Development of Quality Standards for Inclusion of High Recycled Asphalt Pavement Content in Asphalt Mixtures – Phase IV

FINAL REPORT

Hosin "David" Lee, Ph.D., P.E., Professor, Principal Investigator
Iowa Technology Institute
University of Iowa, Iowa City, IA 52242
E-mail: hlee@uiowa.edu
ORCID: 0000-0001-9766-1232

Byungkyu Brian Moon, Graduate Research Assistant
Iowa Technology Institute
University of Iowa, Iowa City, IA 52242
E-mail: byungkyu-moon@uiowa.edu
ORCID: 0000-0002-4213-0773

Chris Williams, Ph.D., Professor, Co-Principal Investigator
Institute for Transportation
Iowa State University, Ames, IA 50010
E-mail: rwilliam@iastate.edu
ORCID: 0000-0002-8833-6232

Sponsored by
Iowa Highway Research Board
(IHRB Project TR-770)

IOWA
Technology Institute

MARCH 2022

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1. REPORT NO. IHRB Project TR-770	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.

4. TITLE AND SUBTITLE DEVELOPMENT OF QUALITY STANDARDS FOR INCLUSION OF HIGH RECYCLED ASPHALT PAVEMENT CONTENT IN ASPHALT MIXTURES – PHASE IV	5. REPORT DATE March 2022 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Hosin "David" Lee, Byungkyu Moon, Chris Williams	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Iowa Technology Institute University of Iowa Iowa City, IA 52242	10. WORK UNIT NO. 11. CONTRACT OR GRANT NO
12. SPONSORING AGENCY NAME AND ADDRESS Iowa Highway Research Board Iowa Department of Transportation 800 Lincoln Way, Ames, IA 50010	13. TYPE OF REPORT AND PERIOD COVERED Final Report 14. SPONSORING AGENCY CODE IHRB Project TR-770

15. SUPPLEMENTARY NOTES

16. ABSTRACT

Public highway agencies encourage the use of recycled asphalt materials (RAM) in constructing pavements to the maximum extent possible with an equal performance. Low temperature cracking potential is a primary concern with high RAM mixtures, which is caused by the aging of asphalt through the oxidation. To minimize a low temperature cracking, various rejuvenators have been utilized in the past instead of bumping down a PG grade of the specified virgin asphalt for high RAM mixes. Although the current Iowa DOT's specification allows RAP materials up to 30% with softer binder, limited construction projects have been performed, which utilized more than 20% RAP materials.

The main purpose of this research is to evaluate high RAM mixtures up to 45% RAP with rejuvenators for Iowa DOT and local public agencies by performing laboratory tests and field implementation. The specific findings from this study include:

- Rejuvenators consistently lowered both critical high and low temperatures of virgin binder of PG 58-28S.
- Due to its high variability, FTIR could not determine the effectiveness of rejuvenators in lowering the aging of RAP binder.
- 34% and 45% High RAP mixtures with rejuvenators were compacted well exceeding 93% field density.
- Based on HWT test results, field mixtures with rejuvenators performed better in rutting performance than ones without.
- Based on DCT test results, field mixtures with soft binder endured the highest fracture energy.
- Based on SCB-IFIT test results, rejuvenators improved cracking resistance of RAP mixtures but not RAS mixtures.
- Based on test results of both DCT and SCB-IFIT, there was a good correlation between test results of SCB-IFIT and DCT.
- Based on a condition survey of test sections performed after one year since construction, all test sections performed very well with very little distress whereas test sections without rejuvenators developed several hairline cracks. Rejuvenators were effective in delaying an initiation of cracking.
- When mixtures with rejuvenators were aged, rutting decreased in HWT test but cracking increased in SCB-IFIT test.
- Both 34% and 45% RAP mixtures with rejuvenators were successfully constructed.

For future studies, an approval process for rejuvenators that incorporates long-term aging of the material should be developed. Increasing the maximum RAM percentage up to 50% should be considered for some mixes with additional options for RAM use and binder formulations, which may provide greater flexibility to contractors and binder suppliers. High RAM project sites should be monitored to determine the effectiveness and limitations of design, construction and performance of high RAM mixtures and develop QA/QC aspect of using softer binders and rejuvenators. Finally, a comprehensive asphalt recycling strategy encompassing high RAM mix up to 50%, CIR and HIR should be developed in consideration of both economic and sustainability analyses.

17. KEY WORDS recycled asphalt pavement, high RAP content, rejuvenators, asphalt aging, Fourier transform infrared, cryo-SEM	18. DISTRIBUTION STATEMENT No restrictions.

19. SECURITY CLASSIF. (of this report) None	20. SECURITY CLASSIF. (of this page) None	21. NO. OF PAGES 71	22. PRICE N/A

ACKNOWLEDGEMENTS

We would like to acknowledge the guidance provided by the following technical advisory committee members:

Jeffrey Schmitt, Iowa DOT, Jeffrey.schmitt@iowadot.us

Ashley Buss, Iowa DOT, ashley.buss@iowadot.us

William Dotzler, Iowa DOT, william.dotzler@iowadot.us

Scott Schram, Iowa DOT, Scott.Schram@iowadot.us

Angela Kersten, Scott County, Angela.Kersten@scottcountyiowa.com

Todd Kinney, Clinton County, tkinney@clintoncounty-ia.gov

Brian Moore, ICEASB, brian.moore@iceasb.org

Scott Dockstader, APAI, scottd@apai.net

Darwin Larson, APAI, darwinl@apai.net

Andrew Cascione, Flint Hills Resources, andrew.cascione@fhr.com

Erv Dukatz, Flyereld Consulting, flyereld@gmail.com

Brett Finnegan, LL Pelling, brettf@llpelling.com

John Hinrichsen, DMACC, Hinrichsen.john@yahoo.com

Theodore Huisman, ISU, thuis@iastate.edu

We would also like to acknowledge the contributions from following organizations in building test sections and providing rejuvenators for this research project:

Cerro Gordo County, Heartland Asphalt, Flint Hills Resources, Colorbiotics, Georgia-Pacific Chemicals, and Namheung Corporation

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1 INTRODUCTION

Public highway agencies encourage the use of recycled asphalt materials (RAM) in constructing pavements to the maximum extent possible with an equal performance. Low temperature cracking potential is a primary concern with high RAM mixtures, which is caused by the aging of asphalt through the oxidation. To minimize a low temperature cracking, various rejuvenators have been utilized in the past instead of bumping down a PG grade of the specified virgin asphalt for high RAM mixes.

According to the 2019 NAPA's report, asphalt mixture producers are steady on their use of Reclaimed Asphalt Pavement (RAP), showing average percent used in asphalt pavement remains at 21.1% (21% or more in 20 states and 19% in Iowa) based on total reported tons of RAP divided by reported total tons asphalt mixtures produced (NAPA 2020). Among states using soft binders (27 states) and rejuvenators (15 states), 18% of RAP mixtures (5% in Iowa) were produced using softer binders whereas 4% of RAP mixtures (3% in Iowa) produced using a rejuvenator.

Asphalt mixture producers continue to decrease their use of recycled asphalt shingle (RAS), using 921,000 tons of RAS during 2019, which is a 12.5 percent decrease from the 1,053,000 tons used in 2018. Only 28 states including Iowa used some RAS in HMA. Among states using soft binders (16 states) and rejuvenators (7 states), 20% of RAS mixtures (0% in Iowa) were produced using softer binders whereas 8% of RAS mixtures (0% in Iowa) produced using a rejuvenator.

Aging process of asphalt is a combination of reversible and permanent changes. Reversible changes are referred to as molecular association like wax crystallization whereas permanent changes occur as a result of physical changes like loss of lighter molecules or chemical changes like oxidation. Oxidation is a chemical reaction between asphalt and oxygen such that carbon and sulfur atoms increase within asphalt molecules. Oxidation is considered as a dominant factor in a long-term asphalt aging phenomenon. The term "rejuvenation" is defined as a restoration of the virgin asphalt condition.

The main purpose of this research is to evaluate high RAM mixtures with both rejuvenators and fractionated RAM materials for Iowa DOT and local public agencies by performing laboratory tests and field implementation. Main tasks of this research are to:

1. Survey Recycled Asphalt Materials (RAM) stockpiles and evaluate different equipment/methods for fractionating RAP materials.
2. Apply FTIR for evaluating rejuvenators and DCT, HWT, SCB-IFIT tests for RAM contents with various rejuvenators.
3. Evaluate the effects of the fractionation and the aging.
4. Build test sections using high RAP contents with various rejuvenators and monitor condition of a test section with high RAP contents.

5. Develop specifications for HMA mixtures with high RAM contents, rejuvenators, and fractionation.

1.1 Key Findings from Previous Phase

In previous phases of this research, the effects of different rejuvenators were evaluated by applying each of them to aged asphalt binder and high-RAP mixtures. It was found that rejuvenators were effective in decreasing the aging level of hardened asphalt binder. The previous study identified the analytical method to find the most appropriate rejuvenators for Iowa's high RAP mixtures, which are resistant to both low temperature cracking and rutting while reducing the production cost and the environmental impacts. Based on the limited laboratory experiments and field test sections, the following conclusions were derived from the phase 3 study:

1. Rejuvenators lowered both PG high- and low-temperature limits of aged asphalt binder.
2. Optimum dosage rate of each rejuvenator was identified using the Bending Beam Rheometer (BBR) test.
3. Fourier Transform Infrared (FTIR) test indicated rejuvenators were effective in restoring original properties of the aged binder.
4. Cryo-SEM was used to capture surface images of the rejuvenated asphalt binders at -165 °C, where significantly less cracking was observed.
5. Rejuvenated asphalt binders exhibited G-R values between the aged asphalt and virgin asphalt. A significant correlation was observed between carbonyl indices and G-R values.
6. Based on the Disc-shaped Compact Test (DCT) result, it was concluded that high-RAP mixtures with rejuvenators were more resistant to a low–temperature cracking than the high-RAP mixtures without it.
7. Test sections using rejuvenators were successfully constructed in Crawford and O'Brien Counties in Iowa. DCT test result of field samples confirmed that rejuvenators improved a low–temperature cracking susceptibility.

2 LITERATURE REVIEW ON REJUVENATORS

First, an extensive literature review was performed on the fundamental characteristics of various rejuvenators and past performance evaluation results are summarized in this chapter. In general, rejuvenators add the aromatic and resin functionality in the aged asphalt, and they can be categorized into the following five types based on their sources: vegetable oil, petroleum aromatic extract, petroleum paraffinic oil, tall oil and naphthenic oil. Literature review results are summarized below with respect to dosage rate, RAP content, the laboratory performance test results for cracking, rutting, moisture susceptibility and low temperature cracking. All performance test results were collected from the published literatures not based on the manufacturer/manufacturer-sponsored research but based on the independently funded research.

2.1. Vegetable Oil

Triglycerides and fatty acids are derived from virgin or waste vegetable oils, which can be used as a rejuvenator. However, virgin vegetable oils are preferred over waste oils because waste oils may contain undesirable oxides due to an extensive heating process. One of the most common vegetable oils is a soybean oil. Three types of rejuvenators are discussed below and laboratory test results of high RAP mixes using them are summarized in Table 2-1.

1) Anova by Cargill
Based on the research performed by Cargill, field cores with 45% RAP and Anova endured 197 cycles before a failure under the overlay tester, which represents 25 times improvement over a control mix without a rejuvenator (Sylvester and Hassan 2017). Asphalt mixtures with 100% RAP and Anova exhibited a rut depth of 4.3 mm at 10,000 passes in Hamburg wheel tracking (HWT) device, which is similar to a control mix without a rejuvenator. Mixes with 50% RAP and Anova exhibited 600 J/m^2 fracture energy at -24˚C.

2) NH300PL and NH303PL by Namheung
These rejuvenators are composed of soybean oil and fatty acids. Asphalt mixes with 30% RAP and NH300PL and NH303PL exhibited 11.5mm and 7.9 mm rut depths at 20,000 passes in HWT test, respectively. The stripping inflection point (SIP) was greater than 10,000 passes for both products.

3) Waste Vegetable Oil and Grease
100% RAP specimens with rejuvenators based on waste vegetable oil (WVO) and waste vegetable grease (WVG) exhibited 5.4 kPa and 5.9 kPa of fracture work density (FWD), respectively, which are similar to the control mix without a rejuvenator (Zaumanis et al. 2015). Asphalt mixtures with WVO and WVG exhibited 11.5mm and 7.9 mm rut depths at 20,000 wheel passes, respectively, along with the SIP greater than 10,000 wheel passes. The specimens with

WVO and WVG exhibited indirect tensile strengths of 3,400 kPa and 3,250 kPa, respectively, which are less than 3,919 kPa of the control mix without a rejuvenator.

4) Delta S by Collaborative Aggregates
35% RAP with Delta S exhibited 13.41 mm rut depth at 20,000 passes with a SIP value greater than 10,000 and FI value of 3.43 (Castro 2017). Under the overlay tester, the 35% RAP with Delta-S failed at 10 cycles, less than 300-cycle requirement.

5) ReJUVN8 by Sripath Technologies
Disk-Shaped Compact Tension (DCT) and Semi-Circular Bending (SCB) test results of 5% RAS with ReJUVN8 were 710 J/m^2 and 0.38 kJ/m^2, respectively. The rut depth was just 2.8mm at 20,000 passes in HWT test (Arguirre et al. 2017).

Table 2-1. The Performance of Rejuvenators based on Vegetable Oils

Rejuvenator	**Dosage**	**RAP Content**	**Cracking**	**Rutting**	**Moisture Susceptibility**	**Low Temp Prop.**
Anova (Sylvester and Hassan 2017)	3-5% of total binder	45% RAP 50% RAP 100% RAP	45% RAP: OT: 197cycles	100% RAP: HWT: 4.3mm@10,000	N/A	50% RAP: DCT: 600 J/m^2 @-24˚C
NH300PL NH3003PL	5% of total binder	30% RAP	N/A	HWT: 11.5mm@20,000 7.9mm@20,000	HWT: Inflect>10,000 Inflect>10,000	N/A
waste vegetable oil or grease (Zaumanis et al. 2015)	12% of total binder	100% RAP	FWD: 5.4 kPa 5.9 kPa	HWT: 4.2mm@10,000 9mm@10,000	HWT: Inflect@8,000 Inflect>10,000	IDT: 3,400 kPa 3,250 kPa
Delta-S (Castro 2017)	5% of total binder	35% RAP	FI: 3.43 OT: 10 cycles	HWT: 13.4mm@19,020	HWT: Inflect>10,000	N/A
ReJUVN8 (Arguirre et al. 2017)	5% of total binder	5% RAS	SCB: 0.38 kJ/m2	HWT: 2.8mm@20,000	N/A	DCT: 710 J/m^2

OT: Texas Over Test, HWT: Hamburg Wheel Tracking, DCT: Disk-Shaped Compact Tension
IDT: Indirect Tensile Test, FWD: Fracture Work Density from IDT test

2.2. Petroleum Aromatic Extract

Aromatic extracts are produced as a by-product of a petroleum refining process to produce lubricating oil. Five rejuvenators are discussed below, and their performance test results are summarized in Table 2-2.

1) Hydrolene by Holly Frontier

With this rejuvenator, Flexibility Index (FI) improved from 4.0 (20% RAP with no Hydrolene) to 4.3 (30% with 4% Hydrolene) but went down to 3.9 (40% RAP with 7.5% Hydrolene) and 3.0 (50% RAP with 9% Hydrolene). However, it did not improve a low temperature cracking behavior using the asphalt concrete cracking device (ACCD) test. The rut depth increased from 3.6 mm to was 4.1 mm in Asphalt Pavement Analyzer (APA) test. It did not have a significant effect on Tensile Strength Ratio (TSR) values (Nazzai and Kim 2019).

2) Cyclogen L by TRICOR
50% RAP and 20% RAP plus 5% RAS exhibited 700 and 900 cycles in overlay tester, respectively. Based on the Indirect Tensile Test (IDT), 50% RAP and 20% RAP plus 5% RAS exhibited low cracking temperatures of -24.4℃ and -22.5℃ (Tran et al. 2012).

3) Valero 130A by Valero
Both 25% and 45% RAP mixtures with Valero 130A passed the requirement of 500 cycles under the overlay tester. However, For the APA test, the rut depth was 3.65 mm, slightly higher than the control mix without a rejuvenator (Bennert et al. 2015).

Table 2-2. The Performance of Rejuvenators Consists of Petroleum Aromatic Extract

Rejuvenator /Reference	**Dosage**	**RAP/RAS Content**	**Cracking**	**Rutting**	**Moisture Susceptibility**	**Low Temp Prop.**
Hydrolene (Nazzai and Kim 2019)	4% 7.5% 9%	30% RAP 40% RAP 50% RAP	5.2 (30%) 4.3 (40%) 3.3 (50%)	$APA_{@8000}$: 4.2mm 3.1mm 4.0mm	TSR: 0.9 0.91 0.81	ACCD -30°C -30.1°C -30.3°C
Cyclogen L (Tran et al. 2012)	12% of total binder	50% RAP; (20% RAP/ 5% RAS)	OT: 700 900	$APA_{@8000}$: 5.0mm 4.1mm	TSR: 0.86 0.9	IDT: -24.4 -22.5
Valero 130A (Bennert et al. 2015)	N/A	25% RAP 45% RAP	OT: 500 cycles 135 cycles	APA: 3.6mm 3.8mm	N/A	N/A

OT: Texas Over Test, HWT: Hamburg Wheel Tracking, DCT: Disk-Shaped Compact Tension, ACCD: Asphalt Concrete Cracking Device, IDT: Indirect Tensile Test, APA: Asphalt Pavement Analyzer, FI: Flexibility Index, TSR: Tensile Strength Ratio, SCB: Semi-Circular Bending

2.3. Petroleum Paraffinic Oil

Paraffinic oil-based rejuvenators are essentially re-refined lubricating oils. Three rejuvenators are discussed and the performance test results are summarized in Table 2-3.

1) Storbit by SOTRIMPEX
Penetration index of the binder with Storbit increased. However, asphalt mixtures with Storbit did not improve low temperature cracking resistance. (Zaumanis et al. 2015)

2) Valero VP165 by Valero
Asphalt mixtures with Valero VP165 improved the fatigue cracking performance with higher cycles under the overlay tester (Bennert et al. 20152). However, the rut depth 25% RAP and 45% RAP with Valero VP165 under the APA was 4.3mm and 4.68mm, respectively, which were slightly higher than control mixtures of 25% RAP (2.28 mm) and 45% RAP (2.42mm).

3) Chevron Delo (400 LE SAE 15 W40)
The TSR values were satisfactory. However, the rut depth with Chevron Delo increased under the APA test (DeDene 2011).

Table 2-3. The Performance of Rejuvenators Consists of Petroleum Paraffinic Oils

Rejuvenator	**Dosage**	**RAP/RAS Content**	**Cracking**	**Rutting**	**Moisture Susceptibility**	**Low Temp Prop.**
Storbit (Zaumanis et al. 2015)	18.26% of total binder	100% RAP	PI: 3.29	N/A	N/A	IDT: 1,900 kPa
Valero VP165 (Bennert et al. 2015)	N/A	25% RAP; 45% RAP	OT: 472 cycles; 771 cycles	APA: 4.3mm; 4.68mm	N/A	N/A
Chevron Delo 400LE SAE 15W30 (DeDene 2011)	4% of T. Binder 8% of T. Binder	25% RAP	N/A	$APA_{@8000}$: 3.4mm (4%) 5.1mm (8%)	TSR: .93 (4%) .80 (8%)	N/A

OT: Texas Over Test, IDT: Indirect Tensile Tension, TSR: Tensile Strength Ratio, APA: Asphalt Pavement Analyzer, PI: Penetration Index

2.4. Tall Oil

Tall oils can be obtained from the paper industry as by-products (pine trees), which is in the same chemical family as some warm-mix asphalt and some emulsifiers. Two rejuvenators are discussed, and the performance test results are summarized in Table 2-4.

1) Sylvaroad RP1000 by KRATON
When Sylvaroad RP1000 was added, the Flexibility Index (FI) values of 30%, 40% and 50% RAP mixtures decreased from 4.5 to 4.2 but increased from 2.7 to 3.0 and 4.2 to 5.2, respectively. Based on APA test results, a rut depth slightly increased for 30%, 40% and 50% RAP mixtures from 3.4mm to 3.8mm, from 3.2mm to 3.7mm, and 3.0mm to 3.6mm, respectively. Based on Asphalt Concrete Cracking Device (ACCD) test results, similar cracking temperatures were observed for three different RAP mixtures. The TSR values for 30%, 40% and 50% RAP mixtures changed from 0.98 to 0.96, same at 0.84, and from 0.83 to 0.84, respectively. (Nazzai and Kim 2019).

2) Distilled Tall Oil
Asphalt mixtures with distilled tall oil exhibited a similar level of IDT test result of 3,943 kPa as the control sample and the HWT test results were satisfactory. However, asphalt mixtures with distilled tall oil exhibited a FWD value of 5.2 kPa, which is smaller than a control mix (5.6 kPa) (Zaumanis et al. 2015).

Table 2-4. The Performance of Rejuvenators Consists of Tree Tall Oils

Rejuvenator	**Dosage**	**RAP/RAS Content**	**Cracking**	**Rutting**	**Moisture Susceptibility**	**Low Temp Prop.**
Sylvaroad RP1000 (Nazzai and Kim 2019)	8% of total binder	30% RAP 40% RAP 50% RAP	FI (wo/w): 4.5/4.2 2.7/3.0 4.2/5.2	$APA_{@8000}$ (wo/w) 3.4/3.8mm 3.2/3.7mm 3.0/3.6mm	TSR (wo/w): 0.98/0.96 0.84/0.84 0.83/0.84	ACCD -29.9°C -32.1°C -34.1°C
Distilled Tall Oil (Zaumanis et al. 2015)	12% of total binder	100% RAP	FWD: 5.2 kPa	HWT_{10000}: 2.9mm	HWT: Inflect>10,000	IDT: 3,943 kPa

IDT: Indirect Tensile Tension, FWD: Fracture Work Density (From IDT), HWT: Hamburg Wheel Tracking, TSR: Tensile Strength Ratio

2.5. Rejuvenators containing Naphthenic oils:

These types of rejuvenators are engineered hydrocarbons for asphalt modification. Three rejuvenators are discussed and the performance test results are summarized in Table 2-5.

1) SonneWarmix RJ by Sonneborn Inc
Asphalt mixtures with SonneWarmix RJ improved both rutting resistance and moisture susceptibility of the 40% RAP and 5% RAS with a much better performance with 35% RAP + 5% RAS mixtures. It improved the fatigue cracking resistance in overlay tester. Based on the Thermal Stress Restrained Test (TSRST) result, it improved the low temperature cracking resistance (Mogawer et al. 2013).

2) BituTech by Engineered Additives
Asphalt mixtures with BituTech exhibited a similar performance as those with SonneWarmix RJ in both rutting resistance and moisture susceptibility. Compared to the asphalt mixtures with SonneWarmix RJ, BituTech further increased the fatigue cracking resistance in overlay tester. The TSRST data showed that BituTech can improve the low temperature cracking resistance (Mogawer et al. 2013).

2) HyPrene L150 by Ergon

Asphalt mixtures with HyPrene L150 endured only 106 cycles under the overlay tester, which is lower than a control mix with 176 cycles. However, OT result has significantly improved to 596 when the RAP content was increased from 25% to 45%. Under APA, the rut depth was 3.13mm for 25% RAP and 4.36mm for 45% RAP mixtures with HyPrene L150, which were slightly higher than the control mixtures of 25% RAP (2.28 mm) and 45% RAP (2.42mm) (Bennert et al. 2015).

Table 2-5. The Performance of Rejuvenators Consists of Naphthenic Oils

Rejuvenator	Dosage	RAP/RAS Content	Cracking	Rutting	Moisture Susceptibility	Low Temp Prop.
SonneWarmix RJ (Mogawer et al. 2013)	9.28% of total binder	40% RAP; 5% RAS; (35% RAP + 5% RAS)	OT: 420 cycles 430 cycles 230 cycles	$HWT_{10,000}$: 4.73mm 12.53mm 1.51mm	HWT: All Inflect >10,000	TSRST: -27.36°C -26.19°C -27.26°C
BituTech (Mogawer et al. 2013)	9.28% of total binder	40% RAP; 5% RAS; 35% RAP+5% RAS	OT: 1,280 cycles 1,020 cycles 380 cycles	$HWT_{10,000}$: 6.25mm 11.43mm 1.58mm	HWT: All Inflect >10,000	TSRST: -27.40°C -24.45°C -25.25°C
HyPrene L150 (Bennert et al. 2015)	N/A	25% RAP; 40% RAP	OT: 106 cycles; 596 cycles	APA: 3.13mm; 4.36mm	N/A	N/A

OT: Texas Over Test, HWT: Hamburg Wheel Tracking, APA: Asphalt Pavement Analyzer, TSRST: Thermal Stress Restrained Test

3 RECYCLED ASPHALT MATERIAL STOCKPILES AND PROCESSING METHODS

For a stockpile of RAP materials, it is most critical to keep moistures away. The moisture absorption of RAP materials is very high because it consists of various particle sizes conglomerated together due to asphalt. The best practice to minimize the accumulation of moisture in stockpiles is to cover the stockpile with a shelter to prevent precipitation from getting to the RAP. Covers or tarpaulins should be avoided as this trap's moisture in the pile. RAP stockpiles should be limited to 20 feet in height to reduce the potential for self-consolidation of the stockpile (West 2010). As a result, most contractors are trying to keep inventories low and produce material only as needed.

In the nation, the estimated amount of RAP stockpiled at the end of the 2019 construction season increased to 138.04 million tons (1.38 million tons in Iowa), which is a 20 percent increase from the 110.31 million tons (0.25 ton in Iowa) at the end of the 2018 construction season (NAPA 2020). 1.143 million tons of RAS (0.0251 million tons in Iowa) were reported as stockpiled at year-end 2019, which is a 16.5 percent decrease from the 1.368 million tons (0.0306 million tons in Iowa) at the end of 2018. In this study, a survey was performed to determine the use and stockpile of RAP and RAS at the end of 2019 and processing methods to fractionate RAM are discussed.

3.1 Survey of RAM Usage and Stockpiles in Iowa

We have performed a survey to estimate the use and stockpile of RAM by the asphalt pavement industry in Iowa. The survey consisted of ten questions, which was sent to thirty-two contractors in Iowa, and seven companies replied. Based on the survey, contractors used mixtures with RAP the most, followed by mixtures with RAS and virgin mixtures. A total RAP stockpile at the end of 2019 construction season was 63,500 tons out of 188,100 tons acquired over the 2019 construction season and a RAS stockpile (by one company) was 10,000 tons out of 2,500 tons acquired over the 2019 construction season. The survey results are summarized at Table 3-1 and Figure 3-1 to Figure 3-4.

Table 3-1. Survey Results about the use and stockpiles of recycled asphalt materials

Asphalt mixture produced (tons)			**Amount acquired in 2019 season (tons)**		**Stockpiles at the end of 2019 (tons)**	
None	RAP	RAS	RAP	RAS	RAP	RAS
447,195	1,013,000 (24% RAP)	682,900 (4% RAS)	188,100	2,500	63,500	10,000

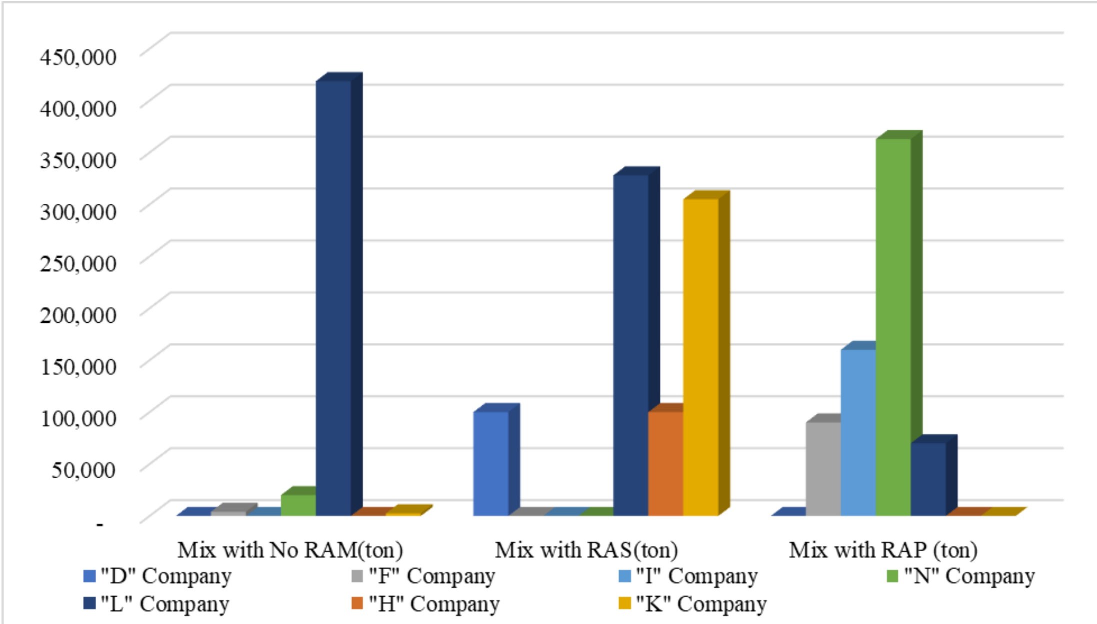


Figure 3-1. Summary of a total tonnage of asphalt mixtures produced in 2019

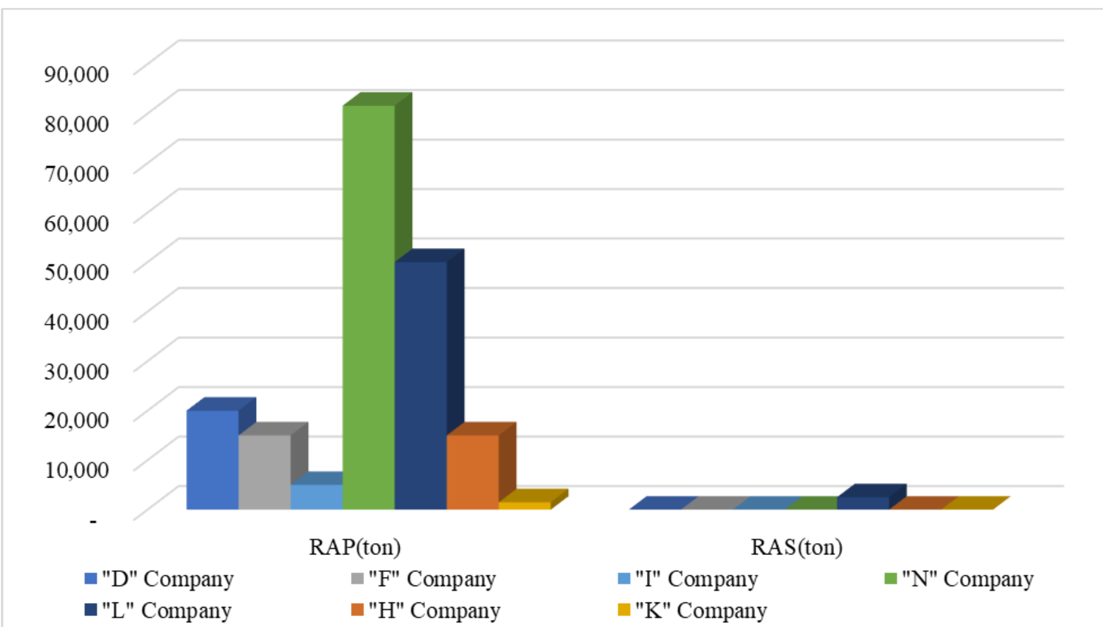


Figure 3-2. Summary of tons of RAP/RAS received to your facilities in 2019

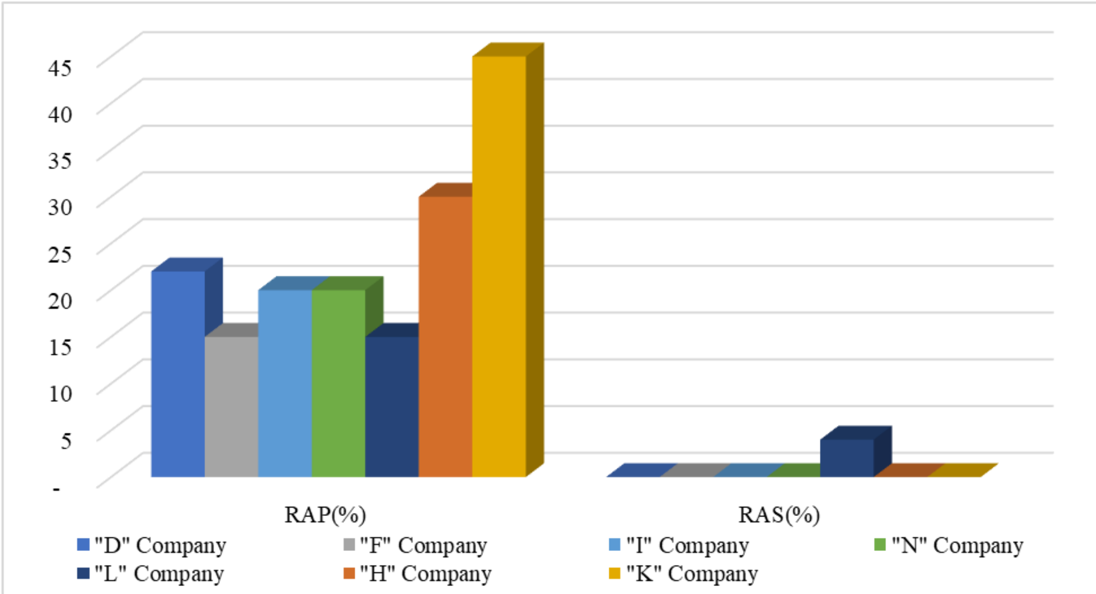


Figure 3-3. Summary of average RAP/RAS percentage used in asphalt mixes in 2019

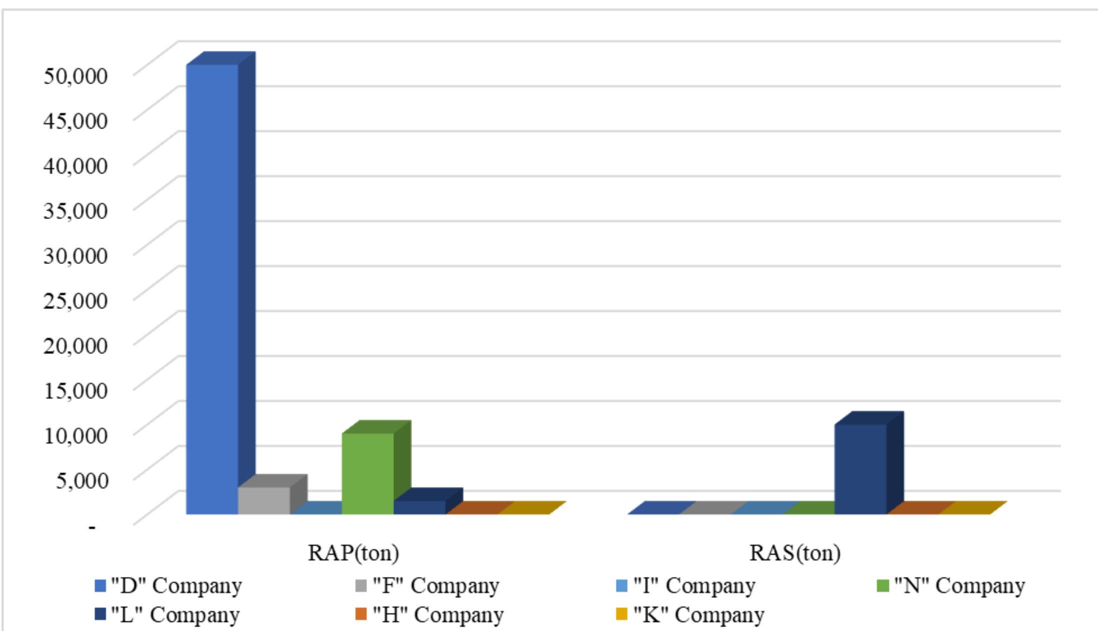


Figure 3-4. Summary of Excess RAP and RAS in inventory at the end of 2019

3.2 RAP Processing Equipment

RAP processing involves steps to create consistent materials that can be used for high RAP mixes. The RAP processing increases a control while lowering a variability. Milled RAP materials from traceable sources produce consistent properties and may not require further processing. It may be desirable to screen or fractionate RAP from a traceable source to remove oversize particles or to separate RAP into coarse and fine stockpiles to increase the amount of RAP that can be used in high RAP mixes. Whether or not the RAP is fractionated, a scalping screen will prevent lumps from entering the hot mix plant, including those that form in even fine fractionated stockpiles (West 2010).

Typical jaw and cone crushers and hammermill crushers create too many fine materials whereas horizontal-shaft impactors, roller, or mill-type breakers break up chunks of pavement not aggregates. Therefore, it is important to set up a crushing operation such that the RAP is screened before it enters the crusher, which will allow the finer RAP particles to bypass the crusher. Figure 3-5 shows a portable RAP crushing unit that is equipped with a screen deck in line before the crusher where only RAP particles retained on the screen will pass through the crusher (West et al. 2016). A simple extracted gradation check of RAP samples should be performed before and after the in-line crusher to determine if it is breaking down RAP aggregates too fine. The advantages and disadvantages of RAP processing methods is summarized at Table 3-2 (West et al. 2016).

Figure 3-5. RAP processing unit with a screen before the crusher (West et al. 2016)

Table 3-2. Pros and Cons of Milling, Screening, and Crushing Operations (West et al. 2016)

Process	Possible Advantages	Possible Disadvantages
Use of Millings Without Further Processing	• Avoids further crushing of aggregate particles in RAP, which may allow for higher RAP contents in mixes. • Lowest cost RAP processing option. • Millings from large projects are likely to have a consistent gradation and asphalt content.	• Requires multiple RAP stockpiles at the plant. • Millings from individual projects are different; therefore, when a particular millings stockpile is depleted, new mix designs must be developed with other RAP.
Screening RAP Before Crushing	• Limits crushing of aggregate particles in RAP, which reduces dust generation.	• Few RAP crushing and screening units are set up to pre-screen RAP.
Crushing all RAP to a Single Size	• Allows the processed RAP to be used in many different mix types. • Generally provides good uniformity from RAP materials obtained from multiple sources.	• Increases the dust content of RAP stockpiles, which will tend to limit how much RAP can be used in mix designs.

3.3 Fractionation Operations

While recycled asphalt materials (RAM) are being widely used around the country, their usage has been limited due to a difficulty in meeting the required aggregate gradation. Creating separate stockpiles through the fractionation process would result in consistent asphalt content and aggregate gradation, which would allow for the use of increased percentages of RAP. Particularly, for high-RAP mixes, a fractionation allows engineers to better control the quality of materials. Fine RAP materials are used in reduced proportions in the mix, thereby decreasing the amount of fine aggregate materials in the high-RAP mixtures. On the contrary, because the asphalt binder content on finer RAP materials would be higher than coarser RAP materials, to maximize the use of RAP asphalt binder, a higher quantity of finer RAP materials should be used than coarser RAP materials.

Among 27 states, not including Iowa, which use a fractionation, 21% of RAP was fractionated, which went down from 24% in 2018 (NAPA 2020). The most common fractionating sizes were 3/4″, 3/8″ and No. 4 and, in some cases, the plus 3/4″ size material was returned to a crusher and the crushed material was then returned to the screening unit (West and Marasteanu 2013). However, in Virginia, RAP materials were fractionated at 1/4″, 5/8″ and 1-inch sieves and, in Illinois, all RAP materials are fractionated by screening into a minimum of two size fractions with the separation occurring on or between the #4 (4.75 mm) and 1/2 in. (12.5 mm) sieves. Table 3-3 shows a fractionation requirement of two sizes for RAP stockpiles in Illinois.

Table 3-3. Illinois DOT's RAP Stockpile Classification System

Fractionated RAP (FRAP)	Homogenous RAP	Conglomerate RAP	Non-Quality
<u>Requirements</u> - May represent more than one aggregates type or quality - At least C quality - Min. two size fractions - 100% pass 1.5, ¾, or 1/2inches	<u>Requirements</u> - Same aggregate - At least C quality - Similar gradation A/C	<u>Requirements</u> - May represent more than one aggregates type or quality - Unknown/Poor Aggregate	<u>Requirements</u> - RAP stockpiles that do not meet the requirements of the stockpile categories

4 LABORATORY EVALUATION OF HIGH RAP MIXTURES WITH REJUVENATORS

The previous research identified FTIR, DCT and HWT tests as potential test procedures for evaluating high RAM mixtures. Because the PAV-aged asphalt samples were used for the FTIR test in the previous study, to be closer to the actual phenomenon, in this study, the binder obtained from RAP was adopted. HWT and DCT tests were then performed on RAM mixtures with various rejuvenators to determine how these rejuvenators affect a moisture susceptibility and a low-temperature cracking of high-RAP mixtures, respectively.

4.1 Fourier Transform Infrared (FTIR) Test on Binder from RAP Materials

Fourier-Transform Infrared (FTIR) test is commonly used to identify certain molecules or functional groups and the concentration of those molecules within a sample. FTIR spectrometers are less expensive than conventional spectrometers since producing an interferometer is easier than the fabrication of a monochromator (Smith 2011). In addition, measurement of a single spectrum is much faster for the FTIR technique as the information at all frequencies can be collected simultaneously (Ramasamy 2010).

The asphalt absorbs different wavelengths and create a unique interferogram of reflected lights, which is then processed using Fourier transform algorithm to derive the transmittance level for each wavelength (Sun et al. 2014). The FTIR measures amounts of Infrared light that are absorbed by asphalt at wavelengths between 4,000 cm^{-1} to 400 cm^{-1}. To analyze the aging condition of asphalt quantitatively, the peak areas of oxygenated functional groups of sulfoxide (S=O) and carbonyl (C=O), which represent the degrees of asphalt aging, should be observed at 1032cm^{-1} and 1699cm^{-1}, respectively (Chen et al. 2014). Rejuvenators are expected to decrease these sulfoxide and carbonyl peaks found in the aged asphalt (Chen et al. 2014; Cong et al. 2015).

4.1.1. FTIR Test Procedure

To run the test using the FTIR equipment, as shown Figure 4-1, the following steps should be taken:

1. Take specific amount of binder (the same for all samples) and dilute it using a solvent (Tetrahydrofuran, THF, was used for this study).
2. Shake very well to make the blend homogeneous (2-3 minutes is adequate).
3. Put salt windows (NaCl in this case) under the instrument and take the background spectrum.
4. Pour adequate amount of the diluted sample between two windows and place them under the instrument.
5. Examine the spectrum and save it.

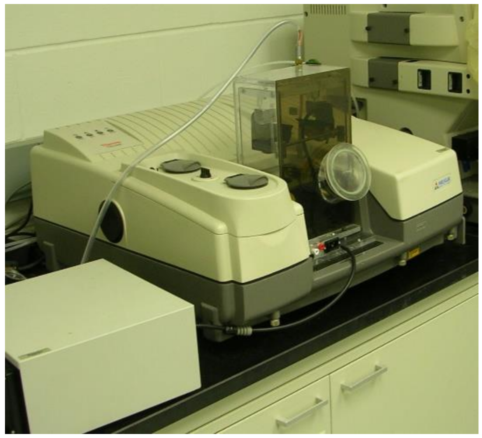


Figure 4-1. FTIR test equipment used for this study

FTIR results for rejuvenated binder can be performed by analyzing FTIR spectra of the sulfoxide (S=O) peak occurring at 1032 cm^{-1}, which corresponds to the oxidation of compounds containing sulfur, and the carbonyl (C=O) peak at 1699 cm^{-1}, which corresponds to the oxidation of carbonyl compounds. The saturated C-H peak occurs at 1459 cm^{-1}, which is used as a reference point. To determine the degree of oxidation, sulfoxide index (SI) and carbonyl index (CI) can be calculated using Equation 4-1 and Equation 4-2, where a larger value indicates a higher degree of oxidation (Chen et al., 2014). Figure 4-2 shows an integration of an area of an example FTIR spectrum using a baseline method.

$$\text{Sulfoxide Index } I_{S=O} = \frac{\sum A(1032cm^{-1})}{\sum A(1459cm^{-1})} \qquad (4\text{-}1)$$

$$\text{Carbonyl Index } I_{C=O} = \frac{\sum A(1699cm^{-1})}{\sum A(1459cm^{-1})} \qquad (4\text{-}2)$$

where,

$\sum A(1032cm^{-1})$, $\sum A(1699cm^{-1})$ and $\sum A(1459cm^{-1})$ are absorption peak areas of sulfoxide, carbonyl and saturated C-H group, respectively

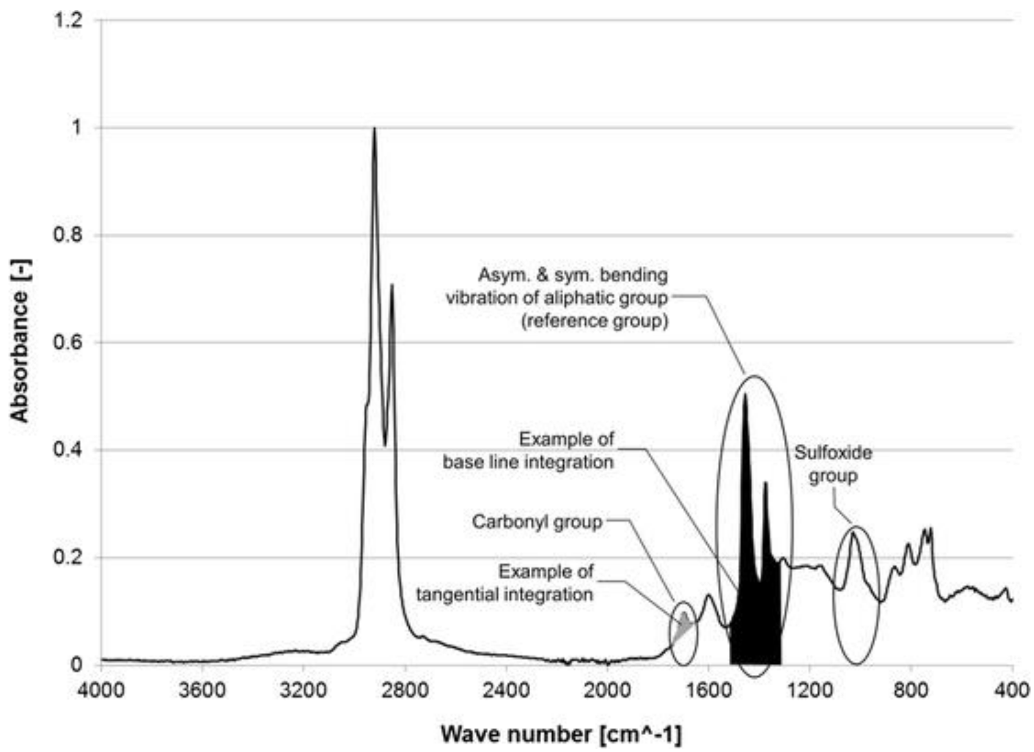


Figure 4-2.FTIR absorbance spectrum of PAV aged asphalt sample (Hofko et al. 2017)

4.1.2. FTIR Test Results

The FTIR tests were performed to determine the effect of rejuvenators on restoring the oxidation of the aged binder to a virgin binder. In the previous study, for the FTIR test, we have used extracted binder from the PAV-binder. However, for this study, to evaluate the actual effect of rejuvenators on RAP, we obtained test samples by scratching asphalt from the heated RAP. As summarized in Table 4-1, A total of six rejuvenators (including three rejuvenators used in phase 3) were evaluated for their effectiveness in restoring RAP binder to a virgin binder.

Table 4-1. Details of rejuvenators

Product name	Property	ID used in Phase3/Phase4	Research Phase
NH300PL	Bio-Based oil	R1	Phase 4
NH303PL	Bio-Based oil	R2	Phase 4
ANOVA	Bio-Based oil	A/R3	Phase 3,4
Cyclogen	Petroleum oil	C/R4	Phase 3,4
Sylvaroad	Refined tall oil	B/R5	Phase 3,4
TUFFTREK4002	Bio-Based oil	R6	Phase 4

1) PAV binders tested during Phase 3

To simulate the long-term aging of the binder, the PAV aging procedure (40-hr, double, at 100 °C under 2.1 MPa) was applied and this PAV-aged binder was blended with varying dosages of three rejuvenators. As can be seen from

Table 4-24-2, there existed significant differences among average values of sulfoxide and carbonyl indices of eight different asphalt binder types.

Figure 4-3 shows the spectrum of each rejuvenator with a single dosage rate to observe differences among rejuvenators. To indicate a chemical reaction between two materials, there should be a new peak for a certain wavenumber or a horizontal shift in spectra. Since all binder types produced similar spectra, it can be concluded that the chemistry of asphalt binder has not been greatly affected by rejuvenators. A consistent vertical shift in spectra was observed with some changes in peak values which may confirm that the reaction between rejuvenators and aged binder is mostly physical rather than being chemical. It should be noted that SI and CI values did not change linearly as the amount of a rejuvenator increased. Therefore, it can be postulated that there might be some chemical reactions between rejuvenators and the aged asphalt binder. It is interesting to note that spectra for aged and virgin binder are very similar although chemical reactions should have occurred during the aging process.

Figure 4-4 (a) shows a plot of the SI values of eight binder types. As expected, the PAV-aged samples exhibited a significant increase in the SI value. The rejuvenated asphalt samples exhibited lower SI value than the PAV-aged asphalt but higher SI value than that of the virgin asphalt binder. Figure 4-34-4 (b) shows CI values of the same samples. As can be seen from Figure 4-34-4, all rejuvenators reduced the oxidation levels of both sulfur and carbon whereas Rejuvenator "C" and Rejuvenator "A" were more effective in reducing the level of carbon oxidation than Rejuvenator "B". Overall, the standard deviations of SI and CI values, shown as error bar representing one standard deviation on top of each bar, seemed to be quite large, which indicates a high variability in FTIR measurements. It can be postulated that these high variabilities in measurements were caused by the FTIR instrument because the same sample was used for six repeated measurements for each binder type.

Table 4-2. Sulfoxide and Carbonyl index values for each binder type performed during Phase 3

	C-H area	S=O area	C=O area	Sulfoxide Index	Carbonyl Index	avg SI	avg. CI	stv. SI	stv. CI
Virgin Binder	12.25	0.821	0.668	6.70	5.45	7.03	5.40	0.612	0.425
	13.05	0.829	0.641	6.35	4.91				
	10.86	0.789	0.595	7.27	5.48				
	8.95	0.693	0.498	7.74	5.56				
	10.22	0.784	0.618	7.67	6.05				
	12.38	0.799	0.612	6.45	4.94				
PAV	20.16	1.562	1.423	7.75	7.06	8.20	7.94	1.042	0.812
	22.02	1.537	1.498	6.98	6.80				
	16.25	1.546	1.4	9.51	8.62				
	18.064	1.58	1.503	8.75	8.32				
	17.56	1.586	1.528	9.03	8.70				
	18.475	1.328	1.508	7.19	8.16				
A7.5	15.623	1.119	0.889	7.16	5.69	7.94	6.31	0.517	0.635
	14.265	1.16	0.861	8.13	6.04				
	12.956	0.982	0.825	7.58	6.37				
	11.251	0.975	0.846	8.67	7.52				
	15.515	1.236	0.936	7.97	6.03				
	14.686	1.194	0.909	8.13	6.19				
A15	17.32	1.231	1.013	7.11	5.85	7.69	5.69	0.560	0.333
	17.23	1.463	1.051	8.49	6.10				
	15.89	1.155	0.85	7.27	5.35				
	16.18	1.2	0.856	7.42	5.29				
	16.98	1.29	1.012	7.60	5.96				
	15.97	1.319	0.891	8.26	5.58				
C8	15.698	0.984	0.9325	6.27	5.94	7.39	6.57	1.049	0.722
	15.248	1.075	0.923	7.05	6.05				
	16.245	1.186	1.135	7.30	6.99				
	14.658	1.285	1.123	8.77	7.66				
	15.021	0.965	1.036	6.42	6.90				
	14.909	1.271	0.8775	8.53	5.89				
C16	17.06	1.325	0.907	7.77	5.32	7.36	5.42	0.531	0.467
	16.258	1.132	0.886	6.96	5.45				
	15.0653	1.12	0.804	7.43	5.34				
	15.135	0.984	0.828	6.50	5.47				
	17.012	1.3	0.805	7.64	4.73				
	12.4057	0.977	0.768	7.88	6.19				
S5	19.08	1.356	1.298	7.11	6.80	7.77	6.95	0.368	0.232
	16.287	1.302	1.156	7.99	7.10				
	17.064	1.321	1.212	7.74	7.10				
	15.954	1.272	1.156	7.97	7.25				
	14.846	1.208	0.989	8.14	6.66				
	16.809	1.29	1.138	7.67	6.77				
S10	15.894	1.202	1.067	7.56	6.71	7.46	5.91	0.173	0.689
	16.517	1.267	0.974	7.67	5.90				
	18.09	1.309	1.059	7.24	5.85				
	17.846	1.301	0.968	7.29	5.42				
	16.891	1.281	1.12	7.58	6.63				
	17.519	1.304	0.863	7.44	4.93				

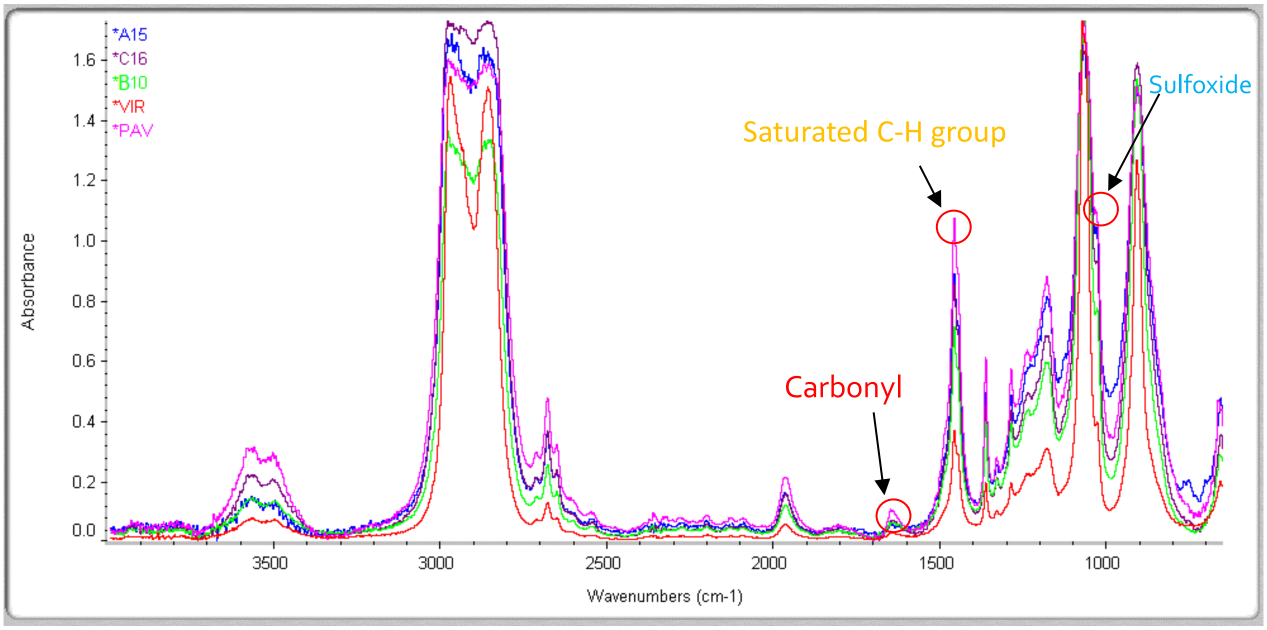
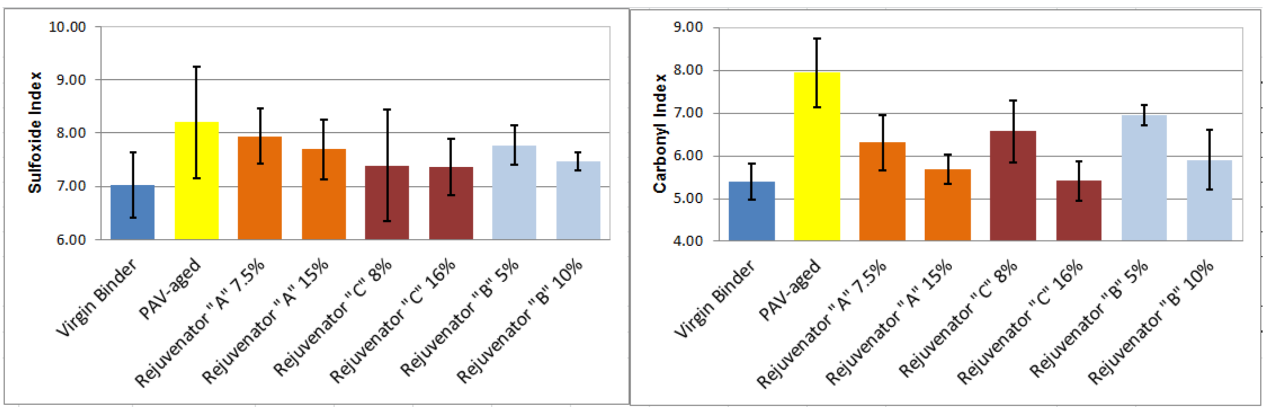


Figure 4-3. FTIR test results of the aged and rejuvenated samples for one dosage of rejuvenators (C16: 16% Rejuvenator “C”; B10: 10% Rejuvenator “B”; A15: 15% Rejuvenator “A”)



(a) Sulfoxide index (b) Carbonyl index

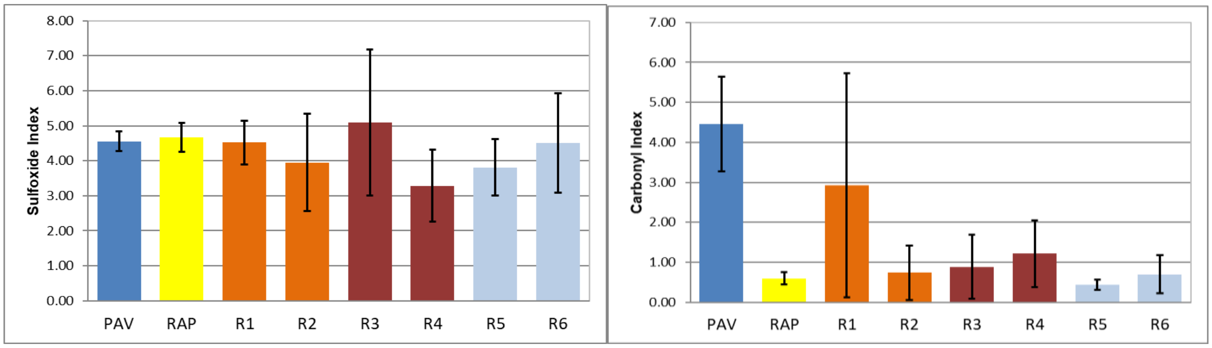
Figure 4-4. Oxidation levels of eight different binder types

2) Scratched binder from RAP tested during phase 4

For this study, test samples were obtained by scratching a binder from the heated RAP. We then mixed the scratched binder with each of six rejuvenators at 10% dosage rate. The FTIR test results are summarized in Table 4-3 and plotted in Figure 4-5. Figure 4-5(a) shows quite similar SI value for PAV-aged and scratched RAP binder of 4.56 and 4.67 respectively and all rejuvenators decreased SI value except R3. Figure 4-5(b) shows CI value of a scratched RAP binder (0.6) was significantly lower than that of PAV-aged binder (4.46). All rejuvenators increased CI value except R5. It can be postulated that carbonyl oxide content is too low in RAP binder compared to that of PAV resulting in consistently lower CI values in all RAP binder with rejuvenators.

Table 4-3. Sulfoxide and Carbonyl index values for each binder type during Phase 4

	C-H area	S=O area	C=O area	Sulfoxide Index	Carbonyl Index	avg SI	avg. CI	stv. SI	stv. CI
PAV	6.653	0.3	0.28	4.51	4.21	4.56	4.46	0.288	1.177
	12.13	0.6	0.52	4.95	4.29				
	11.56	0.5	0.56	4.33	4.84				
	7.05	0.3	0.43	4.26	6.10				
	8.438	0.4	0.24	4.74	2.84				
RAP	13.196	0.705	0.063	5.34	0.48	4.67	0.60	0.408	0.157
	11.728	0.523	0.075	4.46	0.64				
	10.478	0.456	0.0799	4.35	0.76				
	27.317	1.209	0.1958	4.43	0.72				
	13.519	0.644	0.0536	4.76	0.40				
R1	9.119	0.432	0.04	4.74	0.44	4.52	2.92	0.632	2.796
	7.563	0.37	0.08	4.89	1.06				
	17.27	0.685	1.2714	3.97	7.36				
	18.867	0.709	0.3595	3.76	1.91				
	10.375	0.544	0.4	5.24	3.86				
R2	14.082	0.615	0.03	4.37	0.21	3.94	0.74	1.391	0.676
	4.987	0.3	0.03	6.02	0.60				
	14.604	0.399	0.1265	2.73	0.87				
	17.358	0.452	0.0311	2.60	0.18				
	10.248	0.41	0.1882	4.00	1.84				
R3	2.27	0.2	0.03	8.81	1.32	5.10	0.89	2.088	0.797
	11.831	0.48	0.1033	4.06	0.87				
	10.485	0.454	0.0072	4.33	0.07				
	9.086	0.35	0.18	3.85	1.98				
	12.459	0.554	0.0238	4.45	0.19				
R4	15.314	0.665	0.03	4.34	0.20	3.28	1.21	1.025	0.837
	1.81	0.07	0.02	3.87	1.10				
	11.749	0.274	0.199	2.33	1.69				
	13.245	0.507	0.0961	3.83	0.73				
	5.1908	0.106	0.1218	2.04	2.35				
R5	6.615	0.33	0.03	4.99	0.45	3.81	0.44	0.804	0.126
	12.024	0.4	0.05	3.33	0.42				
	10.568	0.312	0.069	2.95	0.65				
	14.826	0.624	0.05	4.21	0.34				
	14.089	0.5	0.05	3.55	0.35				
R6	6.66	0.4	0.04	6.01	0.60	4.51	0.70	1.430	0.482
	8.2	0.43	0.03	5.24	0.37				
	19.238	0.636	0.03	3.31	0.16				
	6.633	0.178	0.07	2.68	1.06				
	19.477	1.031	0.257	5.29	1.32				



(a) Sulfoxide index (b) Carbonyl index

Figure 4-5. Oxidation levels of eight different binder types

4.2 Evaluation of RAP Mixtures with Six Rejuvenators using Hamburg Test

Following AASHTO T324, the Hamburg Wheel-Tracking (HWT) test was performed on specimens submerged under water at a temperature of 50°C. The HWT measures the mixture's ability to resist the moisture sensitivity and rutting. The specimens were prepared with air voids at 7 ± 0.5% with a diameter of 150 mm and a height of approximately 60 ± 0.5 mm.

First, RAP materials were divided into three categories of coarse (sieve size between 25~12.5mm), middle (sieve size between 9.5~1.18mm) and fine (sieve size between 0.6mm~75 µm). To obtain consistent specimens, RAP materials from coarse, middle and fine categories were added in original proportions of 30%, 40%, and 30%, respectively. The specimens with 30% RAP materials and six rejuvenators were subjected to HWT test and HWT test results are plotted in Figure 4-6. As can be seen from Figure 4-6, the control mix (without Rejuvenator) reached maximum rut depth of 20mm at 15,500 passes. Four rejuvenated mixtures (R2 with 4.2mm, R1 with 9.4mm and R6 and R4 with 20mm) exhibited less rutting than the control mix whereas mixtures with R3 and R4 reached maximum rutting depth of 20mm at lower loading repetitions than the control mix.

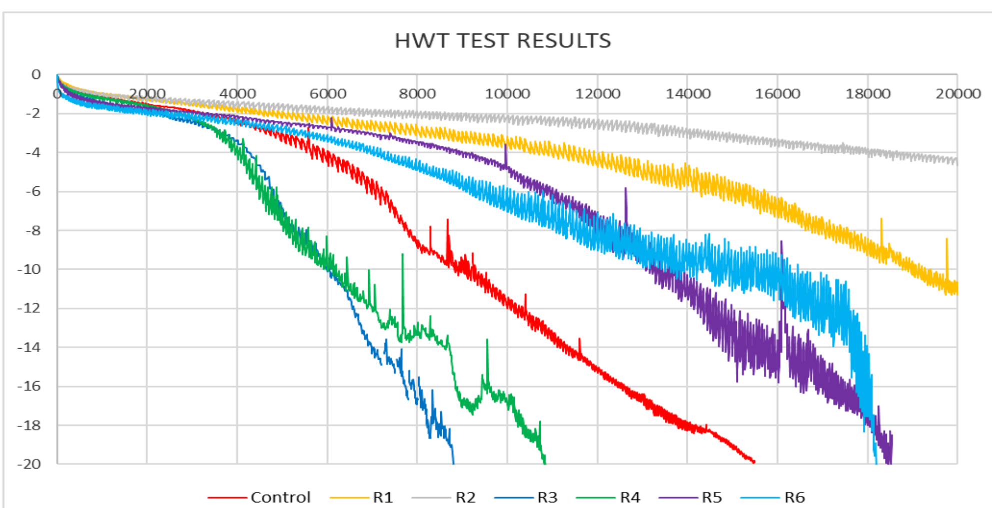


Figure 4-6. HWT test results of 30%RAP mixes with six different rejuvenators

5 LABORATORY EVALUATION OF FRACTIONATED HIGH RAP MIXTURES

The main objective of this task is to determine if a fractionation into two stockpiles (coarse and fine) would improve the performance of high RAP mixes. First, as shown in Appendix A, classified RAP was obtained from a local contractor, which include 4.86% binder and 46% crushed particles. Second, as shown in Table 5-1, to identify the sieve size to divide RAP materials into two stockpiles, RAP materials were sieved. As can be seen from Table 5-1, gradation of RAP materials was coarse due to the conglomerates of RAP materials stuck together with virtually none passing sieve No. 100. To divide RAP materials into two groups with each being similar, sieve No. 4 was selected (54.2% coarse and 45.8% fine).

To evaluate the impact of fractionation of the RAP mixtures, 34% RAP and 45% RAP mixtures were prepared by adding appropriate amounts of aggregates at the laboratory. As can be seen from Table 5-2, different proportions of three aggregate stockpiles were added to 34% and 45% RAP materials resulting in the combined extracted aggregate gradations as shown in Figure 5-1. The extracted aggregate gradation from RAP materials is shown in Appendix A.

Table 5-1. Sieve Test Results of Classified RAP materials

Sieve Size	Weight (g)											Total Weight of each (g)	% remain weight	**% Passing**	**Cumulative % Retained**
	1	2	3	4	5	6	7	8	9	10	11				
1/2"	180.3	92.8	150.3	168.8	188.3	143.4	121.2	126.1	114.7	142.7	150.7	1579.3	9.6	90.4	9.6
3/8"	156.7	131.6	138.5	154.1	153.8	129.6	126.9	173.1	137.5	179.1	156.8	1637.7	9.9	80.5	19.5
No. 4	561.6	507.1	516.9	534.0	522.5	542.9	462.3	519.1	482.3	540.0	529.7	5718.4	34.7	45.8	54.2
No. 8	336.0	387.6	324.9	334.3	358.3	338.0	345.7	315.9	338.5	300.0	322.5	3701.7	22.4	23.4	76.6
No. 16	136.0	201.3	154.1	168.8	218.4	171.1	188.6	158.0	183.6	135.2	152.7	1867.8	11.3	12.0	88.0
No. 30	74.9	167.8	109.1	132.4	126.1	160.2	173.2	143.1	169.9	114.7	147.0	1518.4	9.2	2.8	97.2
No. 50	38.6	31.0	21.6	28.0	6.6	28.5	4.1	66.9	76.9	62.9	60.3	425.4	2.6	0.3	99.7
No. 100	9.7	0.8	3.0	1.0	1.3	1.4	2.4	3.2	4.0	5.0	2.0	33.8	0.2	0.1	99.9
No. 200	2.8	0.9	0.1		0.2	0.1	0.5	0.1	0.7	0.5	0.8	6.7	0.0	0.0	100.0
Pan	1.6	0.1										1.7	0.0	0.0	100.0

Table 5-2. Aggregates Gradation

Mixture		45% RAP					34% RAP					
Aggregate		1/2" Clean	Man. Sand	Nat. Sand	RAP	**Comb.**	1/2" Clean	3/8 AC Stone	Man. Sand	Nat. Sand	RAP	**Comb.**
Percent in mix		16.0	23.0	16.00	45.0	**100.0**	20.0	5.0	22.0	19.00	34.0	**100.0**
% Pass	3/4 in.	100	100	100	100	**100**	100	100	100	100	100	**100**
	1/2 in.	88.4	100	100	95	**95.9**	88.4	100	100	100	95	**96.0**
	3/8 in.	54	100	100	89	**87.7**	54	100	100	100	89	**87.1**
	#4	4.7	81.8	93	71	**66.4**	4.7	90.1	81.8	93	71	**65.3**
	#8	1.8	33.4	79	54	**44.9**	1.8	55	33.4	79	54	**43.8**
	#16	1.7	13.7	61	41	**31.6**	1.7	35.3	13.7	61	41	**30.6**
	#30	1.7	6.7	39	31	**22.0**	1.7	25.8	6.7	39	31	**21.1**
	#50	1.7	3.1	10	20	**11.6**	1.7	20.5	3.1	10	20	**10.7**
	#100	1.6	1.5	0.8	14	**7.0**	1.6	15.6	1.5	0.8	14	**6.3**
	#200	1.4	0.8	0.3	12	**5.9**	1.4	11.4	0.8	0.3	12	**5.2**

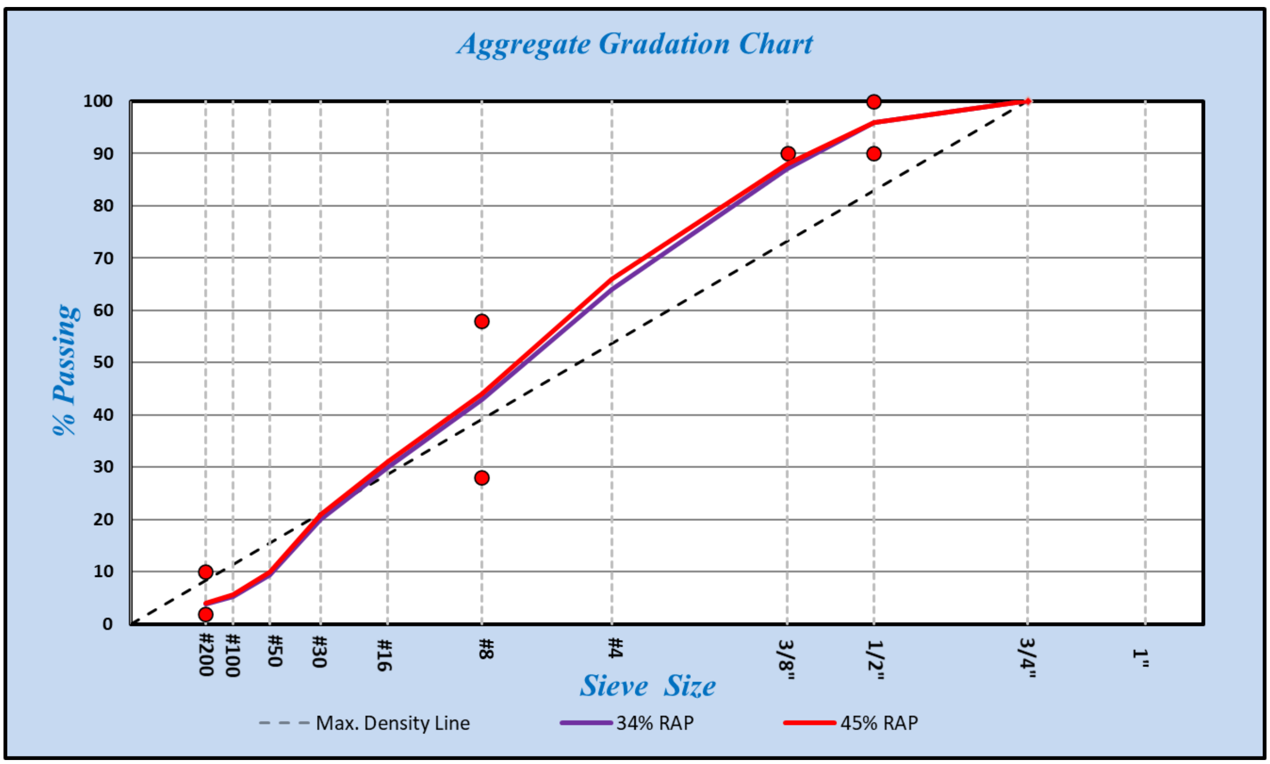


Figure 5-1. Combined extracted aggregate gradations for 34% and 45% RAP mixtures

5.1 HWT Test Results of Fractionated and Non-fractionated Mixtures

Fractionated mixtures were prepared by adding appropriate amounts from two different RAP stockpiles sieved at No.8 whereas non-fractionated mixtures were prepared by adding appropriated amount from a single RAP stockpile. As a result, it is expected that fractionated RAP mixtures will be more consistently graded than non-fractionated mixtures. As summarized in Table 5-3, four mix types of two RAP contents with and without fractionation were prepared.

Table 5-3. Components of 34% and 45% RAP Mixtures

No	ID	Fractionation	Binder	RAP	Total AC (%)
1	34%RAP_No Frac	No	PG58-28S	34%	5.18
2	34%RAP_Frac	Yes	PG58-28S	34%	5.18
3	45%RAP_No Frac	No	PG58-28S	45%	5.39
4	45%RAP_Fract	Yes	PG58-28S	45%	5.39

The HWT test results for both fractionated and non-fractionated mixtures with 34% and 45% RAP are plotted in Figure 5-2. As can be seen from Figure 5-2, for 34% RAP mixtures, fractionated mixture exhibited 5mm rut depth, whereas non-fractionated mixtures exhibited 9.8mm rut depth at 20,000 load cycle. Similarly, for 45% RAP mixtures, 6mm, and 12mm rut depth were observed with fractionated and non-fractionated mixture, respectively. It can be concluded that fractionation of the RAP can improve moisture susceptibility in both 34% and 45% mixtures. It should be also noted that 34% RAP mixtures performed better than 45% RAP mixtures while all mixture met the criterion of a minimum stripping inflection point (SIP) of 10,000 passes.

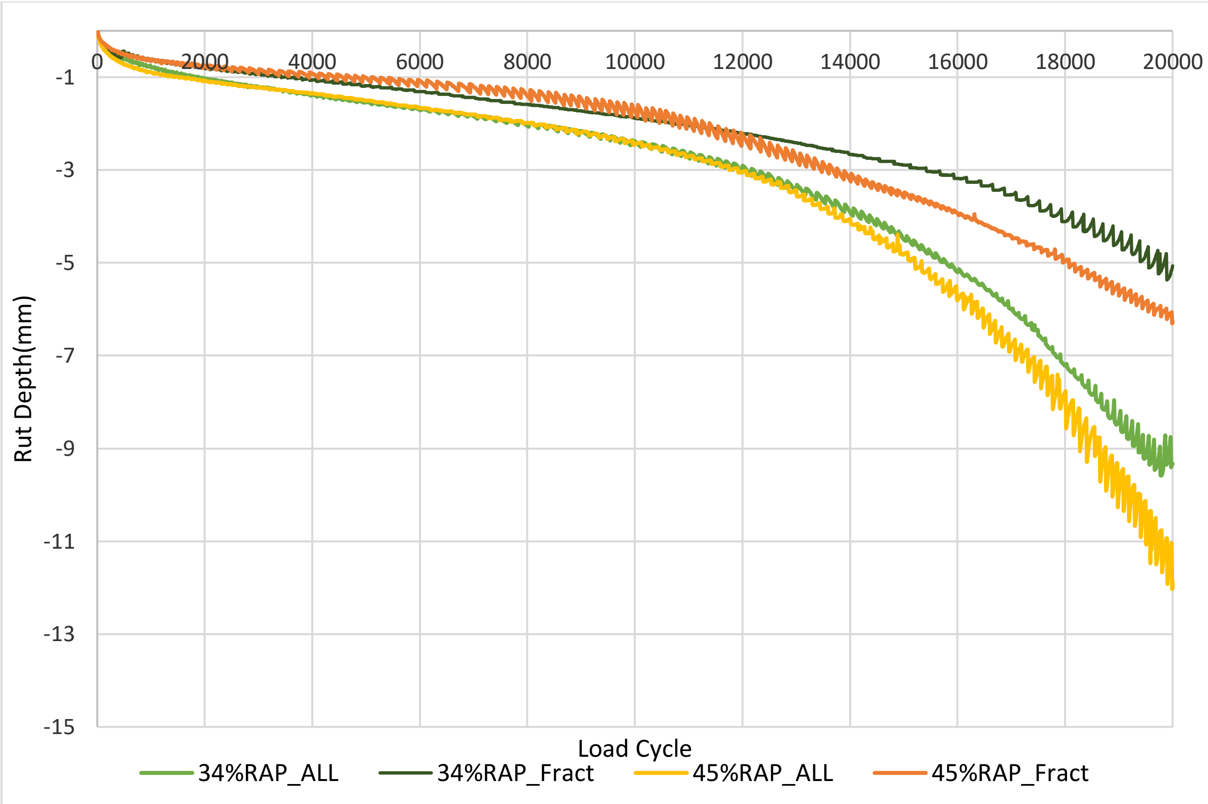


Figure 5-2. HWT test results of fractionated/non-fractionated mixtures with 34% and 45% RAP

5.2 SCB-IFIT Test Results

The SCB-IFIT tests were performed by following the AASHTO TP124. Samples for SCB-IFIT test were made with 150mm diameter and 160mm height and specimens were compacted to a target air void of 7%±0.5%. The compacted samples were then cut for the SCB test specimens with 50 mm thickness discarding the top and bottom 30mm of 160mm tall specimen. The notch was made at 15mm in length and 1.5mm of width. All specimens were conditioned at 25ºC for 2 hours before performing a test.

A typical force-displacement curve from SCB test is illustrated in Figure 5-3, which show work of fracture (W_f) as an area under the curve and a post-peak slope at inflection point after the peak point (m). These parameters were used to calculate a fracture energy (G_F) using Equation 5-1 and flexibility index (FI) using Equation 5-2.

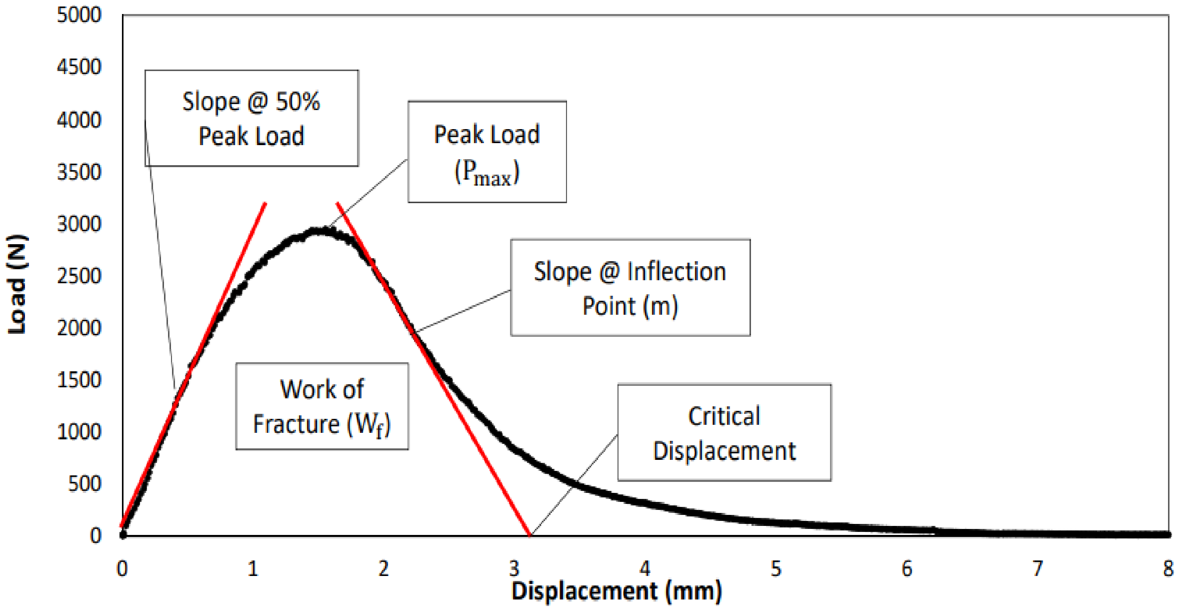


Figure 5-3. A typical force-displacement curve from SCB test and parameters for evaluation

Fracture Energy (G_F) can be calculated using an equation below:

$$G_F = \frac{W_F}{B \times L} \quad (5\text{-}1)$$

where,

W_F is work of fracture,
B is specimen thickness, and
L is ligament length.

The flexible index (FI) can be calculated an equation below:

$$FI = \frac{G_F}{|m|} \times A \quad (5\text{-}2)$$

where,

G_F is fracture energy calculated by dividing work of fracture by the ligament area,
m is the post-peak slope at inflection point after the peak point, and
A is a unit conversion from field to lab. (0.01, lab-compacted specimen)

A total of 16 samples were prepared: four samples for each of four combinations of fractionated/non-fractionated and 34%/45% RAP materials. The SCB-IFIT test results are summarized in Table 5-4 and plotted in Figure 5-4 with an error bar representing one standard deviation. For 34% RAP mixtures, compared to the non-fractionated mixture, fractionated mixture endured the higher fracture energy with almost same post-peak slope, which resulted in the higher

FI value than non-fractionated mixture. Similarly, for 45% RAP mixtures, the fractionated mixture obtained the higher FI than non-fractionated mixture. Given the limited test results, it can be concluded that fractionation can improve a cracking resistance of both 34% and 45% RAP mixtures. It should be also noted that, overall, 34% mixtures performed better than 45% RAP mixtures.

Table 5-4. SCB Test Results for Mixtures

ID	PEAK LOAD (KN)	STDEV	Fracture Energy (J/m^{2})	STDEV	Post-Peak Slope (kN/mm)	STDEV	FI	STDEV
34%RAP_No	4.48	0.11	1283.25	160.80	-5.96	0.49	2.19	0.45
34%RAP_Frac	5.25	0.13	1685.43	21.60	-6.00	0.28	2.81	0.09
45%RAP_No	6.31	0.25	1602.17	123.48	-9.36	0.57	1.71	0.04
45%RAP_Frac	6.36	0.42	1534.39	266.34	-8.30	0.40	1.85	0.31

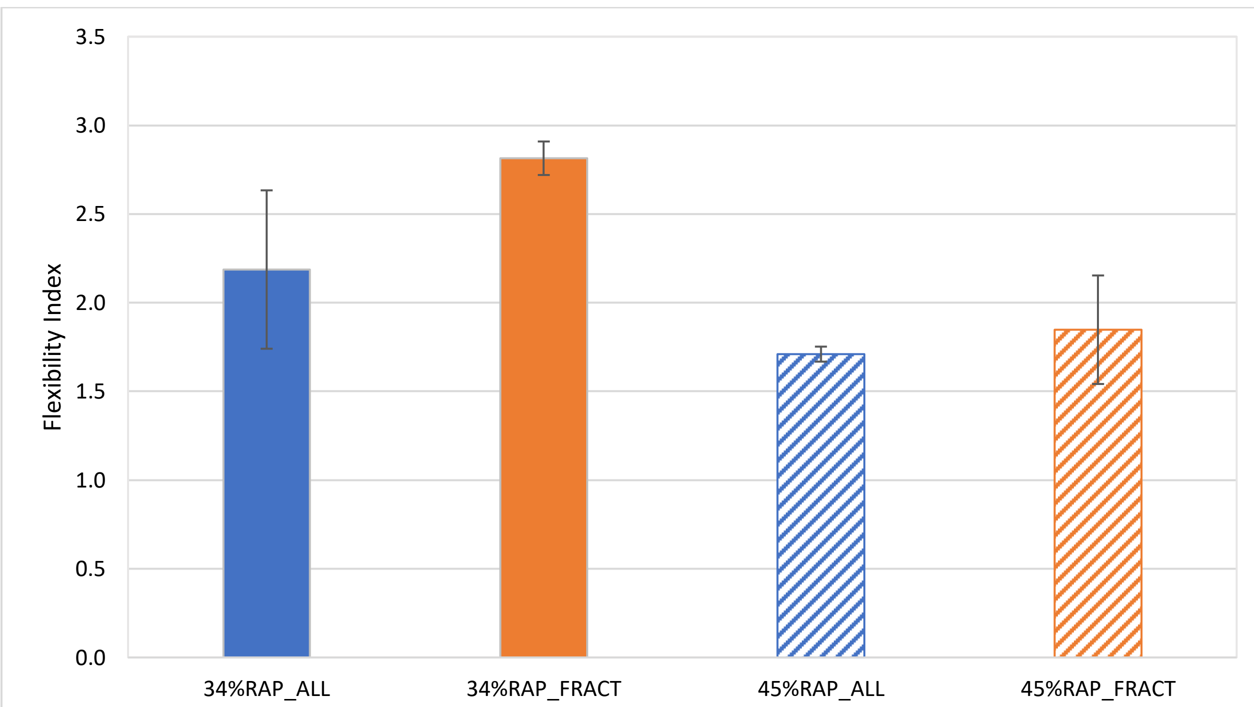


Figure 5-4. SCB test results of 34% and 45% RAP mixtures

6 EVALUATION OF MIXTURES WITH RECYCLED ASPHALT SHINGLE AND REJUVENATORS

Recycled asphalt shingles (RAS) materials were obtained from a local contractor, as shown in Appendix B that shows 98% extracted aggregates passing No.4 sieve with 19.35% binder content. As summarized in Table 6-1, asphalt mixtures were prepared with 11% RAS (27% by binder replacement) and three rejuvenators at a constant dosage rate of 3%. It should be noted only 67 percent of the asphalt binder from RAS was assumed "active," where 67% of the binder from RAS was considered in calculating a total binder content. Table 6-2 shows the aggregate gradations and the combined gradation is plotted in Figure 6-1.

Table 6-1. Description of Asphalt Mixtures 11% RAS and with rejuvenators

No	**ID**	**Rejuvenator**	**Binder**	**Total AC (%)**	**% Binder from RAS**	**% Binder replacement**
1	11%RAS_Control	-	PG58-28S	5.38	1.43	27
2	11%RAS_TUFF	TUFF TREK				
3	11%RAS_300PL	NH 300PL				
4	11%RAS_303PL	NH 303PL				

Table 6-2. Aggregates Gradation

Mixture		3/4 Clean	3/8 to Dust	T4 Man Sand	Sand	RAS	**Combined**
Percent in mix		18.0	12.0	33.0	26.0	11.0	**100.0**
%Pass	3/4 in.	100	100	100	100	100	**100**
	1/2 in.	55	100	100	100	100	**91.9**
	3/8 in.	19	90	100	100	100	**84.2**
	#4	7	29	99	95	95	**72.6**
	#8	2	14	74	90	85	**59.2**
	#16	1	10	40	79	70	**42.8**
	#30	1	8	20	53	50	**27.0**
	#50	1	7	8	16	45	**12.8**
	#100	1	6	5	2	35	**6.9**
	#200	1	5.5	3.8	1	25	**5.1**

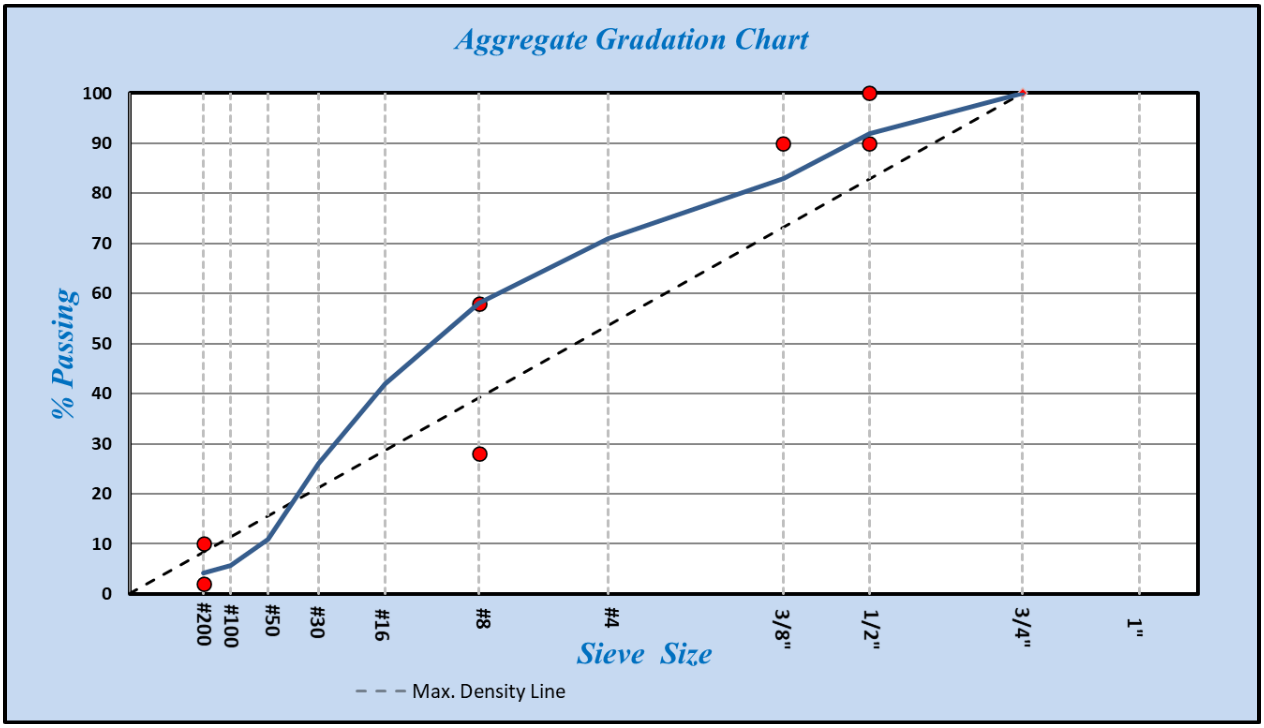


Figure 6-1. Combined aggregate gradation of a mix with 11% RAS

6.1 HWT Test Results

HWT test results of four mixes with 11% RAS are shown in Figure 6-2, where a control exhibited the smallest rut depth of 4.4mm at 20,000 passes, followed by 303PL, TUFF, 300PL. It should be noted that all mixtures met the criterion of a minimum SIP of 10,000 passes. Based on the limited test results, overall, 11% RAS mixtures performed well where rejuvenators might have caused a softening effect on RAS mixtures.

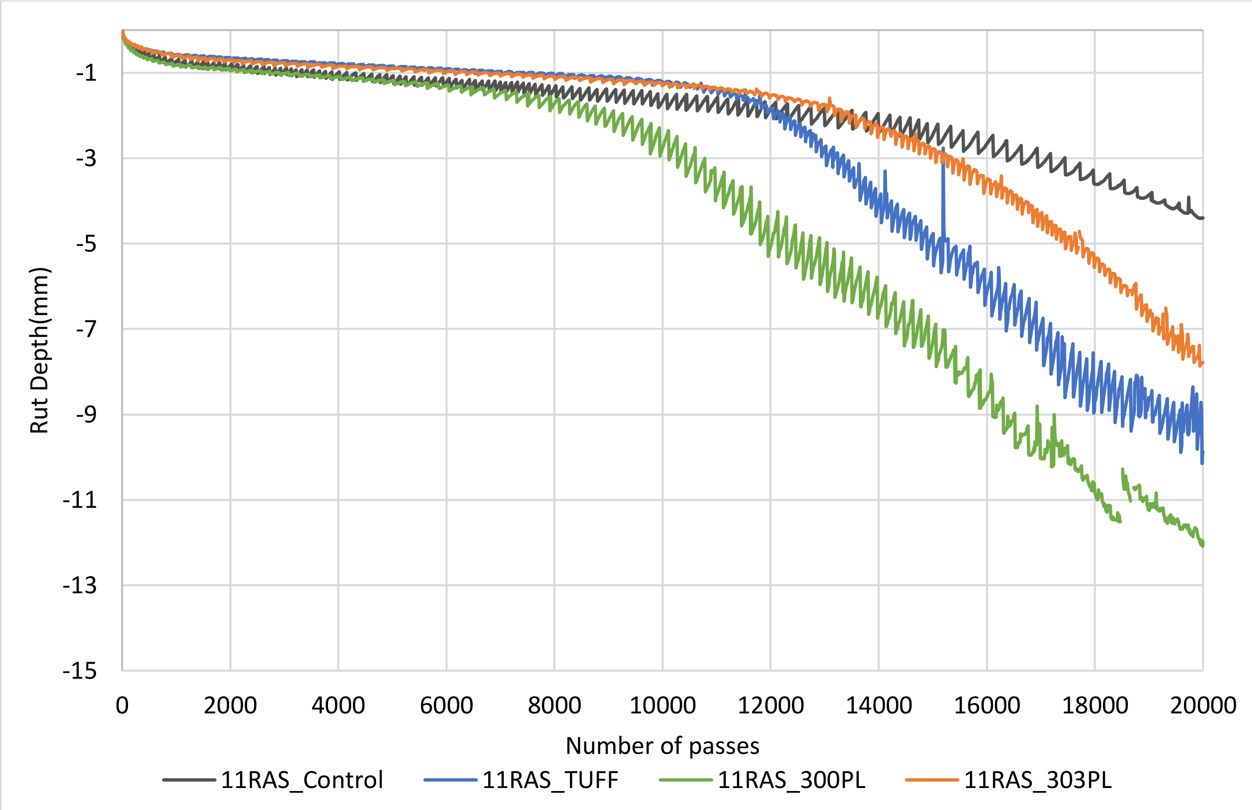


Figure 6-2. HWT test results for 11% RAS mixtures

6.2 SCB-IFIT Test Results

A total of 16 test specimens with 11% RAS were prepared for SCB-IFT test: four specimens with no rejuvenator as a control and three different rejuvenators. The SCB-IFIT test results are summarized in Table 6-3 and plotted in Figure 6-3. 11RAS_300PL exhibited the highest FI value followed by 11RAS_Control, 11RAS_TUFF, and 11RAS_303PL. Overall, all mixtures exhibited similar FI values, indicating three used rejuvenators did not have a significant impact on improving the cracking resistance of RAS mixtures.

Table 6-3. SCB-IFIT test results for 11% RAS mixtures

ID	PEAK LOAD (KN)	STDEV	Fracture Energy(J/m^2)	STDEV	Post-Peak Slope(kN/mm)	STDEV	FI	STDEV
11RAS_Control	2.50	0.09	918.35	66.16	-2.98	0.11	3.09	0.30
11RAS_TUFF	2.36	0.09	811.11	88.24	-2.81	0.21	2.91	0.44
11RAS_300PL	2.49	0.28	934.49	41.16	-2.83	0.74	3.51	0.82
11RAS_303PL	2.03	0.30	684.81	121.10	-2.47	0.50	2.81	0.39

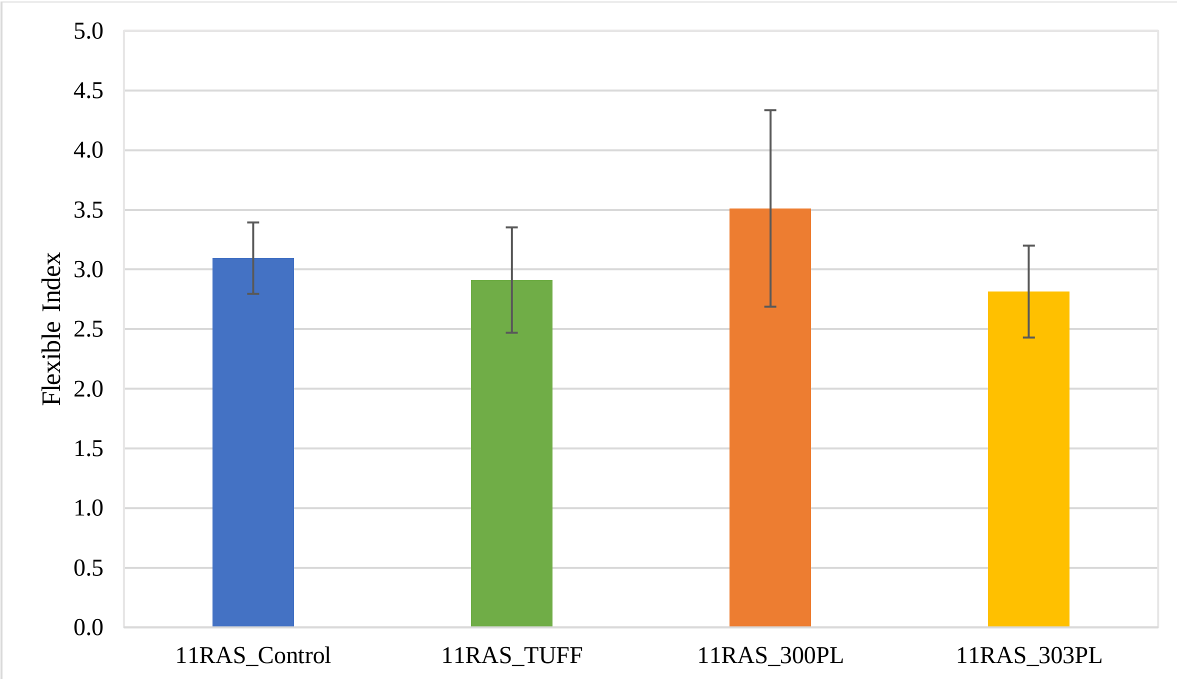


Figure 6-3. SCB-IFIT test results for 11% RAS mixtures

7 FIELD EVALUATION OF HIGH RAP MIXTURES WITH REJUVENATORS

The main purpose of this task is to determine if the high RAP mixes with different amounts of rejuvenators would perform well in the field. To evaluate the effects of rejuvenators on high RAP mixture, on August 3-4, 2020, six test sections with 1.5-inch surface layer (on top of 1.5-inch intermediate layer) of three different RAP contents and two types of rejuvenators were constructed on two-lane highways of S62 and B20 by Heartland Asphalt Co. in Cerro Gordo County, Iowa. A total length of seven test sections was 6.2 miles with each test section being approximately 0.8 mile. Construction operations of fractionated high RAP mixtures with rejuvenators were monitored and field loose mixtures were collected for testing at the laboratory.

7.1 Rejuvenators

Two bio-based rejuvenators were used for building test sections: Invigorate and Tufftrek. To improve the chemical properties of aged elements within RAP, Invigorate, a partially epoxidized soybean oil, is reported to trigger chemical reactions inside RAP to break down asphaltene aggregation and reverse the effects of oxidation (Podolsky, 2021). Invigorate is produced by partially epoxidizing commercial grade soybean oil. Instead of superficially change the viscosity of the binder, it claims to repair the chemical damage in lower-quality binders to address the aged elements within recycled asphalt.

Tufftrek uses renewable oil technology and is a 100% bio-based feedstock. It has both polar and non-polar components and non-polar fatty acid chains orient with the non-polar oily fraction in asphalt, and the polar components orient with the polar asphaltenes. Tufftrek helps disperse the asphaltenes within the oily/maltene fraction, improving molecular mobility of the asphaltenes and converting asphaltene structure from gel to sol with a greater stress relaxation capacity (GP-chemical brochure). Tufftrek acts like an emulsifier by stabilizing asphaltenes as it reduces viscosity, which in turn reduces fatigue and low-temperature cracking..

7.2 Mixture Types for Test Sections

Table 7-1 summarizes six types of mixtures with two different rejuvenators (3% and 5% of Invigorate and 3% and 4.5% of Tufftrek) and three different RAP contents (0%, 34% and 45% by binder replacement). Tufftrek was preblended at the terminal and Invigorate was added to the asphalt at the asphalt mixing plant. It should be noted that the amount of Invigorate may be different from the specified design amount because the asphalt pumping at the asphalt mixing plant may not have been consistent during the blending process. Locations of six test sections with combinations of three RAP contents and two rejuvenators are illustrated in Figure 7-1.

Table 7-1. Description of six test sections with different RAP and rejuvenator amounts

No	ID	Binder	RAP	Rejuvenator	AC (%)
1	R22	PG58-28S	22%	None	5.3
2	R34bump	PG52-34S CIR	34%	None	5.18
3	R34A3*	PG58-28S	34%	Invigorate 3%	5.18
4	R34B3	PG58-28S	34%	Tufftrek 3%	5.18
5	R45A5*	PG58-28S	45%	Invigorate 5%	5.39
6	R45B4.5	PG58-28S	45%	Tufftrek 4.5%	5.39

Figure 7-1. Construction of Six Test Sections in Cerro Gordo County

Combined aggregate gradations for all mixtures are plotted in Figure 7-2. As can be seen from Figure 7-2, all mixtures satisfied the volumetric criteria with similar gradations.

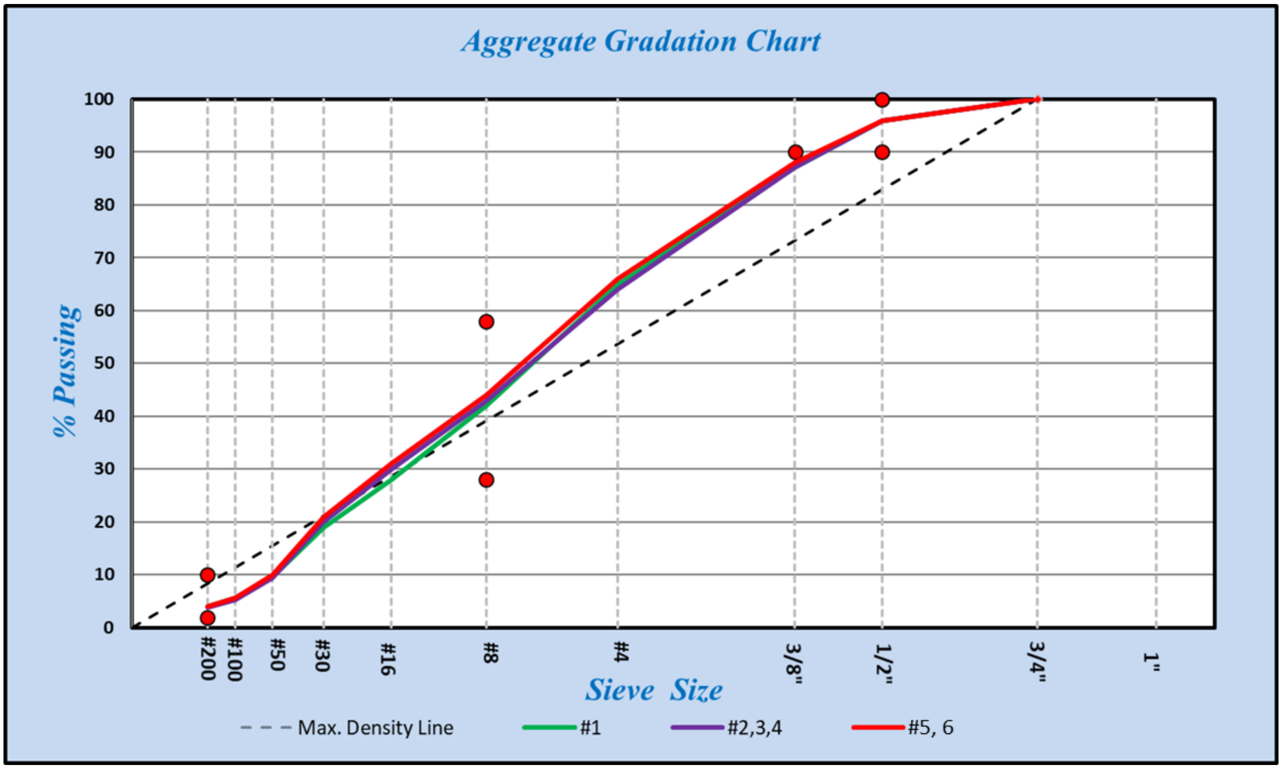


Figure 7-2. Combined aggregate gradation chart for all mixtures

7.3 Performance Grading of Rejuvenated Asphalt Binders

To verify the grade of the control asphalt binder (PG 58-28S) and rejuvenated blends, Dynamic Shear Rheometer (DSR) testing (ASTM D7175-08 and AASHTO T 315-10) and Bending Beam Rheometer (BBR) testing (ASTM D6648-08 and AASHTO T 313-10) were performed by Flint Hills, Inc. on unaged, short-term aged, and long-term aged asphalt blends. The short-term laboratory aging of the samples was performed using a Rolling Thin-Film Oven (RTFO) in accordance with ASTM D2872-12 at 163 °C for 85 minutes. The long-term laboratory aging was performed on the asphalt binders using pressure aging vessel (PAV) as per ASTM D6521-13 for a duration of 20 hours at 100 °C and 2.1 MPa pressure.

The DSR test was conducted to determine critical high temperature at an oscillation frequency of 10 rad/s (1.59 Hz). The test started at an initial testing temperature of 46°C, followed by subsequent testing in 6.0°C increments until a specimen fails. For unaged and RTFO binders, 25-mm diameter parallel plates with 1 mm gap geometry was used, for PAV binders, 8-mm diameter plates with 2 mm gap was used. The critical high temperatures were be obtained when the $|G^*|/\sin(\delta)$ value of specimen reached 1.00 kPa, 2.20 kPa 5.0 MPa for unaged, RTFO and PAV specimens, respectively.

The BBR test was used to evaluate the low temperature grade of samples by measuring the center point deflection of the beam at 240 sec. The stiffness (S) and creep rate (m-value) were determined at a loading time of 60 s. The continuous Performance Grade (PG) range results were determined based on both the critical high and low temperatures of the samples, which indicates the temperature susceptibility of the asphalt binder and the working range of temperatures. The continuous grade range and DSR, BBR test results were summarized in Table 7-2 and plotted in Figure 7-3.

The results clearly showed that addition of rejuvenators decreased both critical high and low temperatures of control binder (PG 58-28S), but similar temperature ranges were observed. In addition, the rutting parameter of the rejuvenated binder blends was strongly affected by the amount of the rejuvenator by decreasing critical high temperature more. It can be postulated that rejuvenators have an impact on softening asphalt binders while maintaining similar temperature susceptibility compared to control binder.

Table 7-2. DSR, BBR Tests Results of Six Different Binders that Used in Field Test Sections

Test/testing temperature(°C)		PG 52-34S CIR	PG 58-28S	PG 58-28S + 3% rejuvenator A	PG 58-28S + 3% rejuvenator B	PG 58-28S + 5% rejuvenator A	PG 58-28S + 4.5% rejuvenator B
DSR (unaged, kPa)	46	1.989	6.628	3.5	2.886	3.963	2.159
	52	0.855	2.756	1.522	1.267	1.713	0.981
	58	0.422	1.140	0.704	0.586	0.794	0.468
	Fail Temp	50.9	58.9	55.3	53.9	56.2	52.0
DSR (short-term aged, kPa)	46	4.4	17.8	11.1	7.4	11.2	5.6
	52	1.8	7.3	4.9	3.1	4.8	2.4
	58	0.862	3.216	2.169	1.413	2.111	1.101
	Fail Temp	50.6	60.6	57.9	54.7	57.6	52.8
DSR (long-term aged, kPa)	19		4042				
	16		6136	4440			
	13	3270	9412	6460	4440	6361	3896
	10	5210		9500	6990	9601	6146
	7	8210			10600	13994	9334
	Fail Temp	10.2	17.5	15.0	12.2	14.9	11.3
BBR Stiffness (20hr PAV, MPa)	-18	115	256	166	129	165	
	-24	288	526	374	316	362	263
	-30	630	676				620
	Low PG	-34.6	-29.4	-32.4	-33.7	-32.6	-34.9
BBR m-value (20hr PAV)	-18	0.418	0.334	0.368	0.406	0.364	
	-24	0.349	0.28	0.3	0.326	0.295	0.353
	-30	0.26	0.243				0.263
	Low PG	-37.2	-32.1	-34.0	-36.0	-33.6	-33.6
Final Continuous PG		PG 50.9-34.6	PG 58.9-29.4	PG 55.3-32.4	PG 53.9-33.7	PG 56.2-32.6	PG 52.0-34.9
PG Temp Range		85.5	88.3	87.7	87.6	87.7	86.9

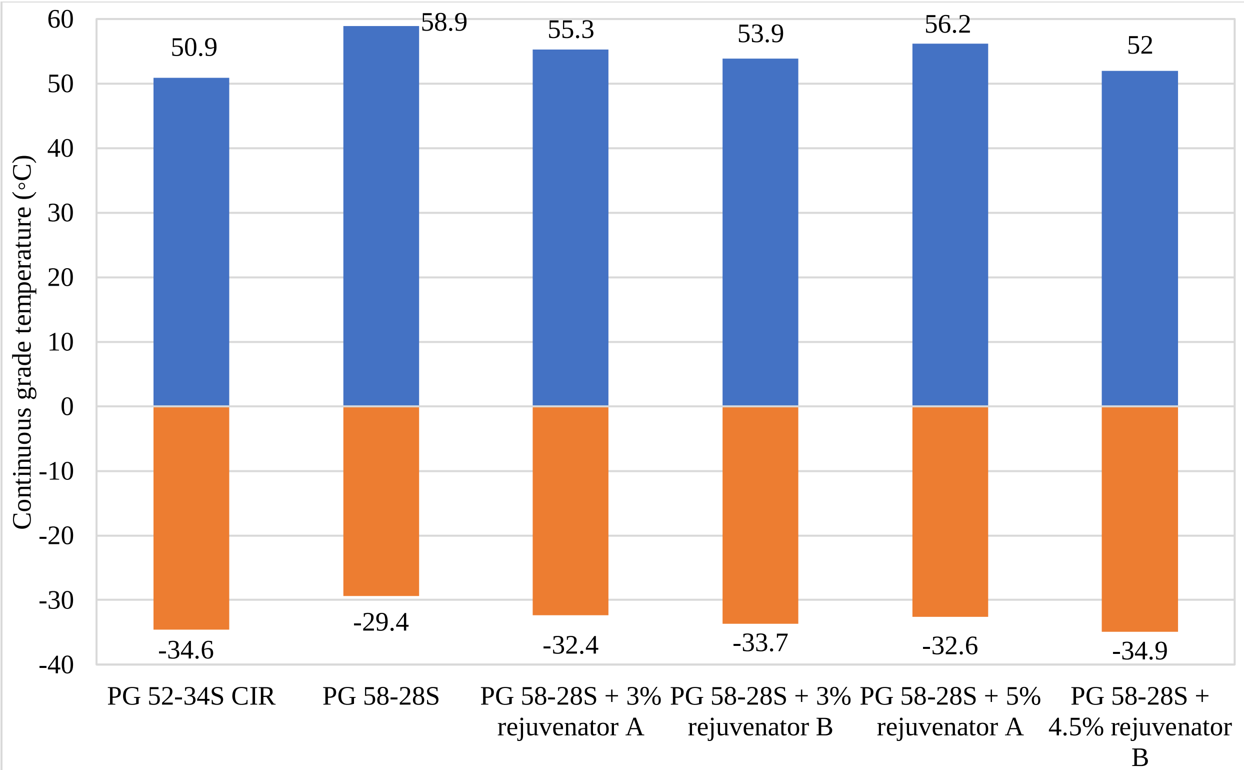


Figure 7-3. Continuous performance grades of six different binders used for field test sections

7.4 HWT test result of Field Mixtures

To prepare HWT test specimens, loose field mixtures with rejuvenators were collected from the field and compacted at the laboratory. In addition, as control samples, HWT test specimens with 34% and 45% RAP without rejuvenators were prepared at the laboratory using the same aggregates, RAP materials and asphalt binder that were collected from the field. The HWT test results of all eight mixtures are plotted in Figure 7-4. As can be seen from Figure 7-4, both field mixtures of 22% RAP and 34% RAP with a softer binder failed at around 8,000 passes due to the moisture damage. However, Tufftrek helped decrease a rut depth whereas Invigorate did not help compared to control mixtures. All mixtures with rejuvenators met the criterion of a minimum Stripping Inflection Point (SIP) of 10,000 passes.

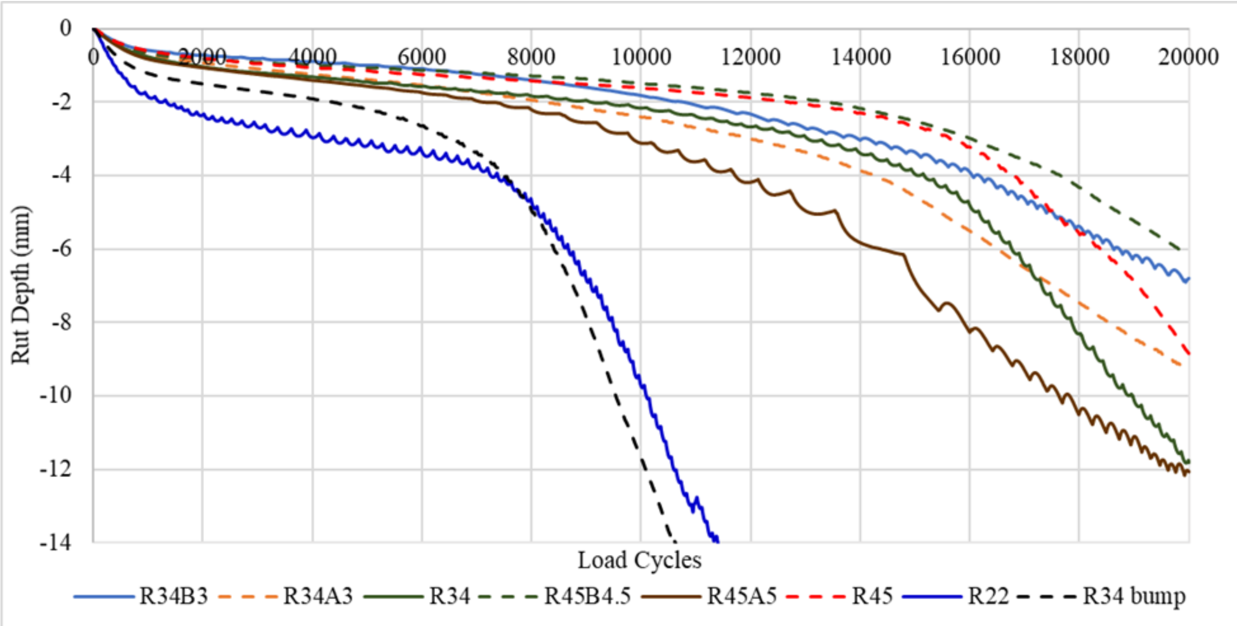


Figure 7-4. HWTT results for all eight mixtures

7.5 Disk-Shaped Compact Test Results

To evaluate low-temperature cracking performance, Disk-shaped Compact Tension (DCT) test was performed following ASTM D7313. Loose mixtures collected from the field test sections were compacted at laboratory at 10°C higher than the low-temperature limit of PG grade of virgin binder. The DCT test results for all mixtures are summarized in Table 7-3 and average fracture energy with standard deviations are plotted in Figure 7-5. As can be seen in Table 7-3, 34R bump mixture endured the highest fracture energy followed by R34A3, R34B3, R45B5 and R45A4.5. It should be noted that average fracture energy value for the R34B3 mix could be considered as 445.5 J/m^2 if one outlier is discarded. Given the limited test results, it can be concluded that 34% RAP with a softer binder produced mixtures more resistant to low-temperature cracking than ones with rejuvenators. For 34% RAP mixes, Invigorate provided a higher resistance to low-temperature cracking than Tufftrek.

Table 7-3. DCT Test Results of Laboratory Compacted Loose Mixtures from Five Test Sections

ID	Mix	Air Voids %	Fracture Energy (J/m^2) @ -18°C	Average Fracture Energy
R34 Bump	34% RAP 52-34 Binder Bump	7.41	429.0	480.3
		7.25	479.0	
		7.09	533.0	
R34B3	34% RAP 3% Rejuvenator B	6.80	298.0	396.3
		7.41	449.0	
		7.55	442.0	
R45B4.5		7.25	344.0	363.0

	45% RAP 4.5% Rejuvenator B	7.12	417.0	
		6.96	328.0	
R34A3	34% RAP 3% Rejuvenator A	7.45	433.0	440.3
		7.39	400.0	
		6.89	488.0	
R45A4.5	45% RAP 4.5% Rejuvenator A	7.11	343.0	332.0*
		6.97	301.0	
		7.29	352.0	

*Due to an inconsistent pumping rate at the asphalt plant, DCT test was performed on additional field samples with the same 45% RAP and 4.5% Invigorate content from a different project to produce an average fracture energy of 477.3 J/m^2.

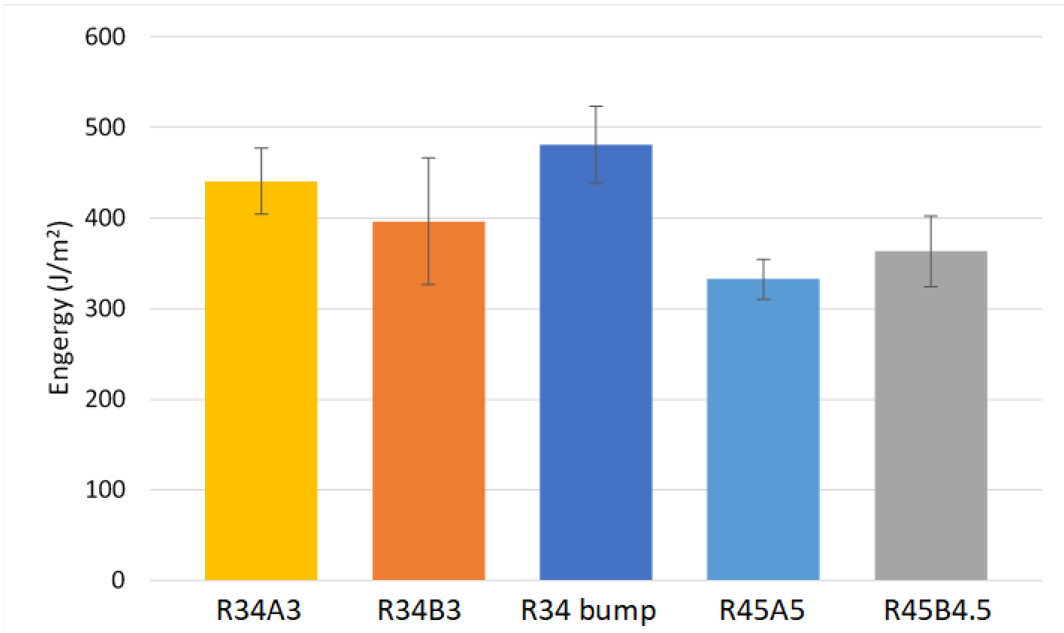


Figure 7-5. DCT test results of laboratory compacted loose mixtures from test sections

7.6 Semi-Circular Bending Test Results

A total of 24 samples were prepared: four samples for each of four combinations of two rejuvenators and two different RAP contents (16 samples) and four samples for two different RAP contents without rejuvenators (8 samples). The SCB-IFIT test results are summarized in Table 7-4 and plotted in Figure 7-6. For 34% RAP mixtures, the R34A3 sample endured the highest fracture energy with the lowest post-peak slope, which resulted in the highest FI value followed by R34B3 and R34 samples. For 45% RAP mixtures, the R45B4.5 sample obtained the highest FI value followed by R45A5 and R45 samples. Given the limited test results, it can be concluded that rejuvenators improved a cracking resistance of high RAP mixtures.

Table 7-4. SCB-IFIT Test Results for 34% RAP Mixtures

ID	PEAK LOAD (KN)	STDEV	Fracture Energy(J/m^2)	STDEV	Post-Peak Slope(kN/mm)	STDEV	FI	STDEV
R34	3.8965	0.431361	1567.5	166.8	-4.746	0.970455	3.459	0.859203
R34A3	3.871	0.27712	1717.0	53.5	-3.77275	0.705399	4.7535	1.10176
R34B3	3.908	0.197404	1671.1	96.9	-4.11125	0.094534	4.06975	0.303543
R45	4.20675	0.419951	1572.9	153.3	-4.893	0.699941	3.25075	0.338219
R45A5	3.952	0.127532	1629.9	136.1	-4.526	0.380986	3.63475	0.505296
R45B4.5	4.2385	0.126668	1835.9	109.5	-4.55325	0.55434	4.1275	0.79939

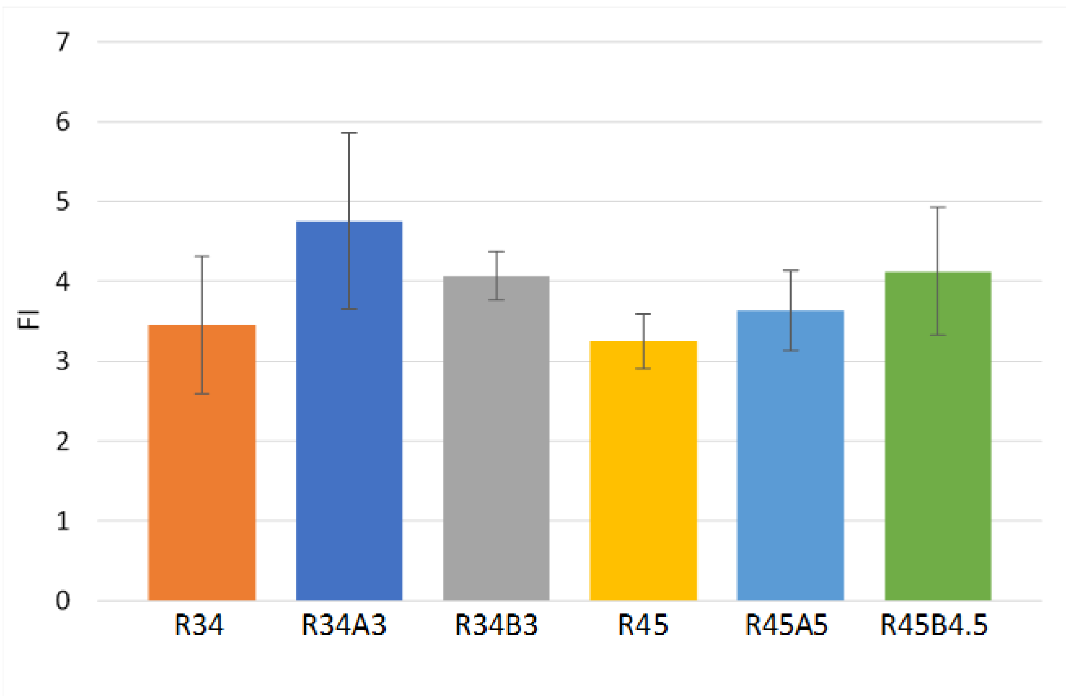


Figure 7-6. SCB-IFIT test results of four samples from test sections and two control samples

7.7 Performance Space Diagram of Flexibility Index versus Fracture Energy

A performance space diagram is plotted in Figure 7-7, where the FI is plotted in y-axis and the fracture energy in x-axis. As can be seen Figure 7-7, for 34% RAP mixtures, compared to R34B3, R34A3 samples increased fracture energy and FI values by 17% and 11%, respectively. For 45% RAP mixtures, however, compared to rejuvenator A, rejuvenator B increased fracture energy and FI values by 14% and 10%, respectively.

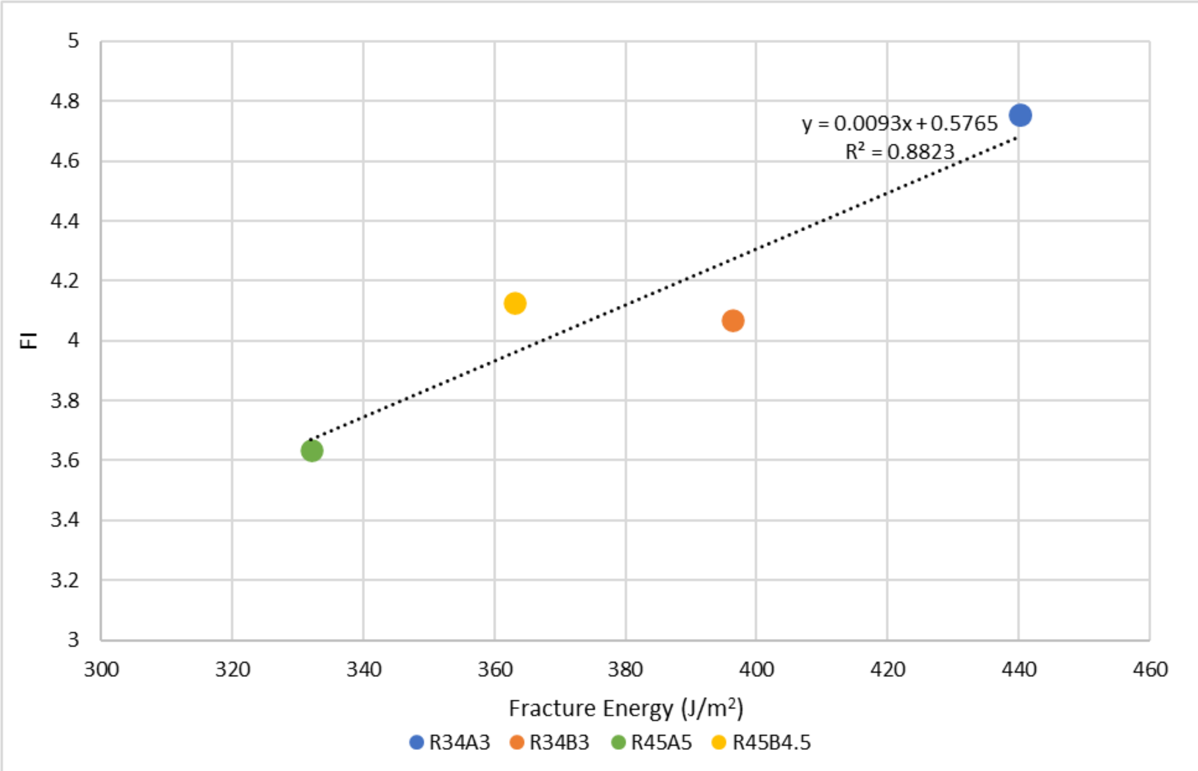


Figure 7-7. Performance space diagram to predict cracking potential at four test sections

7.8 Field Densities of Six Test Sections

Table 7-5 summarizes the field densities measured from six test sections. The test section with 45% RAP and 5% Invigorate exhibited the highest field density followed by 34% RAP and 3% Invigorate. Field densities of the remaining four test sections with Tufftrek and without a rejuvenator were similar and met the minimum density requirement of 93%. The average and standard deviation of field densities of six test sections are plotted in Figure 7-8.

Table 7-5. Field densities of six test sections

No	R22	R34 bump	R34A3	R34B3	R45A5	R45B4.5
1	93.3	94.0	94.0	94.2	95.8	94.8
2	94.7	93.4	94.7	93.9	95.4	95.5
3	94.1	92.7	92.5	93.8	96.3	94.2
4	94.8	93.6	93.2	93.7	95.0	94.6
5	94.4	92.5	93.2	94.3	94.0	92.4
6	92.3	93.8	94.3	93.2	94.6	93.2
7	91.7	95.6	93.9	94.6	95.3	93.6
8	94.5	93.5	94.0	95.1	95.1	92.4
Average	93.7	93.6	93.7	94.1	95.2	93.8
STDEV	1.10	0.88	0.66	0.55	0.66	1.06

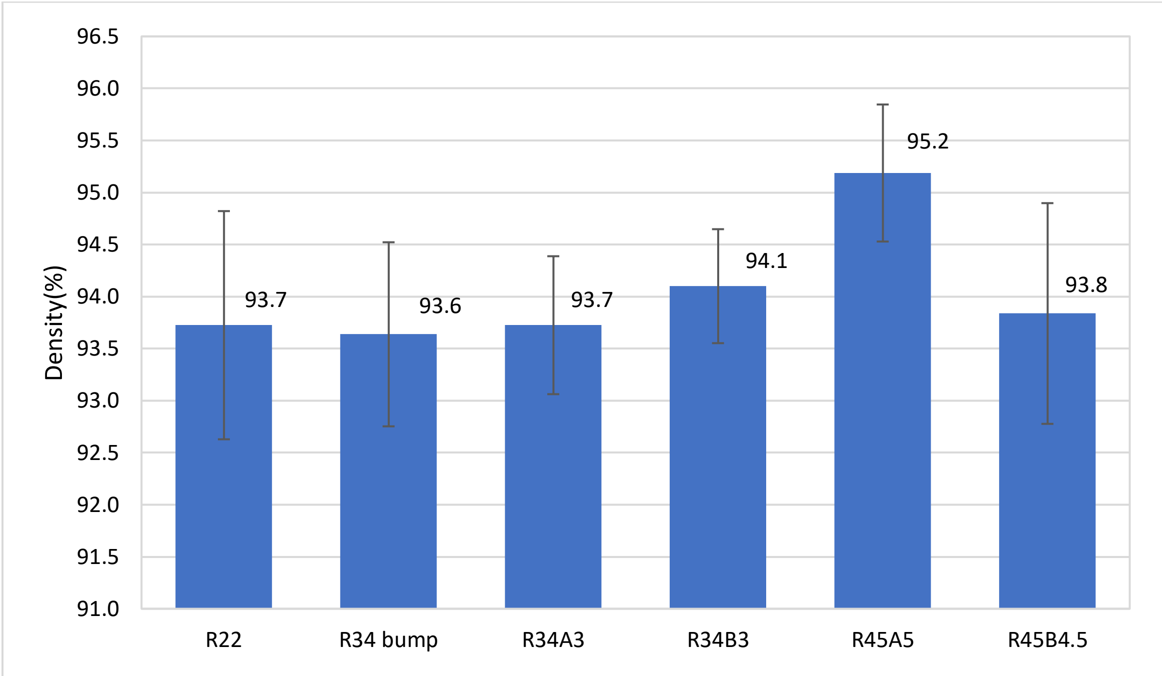


Figure 7-8. Field densities of six test sections

7.9 Condition Survey of Test Sections after One Year

Condition survey of all test sections was performed after one year since construction. Overall, all test sections performed very well with very little cracking and no rutting. As can be seen from Figure 7-9, several cracks were observed from test sections with 22% RAP without rejuvenator and 34% RAP with a softer binder. There was no rutting in all test sections.

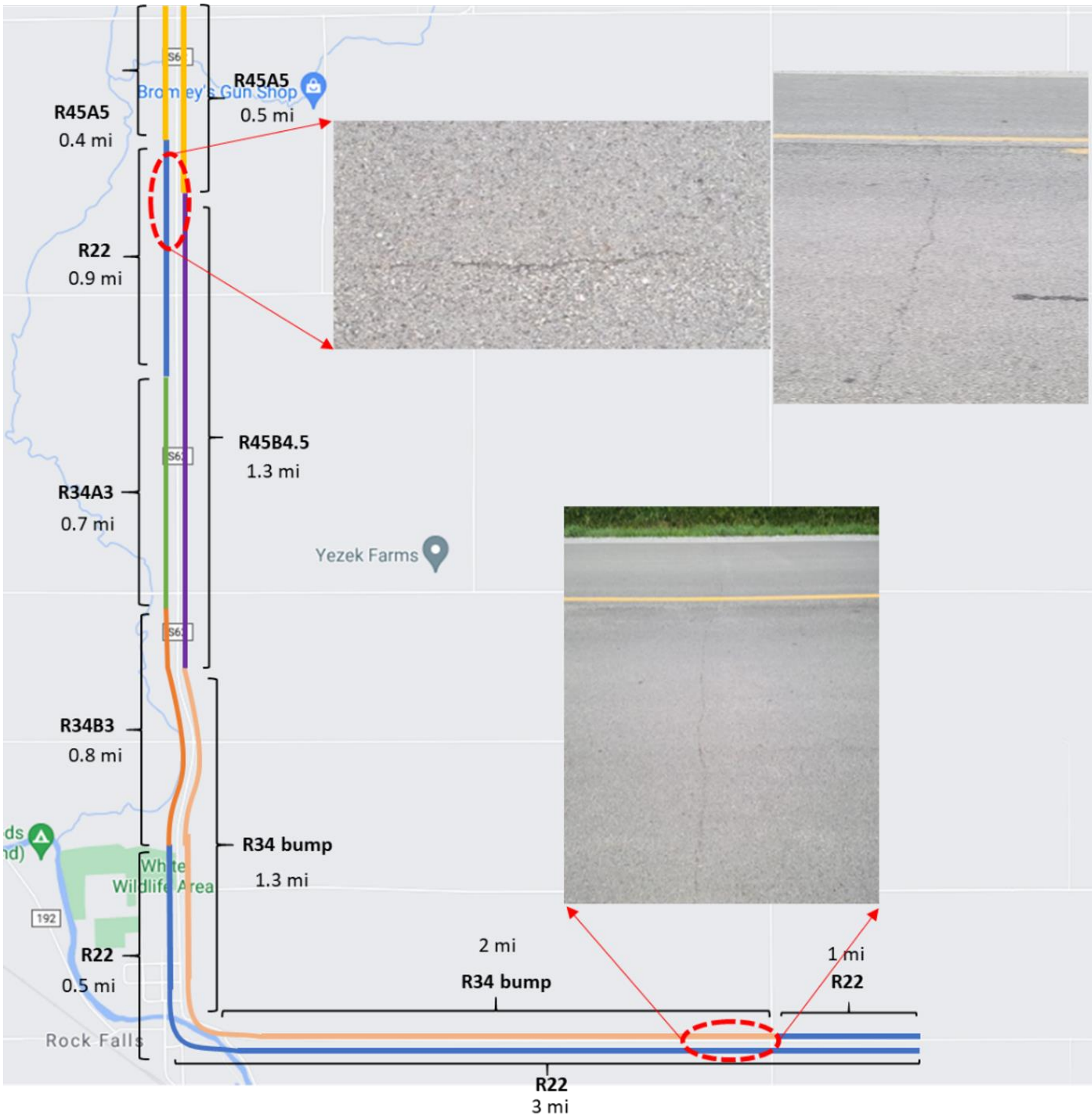


Figure 7-9. Test sections without rejuvenators with cracking in one year after construction

8 AGING OF HIGH RAP MIXTURES WITH REJUVENATORS

Ageing of HMA mixtures has been well researched in the past, but little research has been performed on aging of high RAP mixtures with rejuvenators. The main purpose of this task is to determine if the rejuvenated RAP mixture properties are stable over time without accelerating the aging process. Field mixtures were evaluated to determine if the ageing in the field accelerated or decelerated compared to the laboratory ageing.

Due to the complex field conditions, asphalt binder aging factors are normally evaluated in the controlled laboratory environment (Zhu 2015). In the past, to simulate every one year of aging in the field, the heating for 12 hours in the oven at 85 °C was recommended for each year in the field (Bell, 1994). To simulate five to ten years of aging in the field, AASHTO R 30 recommends a short-term aging in the oven at 135°C for four hours followed by a long-term aging at 85 °C for 120 hours. For a practical and relatively quick ageing method for the mix design, 12 hours or up to 24 hours ageing at 135°C were also suggested (Blankenship 2015). Recently, to match chemical composition changes, a longer aging times at lower temperatures have been proposed (Kim et al., 2018).

8.1 Aging Test Specimens

To evaluate the aging effects on rejuvenated high RAP mixes (45% RAP), the test specimens were prepared using pre-blended binders of PG 58-28S with rejuvenators collected from the field (5% Invigorate and 4.5% TuffTrek). Table 8-1 summarizes compositions of three different mixtures for aging tests.

Table 8-1. Three Laboratory Aged High-RAP Mixtures

No	ID	Binder	RAP Content	Rejuvenator/Dosage rate	Optimum Binder Content(%)
1	R45A5	PG58-28S	45%	Invigorate 5%	5.39
2	R45B4.5	PG58-28S	45%	TuffTreck 4.5%	5.39
3	R45	PG58-28S	45%	None	5.39

8.2 AASHTO R 30: Standard Practice for Mixture Conditioning of Hot Mix Asphalt

AASHTO R 30 is the most widely used asphalt aging procedure for over 25 years. It offers two loose mix aging procedures, two different compaction methods and one long-term oven aging procedure. The conditioning steps for the AASHTO R 30 Ageing procedures are summarized in Table 8-2.

Table 8-2. AASHTO R 30: Standard Practice for Mixture Conditioning

Conditioning Types	Conditioning Procedures
Loose Mixture:	
Mixture Conditioning for Volumetric Mixture Design (Short-term aging)	2h ± 5 min at compaction temperature (above 135 ˚C of mixture temperature or 150°C of oven temperature was used as compaction)
Mixture Conditioning for Short-Term Aging	4h± 5 min at 135 ± 3˚C.
Compacted Mixture:	
Long-Term Aging of Specimen	Addition 120h (5 days) ± 30 min at 85 ± 3°C after short-term aging.

8.2.1 Mixture Conditioning for Volumetric Mixture Design

The mixture conditioning procedure for volumetric mix designs applies to laboratory-prepared, loose mixture only. No mixture conditioning is required when conducting QC/QA testing on plant-produced mixture. Mixture conditioning procedure is described below:

1. Place the mixture in a pan, and spread the mixture to an even thickness ranging between 1 to 2 in. (25 and 50 mm)
2. Place the mixture and pan in a forced-draft oven for 2 h ± 5 minutes at a temperature equal to the mixture's compaction temperature ± 5°F (± 3°C). (Note: The compaction temperature range of an HMA mixture is defined as the range of temperatures where the unaged binder has a kinematic viscosity of approximately 0.28 ± 0.03 pa-s (280 ± 30 mm2 /s) measured in accordance with ASTM D 4402. The target compaction temperature is generally the mid-point of this range. The mixture design compaction temperature should be 300 ± 9°F (150 ± 9°F) for dense graded mixtures and 260 (150) for open graded mixtures).
3. Stir the mixture after 60 ± 5 minutes to maintain uniform conditioning.

Recent NCHRP study (Newcomb et al., 2015) suggested that Step 2 in mixture conditioning to revised to change the conditioning temperature from “the mixture's compaction temperature ± 5°F (± 3°C)” to “135 ± 3˚C for HMA or 116 ± 3˚C for WMA”. The reason for change is that 1) AASHTO R 30 is focused on HMA and does not address WMA, 2) 2 hours of oven aging at 135°C for HMA and 116°C for WMA was found to be sufficient for short-term aging, regardless of compaction temperature.

8.2.2 Short-Term Aging of Loose Mixtures

Mixture conditioning procedure for short-term aging of loose mixtures is described below.

1. Place the mixture in a pan, then spread the mixture to an even thickness ranging between 1 to 2 in (25 and 50 mm)
2. Place the mixture and pan in a forced-draft oven for 4h ± 5 minutes at a temperature of 275 ± 5˚F (135 ± 3˚C)
3. Stir the mixture every 60 ± 5 minutes to maintain uniform conditioning

8.2.3 Long-Term Aging Conditioning of Compacted Samples

The long-term mixture conditioning procedure may be applied to laboratory-prepared samples following short term aging, to plant-mixed HMA, or to compact roadway samples when needed to simulate long term aging effects. This mixture conditioning step is used when samples will be tested for mechanical properties, such as Indirect Tensile creep or strength. Laboratory-prepared mixture should be conditioned following the procedure described for short-term aging above. Plant-mixed material does not need to be short term aged. Mixture conditioning procedure for long-term aging of loose mixtures is described below.

1) Long-term Aging of Laboratory Compacted Mixtures

1. Compact the HMA sample according to T 312 to the level of compaction required for the tests to be conducted. Do not extrude the specimen from the mold.
2. Condition the compacted sample by cooling in the mold to 140° ± 5°F (60° ± 3°C). This typically takes about 2 hours.
3. The ends of the specimen may not be parallel. The ends are squared up by applying a static load in a testing device. Increase the load from 0 kN at a rate of 16 ± 0.01 kip/min. (72.00 ± 0.05 kN/min). Release the load at the same rate when the ends of the specimen are level or when the load reaches a maximum of 12.5 kip (56 kN).
4. Remove the specimen from the testing machine and allow to cool 16 ± 1 hours at room temperature. The sample should be extruded from the compaction mold after cooling for 2-3 hours.

2) Long-term Aging of Field Compacted Mixtures

1. Cool the test specimen at room temperature for 16 ± 1 h
2. Place the specimen in the oven at 185 ± 5°F (85 ± 3°C) for 120 ± 0.5 h
3. After 120 ± 0.5 h, turn the oven off, open the oven doors, and allow the test specimen to cool to room temperature. This typically takes about 16 hours. Do not touch or remove the specimen from the oven until the end of this cooling period.

Recent NCHRP study (Kim et al., 2018) suggested that Step 2 in long-term aging for compacted roadway specimens be changed to modify the conditioning temperature from "185 ± 5°F (85 ± 3°C)" to "95 ± 3°C" and the conditioning duration from "120 ± 0.5 h" to "using equation below (Equation 8-1)". (Typically, 6 to 7 days of oven aging is equivalent to 8 years of field aging and 13 to 17 days of oven aging is equivalent to 16 years of field aging)

$$t_{oven} = \sum_{i=1}^{N} D \times A \times \exp(-\frac{E_a}{R \times T_i}) / 24 \quad (8\text{-}1)$$

where,

t_{oven} = oven aging duration, D = depth correction factor, A = frequency factor,
E_a = activation energy, R = universal gas constant, T_i = pavement temperature.

Recent NCHRP study (Kim et al., 2018) suggested that Step 3 in long-term aging for compacted roadway specimens be removed. The reason for changes is that the single time and temperature combination used in AASHTO R 30 is inaccurate for all climates throughout the country. The procedure claims to age the asphalt by 5-10 field years. However, in some areas the aging from AASHTO R 30 occurs in less than 5 years in the field. To solve these issues, oven aging time should be dependent on climate, and temperature should be increased to 95°C to reduce time in the oven. A temperature of 100°C or higher can cause chemical changes not present in field mixtures (which is why 95°C was recommended). Also, loose mixture should be placed in the oven instead of compacted mixture because it ages faster and more evenly.

8.3 HWT Test of Aged High RAP Mixtures with Rejuvenators

The laboratory mixed and compacted specimens with 45% RAP and rejuvenators of Invigorate and Tufftrek were prepared and conditioned as no-aging, short-term aging, long-term aging following AASHTO R30. The HWT test results of each mixture are summarized in Table 8-3 and plotted in Figure 8-1. For Invigorate mixes, the unaged mix failed at 10,800 passes, the short-term aged mix failed at 16,000 passes and the long-term aged mix exhibited only 1mm rut depth at 20,000 passes. Similarly, for Tufftrek mixes, the unaged mix failed at 8,250 passes, the short-term aged mix failed at 13,880 passes, and the long-term aged mix exhibited only 1mm rut depth at 20,000 passes. For the control mixes without a rejuvenator, the unaged, short-term aged and long-term aged mixes, rut depth were 19mm, 14mm and 1mm, respectively. Overall, both no aging and short-term aged asphalt mixtures with rejuvenators did not perform as well as the mixtures without a rejuvenator. However, based on the limited data, both short-term and long-term aging improved the moisture susceptibility of asphalt mixtures with rejuvenators more than specimens with no rejuvenator.

Table 8-3. HWT Test Results of Aged and Not-aged Mixtures with 45% RAP and Rejuvenators

Item	R45A5			R45B4.5			R45		
	No aging	Short aging	Long aging	No aging	Short aging	Long aging	No aging	Short aging	Long aging
Rut Depth	-20 @10,800	-20 @16,055	-1@20,000	-20 @8,250	-20 @13,880	-1@20,000	-19 @20,000	-14 @20,000	-1@20,000
SIP	4,800	9,600	-	4,800	7,000	-	15,600	13,650	-

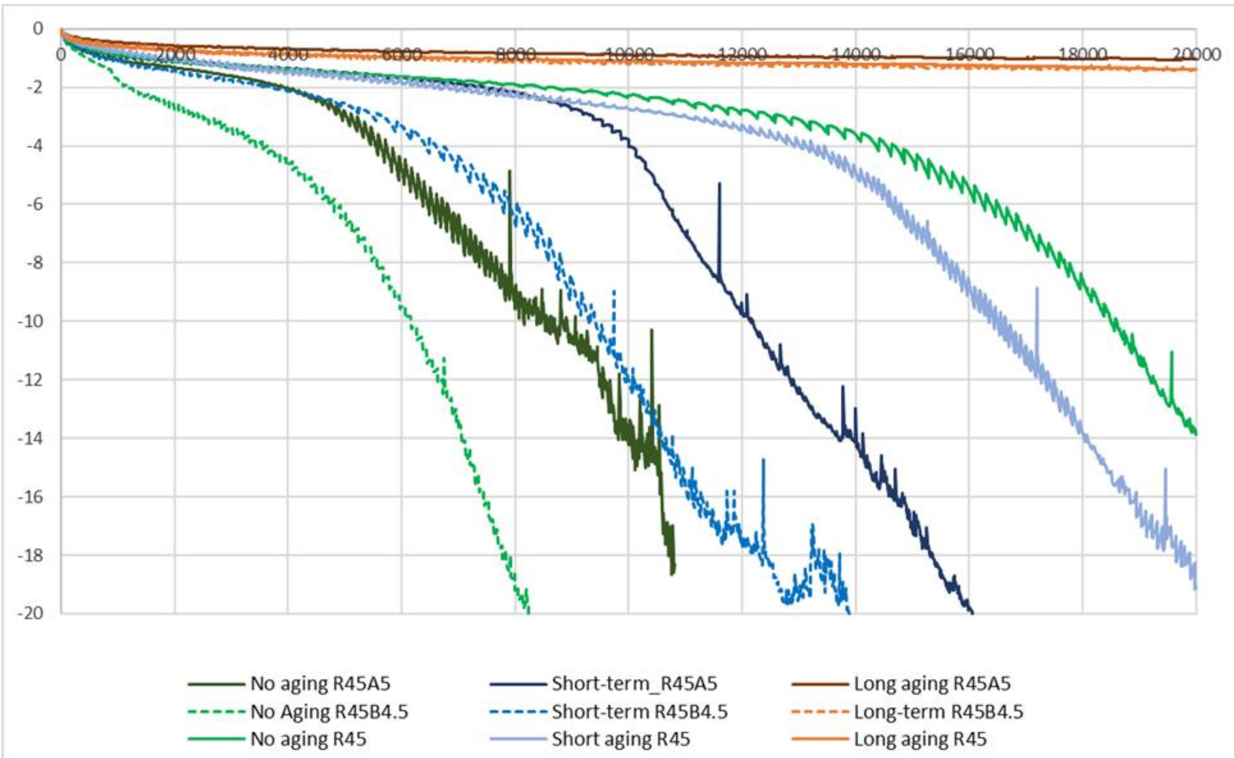


Figure 8-1. HWT test results for three stage aged mixtures

8.4 SCB-IFIT test of Aged High RAP Mixtures with Rejuvenators

The SBC-IFIT tests were performed following the AASHTO TP124. Samples for SCB-IFIT test were made with 150mm diameter and 50mm height and compacted to a target air void of 7%±0.5%. The notch was made at 15mm in length and 1.5mm of width. All specimens were conditioned at 25ºC for 2 hours before performing a test.

Two samples were prepared for each mixture type with three different aging conditions. SCB-IFIT test results are summarized in Table 8-4 and plotted in Figure 8-2. For all aging conditions, R45B4.5 mix exhibited similar fracture energy to the control sample but higher than R45A5 mix. As a result, R45B4.5 mix showed the highest FI than others for all aging conditions. Given the limited test results, although the aging decreased the cracking resistance of all mixes, Tufftrek was more effective in maintaining the cracking resistance than Invigorate as compared to the control sample without a rejuvenator.

Table 8-4. SCB Test Results for Laboratory Aging Mixtures

Mixtures		FRACTURE ENERGY (J/m^2)			Flexibility Index		
		1	2	Average	1	2	Average
R45	No aging	1433.9	1723.2	1,578.5	3.7	3.4	3.55
	Short-term aging	1551.5	859.0	1,205.2	3.7	3.0	3.35
	Long-term aging	1235.5	1537.2	1,386.3	1.4	1.9	1.65
R45B4.5	No aging	1475.4	1520.3	1497.9	4.3	6.3	5.3
	Short-term aging	1499.3	1295.7	1397.5	4.7	4.1	4.4
	Long-term aging	1467.6	1162.9	1315.3	2.2	1.8	2.0
R45A5	No aging	1570.5	1058.9	1314.7	4.4	3.3	3.85
	Short-term aging	1418.2	1300.1	1359.2	3.3	3.6	3.45
	Long-term aging	658.9	705.1	682	0.7	0.9	0.8

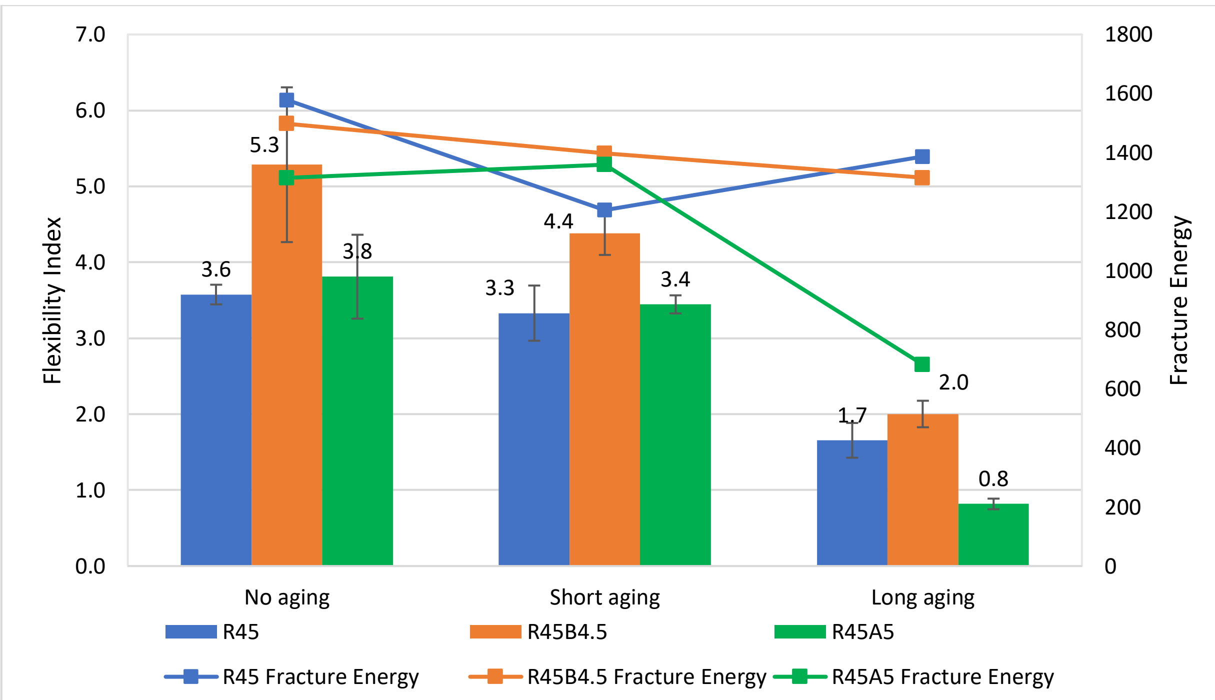


Figure 8-2. SCB-IFIT test results for lab aging mixtures

9 DEVELOPMENT OF SPECIFICATIONS FOR HIGH RAM MIXTURES

The main purpose of this task is to develop a specification for high RAM mixtures with rejuvenators. First, five surrounding state DOT's specifications on the use of RAM materials have been reviewed and compiled. Second, the existing Iowa DOT's specifications were reviewed for a possible modification along with a possible new specification about using rejuvenators.

9.1 Five Surrounding State DOT's specifications on RAM materials

Table 9-1 summarizes specifications from five state DOT's of Wisconsin, Illinois, Missouri, Nebraska and Minnesota on the use of RAM materials. As shown in Table 9-1, Nebraska allows the highest amount of RAP materials up to 65% with softer binder of 58S/H/V/E-34 followed by Missouri which allows up to 50% RAP materials. When both RAP and RAS are used, Missouri adopts a formula that the total RAM binder content is equal to RAP + 2*RAS. Minnesota allows the use of RAP above 20% if 58-28 or 64-28 binder is used. None of these states do not provide specifications for rejuvenators.

Table 9-1. Maximum Allowable RAP/RAS Usage Specification for Five Surrounding States

State	RAP		RAS		RAP and RAS together	
	No-Additives	With Softer binder	No-Additives	With Softer binder	No-Additives	With Softer binder
Wisconsin	25	N/A	20	N/A	25	N/A
Illinois	30	30	N/A	N/A	N/A	N/A
Missouri	30	50	30	40	30	50
Nebraska	N/A	65	N/A	N/A	N/A	N/A
Minnesota	20	>20	N/A	N/A	20	>20
Iowa	20	30	15	15-25	15	15-25

9.2 Iowa DOT's specification on the use of RAM materials

The current Iowa DOT's specification "Section 2303 Flexible Pavement (Revised 10/19/2021)" states:

- *RAP not used in HMA becomes the property of the Contractor.*
- *No adjustments will be made to the contract unit price for required changes to the asphalt binder grade.*
- *For surface mixtures, 70% of the total asphalt binder shall be virgin.*
- *Up to 5% RAS by weight of total aggregate may be used in the design and production of an asphalt mixture. The percentage of RAS used is considered part of the maximum allowable RAP percentage.*

Allowable RAP Usage for each mixture designation and type of RAP materials is summarized in Table 9-2 in IM 510 Appendix C.

Table 9-2. Allowable RAP Usage by Weight (IM 510 Appendix C)

Mix Designation	Aggregate Quality Type	Unclassified RAP	Classified RAP
HMA ST S	A	0%	Limited by binder replacement
HMA ST I	B	10%	No Limit
HMA ST B	B	10%	No Limit
HMA HT S	A	0%	Limited by binder replacement
HMA HT I	A	0%	No Limit
HMA HT B	B	10%	No Limit
HMA VT S	A	0%	Limited by binder replacement
HMA VT I	A	0%	No Limit
HMA VT B	B	10%	No Limit

* ST- standard traffic, HT- high traffic, VT- very high traffic, S- surface, I- intermediate, B- base

Iowa DOT's specification "IM 510 Method of Design of Asphalt Mixtures" states:

For mixtures not containing RAS
When the amount of recycled binder from RAP exceeds 20.0% of the total asphalt binder, the designated binder grade will be adjusted by lowering both the high and low temperature PG grade by 6°C while maintaining the AASHTO M332 traffic designation letter on the contract. The MSCR test temperature shall be the new adjusted high temperature PG grade (i.e. PG 58-28H becomes PG 52-34H with a test temperature of 52°C). If the anticipated RAP binder percent exceeds 30.0% of the total, the selection of the binder grade shall be based on testing performed by the Contracting Authority.

For mixtures containing RAS, adjust the contract binder grade as follows:
a. When the amount of recycled binder is inclusively between 15.0% and 25.0%, adjust the grade by lowering both the high and low temperature PG grade by 6°C while maintaining the AASHTO M332 traffic designation letter on the contract. The MSCR test temperature shall be the new adjusted high temperature PG grade (i.e. PG 58-28H becomes PG 52-34H with a test temperature of 52°C).
b. When the amount of recycled binder exceeds 25.0% of the total asphalt binder, the selection of the binder grade shall be based on testing performed by the Contracting Authority.

When binder replacement exceeds 30.0% (25.0% for mixtures containing RAS), grade selection is based on fracture energy as measured by the Disk-Shaped Compact Tension Test (DCT) (ASTM D7313-07a) at no additional cost to the contracting authority. The average of two specimens shall meet the following minimum fracture energy requirements tested at 10°C warmer than the low climatic temperature (normally specified as the low temperature PG grade on the contract):

- *Very High Traffic (VT) 690 J/m2*
- *High Traffic (HT) 460 J/m2*
- *Standard Traffic (ST) 400 J/m2*

The adjusted grade shall meet the same MSCR recovery requirements as the contract binder grade. No adjustments will be made to the contract unit price for required changes to the asphalt binder grade.

The IM 510 specification can be simplified as follow:

For mixtures not containing RAS:

- If RAP binder > 20% and <= 30%, lower virgin PG grade by 6°C.
- If RAP binder > 30%, the selection of the binder grade shall be based on testing performed by the Contracting Authority.

For mixtures containing RAS:

- If RAM binder >=15.0% and <=25.0%, lower virgin PG grade by 6°C
- If RAP binder > 25%, the selection of the binder grade shall be based on testing performed by the Contracting Authority.
- If RAP binder > 30.0% (or RAM binder > 25.0% for mixtures containing RAS), grade selection is based on fracture energy as measured by DCT.

Currently, there is no Iowa DOT specification that discuss the effective binder content from RAP and RAS but the following is practiced: "100% of asphalt binder from RAP is assumed "active," whereas only 67 percent of the asphalt binder from RAS is assumed "active." The pending research project, NCHRP 09-68 will investigate binder availability in recycled asphalt materials.

Currently, although the current specification allows RAP materials higher than 30%, no such project is being constructed in Iowa. Based on the successful implementation of test sections with RAP materials up to 45%, it is recommended that the current specifications should be modified, which could allow RAP contents up to 50% by binder replacement with simpler and less expensive testing procedures like SCB-IFT test as an alternate test procedure.

10 SUMMARY AND CONCLUSIONS

Previously, Fourier Transform Infrared (FTIR) test indicated that rejuvenators were effective in decreasing the aging level when applied to the PAV binder. When FTIR was performed on the actual binder from RAP, rejuvenators were effective in lowering the aging level evidenced by lower SI values. However, FTIR failed to show the effectiveness of rejuvenators in lowering the aging level based on CI values.

RAP materials were fractionated into two stockpiles separated at No.4 sieve. Fractionated asphalt mixtures were prepared by recombining the equivalent amount from each stockpile as the original stockpile. Based on the HWT test results of fractionated mixtures for both 34% and 45% RAP mixtures exhibited smaller rut depths at 20,000 passes. In addition, fractionated asphalt mixtures exhibited higher FI values than the control mixtures. Therefore, given the limited test results, it can be concluded that fractionation can improve both cracking and rutting resistances of high RAP mixtures.

To determine the effectiveness of rejuvenators in RAS mixtures, 11% RAS mixes (27% by binder replacement) with three different rejuvenators at a 3% dosage rate. The control mix without rejuvenators exhibited the smallest rut depth of 4.4mm at 20,000 passes and all mixtures performed very well to exceed the SIP of 10,000 passes. Overall, all RAS mixtures exhibited similar FI values, indicating little effect of rejuvenators in improving the cracking resistance of RAS mixtures.

To evaluate field performance of rejuvenated high RAP mixtures, six test sections with two different rejuvenators (Invigorate and Tufftrek) and three different RAP contents (0%, 34% and 45%) were constructed in Cerra Gordo county. Tufftrek was preblended at the terminal, but Invigorate was added to the asphalt at the asphalt mixing plant. Tufftrek lowered the high and low critical temperature by 5.95°C and 4.9°C, respectively, whereas Invigorate lowered the high and low critical temperatures by 3.15°C and 3.1°C. It is important to understand the field produced mixes with the Invigorate had lower than expected dosages of the Invigorate as calibration of the additive pump was inaccurate leading to a lower dose than called for in the design. A certified, terminal-blended asphalt formulation is preferred.

The HWT test results indicate both field mixtures of 22% RAP and 34% RAP with a softer binder failed at around 8,000 passes due to a moisture damage. All mixtures with rejuvenators met the minimum stripping inflection point (SIP) criterion of 10,000 passes for standard traffic in Iowa. Based on the DCT tests, the 34% RAP mixtures with softer binder performed better than mixtures with rejuvenators. However, based on the SCB-IFIT test results, 34% RAP with 3% Invigorate exhibited the highest FI value whereas 45% RAP with 5% Invigorate exhibited the lowest FI.

45% RAP and 5% Invigorate exhibited the highest field density followed by 34% RAP and 3% Invigorate. Field densities of the remaining four test sections were similar and met the minimum density requirement of 93%. Based on the condition survey performed after one year since construction, all test sections performed very well with very little cracking and no rutting. However, several hairline cracks were observed from test sections with 22% RAP without rejuvenator and 34% RAP with a softer binder.

Based on the short-term and long-term aging tests performed at the laboratory, the long-term aging enhanced the rutting and moisture susceptibility of rejuvenated mixes. Based on the SCB-IFT tests, the aging decreased the cracking resistance of all mixes. However, Tufftrek was more effective in maintaining the cracking resistance than Invigorate when compared against the control sample without a rejuvenator, but the lower performance from the Invigorate could be from the pump issues resulting in a lower dosage occurring in the mix production

The specific findings from this study are summarized below:

- Rejuvenators consistently lowered both critical high and low temperatures of virgin binder of PG 58-28S.
- 34% and 45% High RAP mixtures with rejuvenators were compacted well exceeding 93% field density.
- Based on HWT test results, field mixtures with rejuvenators performed better in rutting performance than ones without rejuvenators.
- Based on the DCT test results, 34% RAP with a soft binder (34R Bump) mixture endured the highest fracture energy.
- Based on SCB-IFIT test results, rejuvenators could improve cracking resistance.
- Based on test results of both DCT and SCB-IFIT, there is a good correlation between FI values of SCB and fracture energy values of DCT.
- Based on a condition survey of test sections performed after one year since construction, all test sections performed very well with very little distress. Test sections without rejuvenators developed several hairline cracks. Rejuvenators were effective in delaying an initiation of cracking.
- Aging of laboratory prepared mixtures with rejuvenators decreased rutting in Hamburg tests but increased cracking potential in SCB-IFIT tests.
- Both 34% and 45% RAP mixtures with rejuvenators were successfully implemented.

11 FUTURE STUDIES

As discussed at the TAC meeting and subsequent feedback from TAC members, the following tasks are proposed for future studies.

- Develop an approval process for rejuvenators that incorporates long-term aging of the material.
- Perform a feasibility study of a fractionation of RAP materials in two stockpiles.
- Consider increasing the maximum RAM percentage up to 50% for some mixes. Investigate various economic conditions that determine whether the increased stiffness from the RAM can be economically off-set with rejuvenators and softer binder grades. Additional options for RAM use and binder formulations may provide greater flexibility to contractors and binder suppliers.
- Evaluate WMA with high RAM. WMA containing RAP and RAS showed similar cracking and rutting resistance performance compared to HMA with RAP and RAS. Additional study of WMA with RAM could be useful to verify if it meets both economic and sustainability requirements.
- Adopt a test procedure like SCB-IFT test for high RAM mixtures up to 50% as a performance test after evaluating different testing procedures based on evaluation factors such as sample preparation, specimen conditioning and testing, training needs and applicability, new equipment cost, repeatability and field validation.
- Monitor high RAM project sites (3 project sites in each district) to determine the effectiveness and limitations of design, construction and performance of high RAM mixtures up to 50% and develop QA/QC aspect of using softer binders and rejuvenators.
- Develop a comprehensive asphalt recycling strategy encompassing high RAM mix up to 50%, CIR and HIR in consideration of both economic and sustainability analyses.

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APPENDIX A

Appendix B – Classified RAP Stockpile Report (Form 820009r)

820009r (December 2005)

Classified RAP Stockpile Report	**RAP Stockpile ID # ABC18-0098**
Stockpile Owner: LL Pelling	

SOURCE OF RAP	Project No.		Dates of Removal
Route No.	From		To

Removal Depth	JMF No(s)	Mix Type / Size	Crushed Particle %		

LOCATION OF RAP STOCKPILE:
Coralville Plant 16 Classified RAP

County Johnson	Section	Township	Range

Description of stockpile base:

Processing remarks: Prosized @ Plant 16 Coralville (LL Pelling)

STOCKPILE QUANTITY INVENTORY LOG

Date	Quantity	Disposition (Project No. and use)
11-16-18	7700 Ton	*Total initial stockpile quantity*

Average EXTRACTION TEST RESULTS

Gradation		Lab Report nos.	
3/4	—		
1/2	— 95		
3/8	89	Pb =	4.86
No. 4	71		
No. 8	54	Gsb =	2.588
No. 16	41		
No. 30	31	Abs% =	1.36
No. 50	20		
No. 100	14	FAA =	40.1
No. 200	12		

Aggregate Characteristics

Aggregate Type	ClASSIFIED	
Crushed Particles	46	%
Aggr Friction Type 2		%
Aggr Friction Type 3		%
Aggr Friction Type 4		%

APPENDIX B

ABC21-0067
BCS

IOWA DOT

SAMPLE KEY: 2021-01763

SAMPLE TYPE: Verification

Central Materials Bituminous Mix Lab

TEST REPORT: Asphalt Mix Design RAS Test Results

LAB NO.: ABC21-0067

MATERIAL: ASPHALT, RECYCLED ASPHALT SHINGLES (RAS)
INTENDED USE: HMA Other/ Cold-in-Place Paving
SAMPLED BY: Dutra, Mark
SENDER NO: 6MD21-019
PRODUCER: L.L. Pelling Company, Inc.
SUPPLIER: Johnson County Landfill
BRAND NAME: L.L. Pelling RAS
LOT NO.: Single Grind
PLANT: Coralville Plant 16
QUANTITY: 4,000 ton
SAMPLE LOCATION: Stockpile located @ LL Pelling Plant 16 Coralville

DATE SAMPLED: 06-JUL-21 DATE RECEIVED: 06-JUL-21 DATE REPORTED: 23-JUL-21

Asbestos Free paperwork can be provided upon request.

SIEVE ANALYSIS PERCENT PASSING	FINAL AVERAGE
1/2	100.0
3/8	100.0
#4	98.0
% DELETERIOUS AVERAGE	0.10
% AGG. AVERAGE	80.65
% BINDER AVERAGE	19.35

COPIES TO:
DISTRICT 6

Mark Dutra Taylor Maxfield (LL Pelling)

SIGNED: CHRIS BRAKKE
PAVEMENT MANAGEMENT ENG: