 54-6 mixes.

Figure A-26-a shows the J_{nr} and %R values for the RTFO aged virgin and E & R asphalt binders from the US 54-6 field, plant, and lab mixes. The E & R asphalt binders from plant mixes showed lower J_{nr} and higher %R values as compared to the E & R asphalt binders from field mixes. This was related to the extra heating that occurred to the plant samples before the compaction process in the lab, which increased the recycled materials contribution in the mix. This contribution increased the interaction process between the recycled materials' binders and the virgin asphalt binder. Moreover, asphalt binders E & R from lab mixes showed higher %R and lower J_{nr} values as compared to binders E & R from plant mixes. The same results were noticed in Figure A-26-b for E & R binders from the US 63-1 field, plant, and lab mixes.

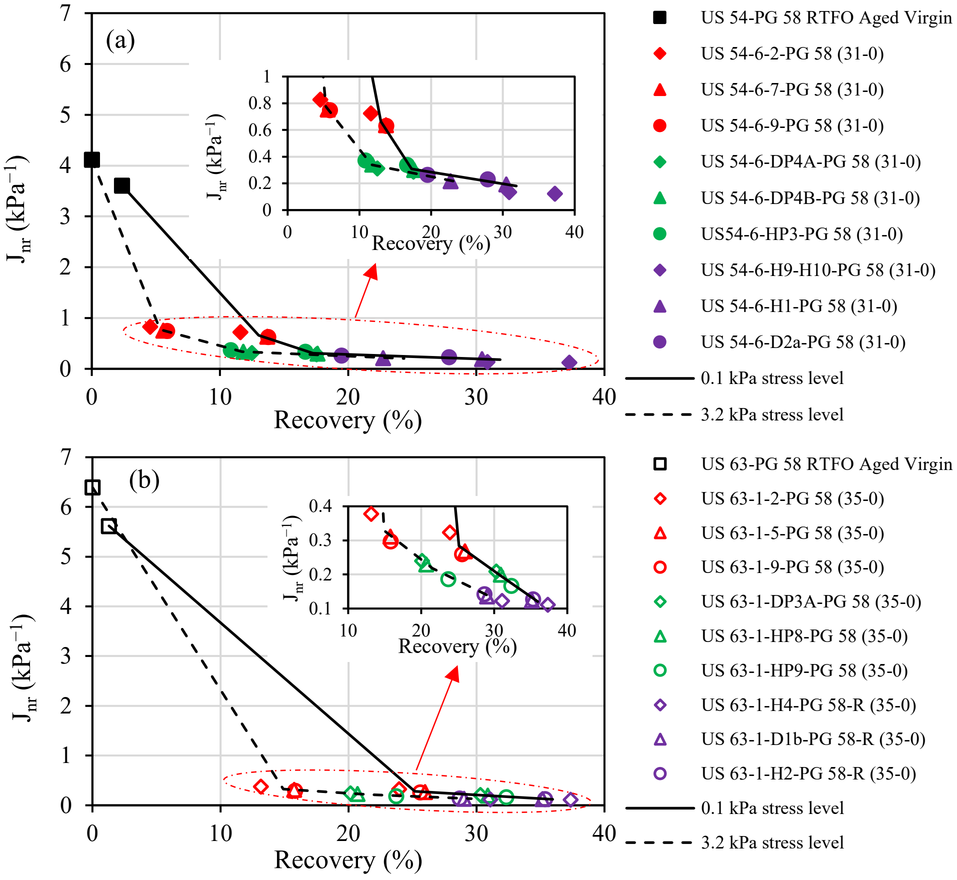


Figure A-26. MSCR Test Results Measured at 60°C for RTFO Aged Virgin and E & R Asphalt Binders from (a) US 54-6 and (b) US 63-1 Field, Plant, and Lab Mixes

Figure A-27 shows the MSCR results, measured at 0.1 and 3.2 kPa stress levels and 60°C temperature, for the RTFO aged virgin and E & R asphalt binders from the US 54-6 and US 63-1 lab mixes. It is worthy to note that RTFO aged PG 46-34 asphalt binder is softer than RTFO aged US 63-1-PG 58-28 or US 54-PG 58-28 asphalt binders because it had the highest J_{nr} and the lowest %R values. For all lab mixes, E & R asphalt binders showed a higher stiffness as compared to the corresponding RTFO aged virgin asphalt binders. This reflects the effect of the stiff asphalt binder component in the RAP on increasing the E & R asphalt binder stiffness values.

Evoflex worked as a rejuvenator and enhanced the contribution of the recycled asphalt binders in the asphaltic mixes. This contribution increased the interaction process between the recycled materials' binders and the virgin asphalt binder. From Figure A-27-a, adding 3% Evoflex to the US 54-6-H5-H6 lab sample slightly increased the %R and decreased the J_{nr} for the E & R asphalt binder as compared to E & R asphalt binders from mixes with 0% Evoflex. However, adding the same percentage of Evoflex to the US 54-6-D1a did not alter the E & R asphalt binder significantly as compared to E & R asphalt binders from the same mixes without Evoflex. Figure A-27-b shows that E & R asphalt binders from US 54-6 lab samples containing PG 46-34 asphalt binder had a lower stiffness by showing higher J_{nr} and lower %R values as compared to E & R asphalt binders from the same mixes containing PG 58-28 asphalt binder. Adding 5% or 20% ECR to US 54-6-PG 46 mixes increased the stiffness (lower J_{nr} values) and elasticity (higher %R values) of the E & R asphalt binders as compared to US 54-6 mixes containing PG 46-34 or PG 58-28 asphalt binders.

Regardless of the used PG virgin asphalt binders, increasing the ABR by RAP from 31 to 35% caused an increase in the stiffness of the E & R asphalt binders, Figure A-27-c. This reflects that the effect of the percentage of the recycled materials on the E & R asphalt binders was effective besides the effect of the PG of the used virgin asphalt binders. Figure A-27-d shows that using a softer asphalt binder (PG 46-34) decreased the stiffness of the E & R asphalt binders. Moreover, using Evoflex increased the stiffness of the E & R asphalt binders by increasing the contribution of the recycled materials in the mixes. This contribution increased the interaction process between the recycled materials' binders and the virgin asphalt binder. Using 10 or 20% ECR increased the stiffness and elasticity of the E & R asphalt binders.

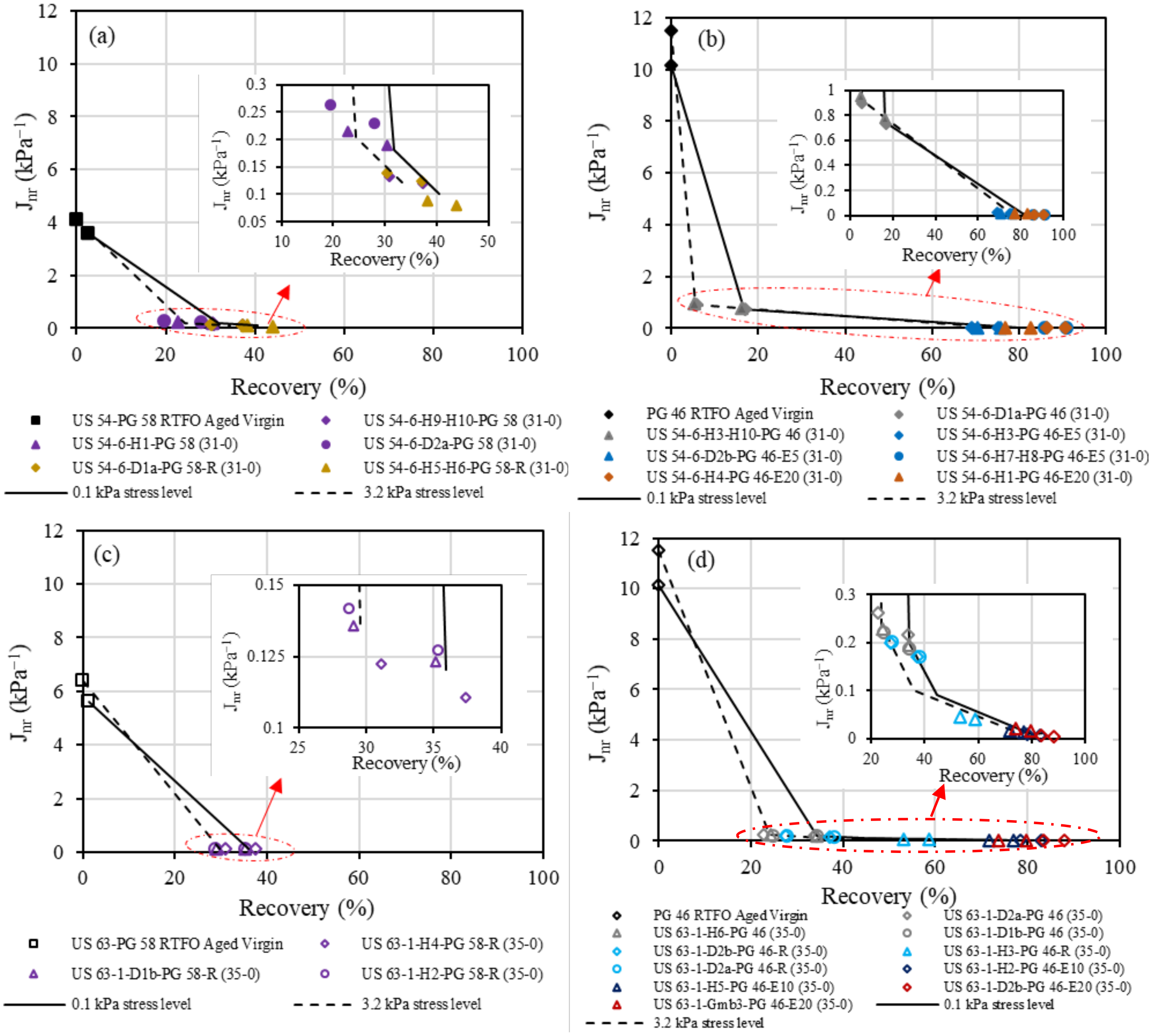


Figure A-27. MSCR Test Results Measured at 60°C for RTFO Aged Virgin and E & R Asphalt Binders from (a) US 54-6-PG 58, (b) US 54-6-PG 46, (c) US 63-1-PG 58, and (d) US 63-1-PG 46 Lab Mixes

The temperature sweep test results for the E & R asphalt binders from the US 54-6 field, plant, and lab mixes containing 31% ABR by RAP and the corresponding RTFO aged virgin asphalt binder are presented in Figure A-28. All E & R asphalt binders showed higher stiffness than the corresponding RTFO aged virgin asphalt binder because of the aged asphalt binder included in the RAP. It can be noted that asphalt binders E & R from the plant and lab mixes had the highest stiffness and the highest rutting parameter. Furthermore, the asphalt binders E & R from the plant mixes were stiffer than asphalt binders E & R from the field mixes. This occurred because the collected samples from behind the paver were reheated and compacted in the Mizzou lab, which increased the contribution of the recycled materials in the mix. This contribution increased the interaction process between the recycled materials' binders and the virgin asphalt binder.

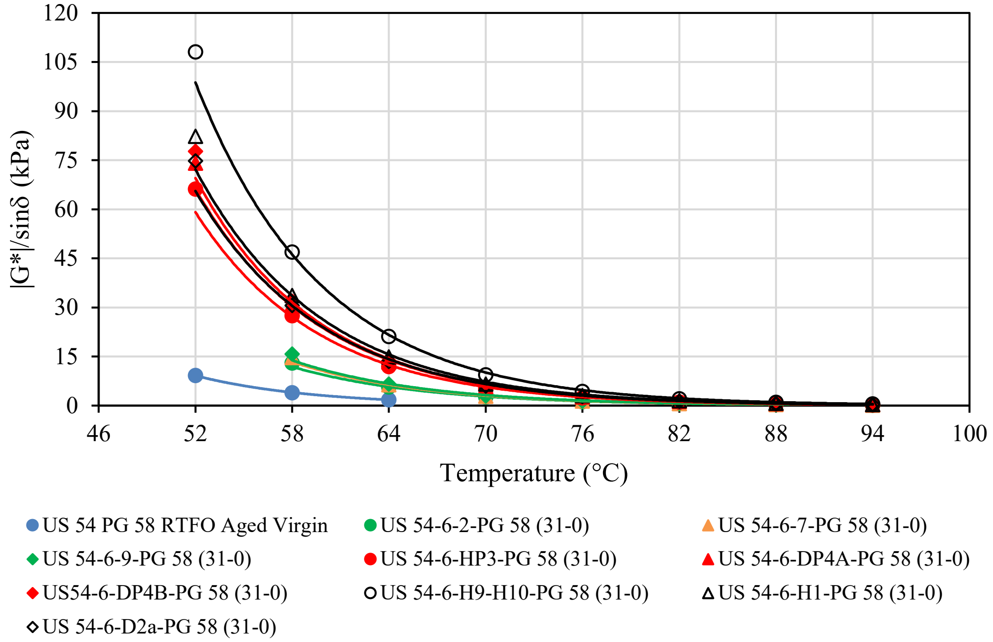


Figure A-28. Temperature Sweep Test Results for the E & R Asphalt Binders from the US 54-6 Field, Plant, and Lab Mixes Containing 31% ABR by RAP and the Corresponding RTFO aged Virgin Asphalt Binder

The temperature sweep test results for the E & R asphalt binders from the US 54-6 lab mixes containing 31% ABR by RAP and the corresponding RTFO aged virgin asphalt binders are illustrated in Figure A-29. Different mixes were mixed in the lab containing rejuvenator, soft asphalt binder, or ECR, using two percentages 5 and 20% by the weight of the binder, with a soft asphalt binder. The rejuvenator was Evoflex, the used percentage was 3% by the weight of the binder and the soft asphalt binder had a PG of 46-34. Asphalt binders E & R from the lab mixes containing ECR had the highest stiffness and the highest rutting parameter. This happened because of the effect of the rubber on increasing the asphalt binder's stiffness and elasticity, which enhanced the resistance to rutting. Asphalt binders E & R from mixes contained PG 46-34 asphalt binder had the lowest resistance to rutting; however, they had a higher rutting parameter than the corresponding RTFO aged virgin asphalt binder.

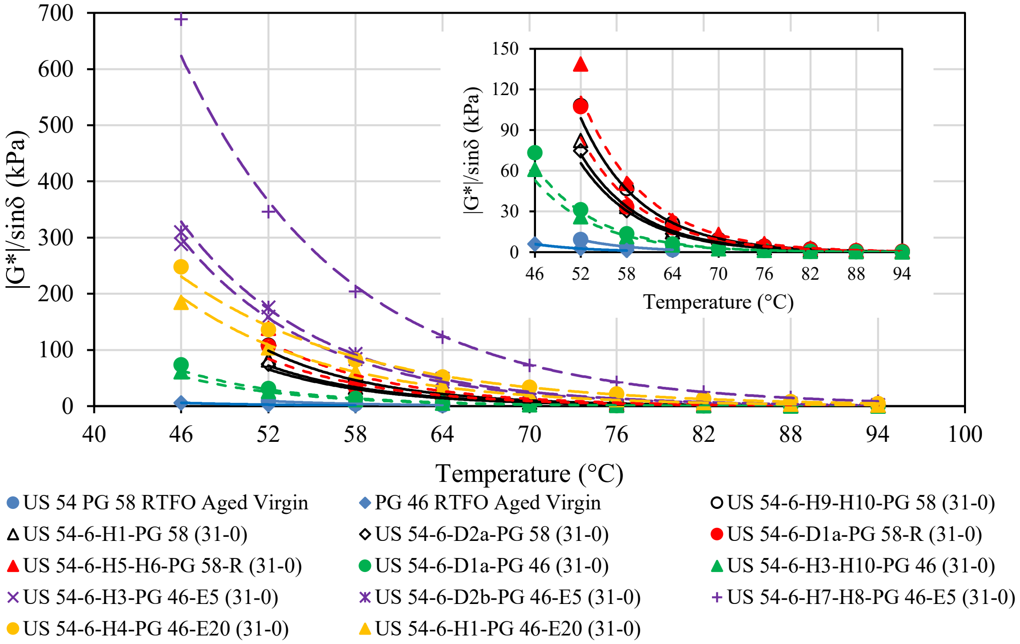


Figure A-29. Temperature Sweep Test Results for the E & R Asphalt Binders from the US 54-6 Lab Mixes Containing 31% ABR by RAP and the Corresponding RTFO Aged Virgin Asphalt Binders

The temperature sweep test results for the E & R asphalt binders from the US 63-1 field, plant, and lab mixes containing 35% ABR by RAP and the corresponding RTFO aged virgin asphalt binder are shown in Figure A-30. All E & R asphalt binders showed higher stiffness than the corresponding RTFO aged virgin asphalt binder because of the aged asphalt binder included in the RAP. The virgin asphalt binder US 63-1 PG 58 was softer than the virgin asphalt binder US 54 PG 58. However, the asphalt binders E & R from the US 63-1 mixes were stiffer than the asphalt binders E & R from the US 54-6 mixes. This occurred due to the higher ABR percentage by RAP included in the US 63-1 mixes. The asphalt binders E & R from the US 63-1 lab mixes had the highest stiffness and the highest rutting parameter. Additionally, the asphalt binders E & R from the plant mixes were stiffer than asphalt binders E & R from the field mixes.

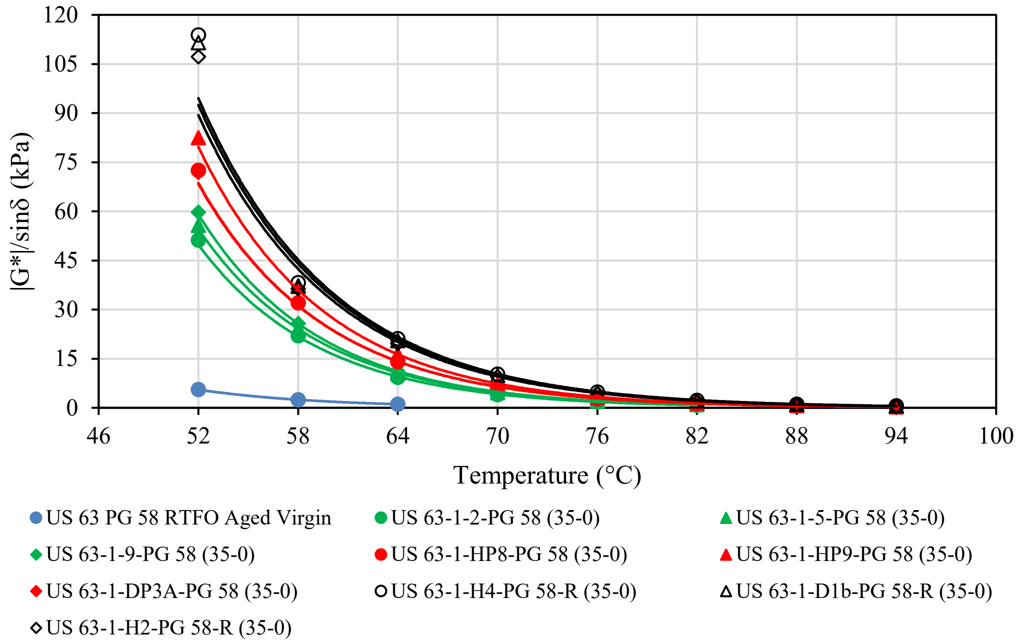


Figure A-30. Temperature Sweep Test Results for the E & R Asphalt Binders from the US 63-1 Field, Plant, and Lab Mixes Containing 35% ABR by RAP and the Corresponding RTFO Aged Virgin Asphalt Binders

The temperature sweep test results for the E & R asphalt binders from the US 63-1 lab mixes containing 35% ABR by RAP and the corresponding RTFO aged virgin asphalt binder are presented in Figure A-31. Different mixes were mixed in the lab containing rejuvenator, soft asphalt binder, or ECR, using two percentages 10 and 20%, with a soft asphalt binder. Using a soft binder (PG 46-34) decreased the resistance to rutting by showing the lowest rutting parameter values for the E & R asphalt binders as compared to the E & R asphalt binders from the other US 63-1 lab mixes. Adding 3.75% Evoflex and 0.5% Evotherm to the soft asphalt binder increased the rutting parameter values, which was related to the effect of the Evoflex on enhancing the recycled materials' contribution in the mix. This contribution increased the interaction process between the recycled materials' binders and the virgin asphalt binder. Adding 10 or 20% ECR to the soft asphalt binder showed significant enhancement in the resistance to rutting due to the role of the rubber in increasing the asphalt binders' stiffness and elasticity. The enhanced stiffness and elasticity are shown in Figure A-32. These photos were taken for the asphalt binder samples E & R from mixes containing ECR after finishing the measurements on the DSR. The asphalt binder connection between the lower and upper plates showed the elastic behavior of the asphalt binders. Moreover, it was very difficult to clean the plates after finishing the measurement on the DSR although the temperature was raised to 94°C, which illustrated increasing the stiffness of the asphalt binders.

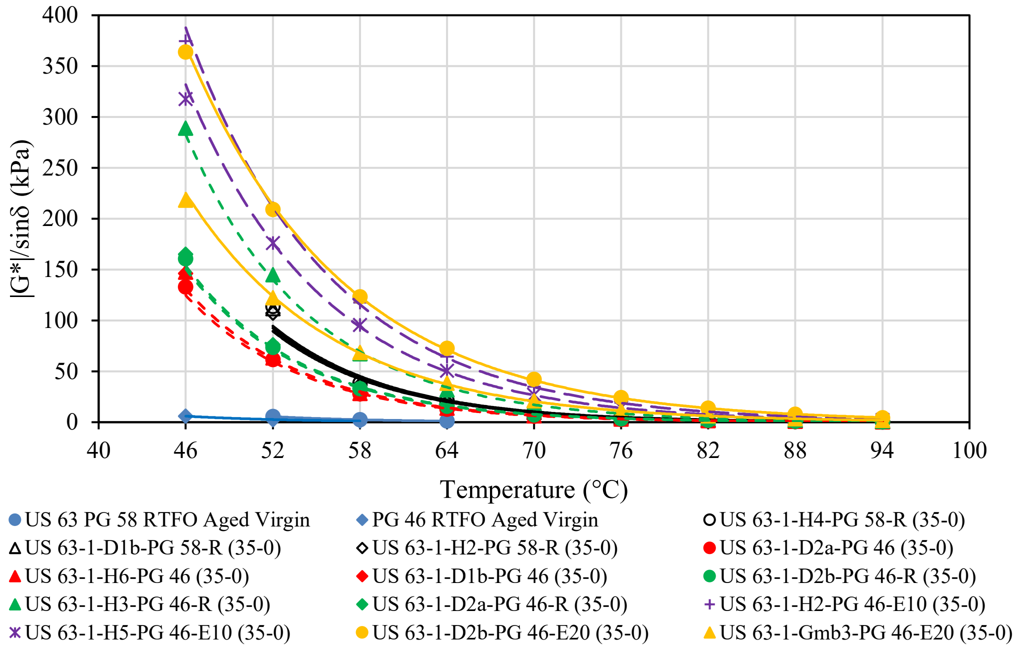


Figure A-31. Temperature Sweep Test Results for the E & R Asphalt Binders from the US 63-1 Lab Mixes Containing 35% ABR by RAP and the Corresponding RTFO Aged Virgin Asphalt Binders

Figure A-32. The Connection between the DSR Upper and Lower Plates for Asphalt Binders E & R from Mixes Containing ECR

The master curve, measured at 60°C for the RTFO aged virgin and E & R asphalt binders from the US 54-6 field, plant, and lab mixes is presented in Figure A-33. The asphalt binders E & R from the field mixes showed higher rutting resistance as compared to the corresponding RTFO aged virgin asphalt binders. The asphalt binders E & R from the lab or plant mixes showed higher resistance to rutting than asphalt binders E & R from the field mixes. This was related to the increased contribution of the asphalt binders included in the recycled materials to the total E & R binders. This contribution increased the interaction process between the recycled materials' binders and the virgin asphalt binder in the lab and plant mixes.

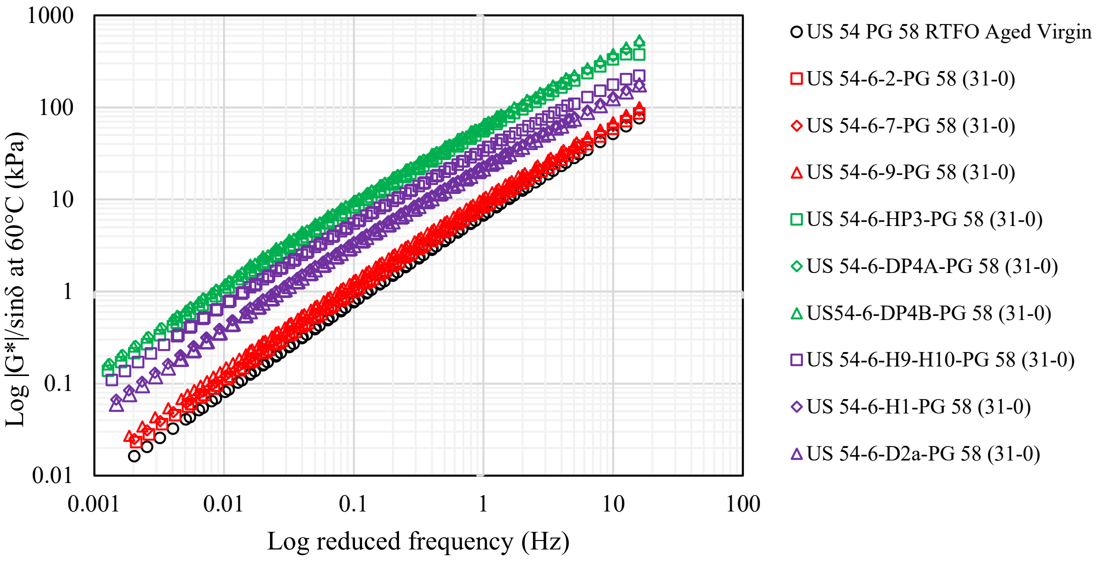


Figure A-33. Master Curve Measured at 60°C for the RTFO Aged Virgin and E & R Asphalt Binders from the US 54-6 Field, Plant, and Lab Mixes Containing 31% ABR by RAP

The Cole-Cole plot measured at 60°C for the same binders is shown in Figure A. Comparing the RTFO aged virgin and the E & R asphalt binders, a shift towards the elastic modulus axis and the right-hand side of the curve occurred to the E & R asphalt binders. This shift referred to enhancement in the elasticity. The maximum shift was observed for binders E & R from the lab mixes. The same results were observed from analyzing the black diagram in Figure A because the maximum shift towards the |G*| axis and the right-hand side of the curve was also observed for the binders E & R from the lab mixes. This shift indicated an increase in the stiffness and elasticity.

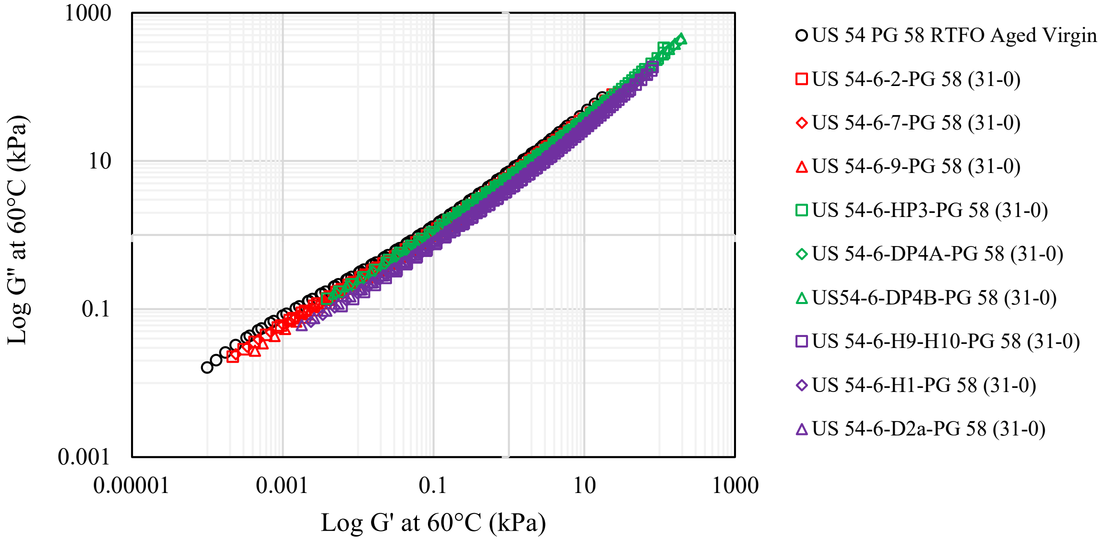


Figure A-34. Cole-Cole Plot Analyzed at 60°C for the RTFO Aged Virgin and E & R Asphalt Binders from the US 54-6 Field, Plant, and Lab Mixes Containing 31% ABR by RAP

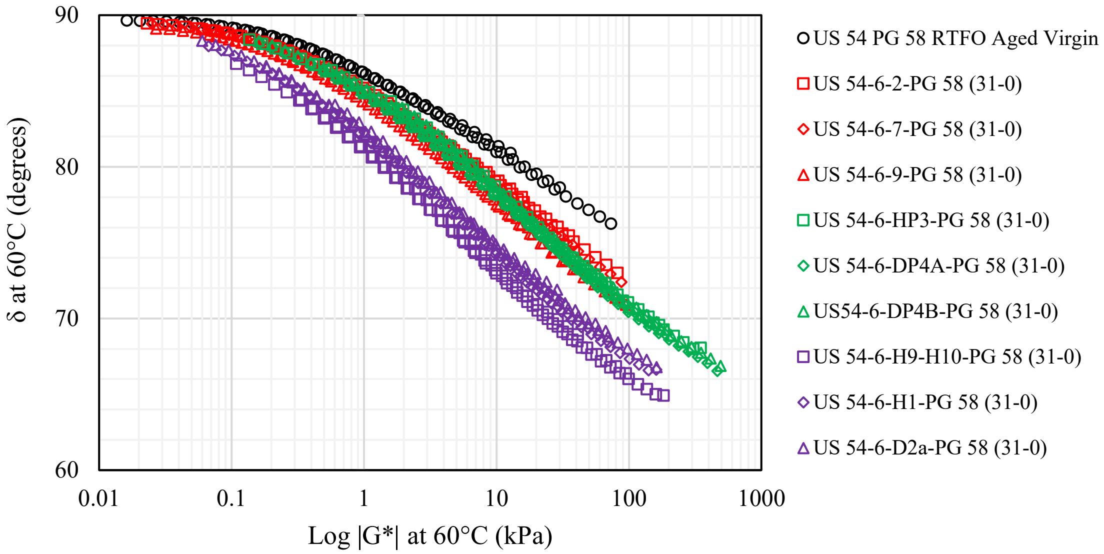


Figure A-35. Black Diagram Analyzed at 60°C for the RTFO Aged Virgin and E & R Asphalt Binders from the US 54-6 Field, Plant, and Lab Mixes Containing 31% ABR by RAP

The master curve measured at 60°C for the RTFO aged virgin and E & R asphalt binders from the US 54-6 lab mixes is shown in Figure A-36. Asphalt binders E & R from US 54-6-H9-H10-PG 58, US 54-6-H1-PG 58, and US 54-6-D2a-PG 58 mixes showed higher resistance to rutting as compared to the RTFO aged virgin asphalt binder because of the aged asphalt binder included in the RAP. Adding 3% Evoflex to PG 58-28 asphalt binder slightly increased the rutting resistance of the E & R asphalt binders. Using soft asphalt binder (PG 46-34) significantly reduced the rutting resistance of the E & R binders; however, they had a higher rutting resistance than the corresponding RTFO aged virgin asphalt binder's resistance. Adding 5% or 20% ECR to the soft asphalt binder significantly increased the rutting parameter for the E & R asphalt binders. This occurred because of the effect of the rubber particles on increasing the stiffness and elasticity of the E & R asphalt binders.

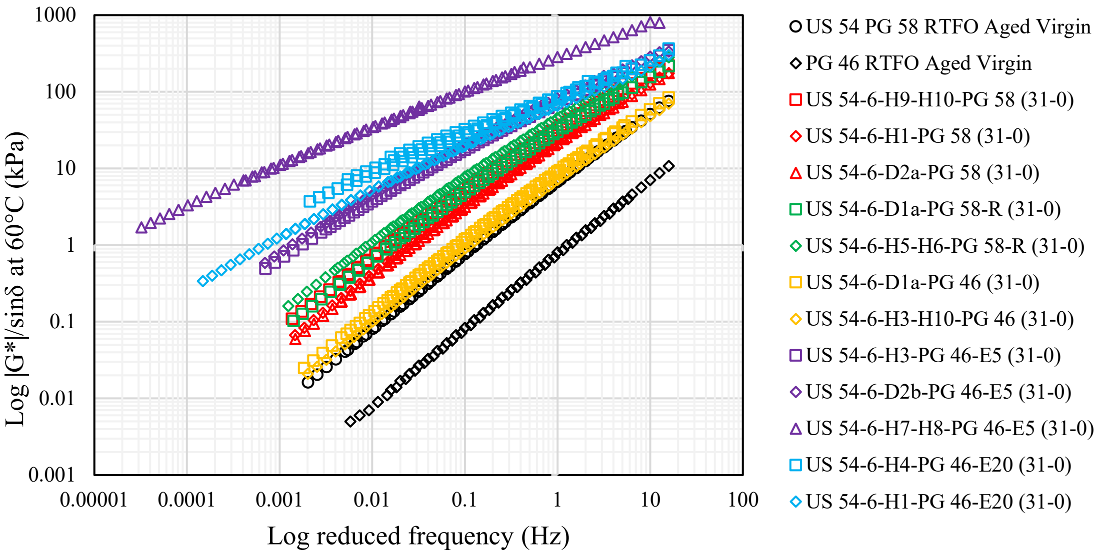


Figure A-36. Master Curve Measured at 60°C for the RTFO Aged Virgin and E & R Asphalt Binders from US 54-6 Lab Mixes Containing 31% ABR by RAP

The Cole-Cole plot analyzed at 60°C for the same binders is shown in Figure A-37. Comparing the RTFO aged virgin and the E & R asphalt binders, a shift towards the elastic modulus axis and the right-hand side of the curve occurred to the E & R asphalt binders. The maximum shift was observed for binders E & R from the mixes containing ECR. The same results were observed from analyzing the black diagram in Figure A-38 because the maximum shift towards the |G*| axis and the right-hand side of the curve was also observed for the binders E & R from the mixes containing ECR.

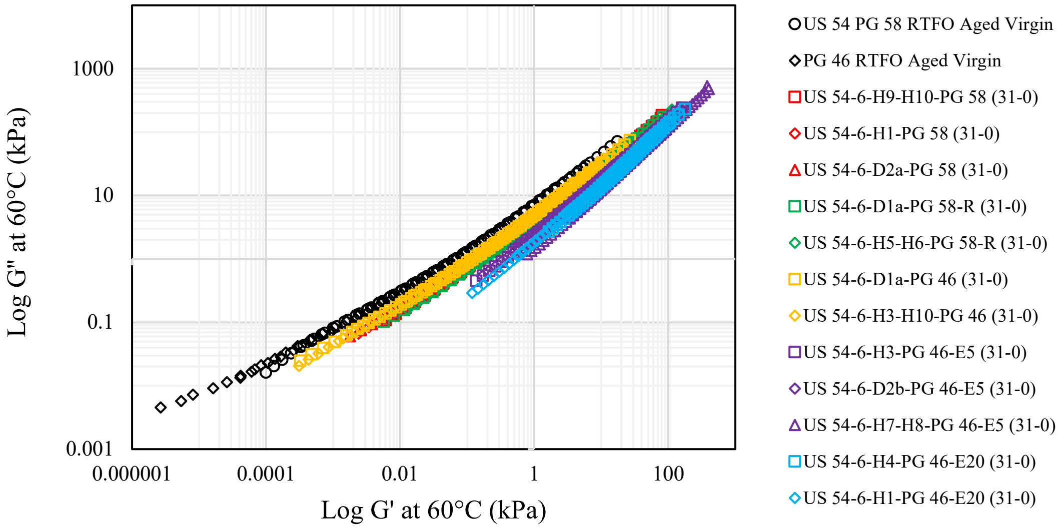


Figure A-37. Cole-Cole Plot Analyzed at 60°C for the RTFO Aged Virgin and E & R Asphalt Binders from US 54-6 Lab Mixes Containing 31% ABR by RAP

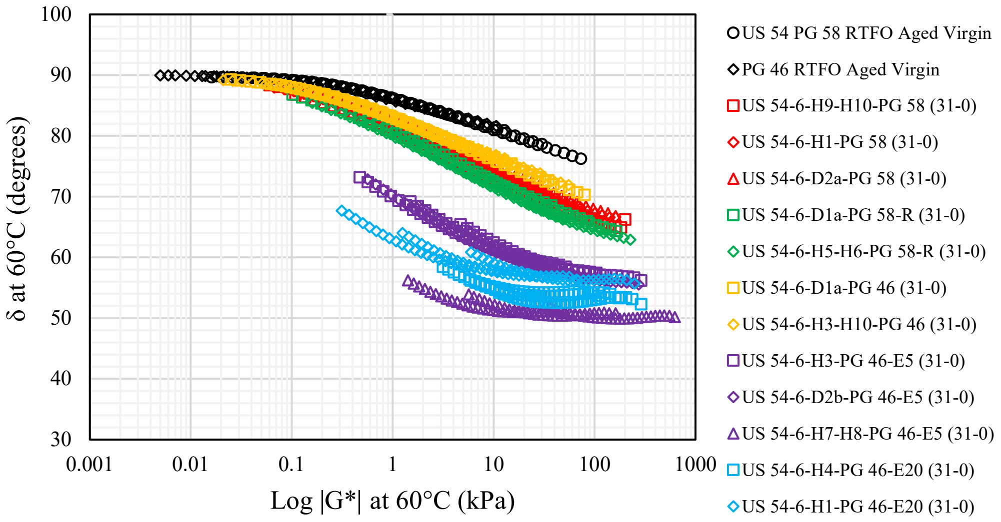


Figure A-38. Black Diagram Analyzed at 60°C for the RTFO Aged Virgin and E & R Asphalt Binders from US 54-6 Lab Mixes Containing 31% ABR by RAP

Figure A-39 shows the master curve measured at 60°C for the RTFO aged virgin and E & R asphalt binders from the US 63-1 field, plant, and lab mixes. The asphalt binders E & R from the field mixes showed higher rutting resistance as compared to the corresponding RTFO aged virgin asphalt binder. This difference in the rutting resistance was greater than what was obtained between the US 54-6 RTFO aged virgin and E & R asphalt binders because of the higher percentage of ABR by RAP included in the US 63-1 mixes; however, US 63-1 PG 58 asphalt binder was softer than US 54 PG 58 asphalt binder. The asphalt binders E & R from the lab or plant mixes showed higher resistance to rutting than asphalt binders E & R from the field mixes. This was related to increased interactions that occurred between the recycled materials and the virgin asphalt binders in the plant and lab mix.

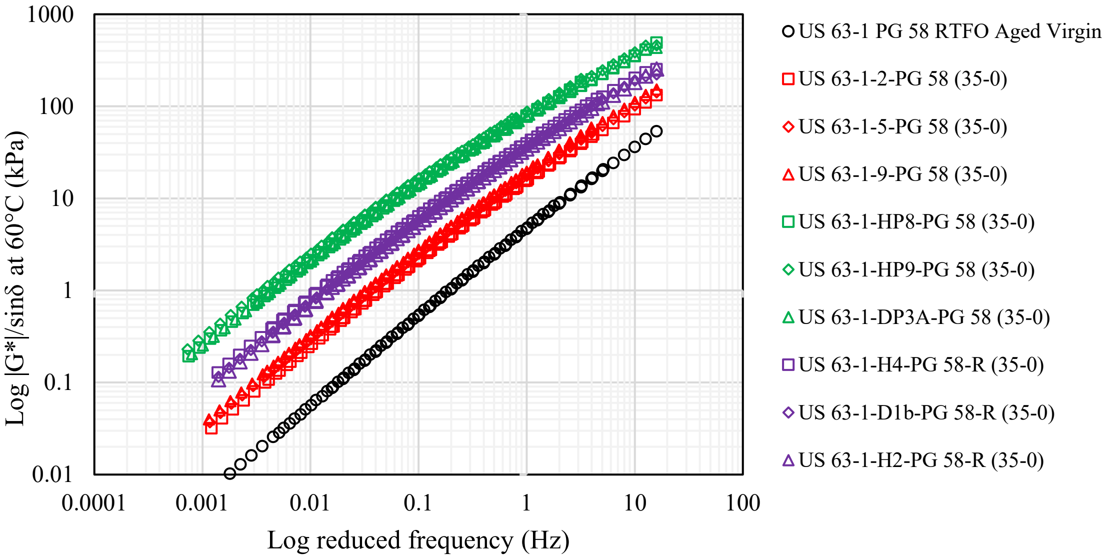


Figure A-39. Master Curve Measured at 60°C for the RTFO Aged Virgin and E & R Asphalt Binders from the US 63-1 Field, Plant, and Lab Mixes Containing 35% ABR by RAP

The Cole-Cole plot measured at 60°C for the same binders is shown in Figure A-40. Comparing the RTFO aged virgin and the E & R asphalt binders, a shift towards the elastic modulus axis and the right-hand side of the curve occurred to the E & R asphalt binders. The maximum shift was observed for the binders E & R from the plant and lab mixes. The same results were observed from analyzing the black diagram in Figure A-41 because the maximum shift towards the |G*| axis and the right-hand side of the curve was also observed for the binders E & R from the lab mixes.

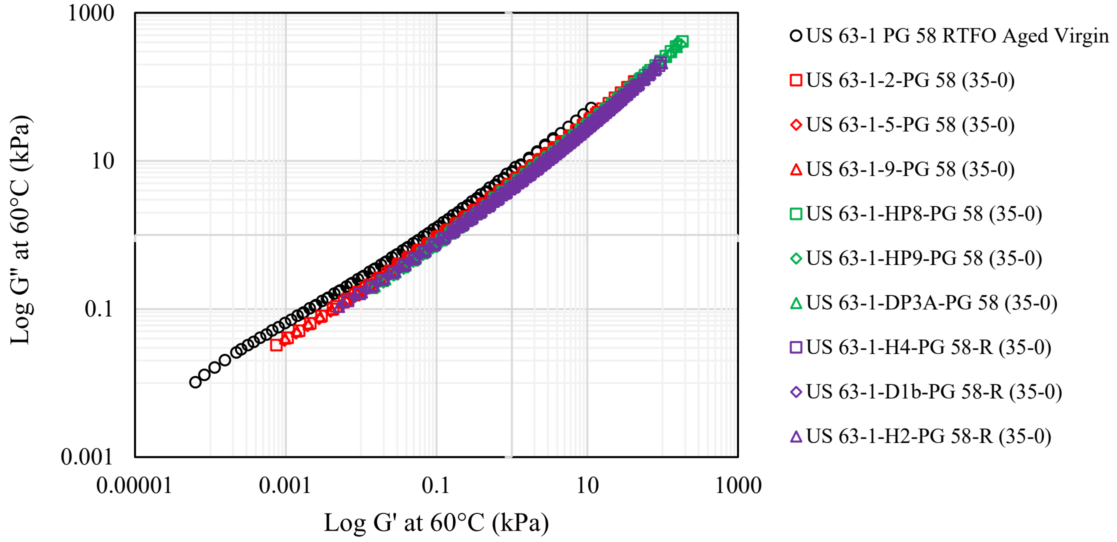


Figure A-40. Cole-Cole Plot Analyzed at 60°C for the RTFO Aged Virgin and E & R Asphalt Binders from the US 63-1 Field, Plant, and Lab Mixes Containing 35% ABR by RAP

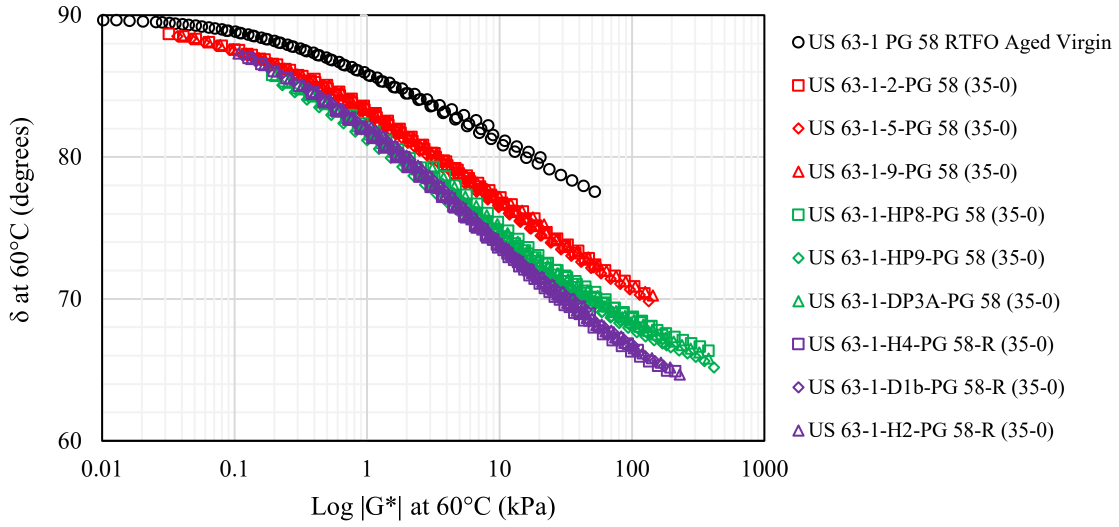


Figure A-41. Black Diagram Analyzed at 60°C for the RTFO Aged Virgin and E & R Asphalt Binders from the US 63-1 Field, Plant, and Lab Mixes Containing 35% ABR by RAP

Figure A-42 presents the master curve measured at 60°C for the RTFO aged virgin and E & R asphalt binders from the US 63-1 lab mixes. Asphalt binders E & R from US 63-1-H4-PG 58-R, US 63-1-D1b-PG 58-R, and US 63-1-H2-PG 58-R lab mixes showed higher resistance to rutting than the RTFO aged virgin asphalt binder because of the aged asphalt binder included in the RAP.

Using soft asphalt binder (PG 46-34) reduced the rutting resistance of the E & R binders as compared to E & R asphalt binders from mixes contained PG 58-28. Adding 3.75% Evoflex and 0.5% Evotherm to PG 46-34 asphalt binder slightly increased the rutting resistance of the E & R asphalt binders as compared to E & R binders from the same mixes but with the same binder and no additives. This was related to the effect of Evoflex on enhancing the blending of the recycled materials with the virgin binder. Adding 10% or 20% ECR to the soft asphalt binder significantly increased the rutting resistance in the E & R asphalt binders, even though we observed that not all of the rubber made it into the recovered binder (some was present in recovered aggregates and fines).

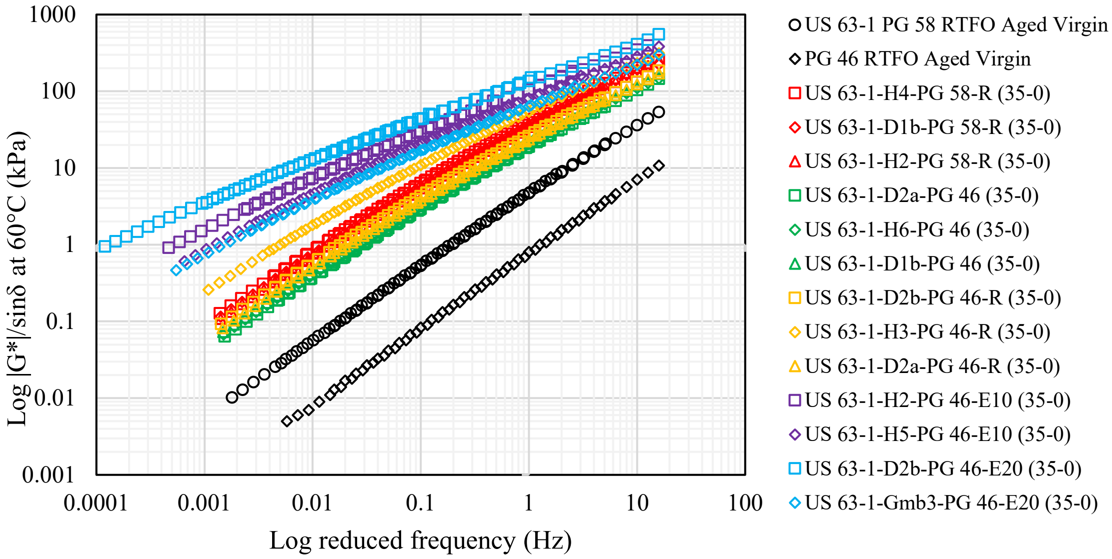


Figure A-42. Master Curve Measured at 60°C for the RTFO Aged Virgin and E & R Asphalt Binders from US 63-1 Lab Mixes Containing 35% ABR by RAP

The Cole-Cole plot analyzed at 60°C for the same binders is shown in Figure A-43. Comparing the RTFO aged virgin and the E & R asphalt binders, a shift towards the elastic modulus axis and the right-hand side of the curve occurred to the E & R asphalt binders. The maximum shift was observed for binders E & R from the mixes containing ECR. The same results were observed from analyzing the black diagram Figure A-44 because the maximum shift towards the |G*| axis and the right-hand side of the curve was also observed for the binders E & R from mixes containing ECR.

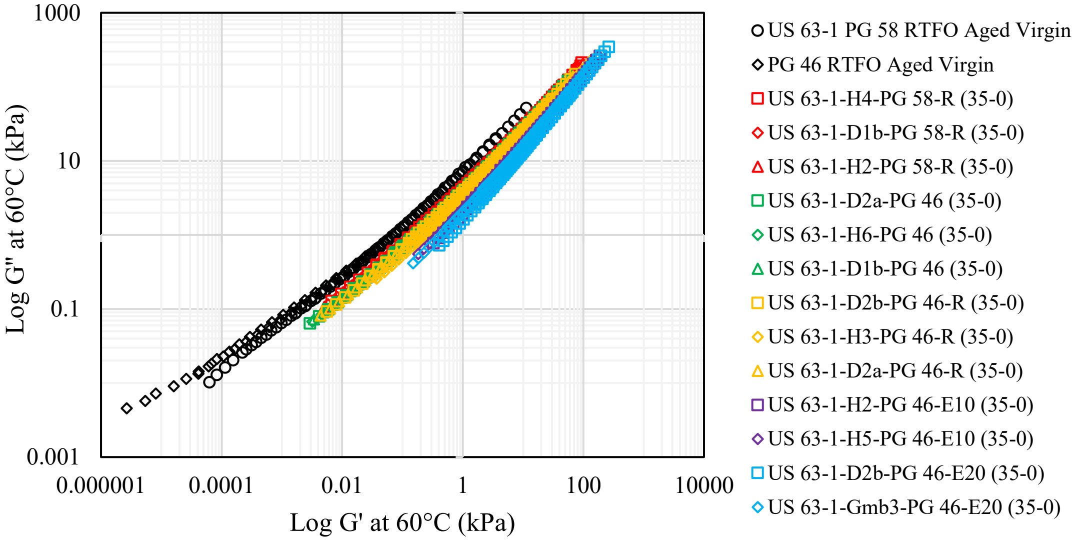


Figure A-43. Cole-Cole Plot Analyzed at 60°C for the RTFO Aged Virgin and E & R Asphalt Binders from US 63-1 Lab Mixes Containing 35% ABR by RAP

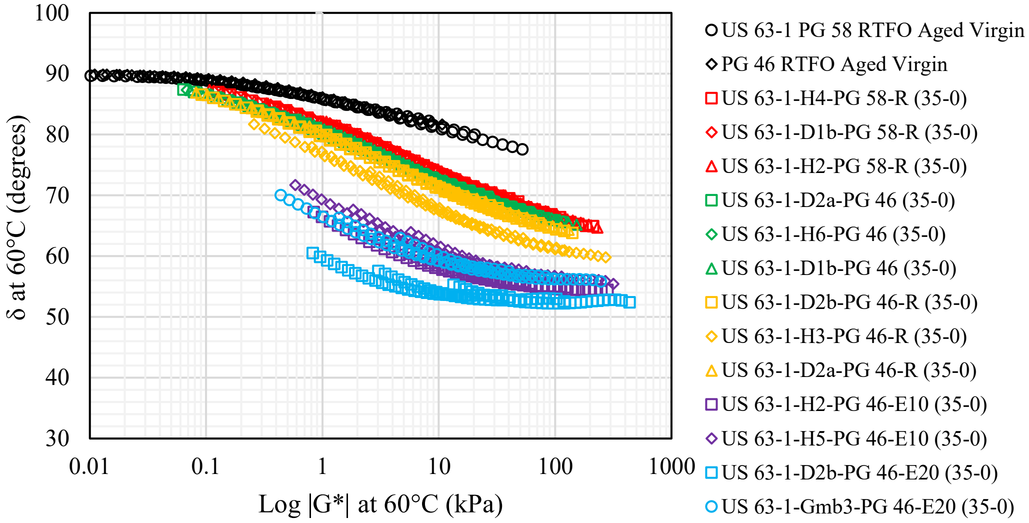


Figure A-44. Black Diagram Analyzed at 60°C for the RTFO Aged Virgin and E & R Asphalt Binders from US 63-1 Lab Mixes Containing 35% ABR by RAP

A.2.3. Relating Asphalt Binders Extracted and Recovered from the Field Mixes Constructed in 2016 to the Corresponding RTFO Aged Virgin Asphalt Binders

In this section, the asphalt binders E & R from the first batch field mixes constructed and collected in 2016 presented in Table 2- are related to the corresponding RTFO aged virgin asphalt binders. The asphalt binders were recovered from 23 samples for 8 different mixes. These mixes either contained RAP, RAS, or both. Moreover, there was a mix that contained neither RAP nor RAS (e.g. US 54-5).

A.2.3.1. Extraction of the Asphalt Binders from Field Mixes Constructed in 2016

The actual and extracted AC percentages for the field mixes constructed in 2016 using different MMDMs are illustrated in Figure A-45. Any point located on the inclined line with an angle of 45° represented samples that had the same percentages of the actual and extracted AC%. The actual AC percentages for the field mixes were ranging between 4.8 and 5.7%. The extracted AC percentages using the ashing MMDM presented in Figure A-45-a were found to be between 4.4 and 5.3%. Most of the samples having extracted AC percentages less than the actual AC percentages. Therefore, the ashing MMDM underestimated the extracted AC percentages. Using the centrifuge MMDM presented in Figure A-45-b increased the accuracy of the extracted AC percentages. The extracted AC percentages using this MMDM were ranging between 4.7 and 5.6%. These extracted AC percentages were near the actual ones. Therefore, the centrifuge MMDM presented more accurate extracted AC percentages. The extracted AC percentages were also calculated using the average ashing and centrifuge MMDMs in Figure A-45-c. The extracted AC percentages using this average ashing and centrifuge MMDMs were located between 4.6 and 5.5%.

To show the effect of the different MMDMs on the extracted AC percentages, the ANOVA results are presented in Table A-2. The p-value (Prob > F) is 0.0028, which was lower than the 0.05 significance level. Thus, there was a significant difference between the means of the extracted AC% using different MMDMs as compared to the mean of the actual AC%. To understand which MMDM has a significant difference, the Tukey honestly significant difference (HSD) test was implemented. The connecting letters report using the Tukey HSD test is illustrated in

Table A-3. Levels that were not connected by the same letter were considered significantly different. This reflected that the mean of the extracted AC percentages using the ashing MMDM was significantly different as compared to the means of the actual or extracted AC percentages using the centrifuge MMDM.

The ashing MMDM was so sensitive and required a skilled operator. In other words, the mineral matter in the total extracted effluent (asphalt binder dissolved in TCE plus mineral matter) was calculated using the 100-ml representative sample taken into the ignition dish. Consequently, if this 100-ml sample was not representative, contained more mineral matter, this underestimated the extracted AC percentage. However, the centrifuge MMDM was more accurate because it did not depend on the skills and accuracy of the operator. The whole mineral matter in the extracted effluent was calculated easily using the centrifuge MMDM if the filterless centrifuge device was available. These explanations illustrated why the ashing MMDM underestimated the extracted AC percentages as compared to the centrifuge MMDM.

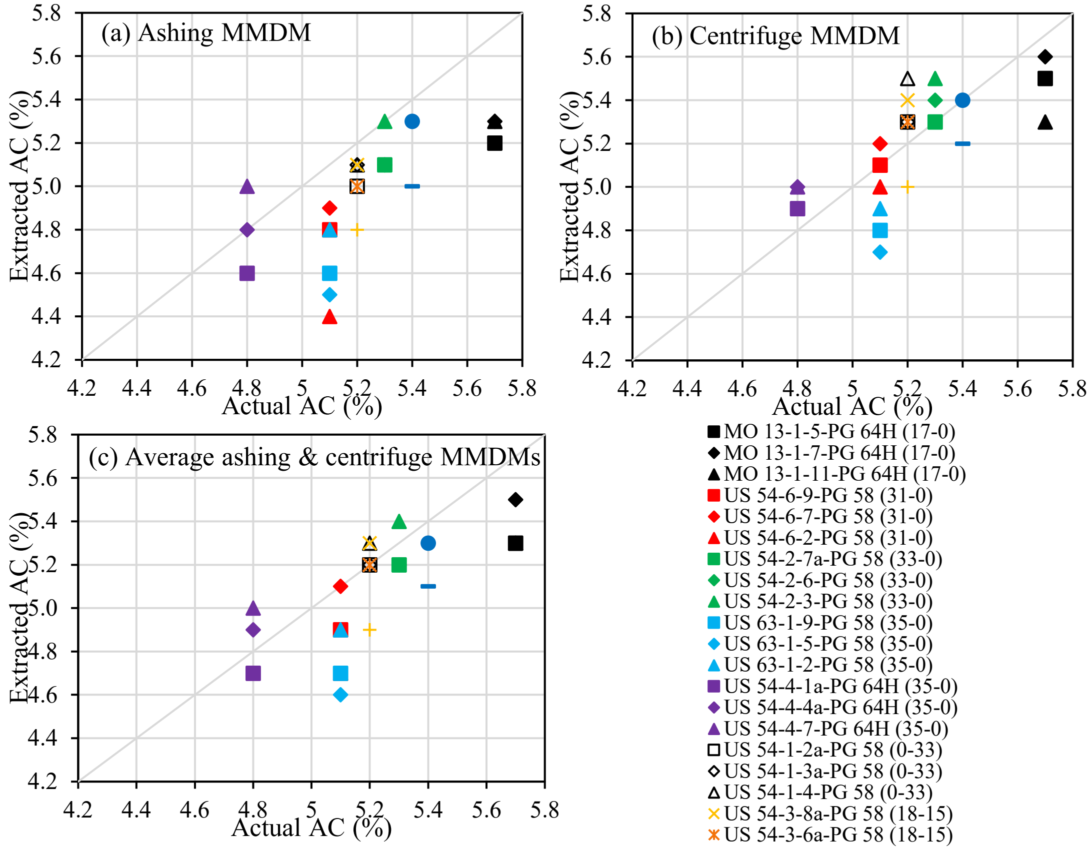


Figure A-45. Actual vs Extracted AC% using Different MMDMs for Field Mixes Constructed in 2016.

Table A-2. ANOVA Results for the Actual and Extracted AC% for the Field Mixes Constructed in 2016

Source	DF	Sum of Squares	Mean Square	F Ratio	Prob > F
Method	3	0.978	0.326	5.067	0.0028
Error	88	5.661	0.064		
C. Total	91	6.639			

Table A-3. Connecting Letters Report using the Tukey HSD Test

Level			Mean
Actual AC%	A		5.22
Extracted AC% using the centrifuge MMDM	A		5.20
Extracted AC% using average ashing & centrifuge MMDMs	A	B	5.08
Extracted AC% using the ashing MMDM		B	4.96

Levels not connected by the same letter are significantly different.

The temperature sweep test results for the RTFO aged virgin and E & R asphalt binders from the MO 13-1 field mixes containing 17% ABR by RAP and PG 64 -22H virgin asphalt binder are presented in Figure A-46. It was observed that using 17% ABR by RAP increased the rutting parameter for the E & R asphalt binders because of the stiffness of the RAP aged binders.

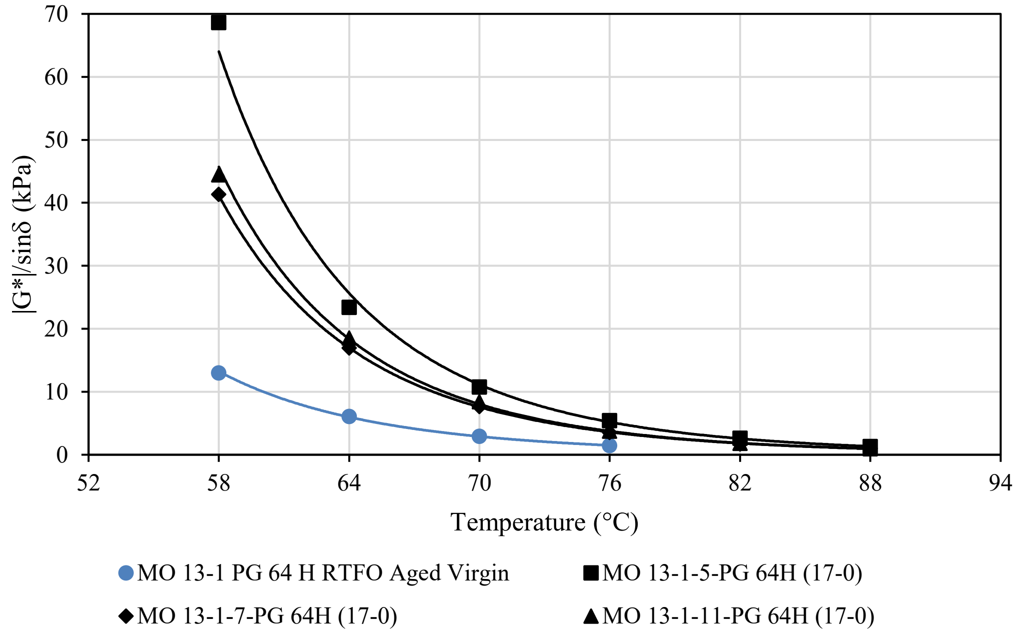


Figure A-46. Temperature Sweep Test Results for the RTFO Aged Virgin and E & R Asphalt Binders from MO 13-1 Field Mixes, Constructed in 2016, Containing 17% ABR by RAP and PG 64-22H Virgin Asphalt Binder

Figure A-47 shows the master curve measured at 60°C for the RTFO aged virgin and E & R asphalt binders from the MO 13-1 field mixes containing 17% ABR by RAP and PG 64-22H virgin asphalt binder. The E & R asphalt binders showed a higher rutting parameter at different frequencies as compared to the RTFO aged virgin asphalt binder. This was attributed to the higher elasticity presented in Figure A-48 and the higher stiffness at high frequencies as illustrated in Figure A-49.

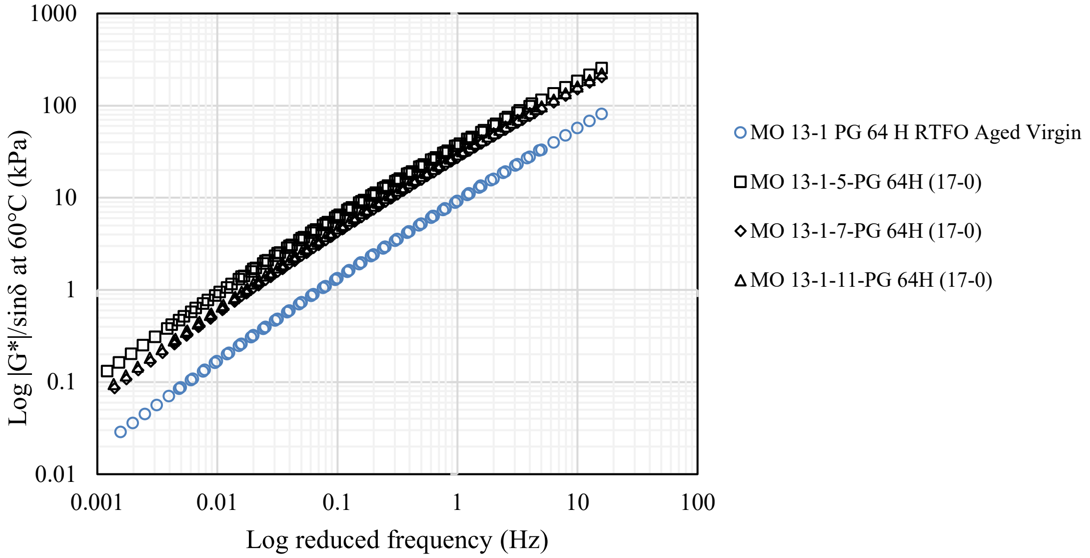


Figure A-47. Master Curve Measured at 60°C for the RTFO Aged Virgin and E & R Asphalt Binders from MO 13-1 field mixes, constructed in 2016, containing 17% ABR by RAP and PG 64-22H virgin asphalt binder

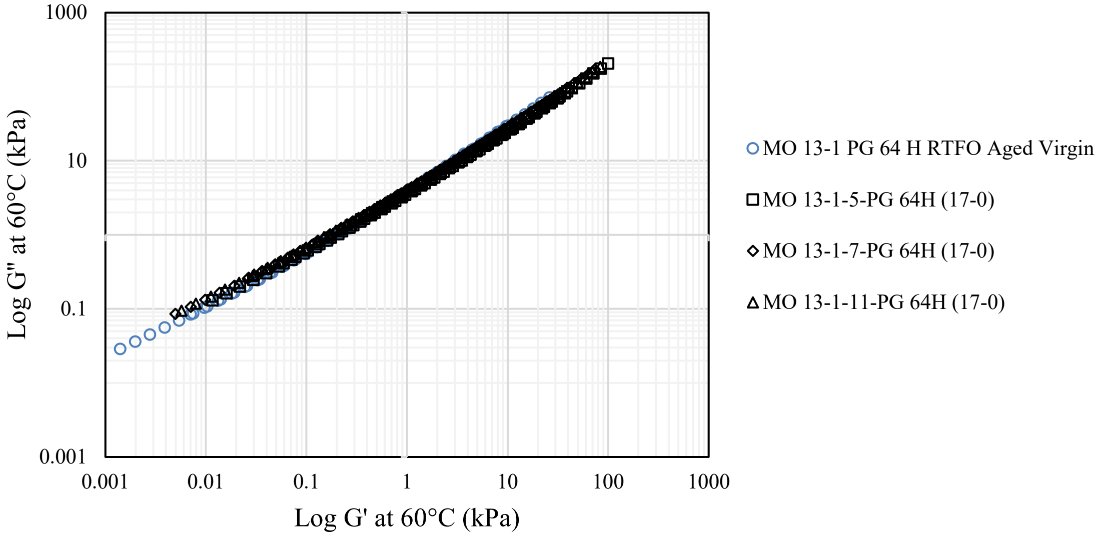


Figure A-48. Cole-Cole Plot Analyzed at 60°C for the RTFO Aged Virgin and E & R

Asphalt Binders from MO 13-1 Field Mixes, Constructed in 2016, Containing 17% ABR by RAP and PG 64-22H Virgin Asphalt Binder

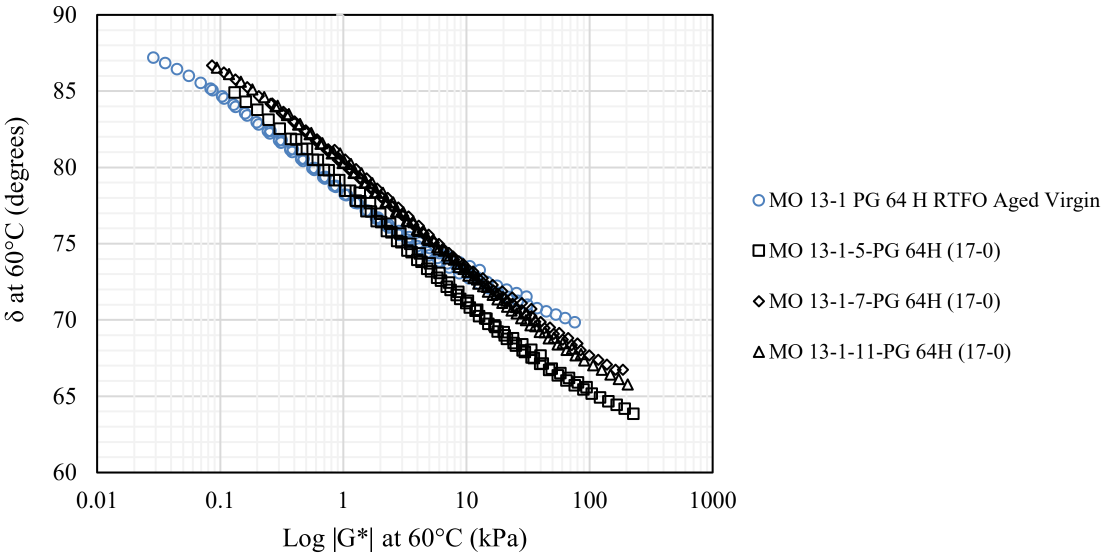


Figure A-49. Black Diagram Analyzed at 60°C for the RTFO Aged Virgin and E & R Asphalt Binders from MO 13-1 Field Mixes, Constructed in 2016, Containing 17% ABR by RAP and PG 64-22H Virgin Asphalt Binder

Figure A-50 shows the temperature sweep test results for the RTFO aged virgin and E & R asphalt binders from the US 54 field mixes containing different percentages of recycled materials (RAP, RAS, or both) and PG 58-28 virgin asphalt binder. The E & R asphalt binders from mixes containing 31% ABR by RAP showed higher resistance to rutting as compared to corresponding RTFO aged virgin asphalt binder. Increasing the ABR by RAP to 33% increased the rutting parameter significantly. Asphalt binders E & R from mixes containing 33% ABR by RAS showed higher resistance values than asphalt binders E & R from mixes containing 31% by RAP and lower rutting parameter values than asphalt binders E & R from mixes containing 33% ABR by RAP. The air-blown asphalt binders included in the RAS were stiffer than the aged binders in the RAP. Consequently, it was concluded that there was no full interaction process between the binder included in the RAS and the virgin binder. Consequently, for the same percentage of recycled materials (33% ABR by RAS or RAP) the E & R asphalt binders from mixes containing RAP were stiffer than the binders E & R from mixes containing RAS. Using 18% ABR by RAP and 15% ABR by RAS with a total ABR of 33% increased the rutting parameter of the E & R asphalt binders as compared to the E & R asphalt binders from mixes containing 33% ABR by RAS. It was important to mention here that not only the virgin asphalt binder and the percentage of the recycled materials affected the performance of the E & R asphalt binder but also the interaction process between the recycled materials components and the virgin asphalt binder altered the properties of the E & R binders.

These results were related to the results obtained in Figure A-51, Figure A-52, and Figure A-53 for the master curve, Cole-Cole plot, and black diagram, respectively. All E & R asphalt binders showed higher rutting resistance at different frequencies as compared to the corresponding RTFO aged virgin asphalt binder. The highest rutting parameter was achieved for asphalt binders E & R from mixes containing 33% ABR percentage by RAP; the highest stiffness and elasticity values were observed for these binders.

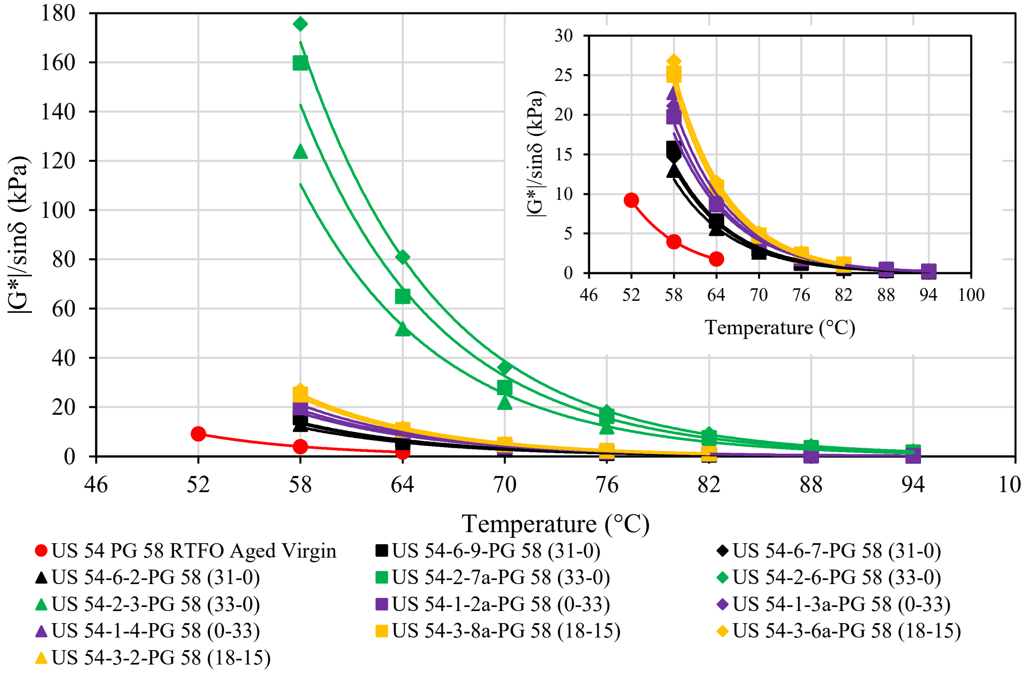


Figure A-50. Temperature Sweep Test Results for the RTFO Aged Virgin and E & R Asphalt Binders from US 54 Field Mixes, Constructed in 2016, Containing Different Percentages of Recycled Materials and PG 58-28 Virgin Asphalt Binder

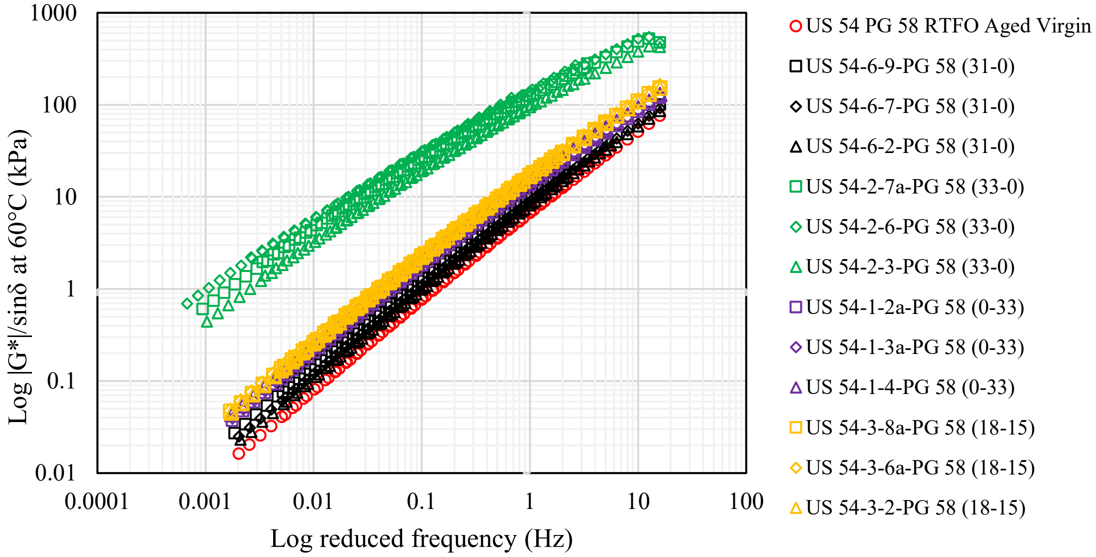


Figure A-51. Master Curve Measured at 60°C for the RTFO Aged Virgin and E & R Asphalt Binders from US 54 Field Mixes, Constructed in 2016, Containing Different Percentages of Recycled Materials and PG 58-28 Virgin Asphalt Binder

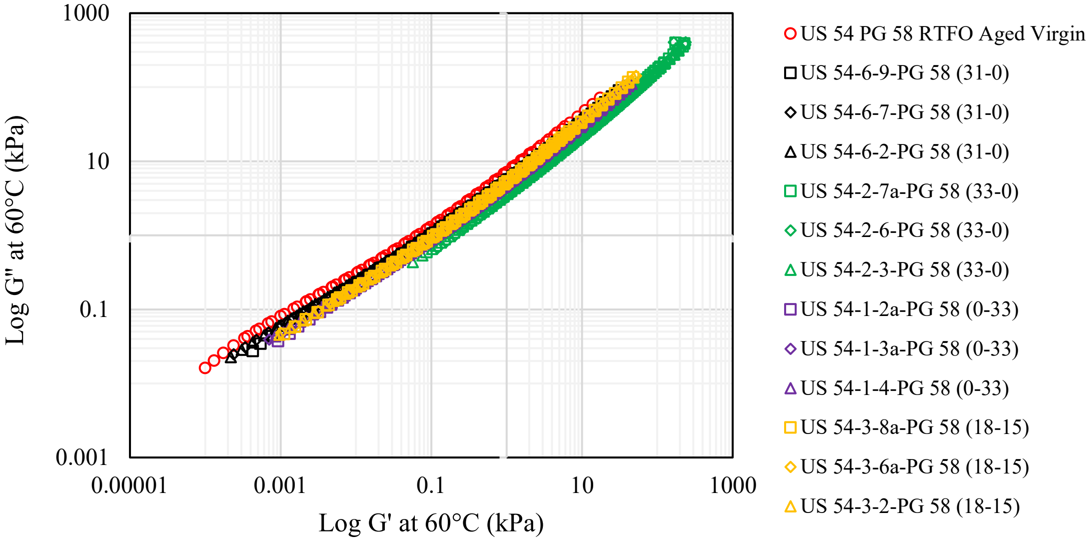


Figure A-52. Cole-Cole Plot Analyzed at 60°C for the RTFO Aged Virgin and E & R Asphalt Binders from US 54 Field Mixes, Constructed in 2016, Containing Different Percentages of Recycled Materials and PG 58-28 Virgin Asphalt Binder

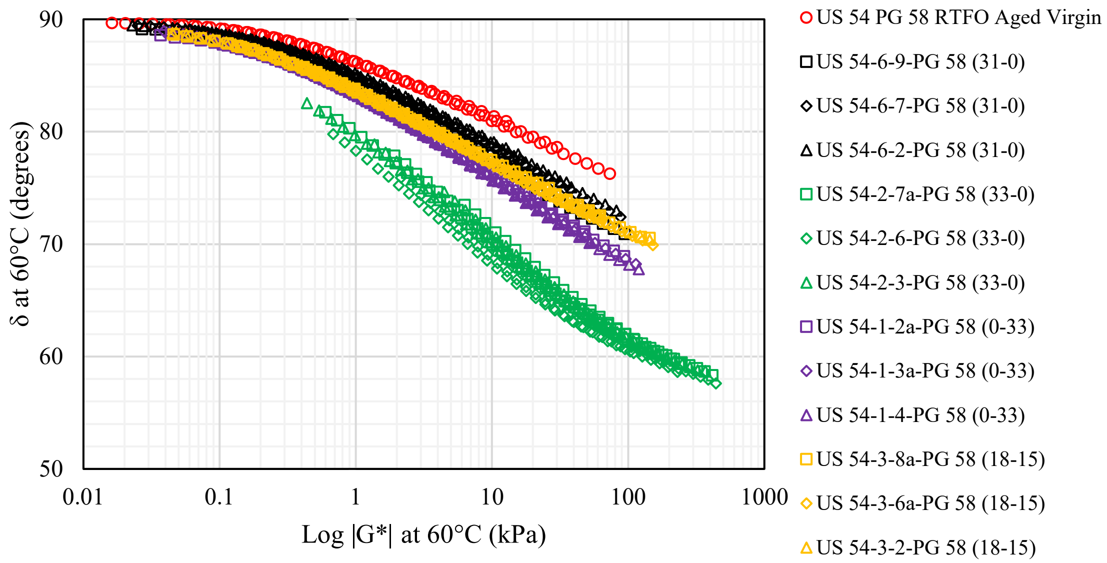


Figure A-53. Black Diagram Analyzed at 60°C for the RTFO Aged Virgin and E & R Asphalt Binders from US 54 Field Mixes, Constructed in 2016, Containing Different Percentages of Recycled Materials and PG 58-28 Virgin Asphalt Binder

Figure A-54 shows the temperature sweep test results for the RTFO aged virgin and E & R asphalt binders from the US 54 field mixes containing PG 64-22H virgin asphalt binder. The asphalt binders E & R from mixes containing no recycled materials showed an increase in the stiffness by presenting higher rutting parameter values than the RTFO binders. Using 35% ABR by RAP increased the E & R asphalt binders' rutting parameter values significantly as compared to the E & R asphalt binders from mixes containing no recycled materials.

Figure A-55 shows the master curve for these binders measured at 60°C and different frequencies. The E & R asphalt binders showed higher rutting resistance as compared to the corresponding RTFO aged virgin binder. The Cole-Cole plot and black diagram measured at 60°C for these binders are presented in Figure A-56 and Figure A-57, respectively. The Cole-Cole plots showed no significant difference between the RTFO aged virgin and E & R asphalt binders from mixes containing no recycled materials. However, the E & R asphalt binders from mixes containing 35% ABR percentage by RAP showed right-hand side shifting for the curves, which indicated more elasticity. The black diagram presented in Figure A-57 illustrates that the asphalt binders E & R from mixes containing 35% ABR by RAP showed different trends as compared to the other binders.

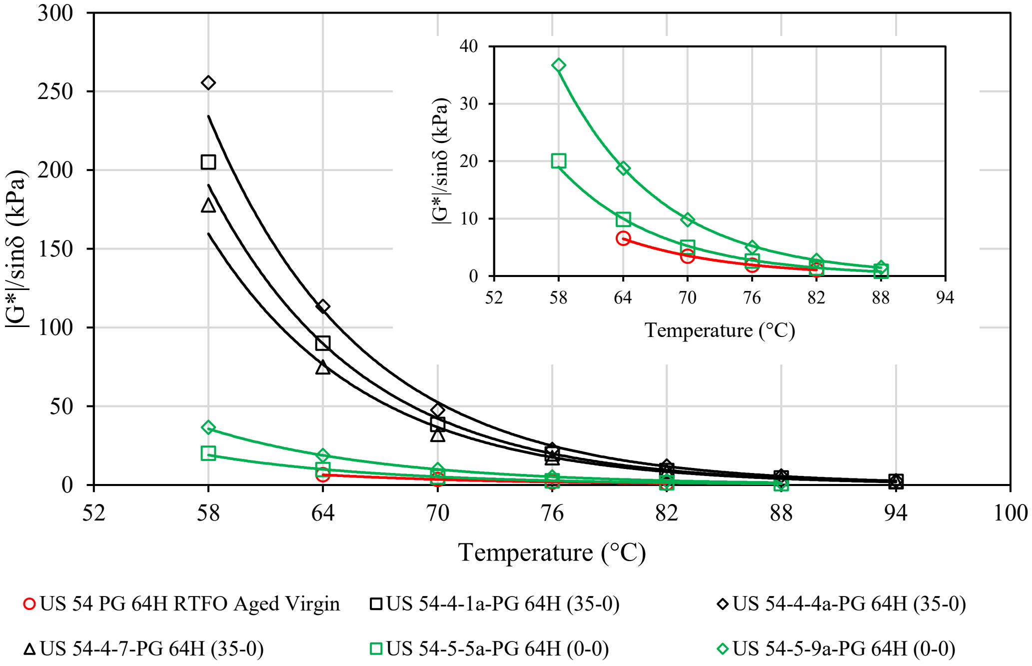


Figure A-54. Temperature Sweep Test Results for the RTFO Aged Virgin and E & R Asphalt Binders from US 54 Field Mixes, Constructed in 2016, Containing PG 64-22H Virgin Asphalt Binder

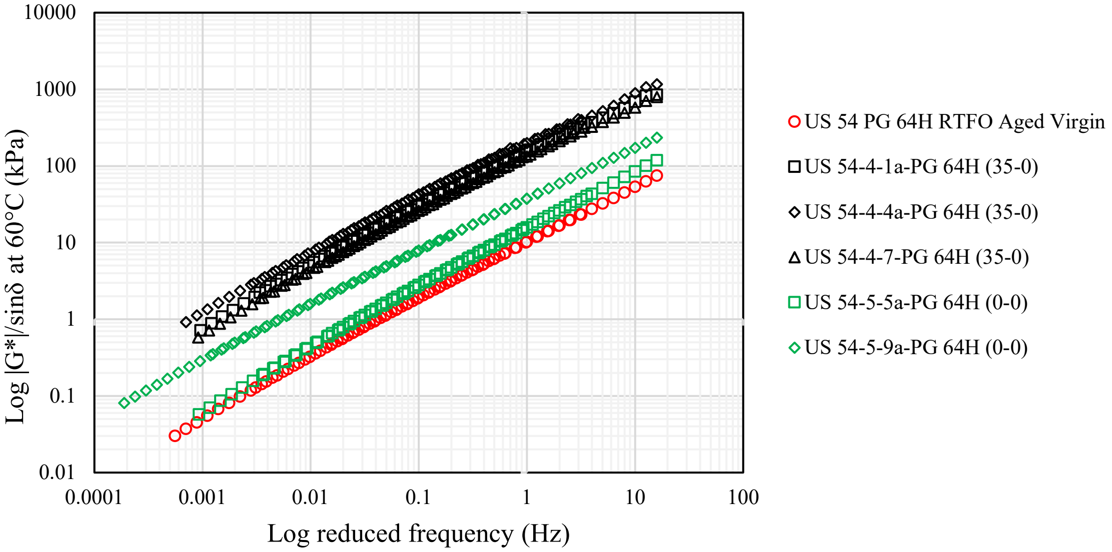


Figure A-55. Master Curve Measured at 60°C for the RTFO Aged Virgin and E & R Asphalt Binders from US 54 Field Mixes, Constructed in 2016, Containing PG 64-22H Virgin Asphalt Binder

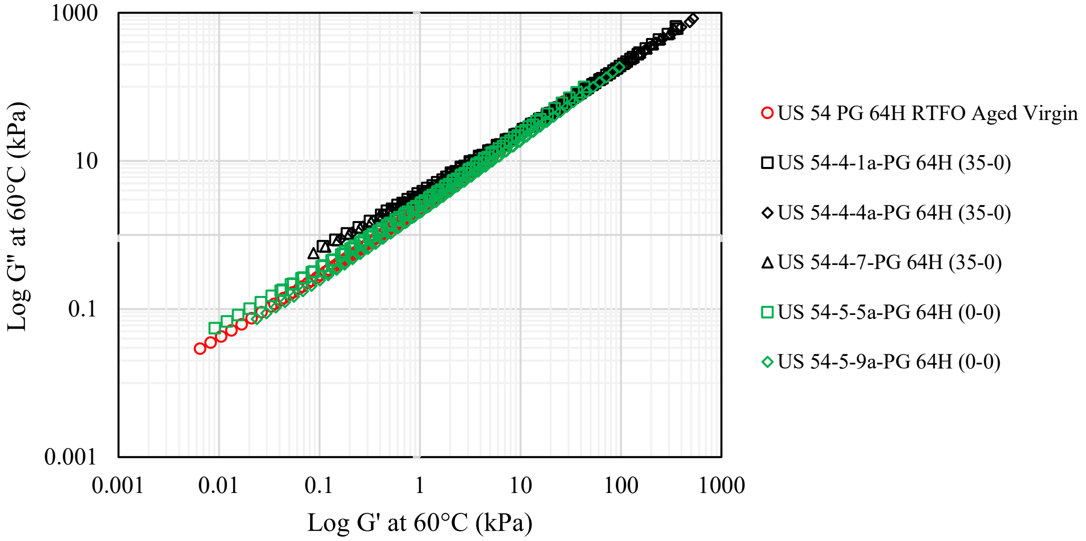


Figure A-56. Cole-Cole Plot Analyzed at 60°C for the RTFO Aged Virgin and E & R Asphalt Binders from US 54 Field Mixes, Constructed in 2016, Containing PG 64-22H Virgin Asphalt Binder

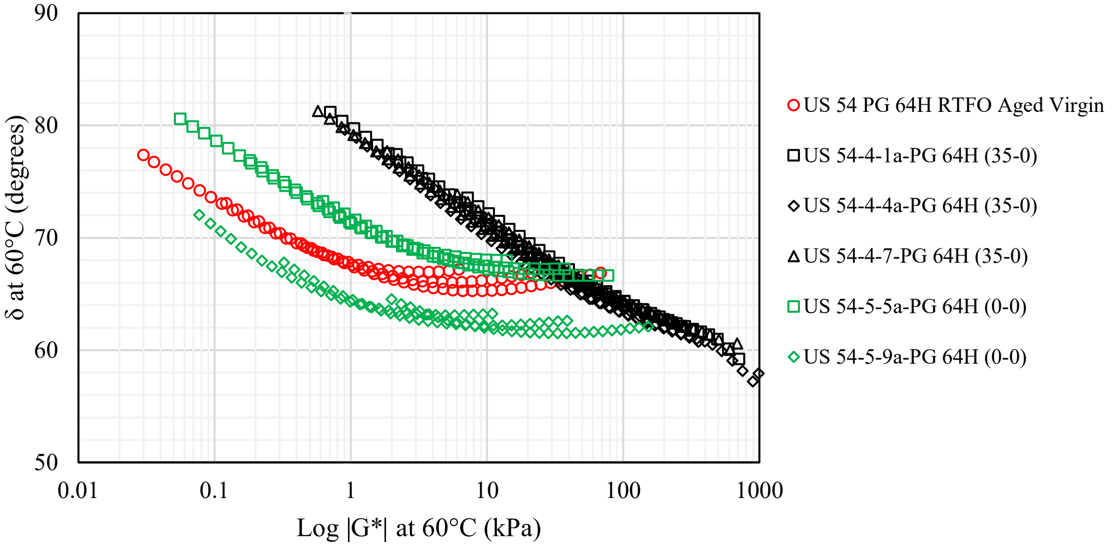


Figure A-57. Black Diagram Analyzed at 60°C for the RTFO Aged Virgin and E & R Asphalt Binders from US 54 Field Mixes, Constructed in 2016, Containing PG 64-22H Virgin Asphalt Binder

Figure A-58 shows the temperature sweep test results for the RTFO aged virgin and E & R asphalt binders from the US 63-1 field mixes containing PG 58-28 virgin asphalt binder. The asphalt binders E & R from mixes containing 35% ABR by RAP showed an increase in the stiffness by presenting higher rutting parameter values than the RTFO binders.

The master curve, Cole-Cole plot, and black diagram measured for these binders at 60°C and different frequencies are presented in Figure A-59, Figure A-60, and Figure A-61, respectively. The asphalt binders E & R from mixes containing 35% ABR percentage by RAP showed higher rutting resistance than the values of the corresponding RTFO aged virgin asphalt binders. This was related to the higher stiffness and elasticity.

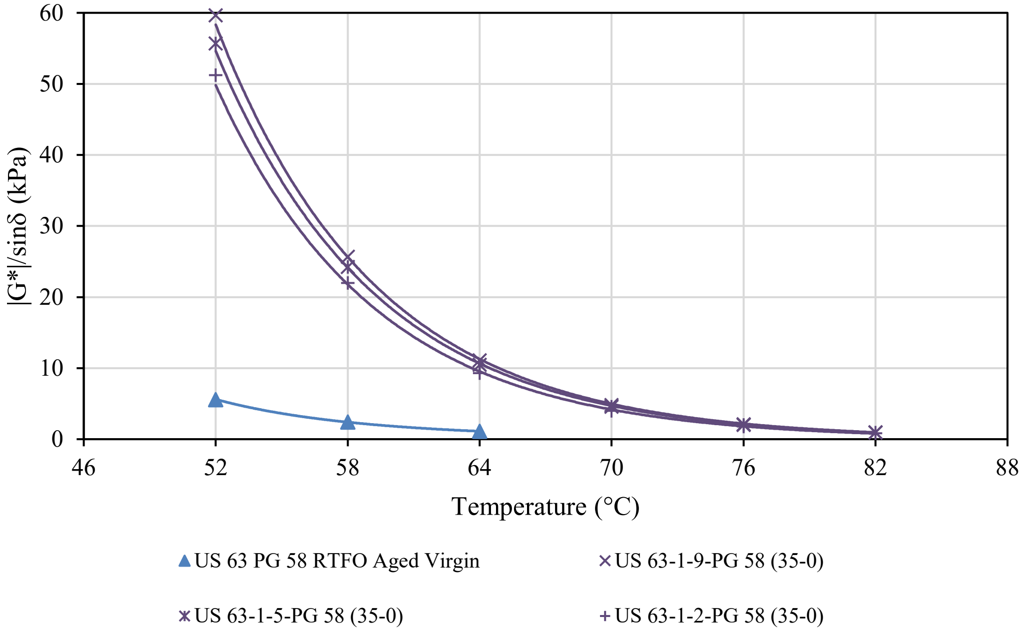


Figure A-58. Temperature Sweep Test Results for the RTFO Aged Virgin and E & R Asphalt Binders from US 63-1 Field Mixes, Constructed in 2016, Containing PG 58-28 Virgin Asphalt Binder and 35% ABR by RAP

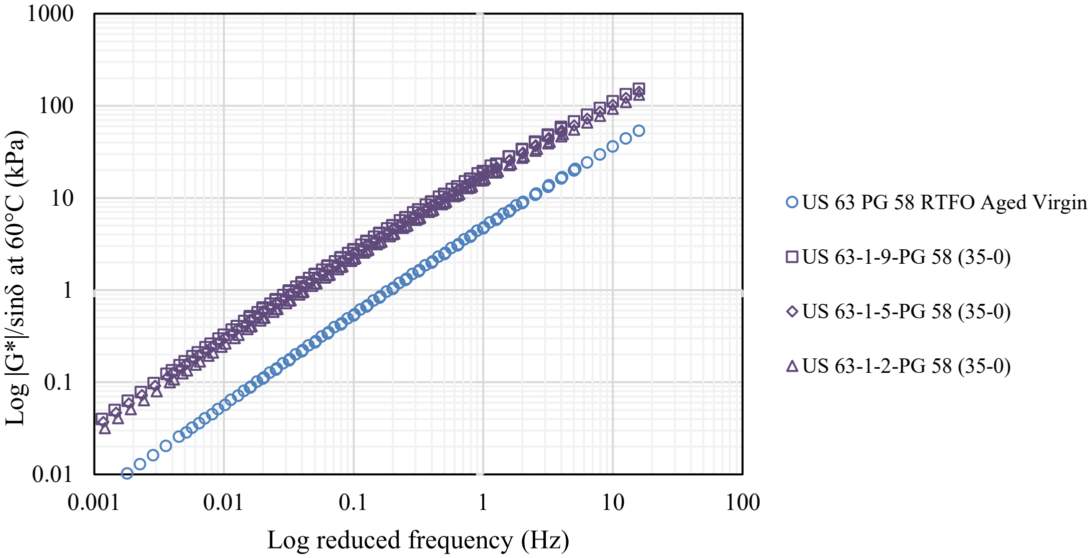


Figure A-0-59. Master Curve Measured at 60°C for the RTFO Aged Virgin and E & R Asphalt Binders from US 63-1 Field Mixes, Constructed in 2016, Containing PG 58-28 Virgin Asphalt Binder and 35% ABR by RAP

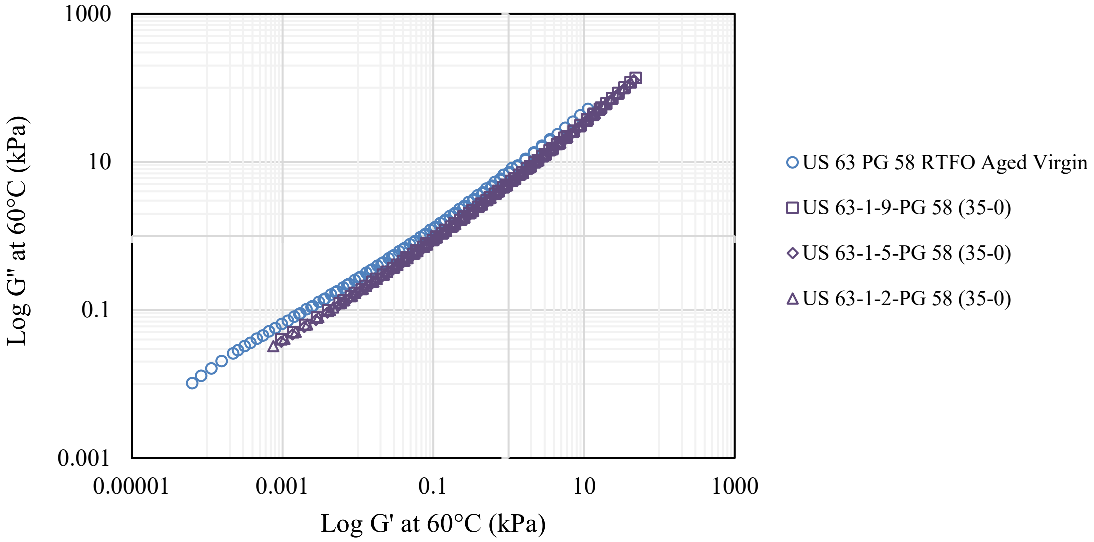


Figure A-60. Cole-Cole Plot Analyzed at 60°C for the RTFO Aged Virgin and E & R Asphalt Binders from US 63-1 Field Mixes, Constructed in 2016, Containing PG 58-28 Virgin Asphalt Binder and 35% ABR by RAP

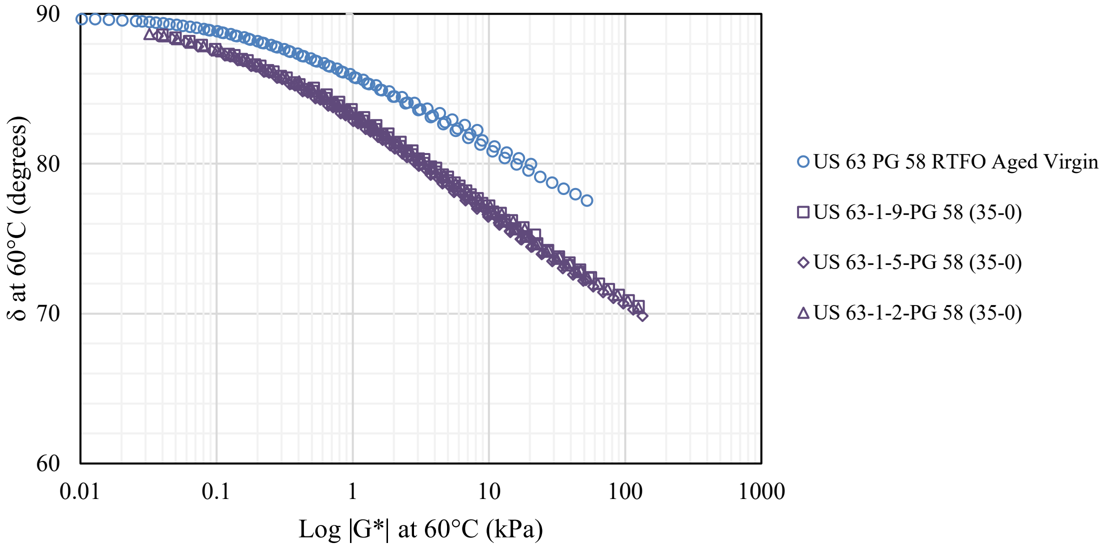


Figure A-61. Black Diagram Analyzed at 60°C for the RTFO Aged Virgin and E & R Asphalt Binders from US 63-1 Field Mixes, Constructed in 2016, Containing PG 58-28 Virgin Asphalt Binder and 35% ABR by RAP

To compare the different E & R binders and the corresponding RTFO aged virgin binders, the high PG temperature for each asphalt binder is presented in Figure A-62. The columns' color indicated the state of the asphalt binder. In other words, the black columns represent the RTFO aged virgin binders, the red ones indicate the binders E & R from mixes containing RAP, the green ones indicate the binders E & R from mixes containing RAS, the purple ones indicate the binders E & R from mixes containing both RAP and RAS, and the blue ones refer to the E & R binders from mixes containing no recycled materials. The high PG temperature increased one to two grades, 6°C per grade, for asphalt binders E & R from mixes containing 17% ABR by RAP, MO 13-1. Using 31% ABR by RAP or 33% ABR by RAS in US 54-6 and US 54-1 mixes respectively increased the high PG temperatures of the E & R asphalt binders by two grades. Increasing the ABR percentage by RAP from 31% to 33% in US 54-2 mixes increased the high PG temperature by another three grades. In other words, the E & R asphalt binders containing 33% ABR by RAP showed a boost in the high PG temperature by five grades as compared to the corresponding RTFO aged virgin asphalt binder. This was related to the high variability of the aged binders E & R from the RAP as discussed in the literature: the asphalt binders E & R from the RAP can be varied from one season and/or stockpile to another.

Using both RAP and RAS with a total ABR of 33% in the US 54-3 mixes showed an increase in the high PG temperature by one grade as compared to the high PG temperature of the E & R asphalt binders from mixes containing the same 33% ABR percentage by RAS only, US 54-1 mixes. This indicated that combining both RAP and RAS in the mixes altered the performance of the E & R asphalt binders. This occurred because the asphalt binders included in the RAP interacted with the virgin asphalt binders easier than the interaction process between the air-blown asphalt included in the RAS and the same virgin asphalt binders. The interaction process was different in the case of the RAS binders due to the stiff nature of the air-blown asphalt. These binders required high heat to ensure good interaction process with the virgin asphalt binder. The extra heating during the preheating and compaction processes for the plant mixes containing RAS collected from behind the paver caused more interaction process between the air-blown binder in the RAS and the virgin asphalt binder. However, for the same field mixes, the interaction process was not fully achieved. Therefore, the asphalt binders E & R from mixes containing 33% ABR by RAP presented higher stiffness than the binders E & R from mixes containing the same virgin asphalt binder and 33% ABR by RAS.

Asphalt binders E & R from mixes containing no recycled materials in the US 54-5 mixes showed an increase in the high PG temperature from one to two grades. Adding RAP by a percentage of 35% ABR to US 54-4 mixes increased the high PG temperature from three to four grades as compared to the RTFO aged virgin binders. Comparing the high PG temperatures of the E & R asphalt binders from US 54-4 and US 63-1 mixes, both mixes contained the same ABR percentage by RAP (35%). However, the US 63-1 mixes contained a softer asphalt binder. This caused an increase in the high PG temperature of the E & R asphalt binders from US 63-1 mixes only two grades, which was lower than the increase for the asphalt binders E & R from US 54-4 mixes (three to four grades). Another reason was the variability of RAP properties.

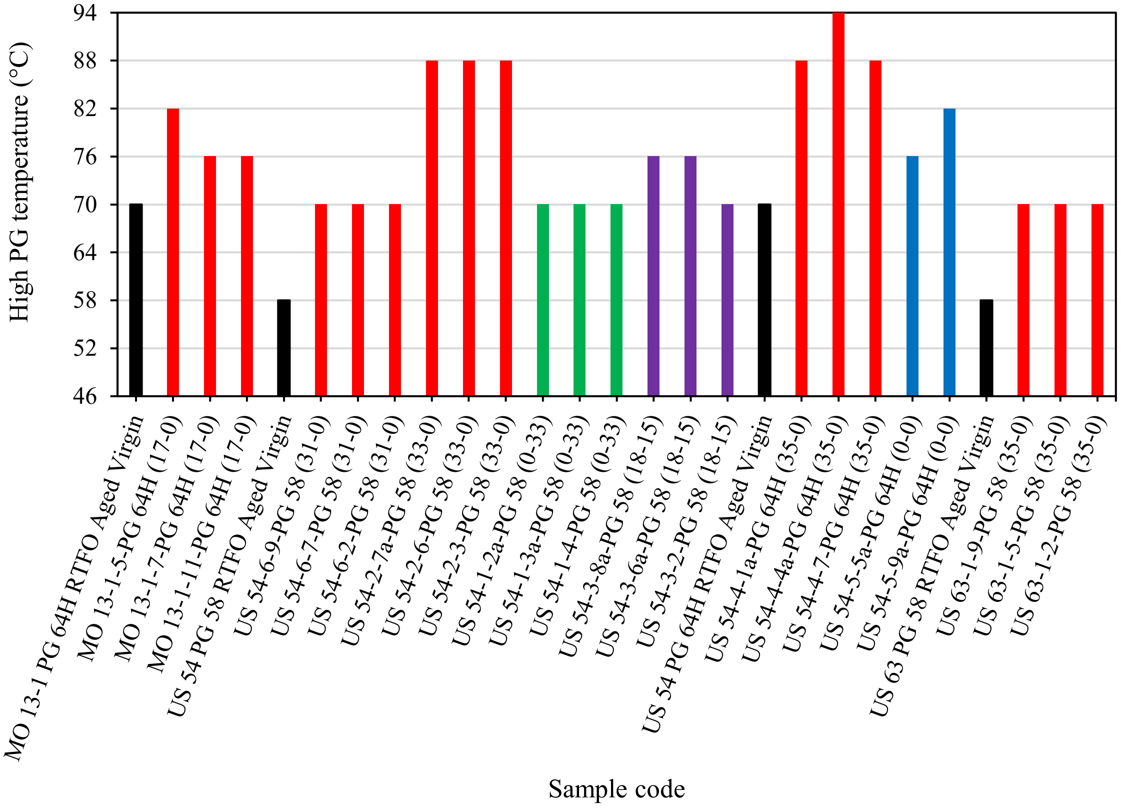


Figure A-62. The High PG Temperatures for the RTFO Aged Virgin and E & R Asphalt Binders from Different Field Mixes, Constructed in 2016

Figure A-63 illustrates the MSCR test results measured at 60°C reference temperature and 0.1 & 3.2 kPa stress levels for the RTFO aged virgin and E & R asphalt binders from MO 13-1 field mixes containing 17% ABR by RAP and PG 64-22H virgin asphalt binder. The asphalt binders E & R from these mixes showed more resistance to rutting by presenting higher %R and lower J_{nr}

values at different stress levels than the values recorded for the RTFO aged virgin asphalt binder. This was related to the stiffness of the asphalt binders included in the RAP.

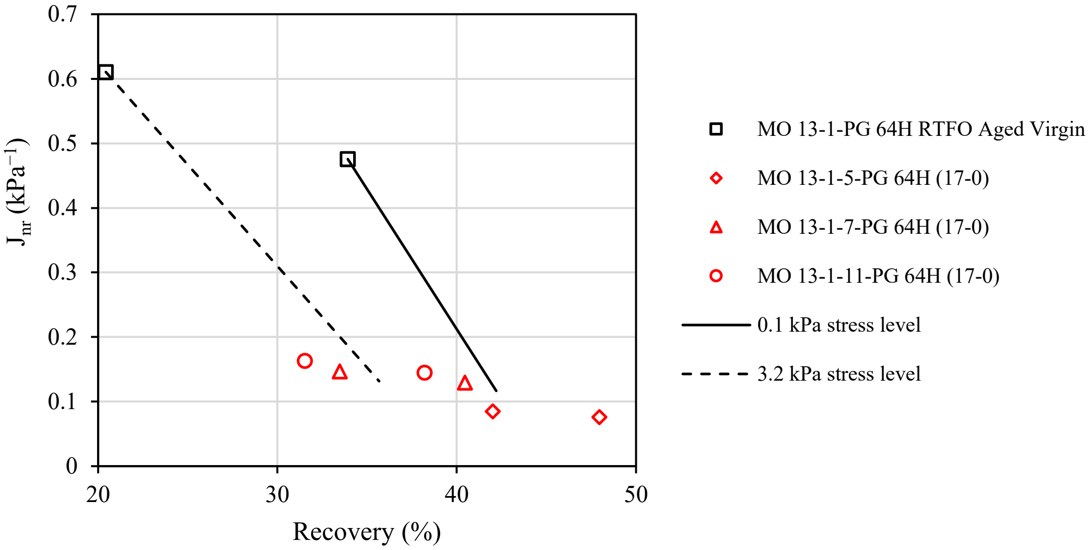


Figure A-63. MSCR Test Results Measured at 60°C for RTFO Aged Virgin and E & R Asphalt Binders from MO 13-1 Field Mixes, Constructed in 2016, Containing 17% ABR by RAP and PG 64-22H Virgin Asphalt Binder

Figure A-64 shows the relation between the %R and J_{nr} measured at 60°C and two different stress levels for the RTFO aged virgin and E & R asphalt binders from US 54 field mixes containing different percentages of recycled materials by RAP, RAS, or both, and a PG 58-28 virgin asphalt binder. All asphalt binders E & R from these mixes presented higher %R and lower J_{nr} values than the RTFO aged virgin asphalt binder’s values. The highest %R and the lowest J_{nr} values were recorded for binders E & R from mixes containing 33% ABR by RAP. The lowest %R and the highest J_{nr} values for the E & R asphalt binders were recorded for binders E & R from mixes having 31% ABR percentage by RAP. This reflected that increasing the percentage of the recycled materials altered the performance of the E & R asphalt binders. Another reason was the high variability of the binders’ properties included in the RAP. For asphalt binders E & R from mixes containing either 33% ABR by RAS or 18-15% ABR by RAP-RAS, the binders had a higher rutting resistance (higher %R and lower J_{nr}) than binders E & R from mixes containing 31% ABR by RAP and lower rutting resistance than binders E & R from mixes containing 33% ABR by RAP.

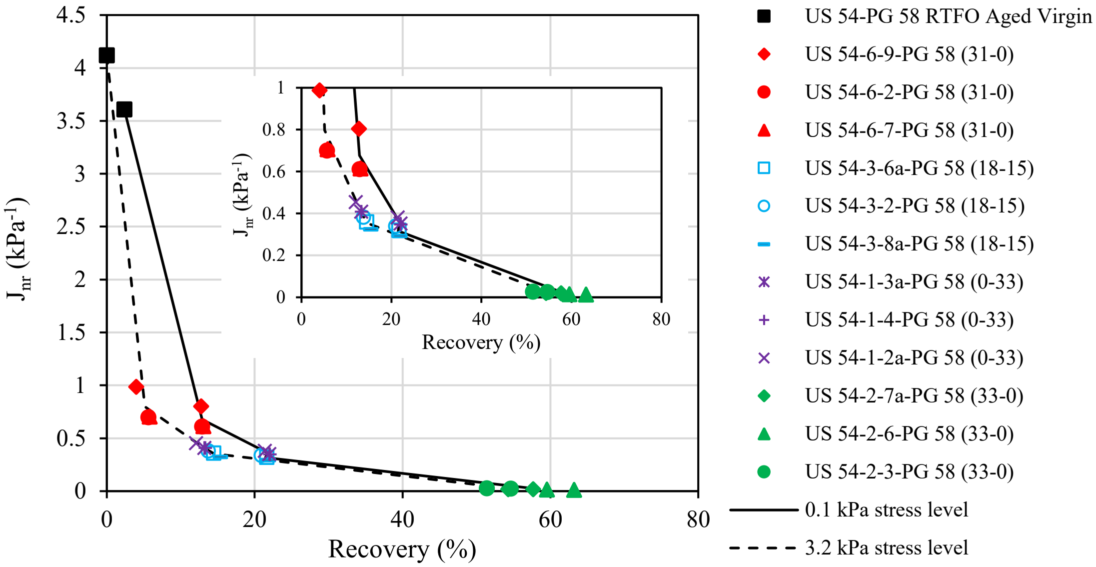


Figure A-64. MSCR Test Results Measured at 60°C for RTFO Aged Virgin and E & R Asphalt Binders from US 54 Field Mixes, Constructed in 2016, Containing Different Percentages of Recycled Materials and PG 58-28 Virgin Asphalt Binder

The MSCR test results at 60°C for RTFO aged virgin and E & R asphalt binders from US 54 field mixes containing PG 64-22H virgin asphalt binder are presented in Figure A-65. The %R values did not show any significant enhancement for the US 54-5-9a E & R asphalt binder as compared to the RTFO aged virgin binder. Moreover, the %R values decreased for US 54-5-5a and all US 54-4 E & R asphalt binders as compared to the RTFO aged virgin binder. However, for the J_{nr}, the E & R asphalt binders introduced lower values than the RTFO aged virgin binders' values. The lowest J_{nr} values were recorded for asphalt binders E & R from mixes containing 35% ABR percentage by RAP.

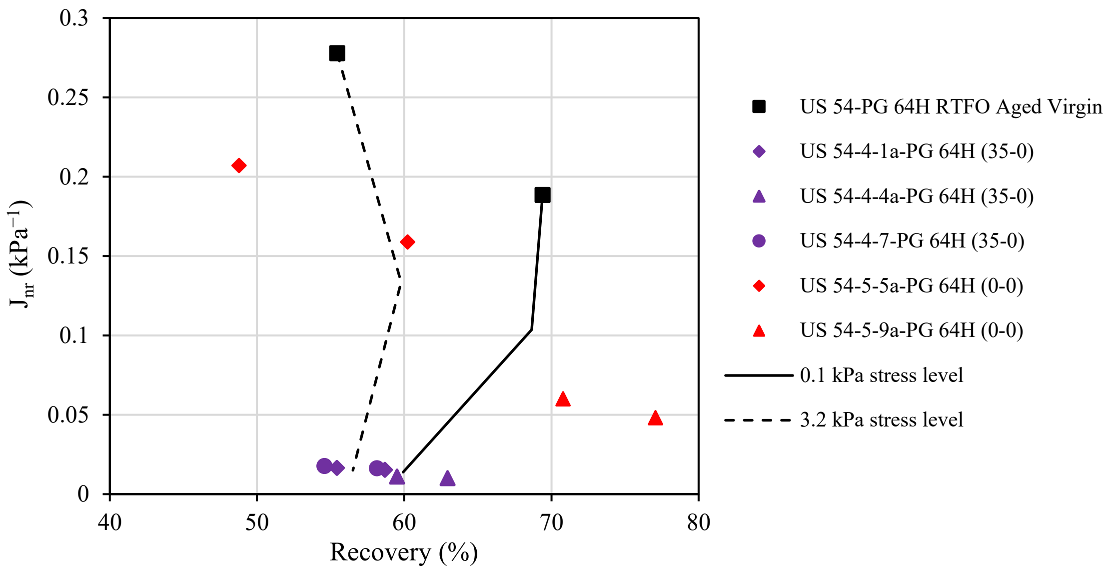


Figure A-65. MSCR Test Results, Measured at 60°C, for RTFO Aged Virgin and E & R Asphalt Binders from US 54 Field Mixes, Constructed in 2016, Containing PG 64-22H Virgin Asphalt Binder

Figure A-66 illustrates the MSCR test results measured at 60°C for the RTFO aged virgin and E & R asphalt binders from US 63-1 field mixes containing 35% ABR percentage by RAP and PG 58-28 virgin asphalt binder. The asphalt binders E & R from these mixes showed higher %R and lower J_{nr} values than the values obtained for the RTFO aged virgin asphalt binder. This occurred due to the stiffness of the binders contained in the RAP.

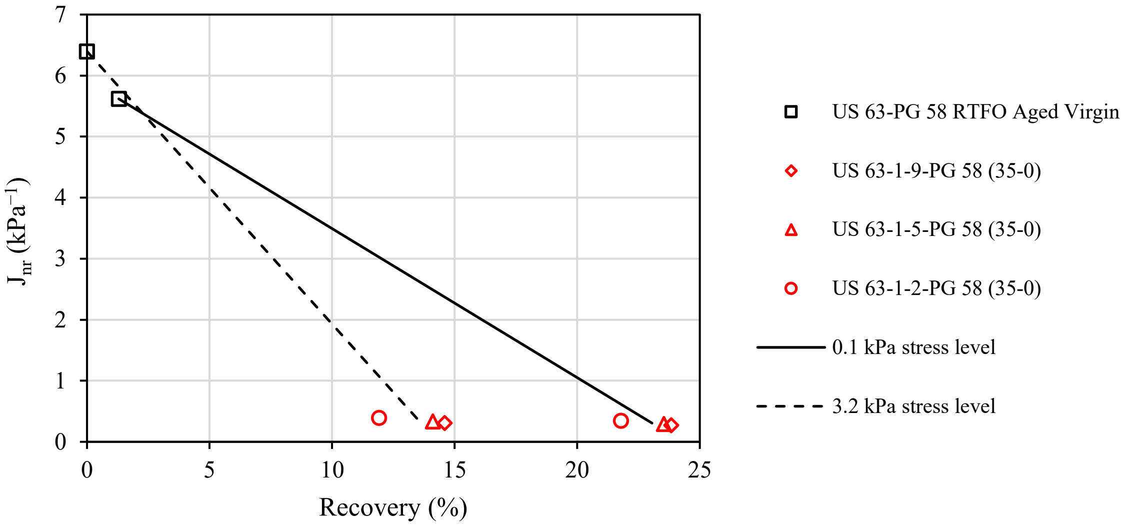


Figure A-66. MSCR Test Results Measured at 60°C for RTFO Aged Virgin and E & R Asphalt Binders from US 63-1 Field Mixes, Constructed in 2016, Containing PG 58-28 Virgin Asphalt Binder and 35% ABR by RAP

Figure A-67 shows the percentage increase or decrease in the %R values for the E & R asphalt binders from field mixes constructed in 2016 as compared to the %R of the RTFO aged virgin binders. The MSCR test's measurements were conducted at 60°C and 0.1 & 3.2 kPa stress levels. Most of the E & R asphalt binders presented higher %R values than the values of the corresponding RTFO aged virgin binders. However, some E & R asphalt binders showed a percentage decrease in the %R values (e.g. E & R binders from US 54-4 and US 54-5-5a mixes). These mixes contained a PG 64-22H virgin asphalt binder. The lowest percentage increase in the %R values was observed for asphalt binders E & R from MO 13-1 mixes. These mixes had a PG 64-22H virgin asphalt binder. Therefore, the asphalt binders E & R from mixes containing a PG 64-22H virgin asphalt binder did not present a significant increase in the %R values as compared to the RTFO aged virgin binders' values.

Contrarily, by using a PG 58-28 virgin asphalt binder, the %R for the E & R asphalt binders enhanced significantly as compared to the corresponding RTFO aged virgin binders. The percentages increase in the %R values at 3.2 kPa stress level (R3.2) for asphalt binders E & R from US 54-PG 58 and US 63-1 mixes were not presented in the figure because the R3.2 values for the corresponding RTFO aged virgin binders were zero. The percentage increase in the R0.1 value for asphalt binders E & R from US 54-6-PG 58 (31-0) reached above 400%. Increasing the ABR percentage by RAP to 33% for US 54-2-PG 58 (33-0) mixes caused a significant increase in the percentage increase in the R0.1 value for the E & R asphalt binders. The percentage increase in the R0.1 value for these binders reached approximately 2400%. The asphalt binders E & R from either US 54-1-PG 58 (0-33) or US 54-3-PG 58 (18-15) mixes had the same percentage increase in the R0.1 value (800%), which was greater than what was obtained for mixes contained 31% ABR by RAP and lower than the values obtained for mixes containing 33% ABR by RAP. By comparing asphalt binders E & R from US 54-4 and US 63-1 mixes, these mixes had the same ABR percentage by RAP (35%), the binders E & R from mixes containing a soft binder, PG 58-28, (US 63-1) showed a higher increase in the percentage increase in the R0.1 value. The value reached more than 1600%. However, the other binders E & R from the other mixes, US 54-4, showed a percentage decrease in the %R values due to the stiffness of the used virgin asphalt binder (PG 64-22H).

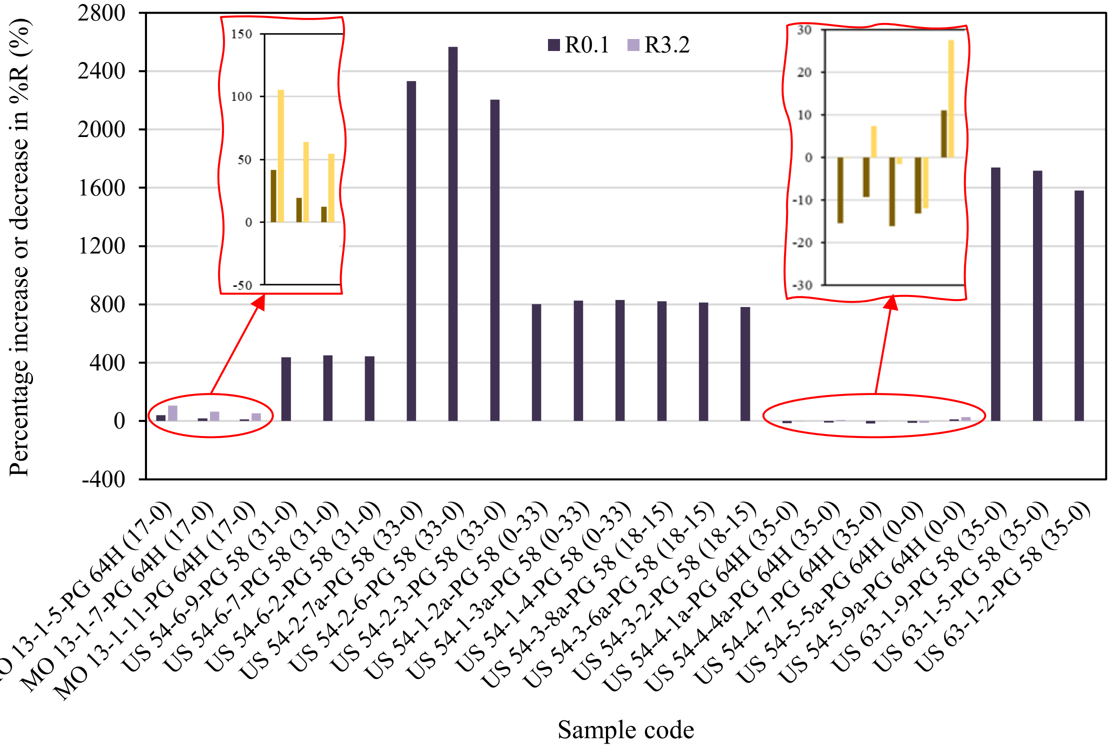


Figure A-67. Percentage Increase or Decrease in the %R Values for the Asphalt Binders E & R from Field Mixes Constructed in 2016 as Compared to the %R Values for the RTFO Aged Virgin Binders; the Measurements were Conducted at 60°C and 0.1 & 3.2 kPa Stress Levels

Figure A-68 shows the percentage decrease in the J_{nr} values for the E & R asphalt binders from field mixes constructed in 2016 as compared to the J_{nr} of the RTFO aged virgin binders. The MSCR test's measurements were conducted at 60°C and 0.1 & 3.2 kPa stress levels. All binders E & R from these mixes presented lower percentages of J_{nr} values than the values corresponding to the RTFO aged virgin asphalt binders. The highest percentage decrease in the J_{nr} values was recorded for asphalt binders E & R from mixes containing 33% ABR percentage by RAP and a virgin asphalt binder having a PG of 58-28. The asphalt binders E & R from mixes containing 30% or more ABR percentage by recycled materials showed a percentage decrease in the J_{nr} values greater than 80%. The lowest percentage decrease in the J_{nr} values was noted for asphalt binders E & R from mixes containing no recycled materials and a stiff asphalt binder as illustrated in US 54-5-5a.

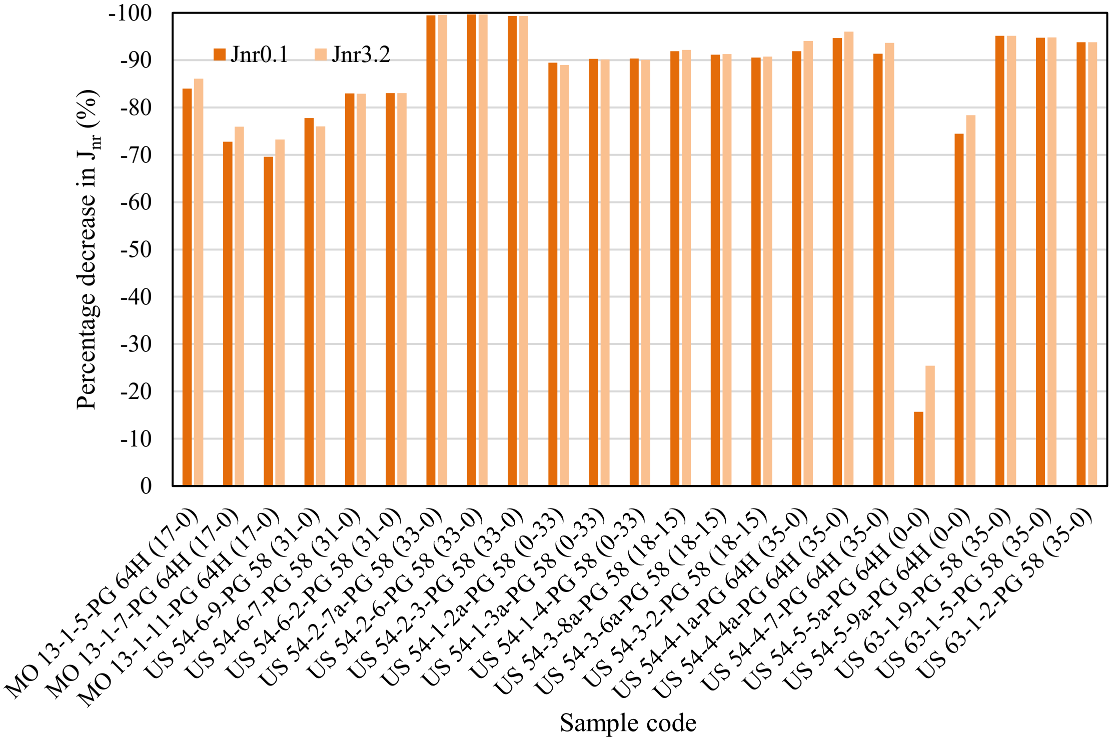


Figure A-68. Percentage Decrease in the J_{nr} Values for the Asphalt Binders E & R from Field Mixes Constructed in 2016 as Compared to the J_{nr} Values for the RTFO Aged Virgin Binders; the Measurements were Conducted at 60°C and 0.1 & 3.2 kPa Stress Levels

In this section, a comparison between the RTFO aged virgin and the E & R asphalt binders from the MO 13-1, US 54-6, US 54-1, and US 63-1 field and plant mixes constructed in 2016 was discussed. The temperature sweep test results for the RTFO aged virgin and E & R asphalt binders from MO 13-1 field and plant mixes containing 17% ABR by RAP are presented in Figure A-69. As discussed in the previous sections, the E & R asphalt from mixes even containing no recycled materials showed a higher rutting parameter as compared to the corresponding RTFO aged asphalt binders. However, the asphalt binders E & R from the plant mixes presented a higher stiffness by showing higher rutting parameter values than the binders E & R from the field mixes. This happened because of the reheating and compaction processes that had occurred to the plant mixes in the lab after collecting from behind the paver. These processes increased the interaction process of the asphalt binders included in the recycled materials and the virgin asphalt binder. The same observations were concluded from Figure A-70: the E & R asphalt binders from plant mixes presented higher PG temperatures by one or two grades as compared to the E & R binders from the field mixes.

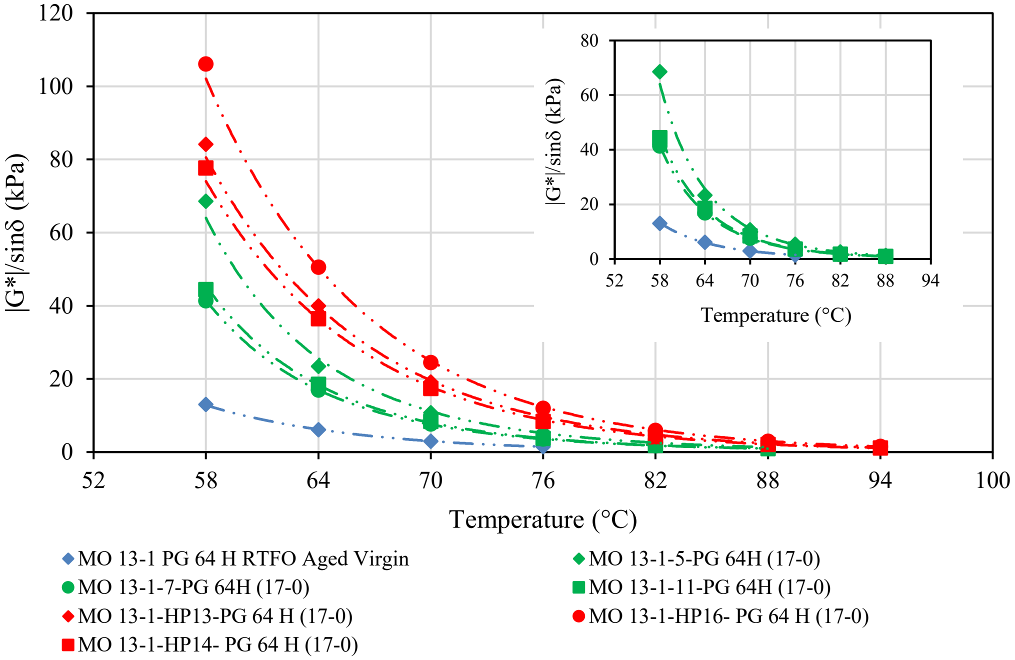


Figure A-69. Temperature Sweep Test Results for the RTFO Aged Virgin and E & R Asphalt Binders from MO 13-1 Field and Plant Mixes, Constructed in 2016, Containing PG 64-22H Virgin Asphalt Binder and 17% ABR by RAP

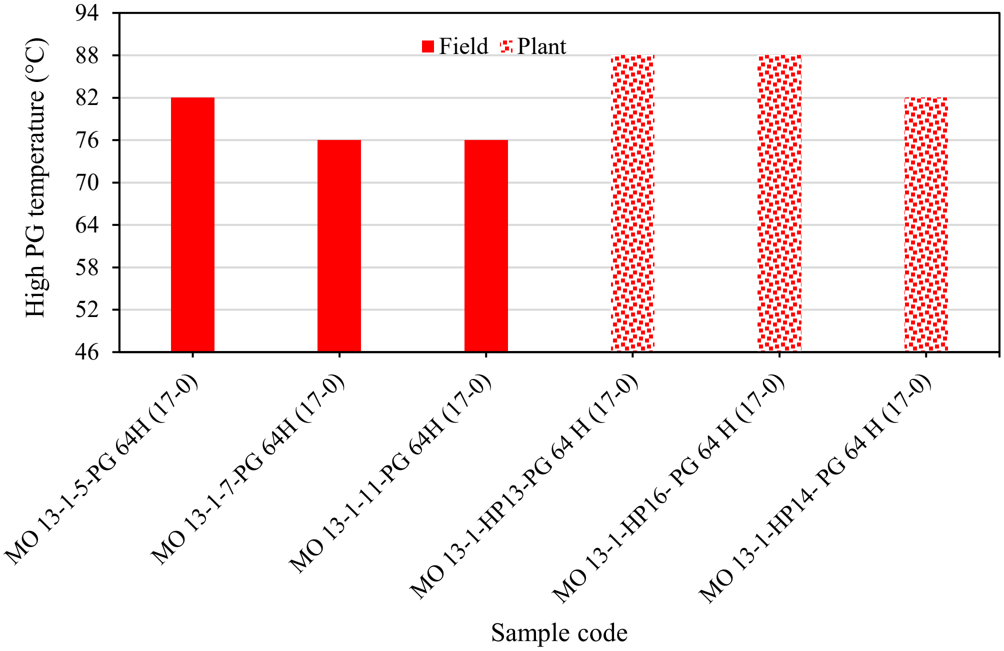


Figure A-70. High PG Temperatures for the E & R Asphalt Binders from MO 13-1 Field and Plant Mixes, Constructed in 2016, Containing PG 64-22H Virgin Asphalt Binder and 17% ABR by RAP

Temperature sweep test results for the RTFO aged virgin and E & R asphalt binders from US 54-6 field and plant mixes constructed in 2016, contained 31% ABR by RAP and PG 58-28 virgin asphalt binder are illustrated in Figure A-71. The same finding presented in Figure A-69 was concluded from Figure A-71. The E & R asphalt binders from the plant mixes presented higher rutting parameter values than the values of the E & R asphalt binders from the field mixes. Figure A-72 presents the high PG temperatures for the asphalt binders E & R from the US 54-6 field and plant mixes containing 31% ABR by RAP and a PG 58-28 virgin asphalt binder. The high PG temperature of the E & R binders from the plant mixes was one grade higher than the high PG temperature of the binders E & R from the field mixes.

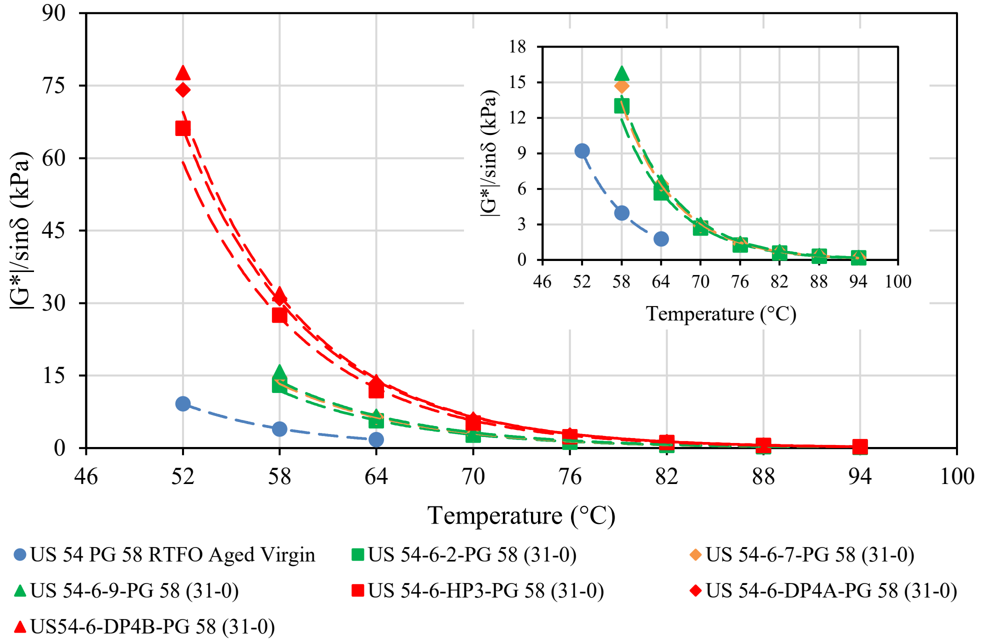


Figure A-71. Temperature Sweep Test Results for the RTFO Aged Virgin and E & R Asphalt Binders from US 54-6 Field and Plant Mixes, Constructed in 2016, Containing PG 58-28 Virgin Asphalt Binder and 31% ABR by RAP

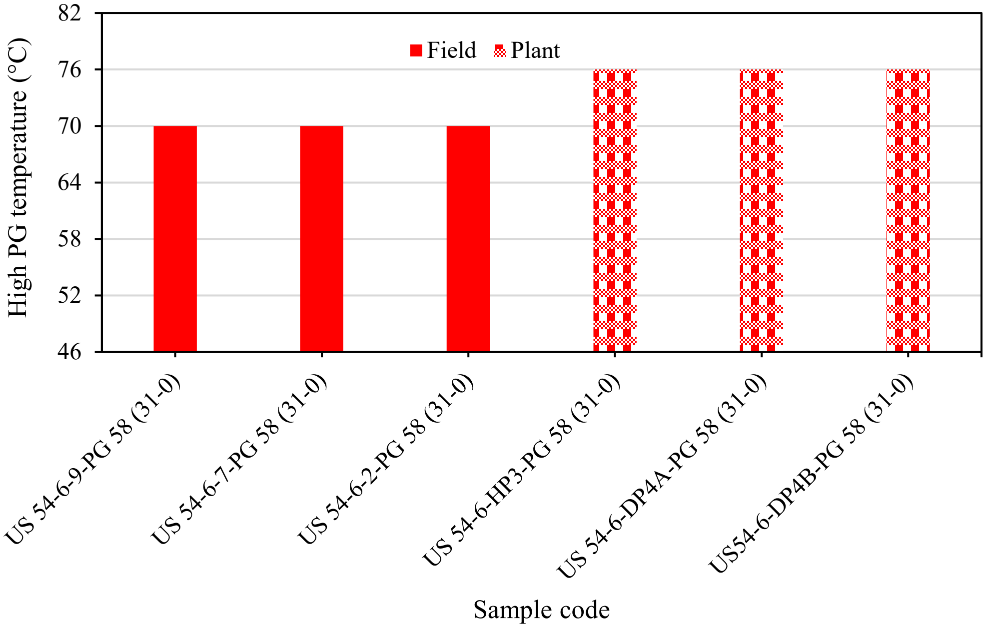


Figure A-72. High PG Temperatures for the E & R Asphalt Binders from US 54-6 Field and Plant Mixes, Constructed in 2016, Containing PG 58-28 Virgin Asphalt Binder and 31% ABR by RAP

Figure A-73 presents the temperature sweep test results for the RTFO aged virgin and the E & R asphalt binders from US 54-1 field and plant mixes containing PG 58-28 virgin asphalt binder and 33% ABR by RAS. For the asphalt binders E & R from the plant samples, the rutting parameter increased significantly as compared to the values for the E & R asphalt binders from the field samples. Even at 94°C, the rutting parameter for the E & R asphalt binders from the US 54-1 plant mixes was at least four times greater than the 2.2 kPa value (specification limit for the RTFO aged binders). Figure A-74 shows the high PG temperatures for the asphalt binders E & R from the US 54-1 field and plant mixes containing PG 58-28 virgin asphalt binder and 33% ABR by RAS. The reheating and compaction processes implemented in the lab for the collected plant mixes have caused a significant increase in the high PG temperature of the E & R asphalt binders. Thus, the high PG temperature for the E & R asphalt binders from US 54-1 field mixes was 70°C. However, the high PG temperature for the E & R asphalt binders from the US 54-1 plant mixes exceeded 94°C. The asphalt binders included in the RAS were very stiff “air-blown asphalt”. So, increasing the heating process caused more contribution of recycled materials in the mix. This altered the performance of the total E & R binder by increasing its stiffness.

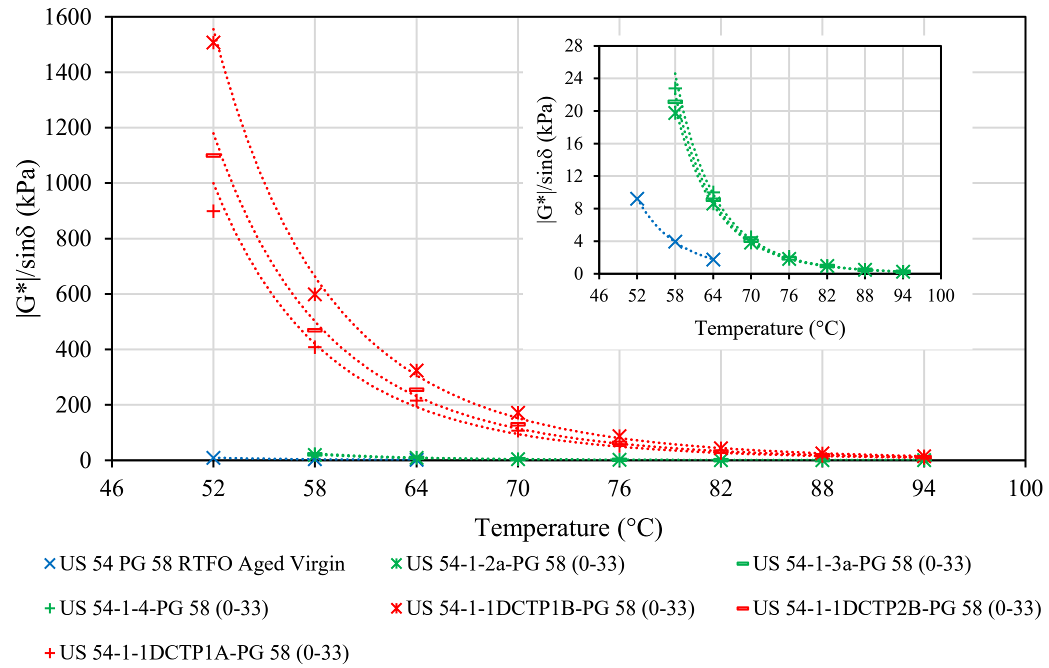


Figure A-73. Temperature Sweep Test Results for the RTFO Aged Virgin and E & R Asphalt Binders from US 54-1 Field and Plant Mixes, Constructed in 2016, Containing PG 58-28 Virgin Asphalt Binder and 33% ABR by RAS

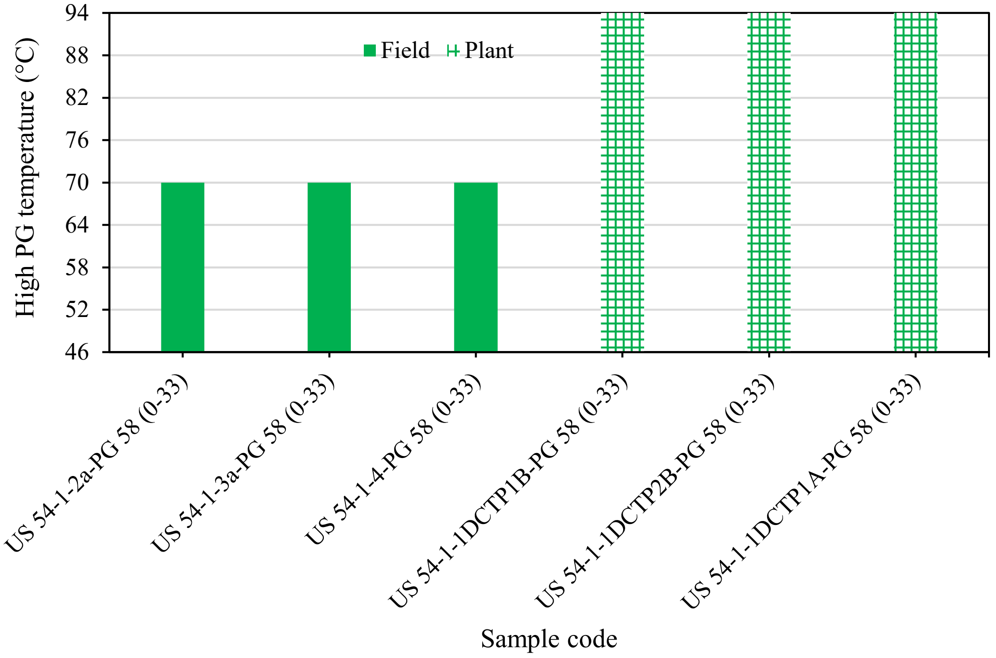


Figure A-74. High PG Temperatures for the E & R Asphalt Binders from US 54-1 Field and Plant Mixes, Constructed in 2016, Containing PG 58-28 Virgin Asphalt Binder and 33% ABR by RAS

Note: The high PG temperatures for the E & R asphalt binders from US 54-1 plant mixes exceeded 94°C.

Temperature sweep test results for the RTFO aged virgin and E & R asphalt binders from US 63-1 field and plant mixes containing PG 58-28 virgin asphalt binder and 35% ABR by RAP are illustrated in Figure A-75. The E & R asphalt binders from the plant mixes presented higher rutting parameter values than the values of the E & R asphalt binders from the field mixes. The US 63 PG 58 asphalt binder was softer than the US 54 PG 58 asphalt binder. However, the asphalt binders E & R from the US 63-1 mixes were stiffer than the binders E & R from the US 54-6 due to the higher percentage of RAP included in the US 63-1 mixes. Figure A-76 shows the high PG temperatures for the asphalt binders E & R from the US 63-1 field and plant mixes containing PG 58-28 virgin asphalt binder and 35% ABR by RAP. The high PG temperature of the E & R binders from the plant mixes was one grade higher than the high PG temperature of the binders E & R from the field mixes due to the occurrence of more interaction process.

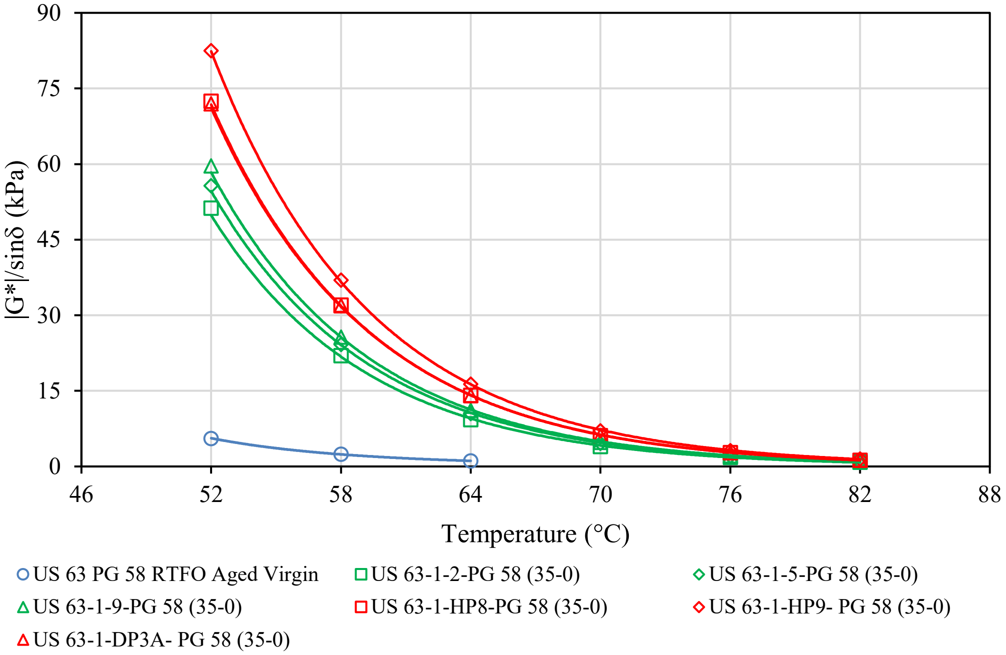


Figure A-75. Temperature Sweep Test Results for the RTFO Aged Virgin and E & R Asphalt Binders from US 63-1 Field and Plant Mixes, Constructed in 2016, Containing PG 58-28 Virgin Asphalt Binder and 35% ABR by RAP

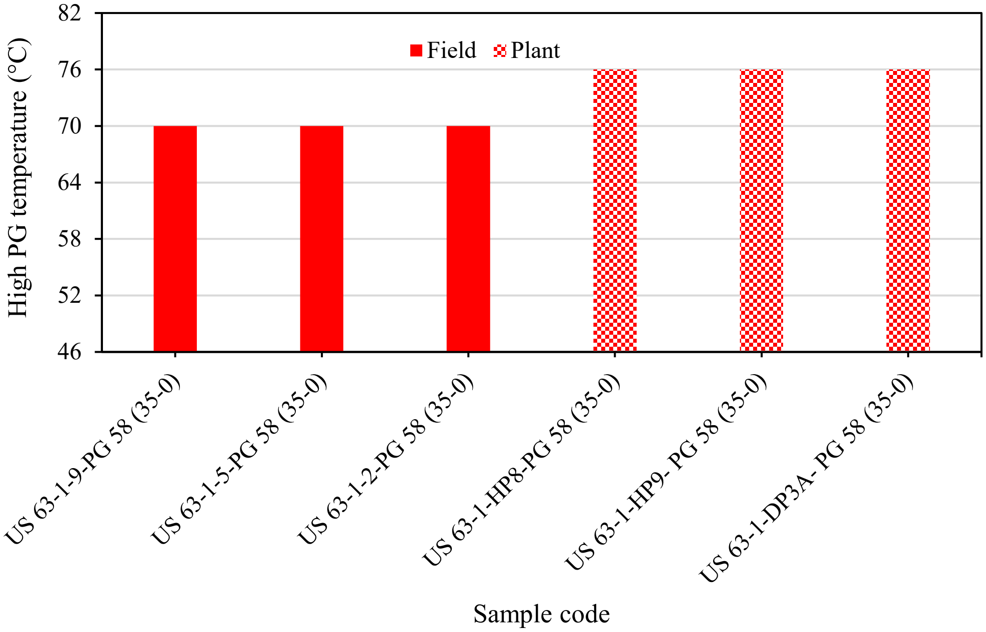


Figure A-76. High PG Temperature for the E & R Asphalt Binders from US 63-1 Field and Plant Mixes, Constructed in 2016, Containing PG 58-28 Virgin Asphalt Binder and 35% ABR by RAP

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