Optimizing the Effective Use of RAP in Local Roadways

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16. Abstract

This report summarizes the research work that was completed to assess the optimum percentages of recycled asphalt pavement (RAP) that can be used in surface course mixtures of local roadways while ensuring durability is maintained. This project was divided into two phases. Phase 1 included conducting a comprehensive laboratory testing on mixtures with different RAP contents and recycling agents. Based on the results of Phase 1, Phase 2 of this project involved constructing eight test sections as a part of a resurfacing project on Hall Road in the City of Columbus. Surface course asphalt mixtures with a similar aggregate blend but different percentages of RAP were used in these test sections. The first section (control section) had a mix with 20% RAP and PG 64-22 binder. While three test sections had mixes with 30%, 40%, 50% RAP, PG 64-22 binder, and Sylvaroad recycling agent, three other sections had mixes with the same RAP percentages and binder but used Hydrolene as the recycling agent. Finally, the last section was constructed using a mixture containing 30% RAP and PG 64-28 binder with no recycling agent. Cores were obtained at different locations within each test section. In addition, specimens were compacted in a laboratory from loose mixtures that were obtained during the construction of each test section. Tests were done on field cores and laboratory-compacted specimens. The test results showed that Hydrolene was more effective than Sylvaroad in improving the fatigue cracking resistance of RAP mixes with more than 0.3 binder. In addition, the tests results showed that the 30% RAP, 40% RAP, and 50% RAP mixes had similar low-temperature cracking resistance to that of the control. The laboratory test results also showed that all mixes had acceptable rutting resistance. The results of the cost analyses conducted in Phase 2 indicated that using a higher RAP content of 40% and recycling agents can reduce the initial cost of an asphalt mixture by at least 15%.

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TABLE OF CONTENTS

Optimizing the Effective Use of RAP in Local Roadways

Executive Summary

This report summarizes the results of a research project that was conducted to: 1) assess the current practices of using recycled asphalt pavement (RAP) in surface course mixtures for local roadways, 2) develop recommendations for a cost-effective method for designing well-performing and durable surface course mixtures with different RAP contents for use on local roadways, 3) evaluate the cost benefits of using different RAP contents in the surface course layer of local roadways, and 4) provide recommendations for quality control methods of RAP used in the surface mixtures of local roadways. This project was divided into two phases. The results of laboratory tests conducted in Phase 1 of this project indicated that the use of RAP adversely affected the fatigue cracking resistance of asphalt mixtures when more than 30% RAP was used. The use of a softer binder (PG 64-28) was not effective in maintaining the fatigue cracking resistance of the mixes when more than 30% RAP was used. On the other hand, the results indicated that using a binder with an appropriate low-temperature performance grade can contribute to satisfactory low-temperature cracking resistance of the RAP mixes. The laboratory test results showed that two of the considered recycling agents (Hydrolene and the Sylvaroad) significantly improved the cracking resistance of mixes with up to 50% RAP. The RAP source was also found to have a significant effect on the fatigue cracking resistance of RAP asphalt mixes, particularly those with more than 30% RAP. Therefore, it is very important to consider the performance grade of the RAP binder in the design of asphalt mixtures with high RAP content. The results of cost analyses conducted in Phase 1 showed that a 50% RAP mix with Hydrolene can be 26% less expensive than the 20% RAP mixes currently being used. In addition, a 50% RAP mix with Sylvaroad can be 13% less expensive than the 20% RAP mixes currently being used.

Based on the results of Phase 1, Phase 2 of this project involved constructing eight test sections as part of a resurfacing project on Hall Road in the City of Columbus. In these test sections, a 1½-in asphalt concrete surface course was placed. The surface course asphalt mixtures were Marshall mixes and had a similar aggregate blend but different percentages of RAP. The first section (control section) had a mix with 20% RAP and PG 64-22 binder. While three sections had mixes with 30%, 40%, 50% RAP, PG 64-22 binder, and Sylvaroad recycling agent (tall oil), three other sections had mixes with the same RAP percentages and binder but used Hydrolene (aromatic extract) as the recycling agent. Finally, the last test section was constructed using a mixture with a 30% RAP and PG 64-28 binder (softer binder). Cores were obtained at different locations within each test section. In addition, specimens were compacted in laboratory from loose mixtures that were obtained during the construction of each test section. Laboratory tests were conducted to evaluate the cracking resistance of the field cores. Furthermore, tests were conducted on the laboratory-compacted samples to examine their cracking and rutting resistance. To this end, semi-circular bending (SCB) tests and indirect tensile strength (IDEAL-CT) tests were conducted to examine the fatigue cracking resistance. In addition, asphalt concrete cracking (ACCD) and asphalt paving analyzer (APA) tests were performed to evaluate the resistance to low-temperature cracking and rutting, respectively. The field performance of the test sections was monitored for several months after construction. In addition, a field testing methodology was developed to evaluate the long-term performance of the RAP test sections.

The laboratory tests results showed that the 30% and 40% RAP mixes with Hydrolene had slightly higher resistance to fatigue cracking than the control mix with 20% RAP. However, the 50% RAP mix with Hydrolene had lower resistance than the control mix. In addition, the results of tests conducted in this study showed that while the 30% RAP mix with Sylvaroad had higher fatigue cracking resistance than the control, mixes with 40% and 50% RAP and Sylvaroad had significantly lower resistance than the control mix. Both the SCB and the IDEAL-CT tests indicated that using the softer binder PG 64-28 in the 30% RAP mix resulted in similar fatigue cracking resistance to that of control mix with 20% RAP and PG 64-22 binder. The ACCD tests results showed that the 30% RAP, 40% RAP, and 50% RAP mixes had similar low-temperature cracking resistance to that of the control mix. The 30% RAP mix with the softer binder (PG 64-28) had the coldest cracking resistance. The APA test results showed that all mixes had acceptable rutting resistance. The results of cost analyses conducted in Phase 2 indicated that using a higher RAP content of 40% and recycling agents can reduce the initial cost of an asphalt mixture by at least 15%. In addition, RAP mixes with Hydrolene have the best cost benefit and can reduce the mix initial cost more than 25% when 40% RAP is used. Finally, preliminary field evaluation showed that there was no observed distresses in the test sections after seven months of construction. Based on the results of this study, it is recommended that local agencies implement the results of this study by using mixtures with up to 0.4 RAP binder replacement (RBR) and aromatic extract recycling agent such as Hydolene in pilot projects in different cities, counties and townships. These mixtures should be designed using the specifications developed in this study.

1. Project Background

Asphalt pavement is the most recycled material in the United States (US) (*1*). Reclaimed asphalt pavement (RAP) contains asphalt binder and aggregates; therefore, using it in new asphalt mixtures results in significant economic savings and environmental benefits. A survey conducted by the National Asphalt Pavement Association (NAPA) reported that more than 76.9 million tons of RAP were used in new asphalt mixtures in 2016, which resulted in more than $2 billion in savings (*1*). The use of RAP also conserves non-renewable natural resources (both asphalt and aggregates) and reduces the energy and emissions needed to obtain them. In addition, using RAP also reduces the amount of construction debris placed into landfills (*2*).

During the past four decades, state transportation agencies have constructed field test sections with different percentages of RAP in the surface layer of its asphalt pavements. The Long-Term Pavement Performance (LTPP) data from 16 U.S. states and two Canadian provinces indicated that overlay mixtures containing at least 30% RAP had the same performance as those with virgin materials only (*3*, *4*). More impressively, test sections containing 50% RAP at the National Center for Asphalt Technology (NCAT) Test Track outperformed companion test sections with all virgin materials in all pavement performance measures through five years of heavy loading (*5*, *6*).

A recent NAPA survey of the asphalt pavement industry reported that the average RAP content in new asphalt mixes across the U.S has steadily increased in recent years, with the national average RAP content around 20%. However, despite all of the economic and environmental benefits of using higher RAP contents in new asphalt mixtures, local public agencies (LPAs) in Ohio have allowed using only small percentages of RAP (i.e., less than 10%) in their roadways, if any. This is mainly attributed to the lack of a mix design procedure for asphalt mixtures incorporating higher RAP contents as well as guidelines for processing RAP utilized in local roadway construction. Furthermore, there is currently limited performance data for local roadways constructed with mixtures incorporating RAP; hence there is lack of confidence in the long-term performance of these mixtures.

Using higher amounts of RAP in new paving mixtures presents a concern that the resultant mixture may be prone to more load and non-load associated cracking during the service life of the pavement. This is due to fact that the asphalt binder contained in the RAP is oxidized/hardened due to aging. Over the past two decades, numerous research studies have been conducted to address issues with using higher percentages of RAP in asphalt mixtures. Most of these studies have focused on developing mix design procedures and specifications for mixtures used on interstates and highway systems only. Therefore, the results of these studies may not be directly applicable for mixtures used on local roads, because traffic volume, traffic type, turning movements, and traffic patterns are different for local roads. Using RAP may influence the performance of local roadways in a different manner. Therefore, research was needed to evaluate the effects of using RAP on the properties and the performance of asphalt mixtures that are typically used on local roadways. Furthermore, since no two sources of RAP are exactly the same, it was important to characterize the properties of the asphalt binder in the RAP as well as the aggregate properties of the RAP.

This project assessed the state-of-the-practice of using RAP in surface mixtures on local roads and examined the feasibility of using higher RAP contents in these mixes. Furthermore, it developed a method to design cost-effective, well-performing, and durable asphalt mixtures with various RAP contents to be used in the surface course of local roadways in Ohio. The project also developed recommendations for quality control of RAP incorporated into these mixes.

2. Research Context

The goal of this research is to assess the feasibility of RAP in the surface course of municipal and local roadways. The specific objectives of this project include:

- Assess the current practices of using RAP in surface course mixtures for local roadways.
- Develop recommendations for a cost-effective method for designing well-performing and durable surface course mixtures with different RAP contents for use on local roadways.
- Evaluate the cost benefits of using different RAP contents in the surface course layer of local roadways.
- Provide recommendations for quality control methods of RAP used in the surface mixtures of local roadways.

This study was divided into two phases that included the following eleven tasks:

Phase 1: Feasibility Study on the Use of RAP in Local Roadways

Task 1. Perform a literature review.
Task 2. Perform an assessment of the current state of the practice for RAP use on local roads in Ohio.
Task 3. Develop draft recommendations for mix design of RAP in the surface course of local roadways.
Task 4. Develop recommendations for quality control methods of RAP.
Task 5. Perform a benefit/cost analysis.
Task 6. Provide recommendations for Phase 2 field testing of mix design recommendations.
Task 7. Prepare and submit an interim report.

Phase 2: Construction and Field Evaluation of the Draft Specification and QC/QA Criteria

Task 8. Develop a Field Evaluation and Testing Methodology.
Task 9. Provide assistance during construction of RAP pavement test sections
Task 10. Perform a field evaluation of test sections.
Task 11. Prepare a final report and present findings.

A summary of the comprehensive literature review performed in this study is presented in Appendix A. Previous studies showed that the inclusion of RAP materials in asphalt mixes affects their performance by changing the rheological properties of the final binder blend and stiffening it (e.g. *7, 8*). All laboratory and field studies reported that the addition of RAP enhanced the rutting performance of asphalt mixtures (e.g. *9-12*). However, conflicting results were reported regarding the cracking performance of RAP mixtures (e.g. *11, 13, 14, 15*). Although numerous studies were conducted on the use of RAP in asphalt mixtures, limited studies focused on RAP asphalt mixtures used in construction of local roads. Therefore, research that evaluates the effects of using RAP on the properties and the performance of asphalt mixtures that are typically used in local roadways was needed.

3. Research Approach

A laboratory testing program was conducted in Phase 1 to identify the factors that affect the performance asphalt mixtures with RAP. To this end, several mixtures were designed with different RAP contents, which included 0%, 20%, 30%, 40, and 50% RAP. Two RAP materials that have binders with different rheological properties were selected in this study. The laboratory testing program also evaluated the effect of using recycling agents (RA) on the performance of asphalt mixtures with high RAP content. Three different types of recycling agents were used, namely, an aromatic oil (Hydrolene), a tall oil (Sylvaroad), and a vegetable oil (soybean). The propensity of the designed asphalt mixtures to fatigue cracking was evaluated using the semi-circular bend (SCB) and the indirect tensile strength tests. In addition, the low-temperature cracking potential was assessed using the asphalt concrete cracking device (ACCD). The susceptibility of the asphalt mixtures to moisture-induced damage was evaluated using AASHTO T 283 (modified Lottman test). Finally, the asphalt pavement analyzer (APA) was utilized to examine the resistance of asphalt mixtures to rutting.

The results of laboratory test conducted in Phase 1 indicated that the use of RAP adversely affected the fatigue cracking resistance of asphalt mixtures when more than 30% RAP was used. The use of a softer binder (PG 64-28) was not effective in maintaining the fatigue cracking resistance of the mixes when more than 30% RAP was used. In addition, the results indicated that using a binder with an appropriate low-temperature performance grade can help in ensuring satisfactory low-temperature cracking resistance of the RAP mixes. The SCB test results showed that Hydrolene RA and Sylvaroad RA can improve the cracking resistance of mixes with up to 50% RAP. The RAP source was also found to have a significant effect on the fatigue cracking resistance of RAP asphalt mixes, particularly those with more than 30% RAP. Therefore, it is very important to consider the performance grade of the RAP binder in the design of asphalt mixtures with high RAP content. The cost analysis conducted in Phase 1 showed that the 50% RAP mix with Hydrolene RA can be 26% less expensive than the 20% RAP mixes currently being used. In addition, this analysis indicated that the 50% RAP mix with Sylvaroad RA can be 13% less expensive than the RAP mixes currently being used. Based on the results of Phase 1, it was recommended to conduct a field testing program to evaluate the performance of mixes with 30%, 40% and 50% RAP that are designed based on the recommendations in the interim report provided in Appendix D. The following subsections summarize the research work that was performed in Phase 2 of this study.

3.1 Testing Program

3.1.1 Description of Field Test Sections

Eight test sections were constructed in September 2018 in the City of Columbus as part of a resurfacing project to evaluate the performance of the mixes with different percentages of RAP designed based on the method recommended in Phase 1 of this study. The test sections were located on Hall Road between Georgesville Road and Bledsoe Road. In these test sections, a 1½-in asphalt concrete surface course was placed. The surface course asphalt mixtures were Marshall mixes and had a similar aggregate blend but different percentages of RAP. The first section (control section) had a mix with 20% RAP and PG 64-22 binder. While three sections had mixes with 30%, 40%, 50% RAP, PG 64-22 binder, and Sylvaroad recycling agent (tall oil), three other sections having mixtures with the same RAP percentages and binder but with Hydrolene (aromatic extract) as the recycling agent. Finally, the last section was constructed using a mixture with a 30% RAP and PG 64-28 binder (softer binder).

3.1.2 Field Test Section Construction

A meeting with the city personnel and representatives of the asphalt paving contractor was held prior to the construction of the test sections to coordinate the construction activities. The existing pavements within the test sections were evaluated prior to construction to identify distressed or repaired areas. Coring locations were identified after milling and were marked to avoid distressed areas. Videos and pictures were taken after milling the existing pavement. The research team also monitored the placement and compaction of the RAP test sections in the City of Columbus. This included measuring the mat temperature and recording the density at core locations. Photos were collected and videos of the test sections were recorded during and after construction.

3.1.3 Laboratory Testing of Cores Samples

Cores were obtained at different locations within the test sections. In addition, loose asphalt mixture samples were obtained at the plant for each mixture used in the test sections. Specimens of the loose mixtures were compacted in the laboratory to achieve target air voids of 7±0.5%. Laboratory tests were conducted on the core and lab-compacted specimens. To this end, the propensity of the cores and lab-compacted specimens to fatigue cracking was evaluated using the semi-circular bend (SCB) and the indirect tensile asphalt cracking test (IDEAL-CT) tests. In addition, the low-temperature cracking potential was assessed using the asphalt concrete cracking device (ACCD). Finally, the asphalt pavement analyzer (APA) was performed on the lab-compacted specimens only to examine their resistance to rutting. A detailed description of each of the tests is provided Appendix A.

3.2 Field Evaluation of Constructed Test Sections

A field and laboratory testing methodology was developed to evaluate the performance of the constructed test sections. Details of that methodology are provided in Appendix C. An interactive database was developed to assist in storing, processing, and analyzing the pavement performance data collected during the evaluations. Main inputs to this database included the various pavement distresses encountered during the field evaluation and the corresponding extent and severity levels. The interactive database was developed using Microsoft Visual Basic for Applications (VBA) and Microsoft Office.

The developed field methodology included evaluating the performance of the test sections by the research team and designated city personnel during the duration of this project. In addition, it included performing annual evaluations by the city personnel for the first five years after construction. All field evaluations involved examining the severity and extent of the distresses developed in these sections. Furthermore, the field evaluations included obtaining three field cores from each test section after 1, 3 and 5 years of construction and testing the field cores using the SCB test.

3.3 Cost Analysis

Cost analysis was performed to compare the costs associated with the construction of the test sections in the City of Columbus. Only the initial cost for the asphalt mixes was considered in the analysis, as no maintenance or repairs were performed during the monitoring period in this project. The initial cost of mixes from the contracts was provided by the City of Columbus. An analysis was also performed to determine the costs incurred due to using the recommended design procedure for high RAP mixes and the additional tests on the extracted and RAP. Based on this analysis, an estimated cost of high RAP mixes was determined.

4. Research Findings and Conclusions

Appendices A and B present a detailed summary of the testing program and the results obtained in Phase 2 of this study, respectively. The following list provides a summary of the main findings and conclusions that were made based on the results obtained in Phase 2 of this study.

- The SCB tests results showed that the 30% and 40% RAP mixes with Hydrolene had slightly higher resistance to fatigue cracking than the control mix with 20% RAP. However, the 50% RAP mix with Hydrolene had lower resistance than the control.
- The SCB and IDEAL-CT tests showed that while the 30% RAP mix with Sylvaroad had higher fatigue cracking resistance than the control mixture, mixes with 40% and 50% RAP and Sylvaroad had significantly lower resistance than the control mix
- The SCB and IDEAL-CT tests showed that Hydrolene was more effective than Sylvaroad in improving the fatigue cracking resistance of RAP mixes with more than 0.3 RAP binder replacement.
- The results of the IDEAL-CT tests showed that all mixes, with the exception of the 50% RAP mix with Sylvaroad, had a cracking test index value higher than 150, which is the minimum value recommended for surface mixes with high RAP contents.
- The softer binder PG 64-28 in the 30% RAP mix resulted in similar fatigue cracking resistance to that of the control RAP mix with 20% RAP and PG 64-22 binder.
- In general, the FI, NFE, and CTI indices of the field cores had similar trends to those of samples compacted in the lab using field-produced mixes but were lower in value.

- The ACCD tests results showed that the 30% RAP, 40% RAP, and 50% RAP mixes had similar low-temperature cracking resistance to that of the control mix. The 30% RAP mix with softer binder (PG 64-28) had the best low-temperature cracking resistance.
- In general, asphalt mixes containing Hydrolene had slightly better resistance to low-temperature cracking than those containing Sylvaroad.
- The rutting potential decreased with the increase in RAP content.
- In general, asphalt mixes containing Hydrolene exhibited higher rut depths in the asphalt paving analyzer test than those containing Sylvaroad. However, all mixes had rut depth values less than 5 mm, which is the maximum rut depth allowed by ODOT for mixes used on roadways with medium traffic. Hence, all mixes had acceptable resistance to rutting.
- The cost analyses conducted in Phase 2 indicated that using a RAP content of 40% with a recycling agent can reduce the cost of an asphalt mixture by at least 15%. In addition, RAP mixes containing Hydrolene were found to be the most cost effective with an estimated cost reduction of more than 25% when 40% RAP is used.
- Preliminary field evaluation showed that there was no observed distresses in the test sections after seven months of construction.

5. Recommendations for Implementation

The following recommendations are made based on the findings of this study:

- The initial performance of the RAP test sections was evaluated and documented in this report; however, it is recommended to monitor the long-term performance of these sections according to the methodology provided in Appendix C. The long-term evaluation data should be used to make final conclusions about the cost-effectiveness of RAP mixes for local roads.
- Mix Design specifications and quality control/assurance criteria for mixtures with high RAP content were developed in this study. It is recommended that LPA agencies in Ohio use these specifications to implement the use of high RAP mixes on local roads. This implementation can start by using mixtures with up to 0.4 RAP binder replacement (RBR) and an aromatic extract recycling agent such as Hydrolene in pilot projects in different cities, counties and townships. The wide use of high RAP mixes by local agencies will reduce the cost of asphalt mixes and their environmental impacts.
- Further evaluation of the effect of recycling agents should be performed. This evaluation should include different types of recycling agents and RAP materials from various sources.

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Appendix A Testing Program

This appendix provides a description of all the materials that were used in this research study. In addition, it also provides a description of the employed tests and protocols, as well as the preparation procedures developed and used to prepare representative samples for these experiments.

A.1 Test Sections Description

Eight test sections were constructed in September 2018 as part of a resurfacing project on Hall Road in Columbus, Ohio, to evaluate the performance of the RAP mixes design using the method recommended in Phase 1 and compare them to a RAP mix typically used by the City of Columbus. Figure A.1 presents a map of the test section location. As shown in this figure, the test sections were located on Hall Road, a two-lane highway, between Georgesville Road and Bledsoe Road. Table A.1 shows the exact locations of each test section. In all test sections, a 1-½ in asphalt concrete surface course was placed. The surface course asphalt mixtures were Marshall mixtures with a 12.5 mm nominal maximum aggregate size (NMAS) and had the same aggregate blend, which consisted of No. 8 limestone aggregates, natural sand, manufactured sand and RAP. The RAP material was obtained from resurfacing projects in Franklin County and was processed according to ODOT Item 401.04 Method 2. The binder was extracted and recovered from the obtained RAP materials in accordance with AASHTO T 164 and AASHTO R 59. Toluene was the solvent used for extraction of the RAP binder. The performance grade was determined for the extracted and recovered RAP binders in accordance with AASHTO M 320. Table A.2 presents a summary of the binder properties of RAP materials. Different RAP contents with corresponding different virgin binder contents, and recycling agents were used in the mixes of test sections. The first section (control section) had a mix with 20% RAP and PG 64-22 binder. In addition, while three sections had mixes with 30, 40, and 50 percent RAP content, PG 64-22 binder, and Sylvaroad recycling agent (tall oil), three other sections had mixes with these RAP percentages and the same binder but used Hydrolene (aromatic extract) as the recycling agent. Finally, the last section was constructed using a mixture with 30% RAP and PG 64-28 binder but did not include any recycling agent. All mixes except the control were designed according to the mix design specifications recommended in Phase 1 of this study. A summary of the properties of the asphalt mixes used in the different sections constructed in this study are shown in Table A.3.

A.3 Test Sections Construction

A meeting with the City of Columbus personnel involved in the design and construction of the test section, as well as representatives of the asphalt paving contractor, was held prior to construction in to coordinate the construction activities. During that meeting, an overview of the project was provided and the field and laboratory sampling and testing plans were discussed. In addition, the anticipated start date for paving of the testing sections was set.

Prior to construction, the test sections were evaluated to identify distressed and repaired areas. Coring locations were identified after milling and marked on the curb to avoid distressed areas. Videos and pictures were taken after milling of the existing pavement. Construction of test sections started on 09/11/2018 and was completed on 09/21/2018. One day was allocated for each test section. The research team monitored the placement and compaction of the test sections. This included measuring the mat temperature and recording the density at core locations. Field density was measured using a PQI 380 asphalt density gauge. Photos were collected and videos of the test sections were recorded during and after construction. Figure A.2 presents some of the photos taken.

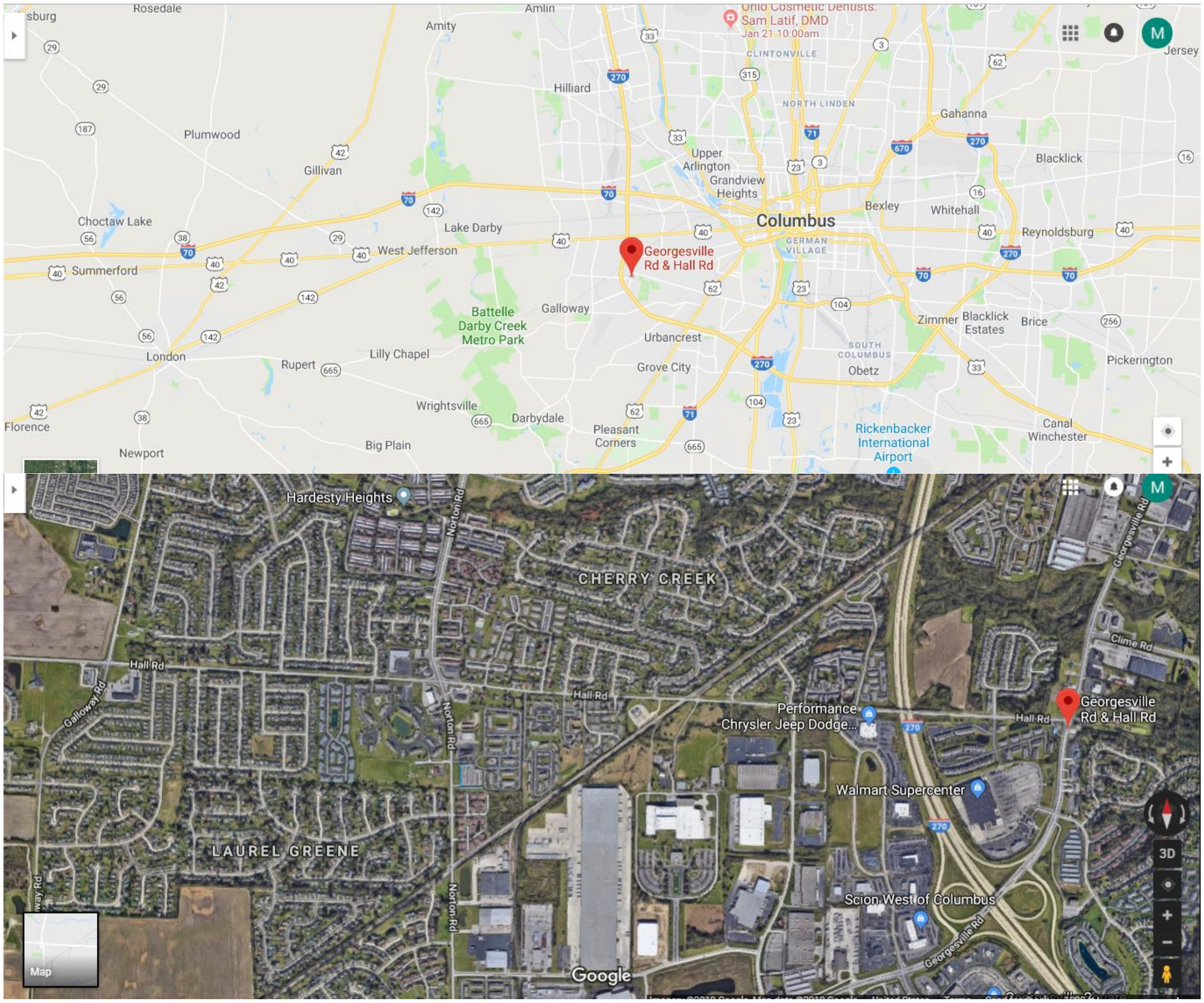

Figure A.1 Location Test Sections in the City of Columbus

Table A.1 Location of Test Sections

Section	**Start**	**End**	**Lane**
30% RAP-Hydrolene	Bledsoe Dr.	Norton Rd.	North Lane
30% RAP-Sylvaroad	Bledsoe Dr.	Norton Rd.	South Lane
40% RAP-Hydrolene	Norton Rd.	Bike Trail	North Lane
40% RAP-Sylvaroad	Norton Rd.	Bike Trail	South Lane
50% RAP-Hydrolene	Bike Trail	Bridge	North Lane
Sylvaroad	Bike Trail-	Bridge	South Lane
Control	Bridge	Georgesville Rd.	North Lane
30% RAP + PG 64-28	Bridge	Georgesville Rd	South Lane

.

Table A.2 Properties of RAP Material

RAP binder Content	High Temperature grade	Low-Temperature Grade (Stiffness)	Low-Temperature Grade (m-value)	Performance Grade
6.1%	86.8	-21.91	-16	82-16

Table A.3 Tested Mixture Properties

Section	% RAP	Virgin Binder type	Virgin AC%	RAP AC%	RBR	RA Dosage
Control	20	PG 64-22	5.1	1.2	0.19	NA
30% RAP	30	PG 64-28	4.4	1.8	0.29	NA
30% RAP-1 - Hydrolene RA	30	PG 64-22	4.4	1.8	0.29	4%
40% RAP-1 - Hydrolene RA	40	PG 64-22	3.4	2.4	0.29	7.5%
50% RAP-1 - Hydrolene RA	50	PG 64-22	2.7	3.0	0.41	9.0%
30% RAP-1 - Sylvaroad RA	30	PG 64-22	4.4	1.8	0.41	4.5%
40% RAP-1 - Sylvaroad RA	40	PG 64-22	3.4	2.4	0.53	7.5%
50% RAP-1 - Sylvaroad RA	50	PG 64-22	2.7	3.0	0.53	9.5%

Figure A.2 Pictures Taken during Constriction of Test Sections in the City of Columbus.

A.4 Laboratory Testing Program

Cores were obtained at different locations within the test sections. In addition, loose asphalt mixture samples were obtained at the plant for each mixture used in the test sections. Specimens of the loose mixtures were compacted in the laboratory to achieve target air voids of 7±0.5%. Laboratory tests were conducted on the core and lab-compacted specimens. To this end, the propensity of the cores and lab-compacted specimens to fatigue cracking was evaluated using the semi-circular bend (SCB) and the indirect tensile asphalt cracking test (IDEAL-CT) tests. In addition, the low-temperature cracking potential was assessed using the asphalt concrete cracking device (ACCD). Finally, the asphalt pavement analyzer (APA) was performed on the lab-compacted specimens only to examine their resistance to rutting. A detailed description of each of those tests is provided below.

A.4.1 Semi-Circular Bending (SCB) Test

The SCB test was conducted on each mixture to evaluate the fatigue cracking performance at an intermediate temperature of 25°C. The SCB tests were performed according to the Illinois SCB Test Method (AASHTO TP 124-16: *Determining the Fracture Potential of Asphalt Mixtures Using Semicircular Bend Geometry (SCB) at Intermediate Temperatures)*. In this method, samples with a 150 mm diameter were compacted to a height of 150 mm. Each sample was cut in half and the ends trimmed to obtain a thickness of 50 ± 1 mm. Each 50-mm-thick sample was then cut in half to create the semi-circular shape. A notch with a depth of 15 mm and a width of 2.5 mm was cut into the center of the sample, as shown in Figure A.3. The SCB test was conducted on at least four samples. The SCB test was performed by loading the sample monotonically to failure at a constant cross-head deformation rate of 50 mm/min. All tests were conducted at a temperature of 25 °C. Load and vertical deformation were recorded until failure. An Instrotek© Auto SCB, Figure A.4, was used to conduct all SCB tests.

Figure A.3 Illinois SCB Sample Preparation and Testing Equipment

Figure A.4 Instrotek© Auto SCB Test Equipment

The main output of the SCB is a load versus deformation plot, as shown in Figure A.5. From this plot, the Fracture Energy (FE) and the Flexibility Index (FI) are calculated using Equations A.2 and A.3, respectively. The fracture energy represents the energy needed to propagate a crack through the pavement layer, whereas the flexibility index identifies brittle mixes that are prone to pre-mature cracking (*2*). Since the Fracture Energy is a function of the peak load and displacement, Nazzal et al. (*3*) recommended normalizing the fracture energy values based on the peak strength mixture. Therefore, the normalized fracture energy (NFE) value (Equation A.4) was used in this study to examine the cracking resistance of the core samples.

$$G_F = \frac{W_f}{Area_{lig}} \times 10^6 \quad (A.2)$$

$$FI = \frac{G_F}{|m|} \times A \quad (A.3)$$

$$NFE = \frac{G_F}{\sigma_{peak}} \quad (A.4)$$

Where,

$|m|$ = absolute value of slope at inflection point
A = unit conversion (0.01)
G_F= fracture energy (Joules/m^2)
W_f = work of fracture, or area beneath load vs. displacement curve (Joules)
$Area_{lig}$ = ligament area, ligament thickness × length (mm^2)
σ_{peak}=peak strength

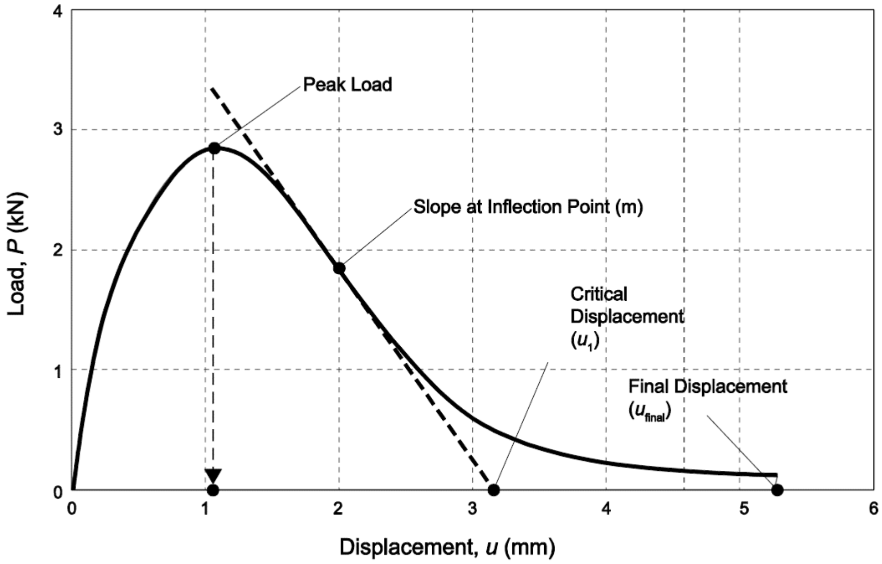

Figure A.5 Plot of Load vs. Displacement Obtained from Illinois SCB Test (*2*)

A.4.2 Indirect Tensile Asphalt Cracking Test (IDEAL-CT)

The IDEAL-CT test was developed by Zhou et al. (4). This test is similar to the conventional indirect tensile strength test but with a new procedure proposed by Zhou et al. (4) to analyze the load-displacement curve (Figure A.6) with inspiration from crack propagation laws proposed by Paris and Erdogan (1963) and Bazant and Prat (1998). Based on this procedure, Equation 4 can be used to calculate the cracking test index (CTI) which was found to correlate well with the cracking performance of asphalt mixtures in the field.

$$\mathrm{CTI} = \frac{G_f}{|m_{75}|} \times \left(\frac{l_{75}}{D}\right) \quad \text{(A.5)}$$

Where,

G_f: is the work of fracture which is the total area under load – displacement curve

D: is sample diameter (mm).

l_{75}: is displacement corresponding to the 75 percent of the peak load at the post-peak stage.

m_{75}: is slope calculated as shown in Figure A.6 using the following equation:

$$m_{75} = \frac{P_{85} - P_{65}}{l_{85} - l_{65}} \quad \text{(A.6)}$$

Where,

P_{85}: is the 85 percent of the peak load at the post-peak stage.

P_{65}: is the percent of the peak load at the post-peak stage.

l_{85}: is displacement corresponding to the 85 percent of the peak load at the post-peak stage.

l_{65}: is the displacement corresponding to the 65 percent of the peak load at the post-peak stage.

The IDEAL-CT test was conducted in this study to evaluate the fatigue cracking properties of the field cores and lab-compacted samples prepared using from mixtures obtained from the field.

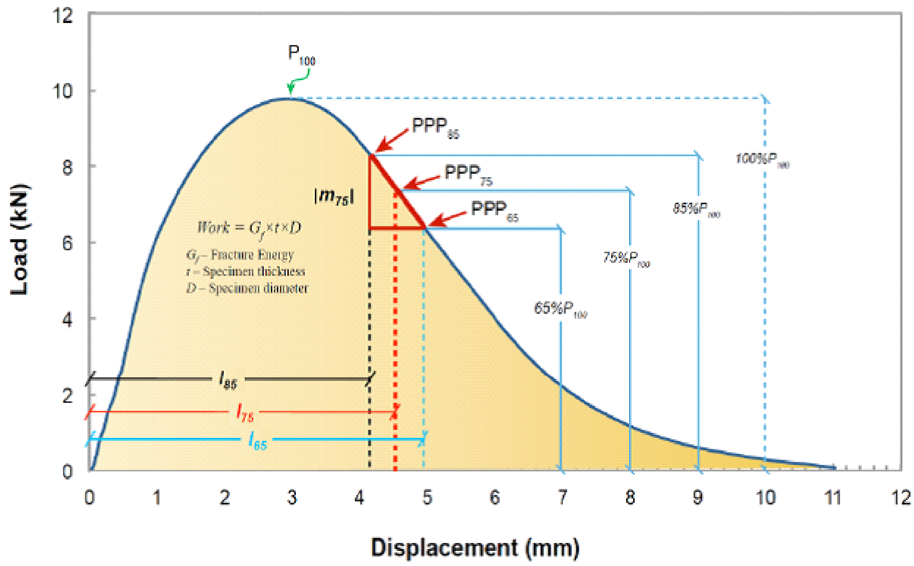

Figure A.6 Illustration of the Slope m_{75} in CTI Calculation (4)

A.4.4 Asphalt Concrete Cracking Device (ACCD)

This test was conducted to evaluate the low-temperature cracking resistance of mixtures evaluated in this study. In this test, a 22.4-mm (0.88-inch) long-notch was cut at the outer surface of a 60-mm (2.3-inch) diameter, 2-inch thick (50.8 mm) specimen to control the location of the crack. The test specimen and the ACCD ring were heated for 60 minutes at 65°C, and the tapered end of the heated ACCD ring was placed in the center hole of the heated test sample. The sample with the ACCD ring was placed in an environmental chamber (Figure A.7). As the temperature decreased, the contraction of the asphalt mix specimen was restrained by the ACCD ring, developing tensile stress within the test specimen and compressive stress within the ACCD ring. The temperature and strain of each ACCD ring were continuously recorded until failure. The temperature corresponding to the maximum slope of the ACCD strain-temperature curve was considered as the onset on thermal cracking. The point at which the slope of the strain-temperature curve is equal to eighty percent of the maximum slope after the onset of cracking is defined as the ACCD cracking temperature. The ACCD test was performed on short-term and long-term aged specimens.

Figure A.7 ACCD Test Setup

A.4.5 Asphalt Pavement Analyzer

The asphalt pavement analyzer (APA) test was conducted according to AASHTO TP 63 (Standard Method of Test for Determining the Rutting Susceptibility of Asphalt Paving Mixtures Using the Asphalt Pavement Analyzer) and ODOT Supplement 1057 (Loaded Wheel Tester Asphalt Mix Rut Testing Method) using the device shown in Figure A.8. This test simulates actual road conditions by rolling a concave-shaped metal wheel at a speed of approximately 23.5 inch/sec (60 cm/sec) over a rubber hose pressurized at 100 psi (689.5 kPa) to 120 psi (827.4 kPa) to generate the effect of high tire pressure (Figure A.9). In this test, the hose stays in contact with the sample's surface while the metal wheel rolls back and forth along the length of the hose for 8,000 cycles.

The APA can simultaneously test three beam samples or six cylindrical samples, with each APA sample consisting of two cylindrical samples. Superpave gyratory compacted specimens measuring 6 inch (150 mm) in diameter and 2.95 inch (75 mm) in height were used in this test. The target air void level within these specimens was 7 ± 1%, as specified in ODOT Supplement 1057. A trial and error procedure was followed in determining the weight of mixture required to achieve the target air void level. The loose mixture was heated to the compaction temperature before being prepared in the Superpave gyratory compactor.

Testing was conducted at a temperature of 120^{o}F (49^{o}C). The specimens were conditioned for a minimum of 12 hours at the test temperature prior to loading. During the test, rut depth measurements were obtained at 5, 500, 1000, and 8000 cycles. The total permanent deformation (or rutting) was calculated as the difference between the rut depth readings at the 8000th cycle and the 5th cycle. A total of four rut depth readings were used to calculate the average rut depth value for each APA sample.

Figure A.8 Asphalt Pavement Analyzer

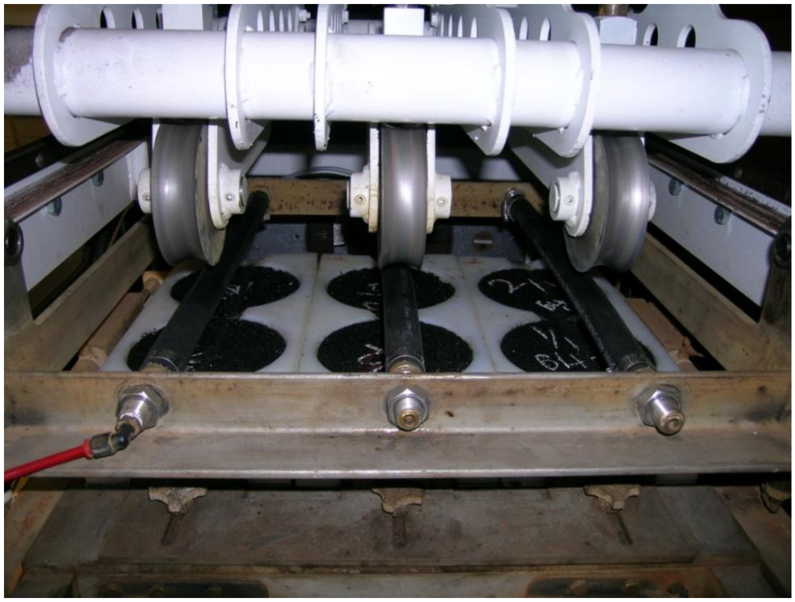
Figure A.9 Repeated Wheel Loading in the APA Device

A.5 Cost Analysis

Cost analysis was performed to compare the costs associated with the construction of the test sections in the City of Columbus. Only the initial cost for the asphalt mixes was considered in the analysis, as no maintenance or repairs were performed during the monitoring period in this project. The initial cost of mixes from the bid document was provided by the City of Columbus. An analysis was also performed to determine the costs incurred due to using the recommended design procedure for high RAP mixes and the additional tests on the extracted and RAP. Based on this analysis, an estimated cost of high RAP mixes was determined.

A.6 Field Evaluation of Constructed Test Sections

A field and laboratory testing methodology was developed to evaluate the performance of the constructed test sections. Details of that methodology are provided in Appendix C. An interactive database was developed to assist in storing, processing, and analyzing the pavement performance data collected during the evaluations. Main inputs to this database included the various pavement distresses encountered during the field evaluation and the corresponding extent and severity levels. The interactive database was developed using Microsoft Visual Basic for Applications (VBA) and Microsoft Office.

The developed field methodology included evaluating the performance of the test sections by the research team and designated city personnel during the duration of this project. In addition, it included performing annual evaluations by the city personnel for the first five years after construction. All field evaluations involved examining the severity and extent of the distresses developed in these sections. Furthermore, the field evaluations included obtaining three field cores from each test section after 1, 3 and 5 years of construction and testing the field cores using the SCB test.

A.6 References

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3- Nazzal, M. D., Kim, S., Kaya, S., Abbas, A., Qtaish, L. A., Holcombe, E., & Hassan, Y. A. (2017). *Fundamental Evaluation of the Interaction between RAS/RAP and Virgin Asphalt Binders* (No. FHWA/OH-2017-24).

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Appendix B Test Results and Data Analysis

This appendix presents the results of the different binder mixtures tests that were conducted in this study. The chapter is divided into several sections. The layout of each section includes the presentation and discussion of the test results.

B.1. Field Density Measurements for Columbus Test Section

The average relative density obtained for each of the test sections in the City of Columbus using the PQI 380 density gauge are presented in Figure B.1. In general, the control and the other test sections had similar average relative densities of about 94%, which indicates that the target density of 93%±1% was achieved. The 50% RAP-HYD test section had slightly higher variability in the in-place density as compared to other sections, as indicated by the error bar in Figure B.1.

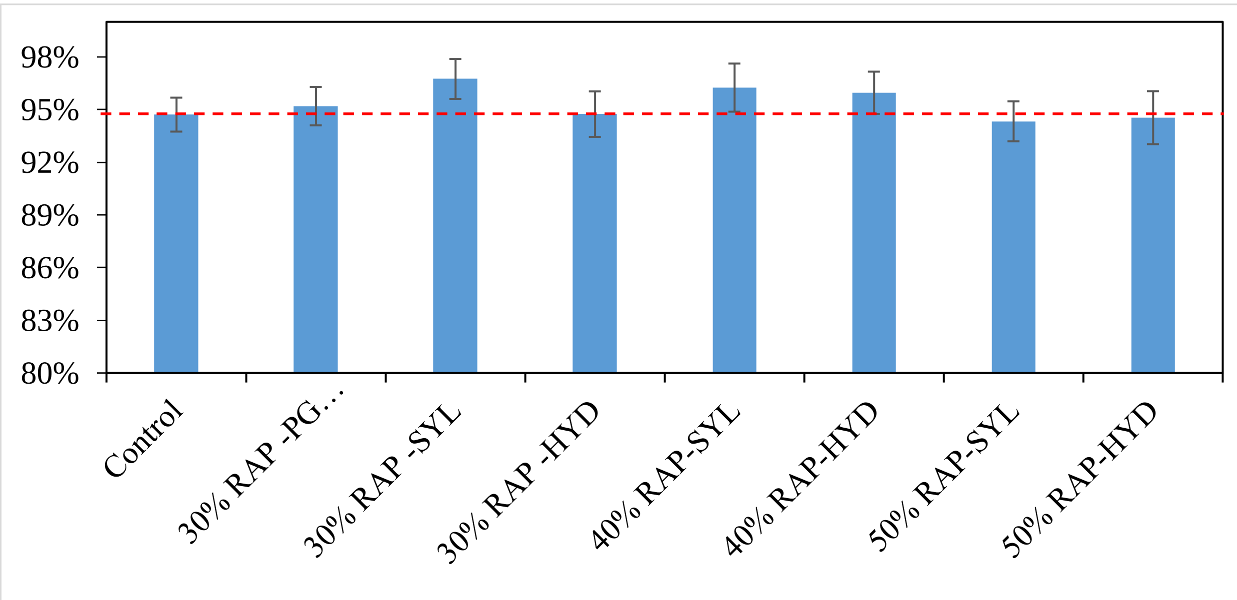

Figure B.1 Average Relative Compaction of City of Columbus Test Sections

B.2. Results of Core Samples Testing

The fatigue cracking of core samples at intermediate temperature was assessed by the Semi-Circular Bend (SCB) and IDEAL-CT tests. In addition, their low-temperature cracking resistance was evaluated using the Asphalt Concrete Cracking Device (ACCD). The results of the performance tests are discussed in this section.

B.2.1 SCB Test Results

Figure B.2 presents the average normalized fracture energy (NFE) values of the core samples obtained from test sections constructed in this study. It is noted that the mixes with 30% RAP and Hydrolene and Sylvaroad had higher NFE values as compared to those in the control mix with 20% RAP. In addition, the 30% RAP mix with a softer binder PG 64-28 had similar NFE values to that of the control mix. While 40% RAP mix with Hydrolene had similar NFE to that of the control, all other mixes with 40% RAP or more had significantly lower NFE value. This suggests that Hydrolene RA was more effective in improving the fatigue cracking resistance of the RAP mixes up to a RAP binder replacement (RBR) of 0.4.

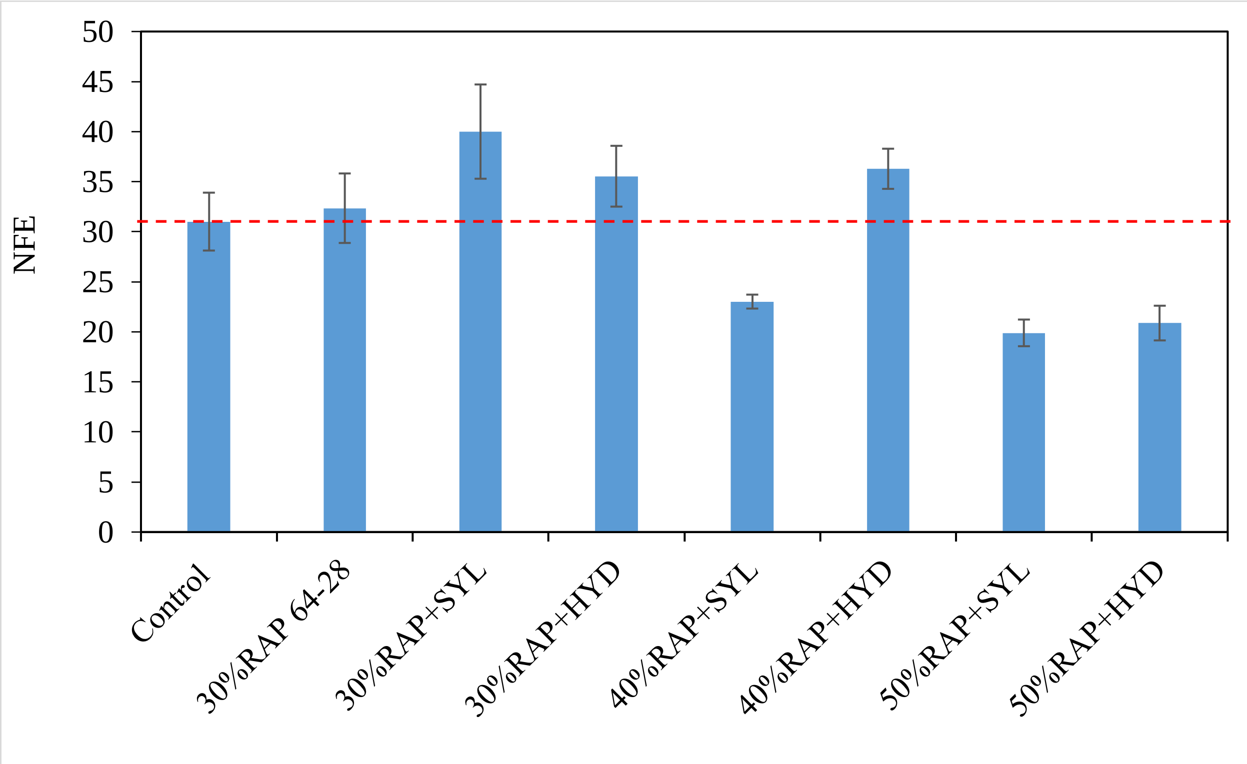

Figure B.2 Normalized Fracture Energy (NFE) for Cores

Figure B.3 shows the average flexibility index (FI) values for the tested field cores. The FI is an indication of the asphalt mix cracking resistance; the higher the FI, the better the cracking resistance. For the 30% and 40% RAP mixes with Hydrolene, the FI values were slightly higher than the FI of the control mix. However, the 50% RAP mix with Hydrolene had lower FI than the control. While the 30% RAP mix with Sylvaroad had higher FI than the control, mixes with 40% and 50% RAP and Sylvaroad had significantly lower FI than the control mix. This suggests that Sylvaroad was effective in improving the RAP mixes with up to 0.3 RBR. The results in Figure B.3 also indicate that using the softer binder PG 64-28 in the 30% RAP mix resulted in an FI value similar to that of control RAP mixes. It is noted that field cores; with the exception of those for 40%RAP+SYL, 50%RAP+SYL, and 50%RAP+HYD, had FI values higher than 10, which is the minimum FI value suggested by Al-Qadi et al. (2) for surface mixes to ensure adequate resistance to fatigue cracking.

B.2.2 Indirect Tensile Asphalt Cracking Test (IDEAL-CT) Results

Figure B.4 presents the average Indirect Tensile Strength (ITS) values of the core samples. It is noted 30% RAP mixes had similar average ITS values to that of the control mix. In addition, mixes with 40% and 50% RAP with Sylvaroad and Hydrolene have higher ITS values compared to those of the control mix. Likewise, the 50% RAP mixes had higher ITS than the 40% RAP mixes.

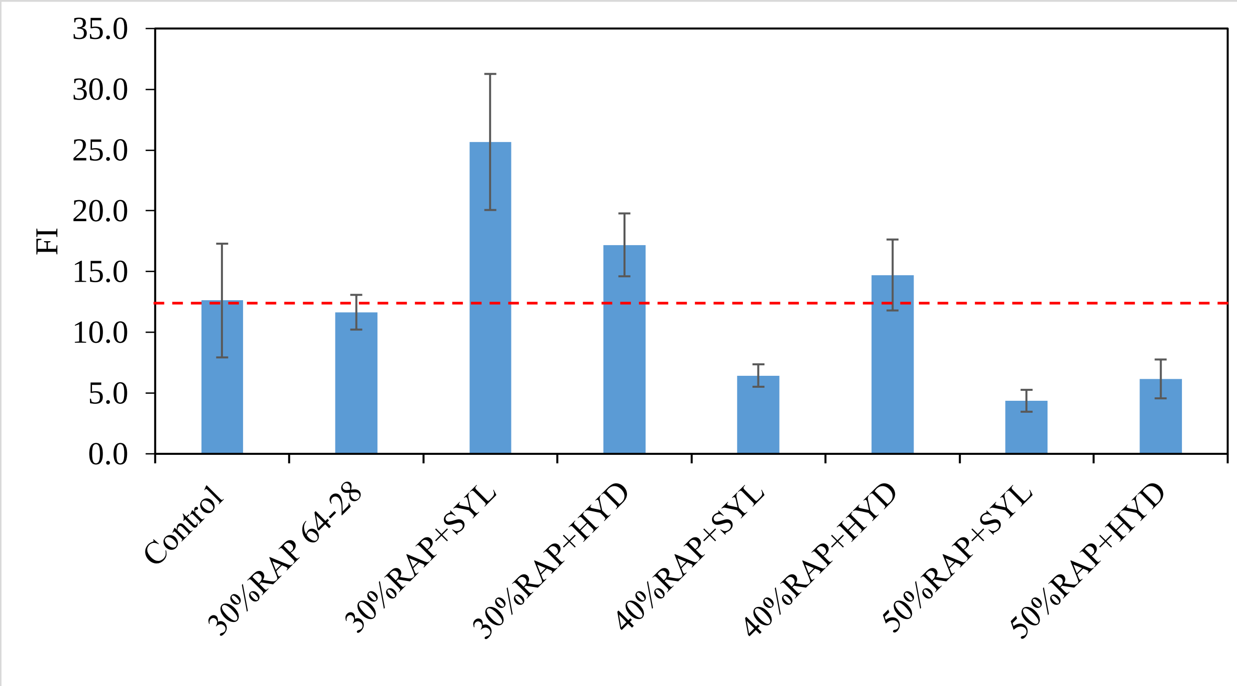

Figure B.3 Flexibility Index (FI) for Field Cores

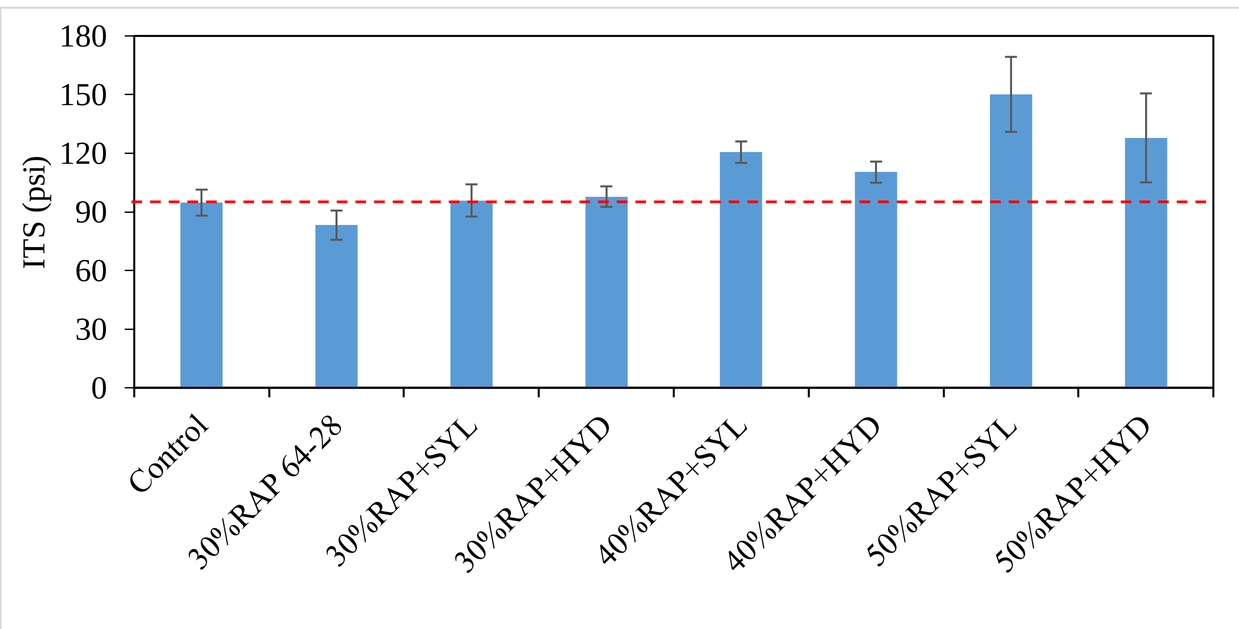

Figure B.4 ITS Values for Field Cores

Figure B.5 presents the average CTI values of field cores tested in this study. While the 30% RAP mixes had similar average CTI values to that of the control mix, mixes containing 40% and 50% RAP with Sylvaroad and Hydrolene RAs had lower CTI values compared to that of the control mix. It is noted that all mixes except the 50% RAP mix with Sylvaroad had CTI values higher than 150, which is the minimum CTI value suggested in a recent study for surface mixes with high RAP contents (2).

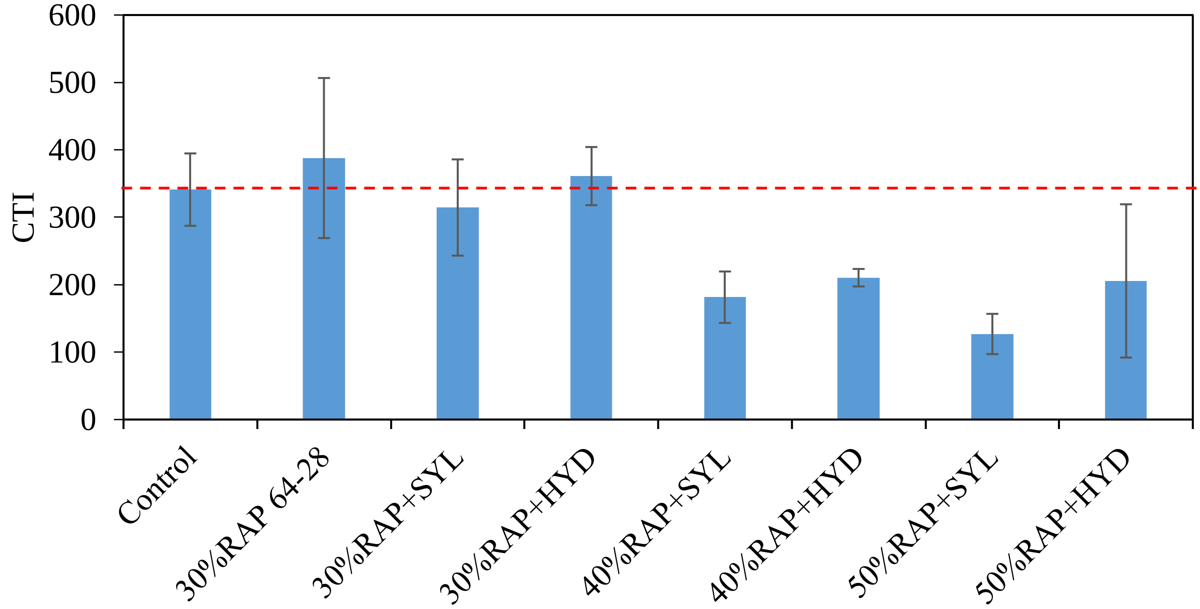

Figure B.5 CTI Values for Field Cores

B.2.3 Asphalt Concrete Cracking Device (ACCD) Test Results

Figure B.6 presents the average cracking temperature obtained in the ACCD test performed on the cores obtained from the test sections. In general, the 30% RAP, 40% RAP, and 50% RAP mixes had similar average cracking temperature to that of the control. It is noted that the mixture with a softer binder (PG 64-28) had the lowest fracture temperature followed by the 40% RAP mix with Hydrolene. It can also be noticed from this figure that mixtures with 50% RAP had slightly warmer cracking temperature than the other mixes.

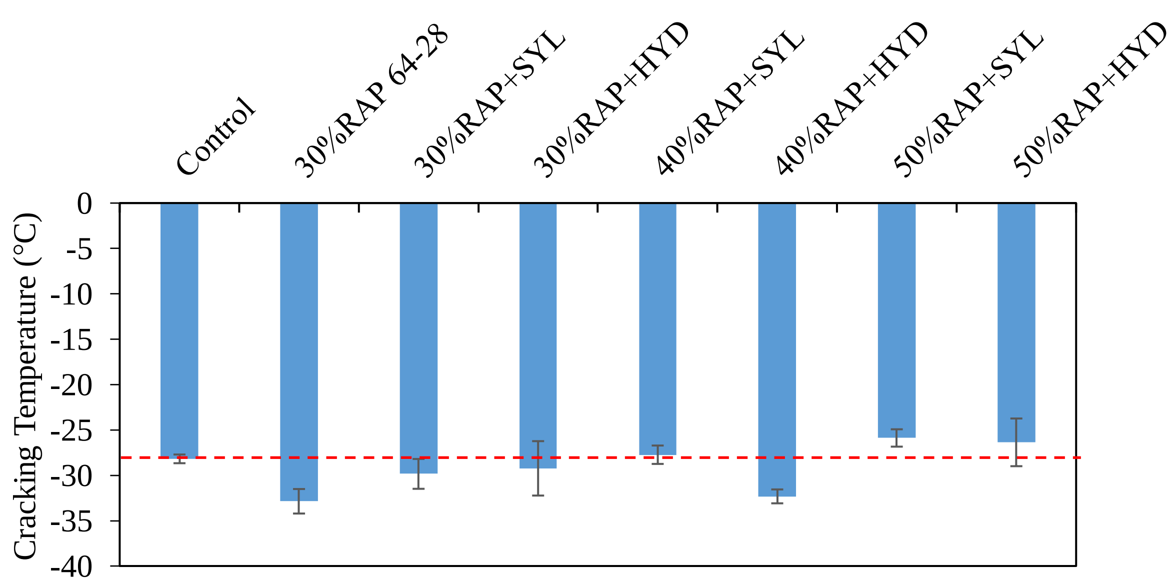

Figure B.6 ACCD Cracking Temperature for Field Cores

B.3 Test Results for Laboratory-Compacted Samples

The fatigue cracking of core samples at intermediate temperature was assessed by the SCB and IDEAL tests. In addition, the low-temperature cracking resistance of the samples was evaluated using the ACCD. Finally, asphalt paving analyzer was used to examine rutting. The results of the conducted tests are discussed in this section.

B.3.1 SCB Test Results

Figure B.7 presents a comparison of the average NFE values for samples compacted in the lab using loose mixtures obtained from the field. While the mixes with 30% RAP and Sylvaroad had higher NFE values as compared to those for the control mix, Sylvaroad mixes with 40% and 50% RAP had lower NFE values than the control mix. In addition, the 30% and 40% mixes with Hydrolene had similar average NFE values to that of the control mix, but the 50% mix with Hydrolene had a lower average value. Finally, the 30% RAP mix with the softer binder PG 64-28 had a similar NFE to that of the control mix. The NFE values for the laboratory-compacted samples showed similar trends to those of the field cores but were slightly lower.

Figure B.8 shows the average FI values for the lab compacted samples. For the 30% and 40% RAP mixes with Hydrolene, the FI values were similar to the FI of the control mix. However, the 50% RAP mix with Hydrolene had lower FI than the control. While the 30% RAP mix with Sylvaroad had higher FI than the control, 40% and 50% RAP mixes with Sylvaroad had significantly lower values. Figure B.8 also shows that 30% RAP mix with the softer binder PG 64-28 had higher FI than that of control RAP mix. It is noted that FI values for the lab compacted samples had similar trends to that of the field cores but were much lower.

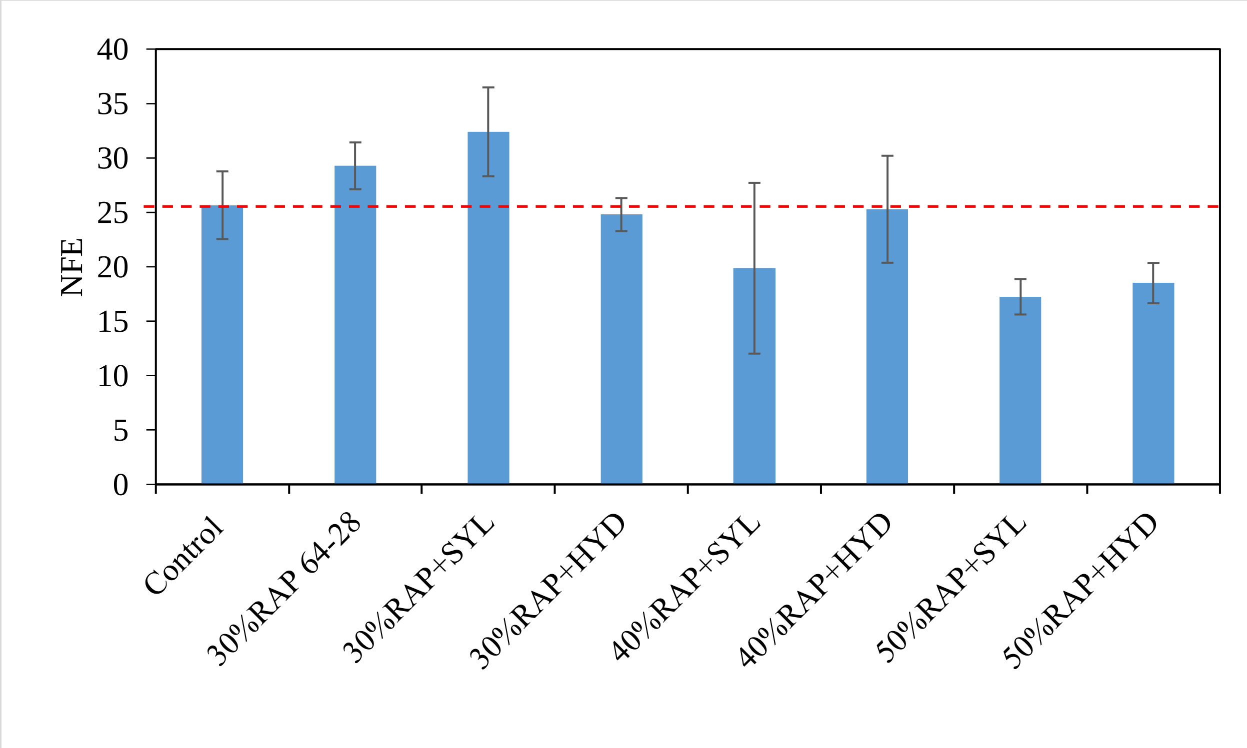

Figure B.7 NFE Values for Lab Compacted Samples

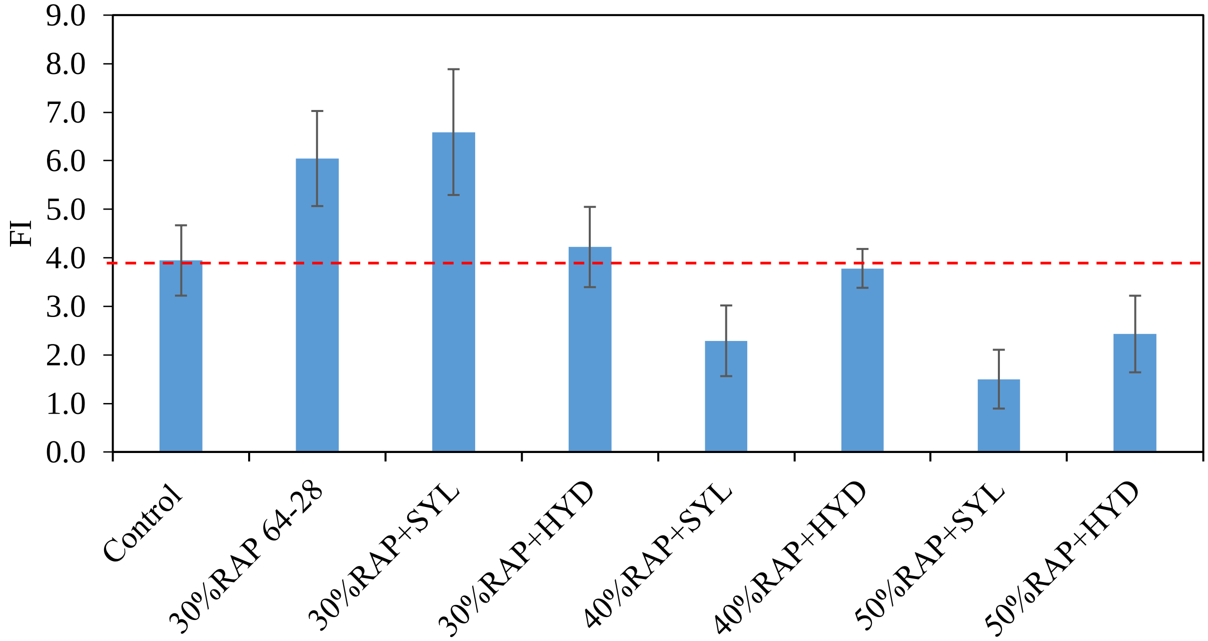

Figure B.8 FI Values for Lab Compacted Samples

B.3.2 Indirect Tensile Asphalt Cracking Test (IDEAL-CT) Results

Figures B.9 presents the average ITS values of the lab compacted samples. It is noted that the 30% RAP mixes had lower average ITS values than that of the control mix. Furthermore, mixes with 40% and 50% RAP with Sylvaroad and Hydrolene had higher ITS values compared to those of the control mix. It is noted that the ITS values for the lab compacted samples showed similar trends to those of the field cores but were higher.

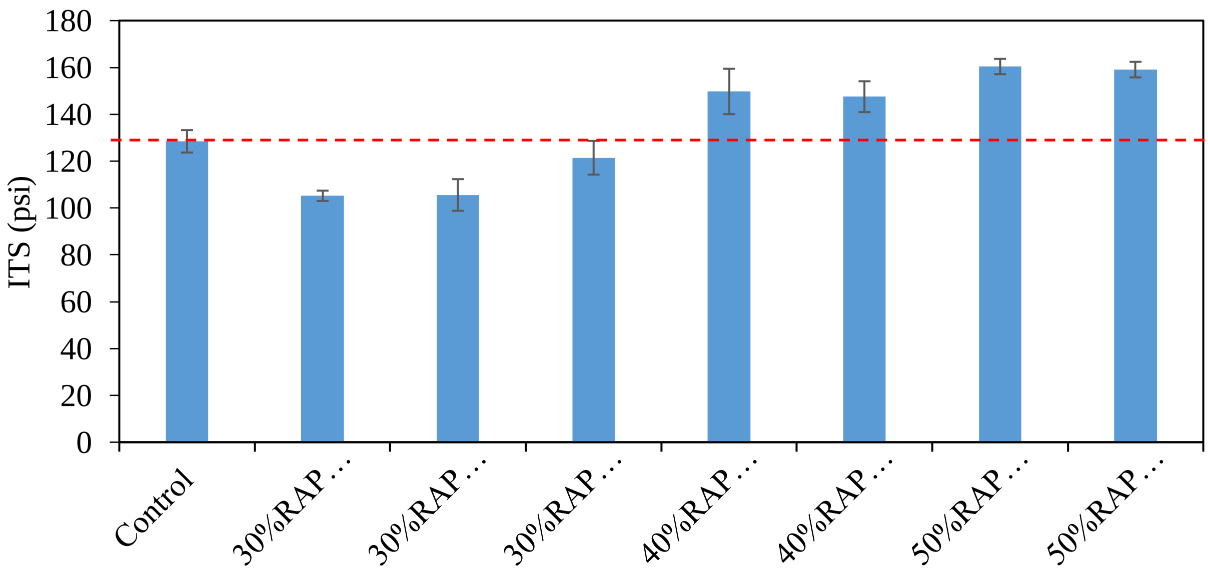

Figure B.9 ITS Values for Lab Compacted Samples

Figure B.10 presents the average CTI values of lab compacted samples tested in this study. For the 30% and 40% RAP mixes with Hydrolene, the average CTI values were slightly higher than the CTI of the control mix. However, the 50% RAP mix with Hydrolene had lower CTI than the control. While 40% and 50% RAP mixes and Sylvaroad had significantly lower average CTI values than the control mix, the 30% RAP mix with Sylvaroad had higher average CTI value This suggest that Sylvaroad was effective in improving the RAP mixes with up to 0.3 RBR. The results in Figure B.10 also indicates that using the softer binder PG 64-28 in the 30% RAP mix resulted in CTI value similar to that of control RAP mixes. It is noted that CTI of field cores had similar trend to that of lab compacted samples but significantly lower.

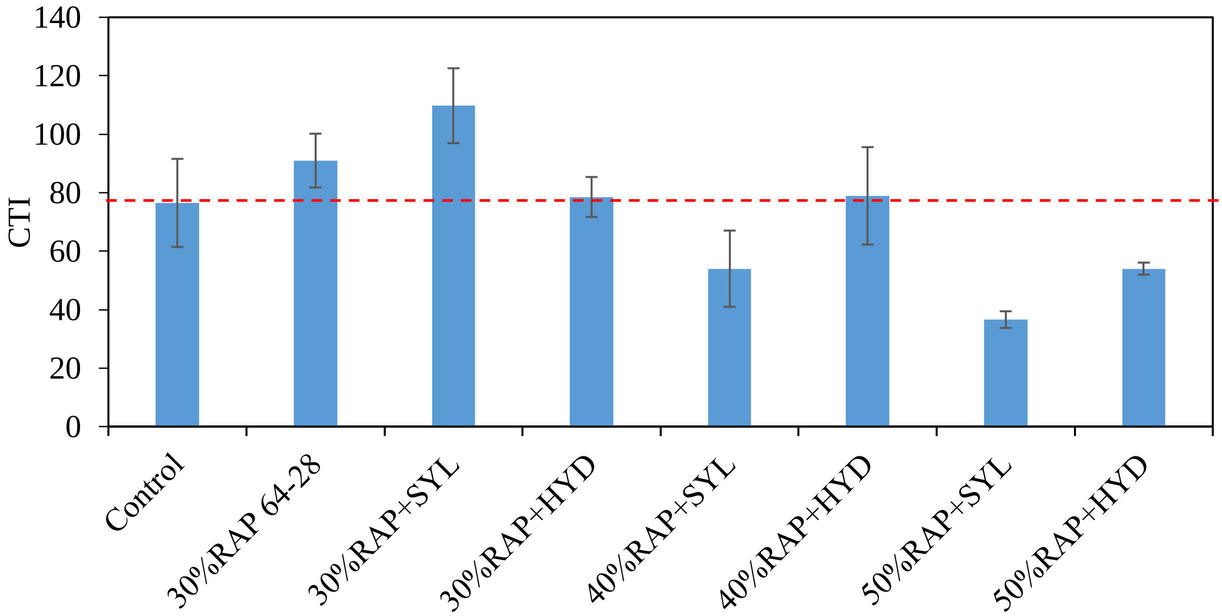

Figure B.10 CTI Values for Lab Compacted Samples

B.3.3 Asphalt Concrete Cracking Device (ACCD) Test Results

Figure B.11 presents the average cracking temperature obtained using the ACCD test conducted on the samples compacted in the lab using mixtures obtained from the test sections. In general, the 30% RAP, 40% RAP, and 50% RAP mixes had an average fracture temperature comparable to that of the control mix. It is noted that the mixture with the softer binder (PG 64-28) had the coldest cracking resistance. In addition, mixtures with Hydrolene had, in general, slightly colder cracking temperatures than those containing Sylvaroad.

B.3.4 APA Test Results

Figure B.12 presents the average rutting values obtained in the APA tests conducted on the lab compacted samples prepared in this study. The use of the softer PG 64-28 binder resulted in higher rutting in mixes with 30% RAP. However, the rutting decreased when increasing the RAP content. In general, mixes with Hydrolene had higher rutting than those with Sylvaroad. All mixes had rutting values less than the 5 mm, which the maximum rutting value allowed by ODOT for mixes used on roadways with medium traffic. Therefore, all mixes had acceptable APA rutting values.

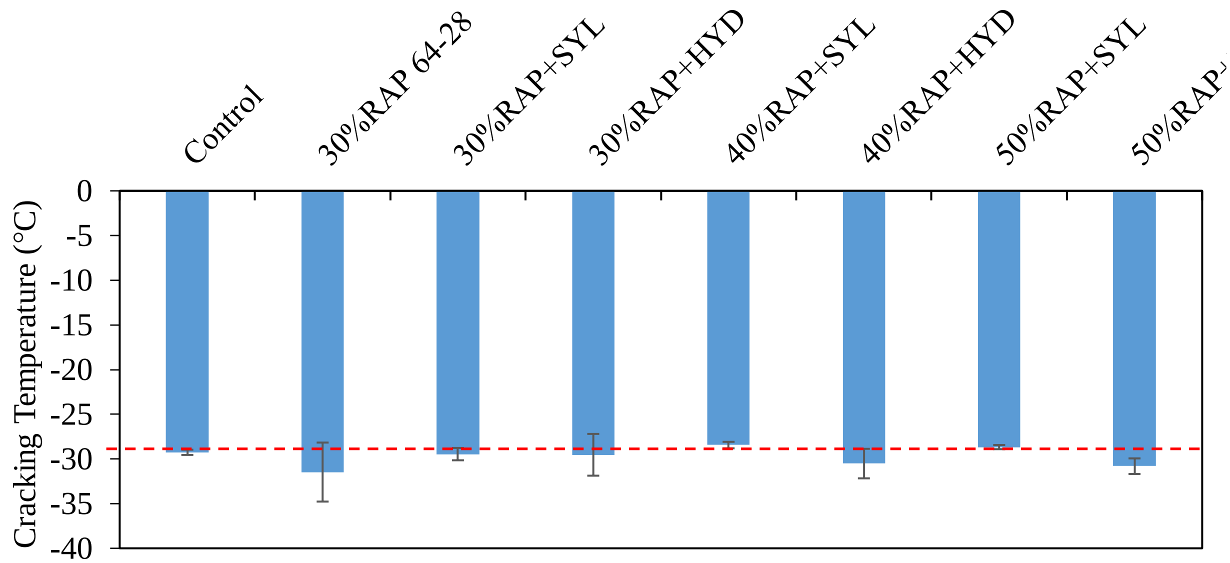

Figure B.11 ACCD Cracking Temperature for Lab Compacted Samples

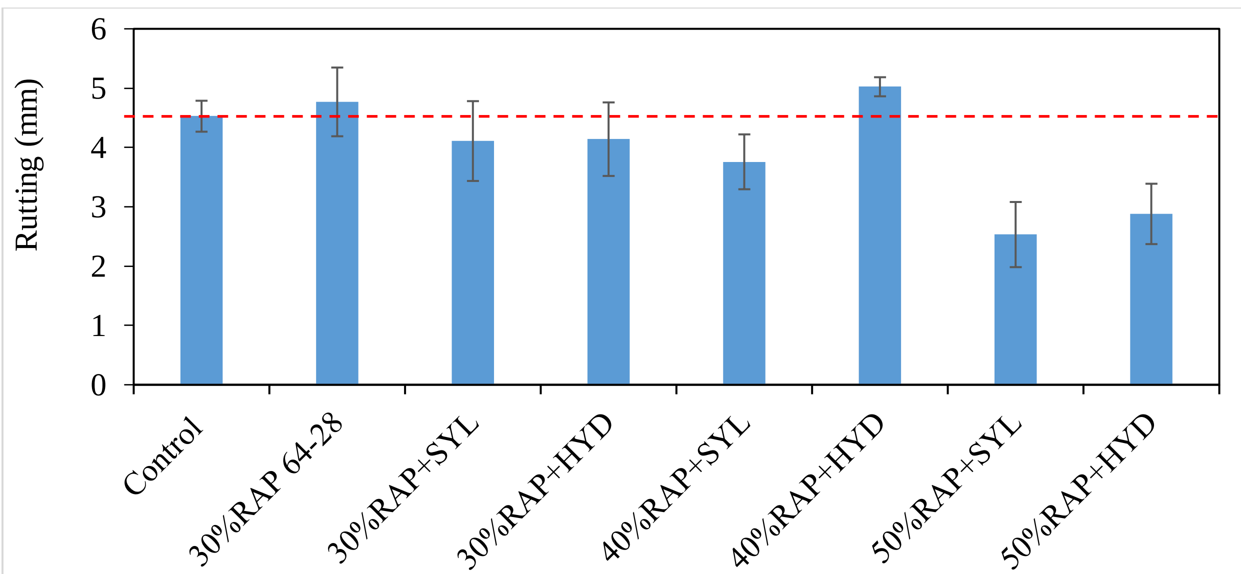

Figure B.12 APA Rutting Values for Lab Compacted Samples

B.4 Cost Analysis Results

Table B.1 presents the initial price of the RAP mixes used in the construction of the test sections, which was obtained from the bid document provided by the City of Columbus. The initial costs of the RAP mixes were lower than the cost of the control mix with 20% RPA that is typically used by the City of Columbus. The cost of the recycling agent was not included in the unit price of these mixes as the recycling agents used for the construction of the test sections were donated. Therefore, the cost of recycling agent was computed based on the dosage used and the unit price of these agents ($634.40/ton for Hydrolene and $1700/ton for Sylvaroad). In addition, the cost to cover expenses of performing the recommended design procedure for high RAP mixes with the recycling agents as well as conducting the additional tests on extracted and recovered RAP binder was estimated based on the information provided by the contractor. It is noted that cost was computed per cubic yard of mix by dividing the expenses provided by the contractor by the total amount used to pave the entire project. This was done assuming one mixture will be used for the entire project. Based on this, the total price for the considered RAP mixes was computed and shown in Table B.2. It is noted that Table B.2 also provides the cost of the considered mixtures materials only. It is clear that increasing the RAP content reduced the cost of the asphalt mixture. However, the cost reduction depended on the type of recycling agent used. The RAP mixes with Hydrolene were the least expensive mixes. The cost of the 30%, 40%, and 50% RAP mixes with different types of recycling agents was compared to that of a virgin mix as well as a 20% RAP mix. Table B.2 shows the cost benefit ratio of the 30%, 40% and 50% RAP mixes in comparison to the control virgin mixture as well as the 20% RAP mix. It is noted that using of higher RAP content and recycling agents can reduce the cost of an asphalt mixture by at least 15% when recycling agent. In addition, RAP mixes with Hydrolene have the best cost benefit and can reduce the mix cost by up to 26.4% when 50% RAP is used.

Table B.1 Price of Test Sections Mixes

Mixture	Unit Price ($/CY)
Control	$310
30% RAP-PG 64-28	$308.00
30% RAP -Hydrolene	$255
40% RAP-Hydrolene	$227
50% RAP-Hydrolene	$223
30% RAP -Sylvaroad	$255
40% RAP -Sylvaroad	$227
50% RAP-Sylvaroad	$223

Table B.2 Total Price of RAP mixes

Mixture	Unit Bid Price ($/CY)	Cost of RA ($/CY)	Other Costs ($/CY)	Materials Cost ($/CY)	Total Cost ($/CY)	Total Cost Reduction	Materials Cost Reduction
Control	$310	NA	NA	91.24	$310	0.0%	0.0%
30% RAP-PG 64-28	$308.00	NA	NA	90.13	$308	0.6%	1.2%
30% RAP-Hydrolene	$255	$0.91	$1.67	76.27	$258	16.9%	16.4%
40% RAP-Hydrolene	$227	$2.28	$1.67	68.58	$231	25.5%	24.8%
50% RAP-Hydrolene	$223	$3.43	$1.67	58.97	$228	26.4%	35.7%
30% RAP -Sylvaroad	$255	$2.45	$1.67	77.81	$259	16.4%	14.7%
40% RAP -Sylvaroad	$227	$6.12	$1.67	72.41	$235	24.3%	20.6%
50% RAP-Sylvaroad	$223	$9.33	$1.67	64.13	$234	24.5%	29.7%

B.5 Results of Field Evaluation

Performance data were collected three and seven months after the construction of the test sections. Figures B.19 through B.21 depict pictures of the test sections taken three and seven months after construction, respectively. It is noted that there was no observed distresses in the test sections after seven months of construction. The pavement condition rating (PCR) for all sections was 100%.

Figure B.13 Site pictures of Columbus Test Sections after Three Months of Construction: a) Control RAP Section, b) 30% RAP (64-22) Section, c) 30%RAP+SYL Section, d) 30%RAP+HYD Section, e)40% RAP+SYL Section, f) 40%RAP+HYD Section, g) 50% RAP+SYL Section, and h) 50%RAP+HYD Section


a.
b.
c.
d.
e.
f.

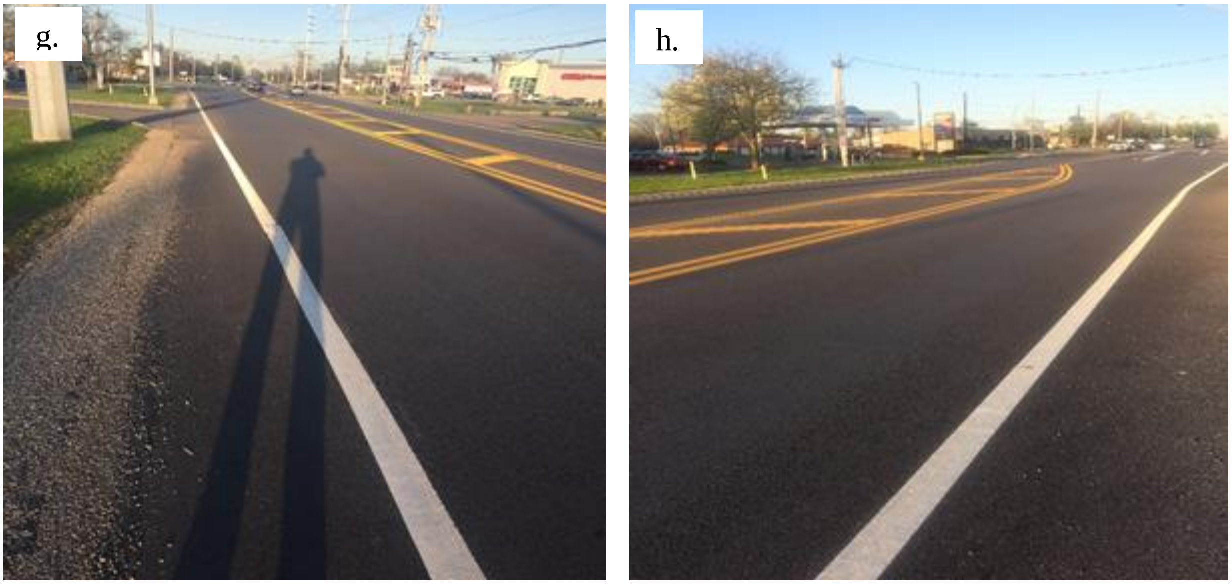

Figure B.14 Site pictures of Columbus Test Sections after Seven Months of Construction: a) Control RAP Section, b) 30% RAP (64-22) Section, c) 30%RAP+SYL Section, d) 30%RAP+HYD Section, e) 40% RAP+SYL Section, f) 40%RAP+HYD Section, g) 50% RAP+SYL Section, and h) 50%RAP+HYD Section

B.6 References

1- Al-Qadi, I. L., Ozer, H., Lambros, J., El Khatib, A., Singhvi, P., Khan, T., & Doll, B. (2015). *Testing Protocols to Ensure Performance of High Asphalt Binder Replacement Mixes Using RAP and RAS*. Illinois Center for Transportation/Illinois Department of Transportation.

2- Bennert, T., Haas, E., & Wass, E. (2018). Indirect Tensile Test (IDT) to Determine Asphalt Mixture Performance Indicators during Quality Control Testing in New Jersey. *Transportation Research Record*, *2672*(28), 394-403.

Appendix C Field Evaluation Methodology

The construction of the test sections in the City of Columbus was completed on 09/21/2018. Field evaluations were performed three and seven months after construction. It is recommended that the sections be evaluated annually for the first five years after construction. The evaluation should include the following steps:

1- Each test section should be inspected visually over its entire length by the evaluation team. This can be done by driving slowly (less than 20 mph) or walking over the test section while videotaping the surface condition. Any readily visible distresses (e.g., potholes, cracks, rutting) should be recorded and rated.
2- Based on the surface condition observed in the first step, the evaluation team should determine if there is a need for subdividing the section.
3- For each test section, select a 100-ft subsection for thorough inspection and evaluation of the different distresses. The thorough inspection should include measuring the severity and extent of each distress. Pictures of distresses should be obtained. The form shown in Figure C.1 should be used to record the obtained data.
4- Input the recorded data into the developed pavement interface for each test section. The tab entitled "View PCR" can be used to determine the variation in the pavement condition rating, based on ODOT method, with time.

The evaluation conducted 1, 3, and 5 years after construction should also include obtaining four 6-inch core samples along the wheel path. The air void of the obtained cores should be measured. Semi-circular bend tests should be then conducted on the obtained cores according to AASHTO TP 124-16 (*Determining the Fracture Potential of Asphalt Mixtures Using Semicircular Bend Geometry (SCB) at Intermediate Temperatures)*.

ASPHALT SURFACE LOCAL ROAD

Section:	Columbus_Hall Rd._50% RAP_64-22_SYL			Construction Date:	9/21/2018
City:	Columbus	Road:	Hall Rd.		
RAP Content	50% RAP	Binder	64-22	Evaluation Date:	12/27/2018
Recycling Agent	SYL			Rated By:	Munir Nazzal

DISTRESS	DISTRESS WEIGHT	DISTRESS PRESENT?		SEVERITY WT.			EXTENT WT.			DEDUCT POINTS
				LOW	MEDIUM	HIGH	OCCASIONAL	FREQUENT	EXTENSIVE	
RAVELING	10	Yes	No	Slight Loss of Sand	Open Texture	Rough or Pitted	< 20%	20% - 50%	> 50%	0.0
BLEEDING	5	Yes	No	Not Rated	Bitumen and Aggregate Visible	Black Surface	< 10%	10% - 30%	> 30%	0.0
PATCHING	5	Yes	No	< 1 ft sq.	< 1 yd sq.	> 1 yd sq.	< 10/mile	10 - 20/mile	> 20/mile	0.0
SURFACE DISINTEGRATION/ DEBONDING/POTHOLES	5	Yes	No	Depth < 1" Area < 1 yd sq.	< 1", > 1yd sq. > 1", < 1 yd sq.	> 1" and > 1 yd sq.	< 5/mile	5 - 10/mile	> 10/mile	0.0
RUTTING	10	Yes	No	1/8" - 3/8"	3/8" - 3/4"	> 3/4"	< 20%	20% - 50%	> 50%	0.0
MAP CRACKING	5	Yes	No	5' x 5' to 9' x 9'	1' x 1' to 5' x 5'	< 1' x 1' or Alligator	< 20%	20% - 50%	> 50%	0.0
BASE FAILURE	10	Yes	No	Barely Noticeable Pitch and Roll	Noticeable Pitch and Roll, Jarring Bump	Severe Distortion, Poor Ride	< 2/mile	2 - 5/mile	> 5/mile	0.0
SETTLEMENTS	5	Yes	No	Noticeable Effect on Ride	Some Discomfort	Poor Ride	< 2/mile	2 - 4/mile	> 4/mile	0.0
TRNASVERSE CRACKS	10	Yes	No	< 1/4", No Spalling	1/4 - 1", > 0.5 Spalled	> 1", > 0.5 Spalled	CS > 100'	100' < CS < 50'	CS < 50'	0.0
WHEEL TRACK CRACKING	15	Yes	No	Single/Multiple Cracks < 1/4"	Multiple Cracks > 1/4"	Alligator > 1/4" Spalling	< 20%	20 - 50%	> 50%	0.0
LONGITUDINAL CRACKING	5	Yes	No	< 1/4", No Spalling	1/4 - 1", > 0.5 Spalled	> 1", 0.5 Spalled	< 50' per 100'	50 - 150' per 100'	> 150' per 100'	0.0
EDGE CRACKING	5	Yes	No	Tight, < 1/4"	> 1/4", Some Spalling	> 1/4", Moderate Spalling	< 20%	20 - 50%	> 50%	0.0
PRESSURE DAMAGE/ UPHEAVAL	5	Yes	No	Bump < 1/2", Barely Noticeable	1/2" - 1", Fair Ride	> 1", Poor Ride	< 5/mile	5 - 10/mile	> 10/mile	0.0
CRACK SEALING DEFIC.	5	Yes	No		Not Considered		< 50%	> 50%	No Sealant	0.0
									Total Deduct =	0.0
									PCR =	100.0

Pictures Taken?	Yes	No	Cores Taken?	Yes	No	No. of Cores:	0

Figure C.1 Performance Evaluation Form

Appendix D Phase 1 Interim Report

Optimizing the Effective Use of RAP in Local Roadways

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Interim Report

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Ohio Department of Transportation **1980 West Broad Street, MS 3280** **Columbus, Ohio 43223**	**Interim Report**
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15. Supplementary Notes

16. Abstract

This report summarizes Phase 1 research work that was completed to assess the optimum percentages of using recycled asphalt pavement (RAP) in surface course mixtures of municipal and local roadways. A statewide survey was conducted to document the current state-of-the-practice for using RAP on local roads in Ohio. In addition, a laboratory testing program was conducted to identify the factors that affect the performance of asphalt mixtures with RAP. To this end, several mixtures were designed with different RAP contents: 0%, 20%, 30%, 40, and 50% RAP by weight. Two RAP materials that have binders with different rheological properties were selected in this study. The laboratory testing program also evaluated the effect of using recycling agents (RAs) on the performance of asphalt mixtures with high RAP content. Three different types of RAs were used, namely, Hyrolene, Sylvaroad, and a soybean. Laboratory tests were conducted to evaluate the propensity of all designed asphalt mixtures to fatigue cracking, low-temperature cracking, moisture-induced damage, and rutting.

The laboratory test results indicated that the use of RAP adversely affected the fatigue cracking resistance of asphalt mixtures when more than 30% RAP was used. The use of a softer binder (PG 64-28) was not effective in maintaining the fatigue cracking resistance of the mixes when more than 30% RAP was used. In addition, the results indicated that using a binder with appropriate low-temperature performance grade can contribute to satisfactory low-temperature cracking resistance of the RAP mixes. The test results also showed that the Hydrolene RA and the Sylvaroad RA had significantly improved the cracking resistance of mixes with up to 50% RAP. However, the 40% and 50% RAP mixes with soybean RA had much lower resistance to fatigue cracking compared to those with the other RAs. The RAP source was also found to have a significant effect on the fatigue cracking resistance of RAP asphalt mixes, particularly those with more than 30% RAP. Therefore, it is very important to determine and consider the performance grade of the RAP binder in the design of asphalt mixtures with high RAP content.

Based upon current market prices, a cost analysis showed that a 50% RAP mix with Hydrolene RA can be 26% less expensive than 20% RAP mixes currently being used. In addition, a 50% RAP mix with Sylvaroad RA can be 13% less expensive than 20% RAP mixes currently being used.

Based on the results of Phase 1, it was recommended to conduct a field testing program to evaluate the performance of mixes with 30%, 40% and 50% RAP that are designed based on the recomendations provided in Appendix E of this report.

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RAP, recycling agent, fatigue cracking, RAP asphalt mixes	**No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161**

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Optimizing the Effective Use of RAP in Local Roadways

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June 2018

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TABLE OF CONTENTS

List of Tables

Optimizing the Effective Use of RAP in Local Roadways

Executive Summary

This report summarizes Phase 1 research work that was completed to: 1) assess the current practices of using recycled asphalt pavement (RAP) in surface course mixtures for local roadways, 2) develop recommendations for a cost-effective method for designing well-performing and durable surface course mixtures with different RAP contents for use on local roadways 3) evaluate the cost benefits of using different RAP contents in the surface course layer of local roadways, and 4) provide recommendations for quality control methods of RAP used in the surface mixtures of local roadways. To achieve the first objective, a statewide survey was conducted to document current state-of-the-practice for using RAP on local roads in Ohio. The survey results indicated that more than half of the Local Public Agencies (LPAs) allow using RAP in surface mixes. The majority of these agencies use Ohio Department of Transportation (ODOT) RAP limits. One third of the responding LPAs indicated that RAP is not allowed in their surface mixes. The survey results indicated that 30% of LPAs believe that currently there is not an obstacle stopping LPAs from increasing the allowed RAP percentages on local roads. However, about 40% of the LPAs think that the concerns about poor performance of asphalt mixes with higher RAP contents is currently the main reason for not using more RAP in surface course layers on local roads. About one third of the LPAs indicated that they did not see premature failure in surface layers with RAP mixes, while about 23% and 37% of LPAs have observed premature thermal cracking and fatigue cracking in surface course layers with RAP mixes, respectively.

A laboratory testing program was conducted to identify the factors that affect the performance asphalt mixtures with RAP. To this end, several mixtures were designed with different RAP contents, which included: 0%, 20%, 30%, 40, and 50% RAP by weight. Two RAP materials that have binders with different rheological properties were selected in this study. The laboratory testing program also evaluated the effect of using recycling agents (RA) on the performance of asphalt mixtures with high RAP contents. Three different types of recycling agents were used, namely, an aromatic oil (Hydrolene), a tall oil (Sylvaroad), and a vegetable oil (soybean). The propensity of all designed asphalt mixtures to fatigue cracking was evaluated using the semi-circular bend (SCB) and the indirect tensile strength tests. In addition, the low-temperature cracking potential was assessed using the asphalt concrete cracking device (ACCD). The susceptibility of the asphalt mixtures to moisture-induced damage was evaluated using AASHTO T 283 (modified Lottman test). Finally, the asphalt pavement analyzer (APA) was utilized to examine the resistance of asphalt mixtures to rutting.

The laboratory test results indicated that the use of RAP adversely affected the fatigue cracking resistance of asphalt mixtures when more than 30% RAP was used. The use of a softer binder (PG 64-28) was not effective in maintaining the fatigue cracking resistance of the mixes when more than 30% RAP was used. On the other hand, the results indicated that using a binder with appropriate low-temperature performance grade can contribute to satisfactory low-temperature cracking resistance of the RAP mixes. The SCB test results showed that the Hydrolene RA and the Sylvaroad RA significantly improved the cracking resistance of mixes with up to 50% RAP. The RAP source was also found to have a significant effect on the fatigue cracking resistance of RAP asphalt mixes, particularly those with more than 30% RAP. Therefore, it is very important to determine and consider the performance grade of the RAP binder in the design of asphalt mixtures with high RAP content.

Based upon current market prices, a cost analysis showed that a 50% RAP mix with Hydrolene RA can be 26% less expensive than 20% RAP mixes currently being used. In addition, a 50% RAP mix with Sylvaroad RA can be 13% less expensive than 20% RAP mixes currently being used.

Based on the results of Phase 1, it was recommended to conduct a field testing program to evaluate the performance of mixes with 30%, 40% and 50% RAP that are designed based on the recomendations provided in Appendix E of this report. The field testing program should include constructing the following test sections at RAP percentages shown below:

- A control section with a surface course mix that includes the currently allowed RAP content.
- A section with a surface course mix that includes 30% RAP and a binder meeting PG 64-28.
- A section with a surface course mix that includes 30% RAP and a binder meeting PG 64-22 and Sylvaroad™ RP1000 recycling agent.
- A section with a surface course mix that includes 40% RAP and a binder meeting PG 64-22 and Sylvaroad™ RP1000 recycling agent.
- A section with a surface course mix that includes 50% RAP and a binder meeting PG 64-22 and Sylvaroad™ RP1000 recycling agent.
- A section with a surface course mix that includes 30% RAP and a binder meeting PG 64-22 and Hydrolene recycling agent.
- A section with a surface course mix that includes 40% RAP and a binder meeting PG 64-22 and Hydrolene recycling agent.
- A section with a surface course mix that includes 50% RAP and a binder meeting PG 64-22 and Hydrolene recycling agent.

2. Project Background

Asphalt pavement is the most recycled material in the United States (US) (*1*). Reclaimed asphalt pavement (RAP) contains asphalt binder and aggregates; therefore, using it in new asphalt mixtures results in significant economic savings and environmental benefits. A survey conducted by the National Asphalt Pavement Association (NAPA) reported that more than 76.9 million tons of RAP were used in new asphalt mixtures in 2016, which resulted in more than $2 billion in savings (*1*). The use of RAP also conserves non-renewable natural resources (both asphalt and aggregates) and reduces the energy and emissions needed to obtain them. In addition, using RAP also reduces the amount of construction debris placed into landfills (*2*).

During the past four decades, state transportation agencies have allowed different percentages of RAP in the surface layer of its asphalt pavements. The resulting pavements have generally performed as well as those made with virgin materials. Long-Term Pavement Performance (LTPP) data from 16 U.S. states and two Canadian provinces indicated that overlay mixtures containing at least 30% RAP had the same performance as those with virgin materials only (*3*, *4*). More impressively, test sections containing 50% RAP at the National Center for Asphalt Technology (NCAT) Test Track outperformed companion test sections with all virgin materials in all pavement performance measures through five years of heavy loading (*5*, *6*).

A recent NAPA survey of the asphalt pavement industry reported that the average RAP content in new asphalt mixes across the U.S has steadily increased in recent years, with the national average RAP content around 20%. However, despite all of the economic and environmental benefits of using higher RAP contents in new asphalt mixtures, local public agencies (LPAs) in Ohio have allowed using only small percentages of RAP (i.e., less than 10%) in their roadways, if any. This is mainly attributed to the lack of a mix design procedure for asphalt mixtures incorporating higher RAP contents as well as guidelines for processing RAP utilized in local roadway construction. Furthermore, there is currently limited performance data for local roadways constructed with mixtures incorporating RAP; hence there is lack of confidence in the long-term performance of these mixtures.

Using higher amounts of RAP in new paving mixtures presents a concern that the resultant mixture may be prone to more load and non-load associated cracking during the service life of the pavement. This is due to fact that the asphalt binder contained in the RAP is oxidized/hardened due to aging. Over the past two decades, numerous research studies have been conducted to address issues with using higher percentages of RAP in asphalt mixtures. Most of these studies have focused on developing mix design procedures and specifications for mixtures used on interstates and highway systems only. Therefore, the results of these studies may not be directly applicable for mixtures used on local roads, because traffic volume, traffic type, turning movements, and traffic patterns are different for local roads. Using RAP may influence the performance of local roadways in a different manner. Therefore, research is needed to evaluate the effects of using RAP on the properties and the performance of asphalt mixtures that are typically used on local roadways. Furthermore, since no two sources of RAP are exactly the same, it is important to characterize the properties of the asphalt binder in the RAP as well as the aggregate properties of the RAP.

This project assessed the state-of-the-practice of using RAP in surface mixtures on local roads and examined the feasibility of using higher RAP contents in these mixes. Furthermore, it developed a method to design cost-effective, well-performing, and durable asphalt mixtures with various RAP contents to be used in the surface course of local roadways in Ohio. The project also developed recommendations for quality control of RAP incorporated into these mixes.

4. Research Context

The goal of this research is to assess the feasibility of RAP in the surface course of municipal and local roadways. The specific objectives of this project include:

- Assess the current practices of using RAP in surface course mixtures for local roadways.
- Develop recommendations for a cost-effective method for designing well-performing and durable surface course mixtures with different RAP contents for use on local roadways.
- Evaluate the cost benefits of using different RAP contents in the surface course layer of local roadways.
- Provide recommendations for quality control methods of RAP used in the surface mixtures of local roadways.

Phase 1 of this study included conducting the following tasks to achieve the outlined objectives:

Task 1. Perform literature review.
Task 2. Perform an assessment of the current state of the practice for RAP use on local roads in Ohio.
Task 3. Develop draft recommendations for mix design of RAP in the surface course of local roadways.
Task 4. Develop recommendations for quality control methods of RAP
Task 5. Perform benefit/cost analysis
Task 6. Provide recommendations for Phase 2 field testing of mix design recommendations.
Task 7. Prepare and submit interim report

A summary of the comprehensive literature review performed in this study is presented in Appendix A. Previous studies showed that the inclusion of RAP materials in asphalt mixes affects their performance by changing the rheological properties of the final binder blend and stiffening it (e.g. *7, 8*). All laboratory and field studies reported that the addition of RAP enhanced the rutting performance of asphalt mixtures (e.g. *9-12*). However, conflicting results were reported regarding the cracking performance of RAP mixtures (e.g. *11, 13, 14, 15*). Although numerous studies were conducted on the use of RAP in asphalt mixtures, limited studies focused on RAP asphalt mixtures used in construction of local roads. Therefore, research that evaluates the effects of using RAP on the properties and the performance of asphalt mixtures that are typically used in local roadways was needed.

5. Research Approach

Appendices A, B, C provide details about the tasks that were conducted to achieve the objectives of Phase 1 of this study. The following subsections summarize the research approach that was pursued in this study.

3.1 Literature Review

A comprehensive literature review was conducted in this study to identify mix design procedures used for asphalt mixtures incorporating RAP and determine the main factors that affect the volumetric properties, performance, and durability of asphalt mixtures with RAP. This also included reviewing all active and completed studies on the use of rejuvenators in asphalt mixtures containing RAP. The current state-of-practice for using recycling agents in asphalt mixtures containing RAP were documented. In addition, recycling agents that have been successfully implemented to improve the performance of asphalt mixtures containing RAP were identified. Appendix A presents a summary of the literature review conducted in this study.

3.2 LPA Current Practice for using RAP in Surface Mixes

A statewide survey was conducted to document current state-of-the-practice for using RAP on local roads in Ohio. A draft survey questionnaire was prepared by the research team and sent to the ODOT Technical Advisory Committee (TAC) for review in December of 2016. Modifications were made and some questions were added/deleted, based on comments received from the TAC. The revised survey was developed in SurveyMonkey (a copy of the survey is provided below) for distribution to different LPAs. The survey invitations were sent on December 21, 2016, and the due date for completing the survey was January 13, 2017.

The survey included 20 questions. The information collected in the survey included: the maximum RAP percentage allowed in the surface course asphalt mixtures for different RAP processing methods, RAP processing and stockpiling (storage) specifications, specifications on RAP properties, mix design specifications, as well as QC/QA procedures for mixtures with RAP. A Microsoft Excel file containing all the responses was downloaded from SurveyMonkey. A total of 40 responses were received. The results were analyzed and compiled. A summary of the survey results is provided in Appendix B.

3.3 Testing Program

3.3.1 Materials

3.3.1.1 Reclaimed Asphalt Pavement (RAP)

RAP materials were obtained from seven different resurfacing projects within Ohio. The binder was extracted and recovered from each of the RAP materials in accordance with AASHTO T164 and AASHTO R59. The performance grade was determined for each of the extracted and recovered RAP binder in accordance with AASHTO M320. Toluene was the solvent used to extract the RAP binders. Based on the obtained performance grades, two RAP materials that have binders with significantly different rheological properties and performance grade were selected in this study: Shelly 2017 Pile RAP-A (hereinafter referred to as RAP-1), and RAP-IR-270 (hereinafter referred to as RAP-2). Table 1 presents the high- and low-temperature grades for the two RAP binders.

Table 1. Continuous Performance Grade of RAP Binders

RAP ID	Continuous High-Temperature Grade, °C	Continuous Low-Temperature Grade, °C
Shelly 2017 Pile –A (RAP-1)	93.1	-14.3
IR 270 (RAP 2)	79.9	-21.1

3.3.1.2 Virgin Asphalt Binder

The target virgin asphalt binder was selected to meet the Superpave specifications for PG 64-22. This binder is typically used in surface course mixes on local roads with medium traffic. In addition, a softer binder meeting the specifications for PG 64-28 (PPA modified) was used. Both binders were obtained from the Shelly Company. All binders were tested in accordance with AASHTO M320 to determine their continuous performance grade.

3.3.1.3 Recycling Agents

Based on results of the literature review conducted in this study and presented in Appendix A, three types of recycling agents (RAs) were selected for evaluation in this study, these included: an aromatic oil (Hydrolene® H90T, hereinafter referred to as Hyrolene), a tall oil (Sylvaroad™ RP1000, hereinafter referred to as Sylvaroad), and a vegetable oil (soybean).

3.3.2 Optimum Recycling Agent Dosage

The optimum rejuvenator dosage was determined based on the method proposed in National Cooperative Highway Research Program (NCHRP) study 9-50 by (Martin et al. 2016). The first step in this method is to determine the continuous high and low temperature performance grades for the blends of the RAP binder and virgin asphalt binder that are prepared based on the percentages of these binders in the asphalt mix. The continuous high- and low-temperature grade of these blends with different RA dosages were then determined. Two different dosage levels were used in this study based on the recommended range provided by the manufacturer.

The dynamic shear rheometer test was conducted on unaged and Rolling Thin Film Oven (RTFO) aged samples of the binder blends to determine the continuous high-temperature grading temperature (PGH). Furthermore, the continuous low-temperature grading temperatures (PGL) were determined using the Bending Beam Rheometer test (BBR) conducted on Pressure Aging Vessel (PAV) aged samples of the binder blends. The PGH determined from the DSR tests on

RTFO aged and the unaged samples were plotted versus the RA dosage. In addition, the S-controlled PGL and m-controlled PGL are plotted versus RA dosage. A linear regression equation was established for each of the PGH and PGL data obtained. The RA dosage rate to restore the target binder PGH using the colder PGH regression line was first computed for each rejuvenator. The PGL of the binder selected RA dosage was then determined using the warmer PGL regression line to verify that it meets the target binder PGL. If the PGL of the selected RA dosage met the target binder PGL, this RA dosage was selected.

3.3.3 Mixtures

To evaluate the effects of the RAP materials on the mixture performance, a job mix formula (JMF) for an asphalt mixture with RAP that was used in construction of a surface course layer in a resurfacing project in the city of Columbus was obtained from the Shelly Company. The considered asphalt mixture had a 1/2 inch (12.5 mm) nominal maximum aggregate size (NMAS) and was designed to meet ODOT specifications for Item 441 for medium traffic surface mixtures. The selected mixture included PG 64-22 asphalt binder. The aggregate blend of the selected mixture used included: 47% limestone #8, 16% natural sand, 17% manufactured sand and 20% reclaimed asphalt pavement (RAP) that was processed using ODOT 401.04 Method 2.

Several asphalt mixes were designed and produced in the lab to evaluate the effects of RAP content and source. These included: a control virgin mixture (no RAP) as well as mixtures with 20% RAP, 30% RAP, 40% RAP, and 50% RAP. Mixtures were designed with RAP-Shelly-2017-PileA (referred hereafter as RAP-1) and RAP-IR 270 (referred hereafter as RAP-2). The aggregate gradation of all mixes were maintained as close as possible to that of the mix in the JMF by adjusting the percentages of virgin aggregates in the mix. The ratio between the percent manufactured sand and natural sand was kept constant for each mix to eliminate performance variability from sand angularity.

Equation 1, which was recommended by NCHRP 752, was used to determine the virgin binder performance grade. Based on that, the PG 64-22 binder was used in the control mix, and the mixes with 20% RAP-1, 30% RAP-1, 40% RAP-1, and 50% RAP-1 along with the different recycling agents. For mixes with recycling agents, the recycling agent was added to the PG 64-22 binder before mixing with aggregates. In addition, the 30%, 40% and 50% RAP-1 and RAP-2 mixes with no recycling agents were prepared with PG 64-28 asphalt binder.

$$T_{C(\mathrm{virgin})} = \frac{T_{C(\mathrm{need})} - (RBR \times T_{C(\mathrm{RAP\ binder})})}{1 - RBR} \quad (1)$$

where

$T_{c(\mathrm{virgin})}$ is the critical temperature (high or low) of the virgin asphalt binder.

$T_{c(\mathrm{needed})}$ is the critical temperature (high or low) needed for the climate and pavement layer.

RBR is the RAP to Binder Ratio. This is the ratio of the RAP binder in the mixture divided by the mixture’s total binder content

$T_{c(\mathrm{RAP\ Binder})}$ is the critical temperature (high or low) of the RAP binder.

The Marshall mix design method was performed to determine the optimum asphalt content for the different considered mixes. A target air void of 3.5% was used in the mix design. A total of eighteen mixtures were designed. A summary of the mix design results for the mixtures is presented in Table 2. It is noted that the RAP was manually sieved on ½’’ and split to ensure the consistency of the RAP portion in each mix. The split RAP was air-dried for 24 hours and then oven-dried for 3 hours at 110 °C.

Table 2. Tested Mixture Properties

Mix	% RAP	Virgin Binder type	Virgin AC%	RBR	G_{mm}
Control	0	PG 64-22	6.3	0	2.429
20% RAP-1	20	PG 64-22	5.3	16%	2.428
30% RAP-1	30	PG 64-28	4.8	25%	2.440
40% RAP-1	40	PG 64-28	4.3	33%	2.448
50% RAP-1	50	PG 64-28	3.8	41%	2.455
30% RAP-1 -Hydrolene RA	30	PG 64-22	4.8	25%	2.439
40% RAP-1 -Hydrolene RA	40	PG 64-22	4.3	33%	2.439
50% RAP-1 -Hydrolene RA	50	PG 64-22	3.8	41%	2.435
30% RAP-1 -Sylvaroad RA	30	PG 64-22	4.8	25%	2.440
40% RAP-1 -Sylvaroad RA	40	PG 64-22	4.3	33%	2.447
50% RAP-1 -Sylvaroad RA	50	PG 64-22	3.8	41%	2.444
30% RAP-1 -Soybean RA	30	PG 64-22	4.8	25%	2.437
40% RAP-1 -Soybean RA	40	PG 64-22	4.3	33%	2.441
50% RAP-1 -Soybean RA	50	PG 64-22	3.8	41%	2.439
30% RAP-2	30	PG 64-28	4.8	25%	2.434
40% RAP-2	40	PG 64-28	4.3	32%	2.433
50% RAP-2	50	PG 64-28	3.8	40%	2.438

3.3.4 Mixture Testing

Tests were performed on the different mixtures to evaluate their resistance to fatigue cracking, moisture damage, low-temperature cracking, and rutting. The propensity of the asphalt mixtures to fatigue cracking was evaluated using the semi-circular bend (SCB) test and indirect tensile strength. The low-temperature cracking potential was assessed using the asphalt concrete cracking device (ACCD). The susceptibility of the asphalt mixtures to moisture-induced damage was evaluated using AASHTO T 283 (modified Lottman test). Finally, the Asphalt Pavement Analyzer (APA) was utilized to examine the resistance of asphalt mixtures to rutting. All tested samples were prepared with air voids of 7 ± 0.5%. In addition, SCB and ACCD tests were conducted on short-term and long-term aged samples. The short-term aging involved placing the loose mixture for four hours at a temperature of 135°C before compacting the samples. The long-term aging was conducted according to AASHTO R30 and involved placing the samples in an environmental chamber for 5 days at 85°C.

3.4 Cost Analysis

A cost analysis for the different RAP content scenarios was conducted. To this end, the cost of surface mixtures with 30%, 40%, and 50% RAP was computed when using a softer binder, PG 64-28, as well as a PG 64-22, with different types of recycling agents in each of these mixes. The cost of the RAP mixes was determined using the price of the recycling agents obtained from the manufacturer and the optimum dosage rate identified in this study. The costs of milling, loading, and storing of RAP costs were not considered as contractors will encounter these costs whether a RAP is used or not. Note, in Ohio, the RAP material is owned and stored by the asphalt contractors. The cost of the 30%, 40%, and 50% RAP with different types of recycling agents was then compared to those of a virgin mix as well as a mix with 20% RAP.

6. Research Findings and Conclusions

Appendices A, B, and D present the results of the literature review, testing program, and analyses of tests conducted in this study, respectively. The following subsections provide a summary of the main findings and conclusions that were made based on the results obtained in this study.

4.1 Literture Review Findings

- For asphalt mixtures with high RAP contents (>20% RAP), it might be necessary to use a softer virgin asphalt binder or a recycling agent (rejuvenator).
- Some studies showed that for asphalt mixtures with more than 20% RAP but less than 30% RAP, the fatigue and low-temperature cracking resistance might be maintained by reducing the low-temperature performance grade of the virgin asphalt binder by one grade. However, for mixtures with more than 30% RAP, other studies showed that the low-temperature performance grade of the virgin binder should be reduced by two grades to maintain the cracking resistance.
- The positive effect of reducing the low-temperature performance grade of the virgin binder may be reduced by the increased storage time in the plant silo.
- Recycling agents were better at improving the mechanical properties of mixes with high RAP contents (>30% RAP) than softer binders. This is thought to be due to the ability of the recycling agents to restore some of the physical and chemical properties of the aged RAP binder.
- Among all types of recycling agents, aromatic extracts resulted in the best improvement to the laboratory performance of mixes with high RAP contents.
- Paraffinic oil recycling agents improved the low-temperature resistance of asphalt mixtures with high RAP contents. However, these recycling agents increased the rutting susceptibility of high RAP mixes and did not improve their fatigue cracking resistance.
- Naphthenic oil recycling agents improved the resistance to thermal cracking and moisture damage of high RAP mixtures and slightly enhanced their fatigue cracking resistance. However, these recycling agents resulted in higher rutting of high RAP mixtures.
- Waste vegetable oil and grease recycling agents improved the fatigue and thermal cracking resistance of high RAP mixtures, particularly when used in mixtures with 50% RAP. However, these recycling agents increased the rutting propensity of these mixtures and had a slightly adverse effect on their moisture susceptibility.
- Hydrogreen recycling agent improved the resistance of high RAP mixes to moisture damage and fatigue cracking. It also reduced the susceptibility of these mixtures to thermal cracking , butslightly increased their rutting potential.
- Sylvaroad recycling agent improved the resistance of asphalt mixtures with 50% RAP to thermal and fatigue cracking. However, there is currently no information on its effect on the moisture sensitivity and rutting resistance of such mixtures.
- Sylvaroad is the most expensive recycling agent, followed by Hydrogreen. Waste engine oils (paraffinic oils) and waste vegetable oils are the least expensive recycling agents.

- For the different types of recycling agents, the low and high-temperature properties and performance grade of asphalt binders decreased linearly with the increase in the recycling agent dosage.
- The recycling agent dose can be selected by determining the amount of recycling agent that needs to be added to the RAP and virgin asphalt binder blend so that it meets the target performance grade at the project site.
- The design of RAP mixes should include evaluating their resistance to rutting, moisture damage, thermal cracking, and fatigue cracking.
- The properties of the RAP that have the greatest impact on the design of mixes with high RAP content include: RAP asphalt content, continuous grade of the recovered RAP binder, and RAP aggregate properties.

4.2 Survey Findings

- About half of the responding LPAs indicated that Marshall mixes designed for medium traffic (ODOT item 441 for medium traffic) are the most commonly used mix.
- More than half of the LPAs allow using RAP in surface mixes. The majority of them are using ODOT limits. However, one third of responding LPAs indicated that RAP is not allowed in their surface mixes. The main reason for this is concerns about the performance of RAP mixtures.
- About half of the responding LPA agencies do not have any RAP processing requirements. About one-third use ODOT Method 1 for processing RAP (Standard RAP),and about 15% of LPAs responding to this survey use ODOT Method 2 for processing RAP (Extended or Fractionated RAP).
- The majority of LPAs do not have any RAP management requirements or quality control/ quality assurance specifications for RAP mix.
- About 30% of LPAs believe that there is no obstacle stopping LPAs from increasing the allowed RAP percentages on local roads. On the other hand, about 40% of the LPAs think that the concerns about poor performance of asphalt mixes with higher RAP contents is the main reason for not using more RAP in surface course layer on local roads.
- About one third of the LPAs did not notice any premature failure in surface layers with RAP mixes. However, about 23% and 37% of LPAs have observed premature thermal cracking and fatigue cracking in surface course layers with RAP mixes, respectively.

4.3 Analysis Findings

- This study suggests that use of softer binder PG 64-28 was not effective in maintaining the fatigue cracking resistance of the RAP-1 mixes when more than 30% RAP was used.
- These results suggest that using a binder with appropriate low-temperature performance grade can help ensure satisfactory low-temperature cracking resistance of the RAP mixes.
- Hydrolene RA and Sylvaroad RA significantly improved the cracking resistance of mixes with up to 50% RAP.
- The Hydrolene RA was more effective than the Sylvaroad RA.
- RAP mixes with Soybean RA had better performance than those with softer binder (PG 64-28). However, mixes with 40% and 50% RAP with Soybean RA had much lower resistance to fatigue cracking when compared to high RAP mixes and the other RAs.

- The properties of RAP binder have a significant effect on the binder fatigue cracking resistance of RAP asphalt mixes, particularly those with more than 30% RAP. It is believed that this attributed to the effect of the RAP binder properties on the adhesion of the binder in high RAP mixes. Therefore, it is very important to determine the performance grade of the RAP binder when designing high RAP mixes.
- Cost analyses showed that a 50% RAP mix with Hydrolene RA can be 26% less expensive than RAP mixes currently being used.
- Cost analyses showed that a 50% RAP mix with Sylvaroad RA can be 13% less expensive than RAP mixes currently being used.

6. Recommendations for Implementation

It is recommended to conduct a field testing program to evaluate the performance of mixes with 30%, 40% and 50% RAP that are designed, based on the recomndations provided in Appendix E. The field testing program should include constructing the following test sections:

- A control section with a surface course mix that includes the currently allowed RAP content (20%).
- A section with a surface course mix that includes 30% RAP and a binder meeting PG 64-28.
- A section with a surface course mix that includes 30% RAP and a binder meeting PG 64-22 and Sylvaroad™ RP1000 recycling agent.
- A section with a surface course mix that includes 40% RAP and a binder meeting PG 64-22 and Sylvaroad™ RP1000 recycling agent.
- A section with a surface course mix that includes 50% RAP and a binder meeting PG 64-22 and Sylvaroad™ RP1000 recycling agent.
- A section with a surface course mix that includes 30% RAP and a binder meeting PG 64-22 and Hydrolene recycling agent.
- A section with a surface course mix that includes 40% RAP and a binder meeting PG 64-22 and Hydrolene recycling agent.
- A section with a surface course mix that includes 50% RAP and a binder meeting PG 64-22 and Hydrolene recycling agent.

The majority of previous studies have introduced the recycling agent to the mixtures by adding it to the binder prior to mixing with the RAP and aggregates. Future research should evaluate different methods to introduce the recycling agents to the asphalt mix to determine the optimal one.

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Appendix A Literature Review

A.1 Introduction

In response to the increased cost of asphalt mixtures and the Federal Highway Administration's policy to increase environmental stewardship (FHWA 2015), there has been a growing interest to increase the amounts of Reclaimed Asphalt Pavement (RAP) used in asphalt mixtures. RAP is typically obtained from pavement resurfacing by surface milling or from pavement reconstruction activities that involve full-depth removal. A survey conducted by the National Asphalt Pavement Association (NAPA) reported that more than 71.9 million tons of RAP were used in new asphalt mixtures in 2014, which resulted in more than $2.6 billion in savings (*1*). The use of RAP also conserves non-renewable natural resources (both asphalt and aggregates) and reduces the energy and emissions needed to obtain them. In addition, using RAP also reduces the amount of construction debris placed into landfills (*2*).

Although using RAP in new asphalt mixtures has several economic and environmental benefits, transportation agencies have been reluctant to allow producers to use more than 20% RAP in the surface layer. One of the main reasons for the hesitance of these agencies is a lack of guidelines for designing mixtures with higher percentages of RAP. Another reason is the variability of RAP and the lack of specifications for processing and controlling the quality of RAP materials incorporated in asphalt mixtures. Finally, there is currently a lack of confidence in the performance of surface course mixtures incorporating higher RAP contents, which can be attributed to the relatively scarce performance data for roadways constructed using these mixtures. Several research studies have been performed to address these issues. The following subsections provide a summary of these studies.

A.2 Performance of RAP Mixes

RAP material contains asphalt binder that is hardened due to aging and thermal oxidization, which increased the stiffness of the RAP mixture. Mixtures that are too stiff are less workable, difficult to compact and might be more prone to field failures. Therefore, increasing the RAP content in asphalt mixes requires a comprehensive understanding of the effects of RAP on pavement performance. Numerous studies have been performed to evaluate the laboratory and field performance of asphalt mixes with RAP. A summary of these studies is provided below.

A.2.1 Lab Studies

Table 1 summarizes the results of previous laboratory studies. In general, laboratory studies reported that the use of RAP in asphalt mixtures improves their rutting resistance (e.g. *3, 5, 9, 11, 13*). There was no consensus on the effect of RAP on resistance to fatigue cracking, as it depended on different factors. Zhang et al. (*3*) used the indirect tensile strength (IDT) test to evaluate the thermal and fatigue cracking resistance of laboratory-produced and field-produced mixes with different RAP contents ranging from 0% to 50%. The results of their study indicated that mixes with a low percentage of RAP (17% RAP) had similar fatigue performance to those of the control mix without RAP. In addition, for mixes with more than 17% RAP, the effect of RAP on fatigue cracking depended on the target performance grade (PG).

Table 1. Summary of Laboratory Studies on the Performance of RAP Mixes

Study	Test Methods	Material Information	Properties				RAP %
			Fatigue Cracking	**Rutting**	**Moisture Susceptibility**	**Low-Temperature**	
Zhang et al. (3)	Dynamic modulus, flow number, & indirect tensile strength (IDT)	Superpave, two binders PG 70-28, PG 58-28	Did not affect at < 17% RAP; the effect depended on the target PG when more than 17% used	The addition of RAP increased the rutting resistance		No significant effect it with use of softer binder	0, 17, 30, and 50 (Lab Mix) & 30 (Field Mix)
Aurangzeb et al. (4)	Flexural beam fatigue test		The addition of RAP to mixtures slightly improved fatigue life				0 to 50
Al-Qadi et al. (5)	Complex modulus, Hamburg wheel tracking (HWT), & bending beam fatigue (BFF)		The addition of RAP to mixtures slightly improved fatigue life	The addition of RAP increased resistance to rutting			0 to 50
McDaniel et al. (6)	Testing of recovered RAP binder, push-pull test & low-temperature IDT		40% RAP mixes exhibited higher fatigue resistance followed by control mix		Increasing RAP content increased the high-temperature properties of the recovered binders.	For 40% RAP, resistance decreased even with binder grade bumping. No effect up to 25% RAP	0, 15, 25, and 40
Mogawer et al. (7)	Overlay tester (OT) &, HWTD and BBR on recovered RAP binder	Field mixes, binders: PG 64-22 adjusted to PG 58-28, PG 64-28 adjusted to PG 52-34, & PG 64-28	Decreased cracking resistance with increasing RAP content. For all RAP mixes except one, cracking resistance improved when using the softer PG virgin binder		Only one of the RAP mixes (30 percent) failed the moisture damage test in the HWTD	Recovered binder showed warmer in Tcr with increasing RAP content. The use of a softer virgin binder may improve resistance to low-temperature cracking	≥ 40
Hajj et al.(8)	BBF	Three sources of RAP and two binders: PG 64-22 & PG 64-28NV	Fatigue resistances of polymer-modified mixes were significantly higher than those prepared with unmodified binders regardless of the RAP content. The fatigue resistances of polymer-modified mixtures with 15 percent and 30 percent RAP were significantly better than the virgin mixes with neat binder				0, 15, and 30

Table 1. Summary of Laboratory Studies on the Performance of RAP Mixes (continued)

Study	Test Methods	Material Information	Properties				RAP%
			Fatigue Cracking	Rutting	Moisture Susceptibility	Low-Temperature	
Li et al. (9)	Dynamic modulus test, semi-circular bend (SCB)	RAP from different sources		RAP source significantly affected dynamic modulus values at high temperatures		Up to 20% RAP no effect. Mixes with 40% RAP had significantly lower fracture resistance. RAP source was not a significant factor.	0,20, and 40
Shu et al. (10)	IDT, IDT Creep, resilient modulus, &BBF	Marshall mixes. PG 64-22.	Fatigue cracking negatively affected by the addition of RAP. Beam fatigue results indicated that the higher RAP contents were more resistant to fatigue			Mixes became more brittle with greater quantities of RAP.	0, 10, 20, and 30
Zhao et al. (11)	HWT, AASHTO T 283, IDT & BBF	Mixes were designed using Marshall mix design, PG 64-22	Increasing the RAP content of the HMA mix did not show a significant effect	Rutting resistance was improved by adding RAP to the mixes	Improved resistance to moisture-induced damage		0, 30, 40, and 50
Behnia et al. (12)	Displacement-controlled tensile loading (DCT)					Fracture energy decreases with significant increase in the RAP content.	0 to 50
Apeagyei et al. (13)	HWT & flow number			The addition of RAP decreased rutting due to binder grade bumping			0 to 25
Hajj et al. (14)	AASHTO T 283 & Thermal Stress Restrained Specimen Test (TSRST)	Marshall field mixes			Acceptable moisture damage resistance improved with the use of the softer virgin binder	Similar up to 15%. 50% RAP reduced resistance to low-temperature cracking. Using a softer binder improved resistance to low temperature cracking.	0, 15, and 50
Tabaković et al. (15)	BBF		The addition of RAP to mixtures slightly improved fatigue life				10 to 30

Mogawer et al. (*7*) used the overlay tester (OT) device to examine the fatiguing cracking resistance of asphalt mixes with up to 40% RAP. Their results indicated decreasing resistance to cracking with increasing RAP content. In all mixes except the one with 40% RAP, cracking resistance was improved when using a softer PG virgin binder. McDaniel et al. (*6*) used the push-pull test to evaluate mixes with 0%, 15%, 25%, and 40% RAP. The results of their study indicated that mixes with 40% RAP exhibited the highest fatigue resistance followed by the mixes without any RAP. Furthermore, the mixes with 15% and 25% RAP had similar fatigue performance. In addition, Aurangzeb et al. (*4*), Al-Qadi et al. (*5*), and Tabaković et al. (*15*) used the flexural beam fatigue test to analyze mixtures with different RAP contents that ranged between 0% and 50%. They concluded that the addition of RAP slightly improved the fatigue resistance of asphalt mixes. It is worth noting that recent studies indicated that the flexural beam fatigue test is highly variable and might not detect the effect of RAP on fatigue cracking performance (*16, 17*). In general, laboratory studies indicated that using up to 20% RAP did not significantly affect the fatigue cracking resistance of asphalt mixes.

Zhang et al. (*3*) found no significant effect of the RAP on low-temperature performance of asphalt mixes. Li et al. (*9*) used the semi-circular bend (SCB) test to evaluate the low-temperature cracking resistance of ten mixes with varying RAP contents that ranged between 0 and 40%. Mixes with 20% RAP had comparable fracture resistance to the control mixtures. However, mixes with 40% RAP had significantly lower low-temperature fracture resistance. Behnia et al. (*12*) used the disk-shaped compact tension test to assess the effect of RAP on the low-temperature fracture properties of asphalt mixes and to evaluate the effect of reducing the virgin binder grade to compensate for the increased stiffness of mixes with high RAP contents. The results of their study indicated that mixes with 30% RAP with a softer binder had acceptable low-temperature fracture properties compared to the mixes without RAP. Hajj et al. (*14*) used the Thermal Stress Restrained Specimen Test (TSRST) to evaluate thermal cracking of mixes with 0%, 15%, and 50% RAP. The results of their study indicated that mixes with 0% and 15% RAP exhibited similar TSRST fracture temperatures. However, mixes with 50% RAP had lower thermal cracking resistance.

A.2.2 Field Studies

The field performance of pavement sections with RAP mixes was reported in previous studies. Anderson and Daniel (*18*) compared the long-term performance of roadway sections constructed with mixes of high RAP content (>20% RAP) to those without any RAP. The results of their study indicated that the high RAP sections exhibited slightly higher degree of cracking, lower ride quality and better rutting resistance than the virgin sections; however, the differences were not statistically significant. Dong and Huang (*19*) examined the data from the Long-Term Pavement Performance (LTPP) Specific Pavement Study 5 (SPS-5) program and found that the addition of 30% RAP in the overlay accelerated the initiation of longitudinal cracks in the wheel path but did not affect the initiation of the other types of cracking. Maupin et al. (*20*) examined the performance of ten test sections that used mixes with more than 20% RAP and compared them to control sections that had mixes without RAP. All mixes in this study were prepared using a PG 64-22 asphalt binder. Maupin et al. (*20*) found no significant differences between the performance of sections with high RAP content mixes and the control sections.

Zaghloul and Holland (*21*) examined 47 pavement sections containing up to 15% RAP for the long-term performance in three California environmental zones: desert, mountain, and north coast. The performance of the RAP sections was compared on the same route with other treatments. The in-situ structural capacity, distress condition, and roughness condition were estimated by using developed deterioration models. Also, all treatments based on the field-observed conditions were estimated by using service lives. The results of the studies indicated that, for all three environmental zones, there were no significant differences between the long-term performance of sections containing RAP and those with other treatments.

West et al. (*22*) examined the performance of the field test sections that were built as part of the LTPP SPS-5 program and included using mixes with 30% RAP. The results of their analysis showed that overlays using mixes containing 30% RAP were found to perform as well as those constructed with virgin mixes in terms of International Roughness Index (IRI), rutting, block cracking, and raveling. About a third of the projects had more longitudinal cracking or transverse cracking in the overlays containing RAP compared to the virgin mix overlays. Anderson (*22*) examined the long-term performance data for high RAP content pavement sections from eight states and one Canadian province. The examined sections included mixes with different RAP percentages varying between 0 and 45%. Anderson (*22*) found that pavements constructed using high RAP contents had similar performance to those constructed using virgin materials. However, the sections with high RAP content had, in general, more cracking and rutting, but the differences were not significant. Hong et al. (*23*) analyzed the performance of the Texas SPS-5 experimental sections from the LTPP program. The test sections with 35% RAP mixes were compared to the sections with virgin mixes in the Texas field project. The results of these analyses indicated that the test sections containing RAP had higher cracking but comparable roughness and less rutting after 16 years of service. In addition, the overall evaluation suggested that a well-designed mix with 35% RAP could satisfactorily perform as that with virgin materials.

A.3 The Use of Softer Asphalt Binders

Different studies evaluated the effect of using softer virgin asphalt binders when more than 20% RAP is utilized in an asphalt mixture to counteract the stiffening effect of the RAP binder. Mogawer et al. (*7*) indicated that the low-temperature properties of RAP mixes might be improved by using a softer virgin binder. However, their results indicated that the softer binder did not improve the fatigue cracking resistance when 40% RAP was used. Mogawer et al. (*7*) concluded that the positive effect of bumping down the binder grade may be nullified by the increased storage time in the plant silo. Hajj et al. (*14*) reported that the binders recovered from mixes with 50% RAP met the high-temperature grade requirement but did not meet the low-temperature requirement when a softer virgin binder is used. However, the tests on the mixes showed that using a softer binder improved their resistance to moisture damage and thermal cracking. The results of a study reported by Zhang et al. (*3*) indicated that the use of softer binder in mixes with 30% RAP did not have a significant effect on their thermal cracking resistance but decreased their rutting resistance. The overlay tester results performed by Zhou et al. (16) indicated that fatigue cracking of RAP mixes was only improved by using a polymer modified binder that is two grades softer. The study by Shah et al. (*25*) with 40% RAP and West et al. (*26*) with 55% RAP also showed that there was no clear benefit of reducing the binder grade by one level. Bennert et al. (*27*) evaluated the laboratory performance of plant-produced mixtures with 50% RAP or more. The results of the study showed a marginal improvement in low-temperature cracking properties when softer grade of binder was used. In addition, using a softer asphalt binder did not improve the intermediate temperature cracking performance. Apeagyei et al. (*13*) and McDaniel et al. (*6*) also indicated that binder grade bumping decreased rutting resistance.

A.4 Recycling Agents (Rejuvenators)

Although bumping the PG grade of a virgin asphalt binder (i.e. using softer binder) has been used by some transportation agencies in RAP mixes, the use of a recycling agent (RA) or rejuvenators might be more beneficial when using high RAP contents as those agents might help to restore the physical and chemical properties of the aged RAP binder, not just softening them (*28,29*). Shah et al. (*25*) indicated that the mechanical properties of RAP mixtures using the rejuvenator were better than those containing the softer binder and that 10% more RAP could be incorporated in Superpave mixtures by using a rejuvenator, rather than using a softer binder. Im, et al. (*30*) concluded that more RAP can be used in asphalt mixes if the use of RAs is permitted. They suggested that a RA can make the final binder blend in high RAP mixes meet the specification requirements for both high and low PG grades for PG 70-22 or PG 64-22 binders. RAs are additives that have chemical and physical characteristics that enable them to diffuse in and react with the aged asphalt binder and restore its adhesive and mechanical properties (*31*). Typically, RAs should contain a high proportion of maltenes that help re-balance the composition of an aged binder that lost a portion of its maltenes during construction and pavement service life (*32*). In addition, they would also allow a significant increase in the amount of RAP used in the mix design, and, perhaps even provide a chance for total (100%) mix recycling (*33*).

It is important to distinguish RAs from softening agents. The polarity and molecular weight of asphalt binders increase by oxidative aging, which causes the solvent phase in the asphalt binder to mutate from non-polar to polar or associated micelles (*34*). While softening agents add lower molecular weight and/or low polarity oils to supplement the solvent phase in the asphalt colloidal structure, RAs break up micelle association and agglomerations to disrupt structures formed by aging using hydrocarbons (*17*). Therefore, softening agents can lower the viscosity but do not restore the stiffness and phase angle. Examples of softening agents include asphalt flux oils (generally blended with bitumen to reduce the viscosity), lube stock (a fraction of crude oil that has a viscosity similar to lube oils), lubricating or crankcase oils (usually highly aliphatic), or slurry oils (oil bottoms from the catalytic cracking process) (*34*).

A.4.1 Recycling Agent Working Mechanisms

The working mechanism of RAs depends on two processes, which are the uniform dispersion of the recycling agents within the recycled mixture and their diffusion into the aged binder coated on the outside of the aggregate (*35*). The first process “dispersion” is known as mixing caused by physical processes. Through mechanical mixing at the plants, the RA will be distributed uniformly over the virgin binder and the mixture (*35*). Thus, the efficiency of RAs can be expressed as a function of mixing time. The mechanical mixing at the plant is usually adequate to achieve uniform dispersion of the RA within the recycled mixture, although in some cases the aged binder tends to quickly absorb any hydrocarbon-type liquid before that liquid is uniformly distributed throughout the mixture (*17*).

Diffusion is the second process in which the constituent moves from a higher concentration to a lower concentration (*17*). RAs spread into the aged binder in four steps according to Carpenter and Wolosick (*36*). In the first step, the rejuvenator forms a very low viscosity layer surrounding the aggregate particles coated with aged asphalt binder. In the second step, it starts to penetrate into the aged binder and softens the binder. In the third step, the rejuvenator penetrates into the aged binder, and the viscosities of both inner and outer layers are gradually decreased. Finally, by passing time, equilibrium is reached over the majority of the recycled binder film (*37*). The study showed that the RA’s diffusion into the aged binder occurred during mixing, construction, and a period after construction. The diffusion rate can be influenced by different factors, including: the size and shape of molecules or agglomerations, intermolecular forces, temperature, structural rigidity of the diffusing molecules, and microscopic structure of a relatively stationary phase. The temperature was found to have the highest influence on the diffusion rate (*37*). The diffusion rate is governed by the viscosity of the maltene phase rather than the viscosity of the recycled binder as a whole. Adding the diluent oil fractions and/or raising the mixing and compaction temperatures can accelerate the diffusion process (*35*), while incomplete diffusion can have adverse effects on the performance of the resulting binder and asphalt mix (*17, 29*). Better diffusion can happen if the RA is mixed with the recycled materials before mixing them with the virgin binder and aggregate, despite the increase in the production cost (*17*).

A.4.2 Types of Recycling Agents

Different RAs have been developed during the past decade, which can be classified as organic and petroleum based on the material and process used to manufacture them. Table 2 presents a description of the main types of organic and petroleum RAs. Petroleum RAs are produced through refining and modification of light and heavy crude oil. These rejuvenators include mainly aromatic, napthenic and paraffinic oils with varying molecular weights. Petroleum type rejuvenators can also be found as a mix of aromatic oil and resin compounds with small concentrations of saturates (*31*). Organic RAs are typically made from vegetable oils, which are categorized into three groups based on their sources: 1- major oils (from human and animal-feed consumption and plants), 2- minor oils (with fatty acid profiles), and 3- non-edible oil (plants cultivated for food production). Table 3 provides the cost, dosage, and other characteristics for the different types of petroleum and organic RAs. Organic RAs require a smaller dose as compared to petroleum RAs to cause a similar effect on the aged asphalt binder. In addition, organic RAs are in general less expensive than petroleum RAs.

Table 2. Description of Different Types of RAs (*17, 35*)

Category	**Type**	**Recycling Agent Example**	**Description**
Petroleum	Paraffinic Oils	Waste Engine Oil (WEO) Waste Engine Oil Bottom (WEOB) and Hydrolene SP125	Refined used lubricating oils. Consist of straight or branched chains of hydrogen and carbon atoms containing at least 18% of aromatics
	Aromatic Extracts	Hydrolene and Cyclogen L	Refined crude oil products with polar aromatic oil components
	Naphthenic Oils	SonneWarmix RJ™ and Ergon HyPrene	Engineered hydrocarbons for asphalt modification
Organic	Triglycerides & Fatty Acids	Waste Vegetable Oil (WV Oil) and Waste Vegetable Grease (WV Grease)	Derived from vegetable oils
		Evoflex	Consists of fatty acid derivatives
	Tall Oils	Sylvaroad™ RP1000 and Hydrogreen (formerly BITUTECH RAP)	Paper industry by-products Same chemical family as liquid antistrip agents and emulsifiers

Table 3. Characteristics of Different Types of RAs (*29*, *35*, *38*)

RA	Min Dose (%)	Max Dose (%)	Category	Refined or Waste	Polarity	Cost per Ton of Material
Paraffinic Oils	16.0	25.0	Petroleum	Waste	Slight	$418
Aromatic Extracts	11.5	27.8	Petroleum	Refined	Very	$1200
Naphthenic Oils	9.1	18.4	Petroleum	Refined	Very	$1427
Triglycerides & Fatty Acids (WV Oil)	7.4	16.4	Organic	Waste	Non	$600
Triglycerides & Fatty Acids (WV Grease)	8.1	16.4	Organic	Waste	Mild	$664
Hydrogreen Tall Oils	9.4	18.8	Organic	Refined	Mild	$1445
Sylvaroad	8.0	18.8	Organic	Refined	Mild	$2161

A.4.3 Effect of Recycling Agent on Performance of RAP Mixes

Several laboratory studies have been conducted during the past few years to evaluate the effects of the different types of RAs on the mechanical properties and performance of mixes with RAP. Table 4 presents a summary of the results of these studies. In general, all of the paraffinic oils resulted in higher rutting susceptibility. In addition, all of them except the Hydrolene SP125 did not improve the fatigue cracking resistance of mixes with high RAP content (>40% RAP). In general, the paraffinic oils improved the low temperature properties of the RAP mixes. Aromatic extracts and oils improved the resistance of high RAP mixes to fatigue and thermal cracking as well as to moisture damage. In addition, they slightly increased the rutting of high RAP mixes, but within acceptable limits. Naphthenic oils increased rutting but improved the RAP mixture's resistance to thermal cracking and moisture damage. In addition, they had slightly improved the fatigue cracking resistance. Triglycerides and fatty acid recycling agents decreased the moisture and rutting susceptibility of RAP mixes. They improved the fatigue and thermal cracking resistance, particularly when used in mixes with 50% RAP (*38*). Hydrogreen (tall oils) reduced the resistance to low-temperature cracking and slightly increased rutting of RAP mixes. However, they improved resistance to moisture damage and fatigue cracking. Veeraragavan et al. (*38*) reported that Sylvaroad (tall oil) improved thermal and fatigue cracking resistance of mixes with 50% RAP, but they did not evaluate the effect of this RA on moisture sensitivity or rutting of the RAP mixes.

Evoflex is another type of rejuvenator that some asphalt paving contractors have used, along with Evotherm M1 (a warm mix asphalt additive), in asphalt mixtures containing RAP and Recycled Asphalt Shingles (RAS). Limited studies have evaluated the effects of Evoflex on the performance and mechanical properties of mixes with high RAP contents. A recent study by Texas DOT evaluated the effect of Evoflex on the rutting and fatigue cracking resistance of mixes with 10% RAP and 5% RAS. The results of that study indicated that Evoflex improved the fatigue cracking resistance of the RAP/RAS mix but increased its rutting. That study also showed that the RAP/RAS mix had better rutting and fatigue cracking performance when Hydrogreen was used as the recycling agent.

Table 4. Summary of Previous Laboratory Studies on the Effect of RAs on RAP Mixes Performance

RA Type	RA Name	Resistance to:				Study
		Rutting	Thermal Cracking	Moisture Damage	Fatigue Cracking	
Paraffinic oil	Waste Engine Oil (WEO)	Increased rutting susceptibility but still passed and was lower than virgin mix	Improved but still was worse than virgin mixture	Improved	Reduced	(29) (39) (40)
	Waste Engine Oil Bottom (WEOB)	Increased rutting susceptibility but still passed and was lower than virgin mix	Improved but still was worse than virgin mix	Improved	Reduced (both tensile strength and fracture energy) (worst)	(29) (39) (40)
	Holly Frontier Hydrolene SP125	Increased rutting susceptibility but still passed and was lower than virgin mix	Improved and was better than virgin mix	Improved	Improved	(29) (39) (40)
	Valero VP 165	Increased rutting resistance based on binder testing	Decreased, but still was within the range	Improved	Reduced	(41)
Aromatic Extracts	Hydrolene	Slightly increased rutting but has the least rutting depth among all RAs	Improved properties and was better than virgin mix	Improved	Improved the fatigue cracking resistance, but was worse than virgin mix	(29)
	Cyclogen L	Increased the rutting of 50% RAP mix but still rutting was acceptable	Improved for 50% RAP mix	Improved	Improved for 50% RAP mix	(35) (39) (40)
Naphthenic Oils	SonneWarmix RJ™	Rut depth passes increased	Improved and was better than virgin mix	Improved	Slightly improved, but was worse than virgin mix	(40) (42)
Triglycerides & Fatty Acids	Waste Vegetable Oil (WV Oil)	Has the second highest rutting depth, rutting susceptibility increased	Improved and was similar to the virgin mix	Reduced resistance	Improved significantly when more than 11% used	(29) (40)
	Waste Vegetable Grease (WV Grease)	Has the highest rutting depth passes, significantly increased rutting susceptibility	Improved but still was worse than virgin mix	No effect	Slight improvement	(29) (40)
	Evoflex	Increased rutting	Not reported	Not reported	Improved	(30)
Tall Oils	Sylvaroad	Not reported	Improved	Not reported	Improved	(38)
	Hydrogreen	Increased rutting susceptibility but still passed and was lower than virgin mix	Reduced (worst)	Improved	Improved	(29) (40) (30)

A.4.4 Optimum Recycling Agent Dose

When using recycling agents in RAP asphalt mixes, selecting their appropriate dosage is very important and can significantly affect their ability to restore the properties of the aged RAP binder. Normally, the RA dosage is recommended by the manufacturers based on their experience, and small dosages are typically preferred. However, the dosage for a particular RA cannot be fixed for asphalt mixtures with different types and amounts of recycled materials, since the mixture may be affected by other factors such as the binder PG grade, the binder source, and the aggregate type (*17*).

The effect of an RA on the aged RAP binder increases with the increase in RA dosage. However, using a higher RA dosage will be costly and potentially detrimental to the performance of the RAP mixture, particularly for rutting (*17*). The results of previous studies indicated that for different types of RAs, the low and high-temperature properties and performance grade of the asphalt binder decrease linearly with the increase in the RA dosage. In addition, some studies reported a linear reduction in the intermediate temperature fatigue parameter ($G^*\cdot\sin\delta$) with the increase in RA dosage at least until passing the Superpave requirement of 5,000 kPa (*33*).

Zaumanis et al. (*33*) conducted a laboratory study to determine the optimum dose of different types of RAs, which included: aromatic extract, waste engine oil, waste vegetable oil, organic oil, waste vegetable grease and distilled tall oil. Based on their study, they recommended using Equations 1 and 2 to determine the RA dose to ensure adequate low temperature and fatigue cracking resistance, respectively, and setting the minimum dose as the higher value obtained from these equations. In addition, they recommended using Equation 3 to determine maximum RA dose to ensure sufficient rutting resistance. The optimum dose should be selected to be between the computed maximum and minimum RA dose value.

$$\text{Max dosage\%} = \frac{(\text{high PGtarget} - \text{high PGRAP}) \times (-\%\text{trial})}{(\text{high PGRAP} - \text{high PGtrial})} \quad (1)$$

$$\text{Min dosage}_{\text{low PG}}\ \% = \frac{(\text{low PGtarget} - \text{low PGRAP}) \times (-\%\text{trial})}{(\text{low PGRAP} - \text{low PGtrial})} \quad (2)$$

$$\text{Min dosage}_{\text{intermed PG}}\ \% = \frac{(5000 - \text{Intermed PGRAP}) \times (-\%\text{trial})}{(\text{Intermed PGRAP} - \text{Intermed PGtrial})} \quad (3)$$

Where (%trial) is the rejuvenator dosage for trial blend (%), high PG_{target} is the specified high PG temperature (°C), high PG_{RAP} is the RAP high PG temperature (°C), high PG_{trial} is the high PG temperature for trial blend (°C), and the same notations for low and intermediate PG.

Recently, Martin et al. (*43*) proposed a method for selecting the optimum RA dosage. The method involves preparing three asphalt binder blends: one with no RA, one with a high RA dosage, and one with a low RA dosage. The following steps are then used to determine the optimum RA dosage:

1. Plot original PG at high temperature (PGH), Rolling Thin Film Oven (RTFO) aged PGH, S-controlled PG at low-temperature (PGL), and m-controlled PGL values versus RA dosage.
2. Establish linear regression equations for each value versus RA dosage.
3. Select initial RA dosage rate in 0.5% increments to restore the target binder PGL using the warmer PGL regression line between S-controlled and m-controlled PGLs.

4. Check PGH at initial RA dosage versus target binder PGH using the colder PGH regression line between original and RTFO PGHs.
5. If target binder PGH was not met, increase/decrease the RA dosage in 0.5% increments while maintaining the target binder PGL.

Martin et al. (*43*) also recommended that the selected RA dose should be verified by preparing and testing the RAP mixtures using that RA dose to check the stiffness, rutting, as well as intermediate and low-temperature cracking resistance.

A.5 Mix Design Methods for RAP Mixes

It is generally held that incorporating small amounts of RAP (up to 15%) in an asphalt mixture does not require altering the mix design (*7*). However, incorporating higher percentages of RAP requires mix designs that include adjustments for aggregates and aged asphalt binder that is introduced into the mixture by adding the RAP. In addition, designing mixes with higher RAP contents using Marshall or Superpave mix design methods may not ensure their satisfactory performance. Several studies have been conducted to develop a new approach to designing mixtures with RAP. The selection of aggregate gradation for high RAP mix may need to consider the fact that milling and crushing processes may significantly increase the amount of fines in RAP. Fractionation of RAP into different sizes is necessary for uniform production of high RAP mixes (*44*). NCHRP Report 452 highlighted important considerations in the design of HMA incorporating RAP materials (*45*). According to this design procedure, the design of HMA incorporating RAP materials is similar to regular mixtures by treating RAP aggregate as another stockpile. Therefore, this design procedure requires extraction of the binder and recovery of the aggregates for determination of their gradation, angularity, and the amounts of flat and elongated particles. The sand equivalent requirement was waived for RAP aggregates.

Abdulshafi et al. (*46*) developed a method that efficiently determines the RAP content limits in intermediate course mixes. The method involves preparing samples of mixtures with different RAP contents ranging between 0 and 30% and testing them according to AASHTO T-283. Load and deformation are continuously obtained during the testing, and are used to compute the energy needed to fail a sample using Equation 4, which was referred to as the absorbed energy. The mix that has the greatest absorbed energy level is selected as having the optimum RAP content. Abdulshafi et al. (*46*) also proposed minimum acceptable criteria in Table 5 for the indirect tensile strength and absorbed energy values to be used when designing mixes with RAP.

$$AE = (0.5 \text{ x } P \text{ x } d)/t \quad (4)$$

where AE is the absorbed energy in the IDT test, P is the ultimate load in the IDT test, d is the vertical deformation at the ultimate load (P), and t is the sample thickness.

Table 5. General Indirect Tensile Strength Values for Asphalt Mixes (*46*)

Asphalt mix	ITS Before Aging (psi)	ITS After Aging	AEV Before Aging (psi)	AEV After Aging (psi)
Low Strength	>80	>70	>50	>45
Acceptable	90 – 130	80 – 120	70 – 120	55 – 90
High Strength	130 – 300	100 – 240	120 – 200	110 – 180

NCHRP report 752 evaluated current procedures used to design mixes with RAP contents ranging between 25% and 55% (*26*). This report suggested to distinguish mixes containing RAP by the proportion of RAP binder to the total binder, referred as RAP binder ratio (RBR). The report recommended several important revisions to AASHTO R 35 and M 323 to improve the mix design with high RAP contents. These included using Equation 5 for selecting the performance grade of the virgin binder in high RAP content mixes, which requires determining the performance grade of the recovered RAP binder, the RAP binder ratio, and the required high and low critical temperatures for the project location. It is worth noting that Equation 5 might require using a softer grade of the virgin binder or recycling agent to meet the low critical temperature for the project location. The report also recommended additional tests for further evaluating the mix designs, which included: 1- AASHTO T-282 or AASHTO T-324 for moisture-damage testing, 2- Semi-Circular Bend (SCB) test or the disc-shaped compact tension test for examining thermal cracking resistance, and 3- Asphalt Pavement Analyzer, Hamburg, or Flow Number tests for examining rutting when a softer grade of virgin binder or a recycling agent is used.

$$T_{C(\text{virgin})} = \frac{T_{C(\text{need})} - (RBR \times T_{C(\text{RAP binder})})}{1 - RBR} \quad (5)$$

where $T_{c(\text{virgin})}$ is the critical temperature (high, intermediate or low) of the virgin binder, $T_{c(\text{need})}$ is the critical temperature (high or low) needed for the climate and pavement layer, RBR is the RAP to binder ratio, and $T_{c(\text{RAP Binder})}$ is the critical temperature (high or low) of the RAP binder.

Zhou et al. (*47*) evaluated the mix design considerations and recommendations for high RAP content mixtures. They found that RAP content influences the optimum asphalt content, rutting, moisture resistance, and cracking resistance. Optimum asphalt content generally increased with higher RAP content, but the increase was small when RAP content was below 20%. Furthermore, increasing RAP content always improved rutting and moisture resistance, but cracking resistance worsened particularly when 30% RAP content or more was used. Zhou et al. (*47*) suggested increasing the optimum asphalt binder content by lowering the design air void value or reducing the number of gyrations used to determine the design air void (N_{design}). The researchers also recommended a balanced approach to design mixes based on using Hamburg wheel tracking and overlay tester to ensure the rutting and cracking performance of the designed mixes, respectively. Im et al. (*30*) indicated that RAP mixtures designed using the mix design method proposed by Zhou et al. (*47*) had similar or better field performance than virgin asphalt mixes. Im et al. (*30*) suggested that cracking performance of asphalt mixes is related to the existing pavement structure. Therefore, they recommended a RAP mix design system for project-specific conditions, including traffic, climate, and existing pavement conditions. Based on their study, Im et al. (*30*) recommended using recycling agents when higher RAP contents are used in the mix.

A.6 Management of RAP Quality

Several studies and surveys indicated that one of the key reasons for not including higher RAP contents in asphalt mixtures was the lack of guidelines for processing, handling, and characterizing RAP prior to mix design. A common misconception exists that RAP stockpiles are highly variable and, thus, using higher RAP contents in new asphalt mixes will lead to more variability in the mix. However, several studies indicated that well-managed RAP stockpiles have a more consistent gradation than virgin aggregates (26, *48, 49, 50*). Therefore, West (*26*) indicated that requirements to limit the RAP to single-source materials are not justified.

NCHRP report 752 developed guidelines for RAP management to ensure that high RAP content asphalt mixes can be produced with the same uniformity and quality as virgin asphalt mixes (*26)*. According to this report, RAP stockpiles should be periodically sampled for quality control testing with the aid of a loader or other power equipment to make miniature sampling stockpiles to minimize variation in samples due to segregation. Table 6 provides the RAP test methods, sampling frequencies, and variability guidelines recommended in NCHRP report 752. As shown in this table, properties of RAP that are needed for the mix design and should be tested include RAP asphalt content, and RAP aggregate properties as well as continuous grade of the recovered RAP binder when high RAP contents are used. It was also recommended to use the ignition method for determining the asphalt content, except for certain types of aggregate that are affected by the high temperatures used in this method. Furthermore, it was recommended to recover RAP aggregates for determining its gradation and specific gravities using either the ignition method or the solvent extraction method. Estimating the bulk specific gravity of RAP aggregate by determining its effective specific gravity and estimating an asphalt absorption value was not recommended, as this procedure yields unrealistic VMA for mixes with high RAP contents.

According to a report recently published by NAPA to document the current best practices for management of RAP, different types of solvents have been used for the extraction of RAP binders, which included: trichloroethylene (TCE), toluene, and normal-propyl bromide (*50*). Debate continues about the type of solvent that should be used especially when determining the continuous grade of the RAP binder (*26*). Recent work by the authors on a limited number of binders have shown that the use of TCE may reduce the stiffness of the recovered asphalt binder, especially for binders with lower performance grades such as PG 64-22.

Table 6. NCHRP Report 752 Recommended Sampling and Testing of RAP (*26*)

Property	**Test Method(s)**	**Frequency**	**Minimum # Tests per Stockpile**	**Maximum Standard Deviation**
RAP Asphalt Content	AASHTO T 164 or AASHTO T 308	1 per 1,000 tons	10	0.5
RAP Recovered Aggregate Gradation	AASHTO T 30	1 per 1,000 tons	10	5.0 all sieves 1.5 on 75 micron
Recovered Aggregate Bulk Specific Gravity	AASHTO T 84 and T 85	1 per 3,000 tons	3	0.030
RAP Binder Recovery and PG Grading	AASHTO T 319 4 and AASHTO R 29	1 per 5,000 tons	1	N/A

Recently, NAPA published a report to document the current best practices for management of RAP (*50*). The report had similar recommendations as NCHRP report 752 regarding RAP sampling and testing. The report recommended proper remixing of the RAP stockpile to prevent segregation. In addition, the report identified several approaches to minimize the moisture content of RAP in a stockpile, which increases the asphalt plant’s production rate and drying costs. These approaches included covering the stockpile in a shelter or placing it on a drainable slope and correcting irregularly shaped stockpiles with surface depressions that will pond water.

The NAPA report also recommended reusing asphalt mixtures wasted during the plant start-up, transition between mixes, and shut-down phases, but managing them separately from RAP. This is mainly because the binder in the waste material is not aged like the RAP binder and that the waste mixture has a different gradation than the RAP material.

The processing of RAP generally involves crushing it, which tends to create a large amount of fines in the processed RAP. Therefore, the NAPA report (*50*) recommended to screen the RAP before processing it to reduce the amounts of fines. In addition, the type of crusher used to process the RAP is very important, as the use of different crushers may affect the RAP gradation. The NAPA report (*50*) also recommended that RAP not be processed in a crusher when it is wet, as the presence of moisture will cause the fines to stick together and increase the effort required for crushing. In addition, this report suggested that if the RAP is inconsistent, it should be fractionized and stored in different sized stockpiles.

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Appendix B Survey Results

A statewide survey was conducted to document current state-of-the-practice for using RAP on local roads in Ohio. A draft survey questionnaire was prepared by the research team and sent to the ODOT Technical Advisory Committee (TAC) of this project for review in December of 2016. Modifications were made and some questions were added/deleted based on comments received from the TAC. The revised survey was implemented in SurveyMonkey for distribution to different local public agencies (LPA). The survey invitations were sent on December 21, 2016, and the due date for completing the survey was January 13, 2017.

The survey included 20 questions. The information collected in the survey included: the maximum RAP percentage allowed in the surface course asphalt mixtures for different RAP processing methods, RAP processing and stockpiling (storage) specifications, specifications on RAP properties, and mix design specifications as well as QC/QA procedures for mixtures with RAP. A Microsoft Excel file containing all the responses was downloaded from SurveyMonkey. A total of 40 responses were received. The results were analyzed and compiled.

Figure B.1 summarizes the answers to the survey question regarding type of asphalt mixture is the most commonly used by the agency for surface courses. About half of the responding LPAs indicated that Marshall mixes designed for medium traffic (ODOT item 441 for medium traffic) are the most commonly used mixes. In addition, about 12.5% of surveyed LPAs indicated that they are using Marshall mixes designed for heavy traffic. Less than one tenth indicated that the most used mix is a Superpave mix.

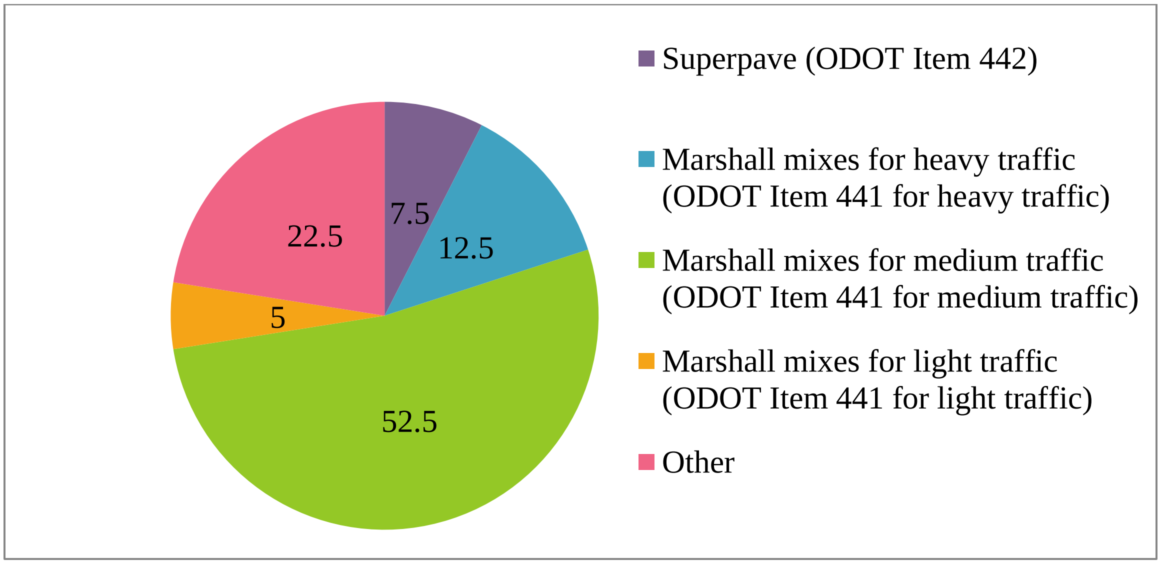

Figure B.1. Mix design method used by LPAs

Figure B.2 summarizes the survey response regarding the Ohio LPAs current practices for using RAP in surface asphalt mixtures. As can be seen from that figure, more than half of the LPAs allow using RAP in their surface mixes. Figure B.3 shows the maximum RAP percentages allowed in surface course mixes by those LPAs. The majority of LPAs are using ODOT limits. In addition, less than one tenth are using up to 20% RAP in their surface mixes. It is worth noting that about one third of responding LPAs indicated that RAP is not allowed in their surface mixes. The main reason for this is concerns about RAP mixtures performance.

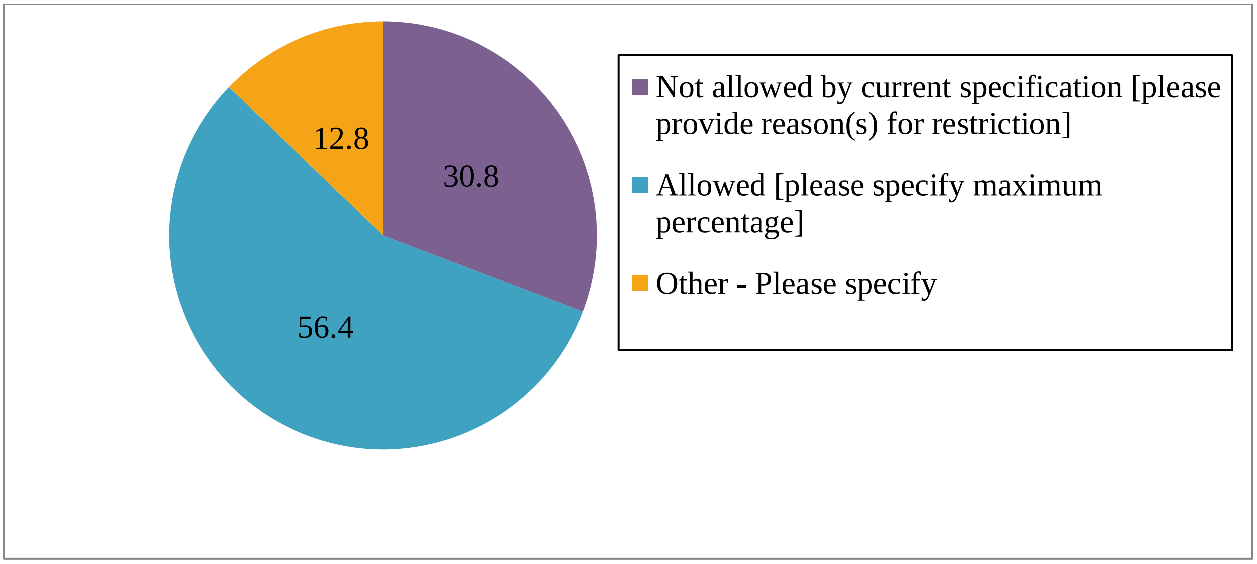

Figure B.2 Current LPA Practices for using RAP in surface mixes

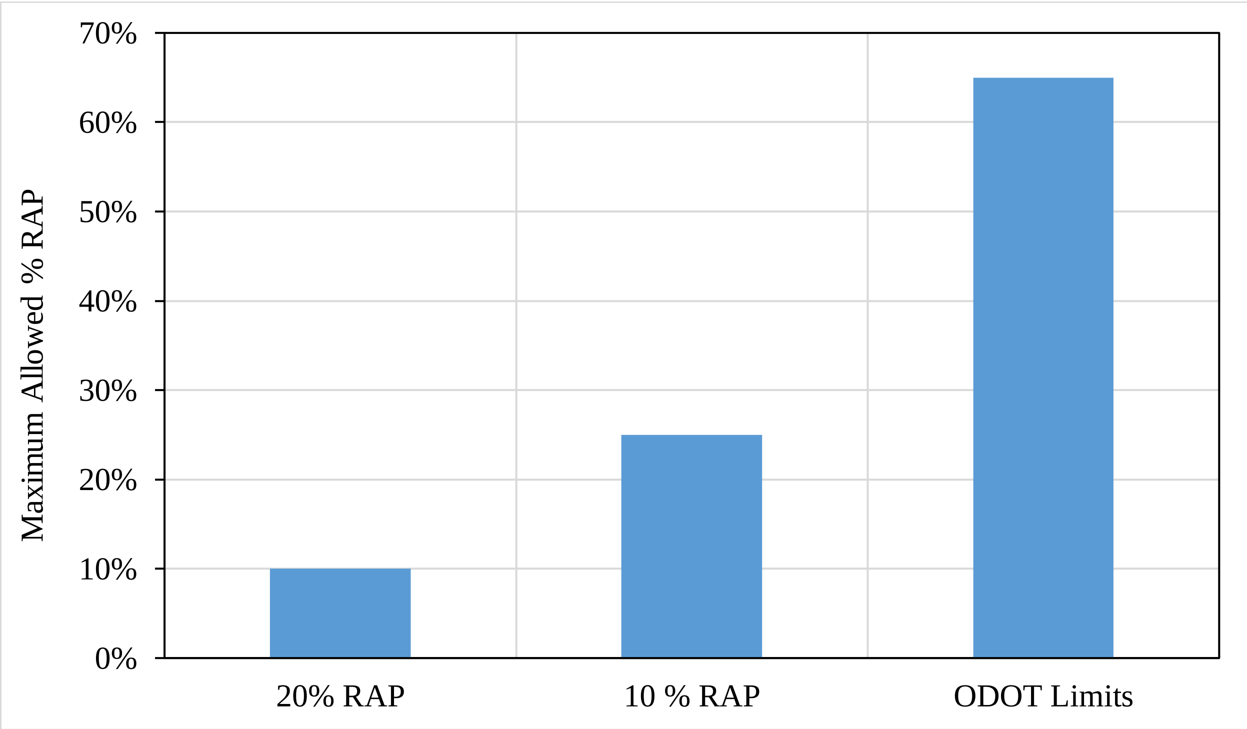

Figure B.3 Maximum RAP allowed in surface mixes on local roads

Figure B.3 presents the typical RAP content used in surface asphalt mixtures on local roads. About half of LPAs use less than 10% RAP in their surface course mixes. In addition, about 15% use up to 20% RAP in their surface mixes. It should be noted that about quarter of LPAs do not know the exact amount of RAP used in the asphalt mixes.

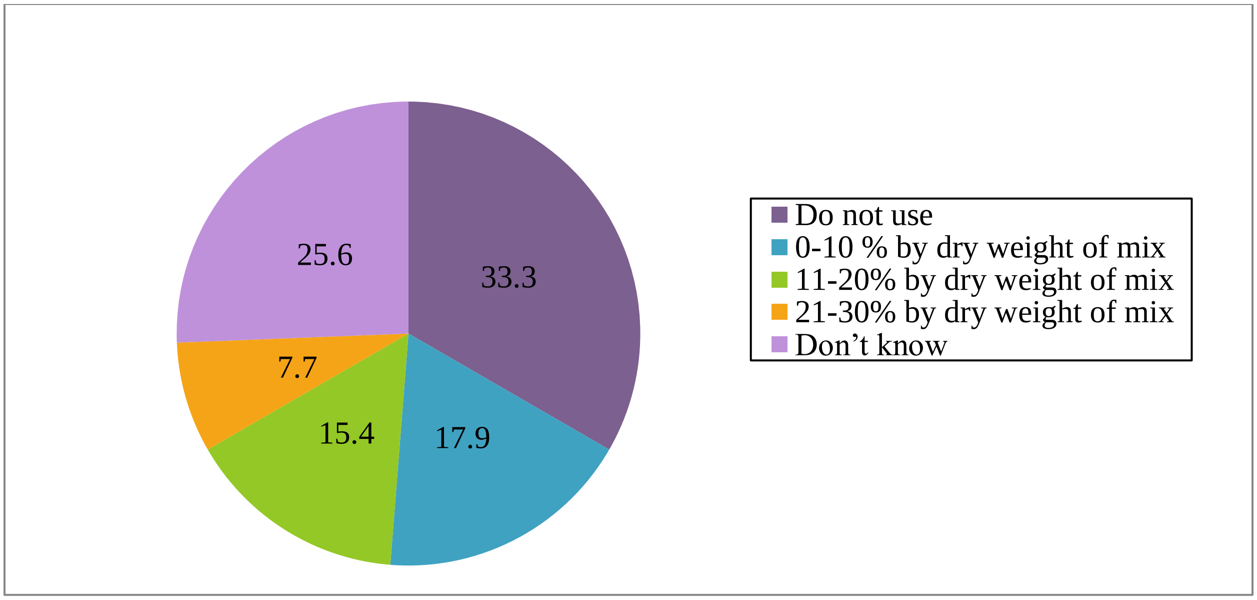

Figure B.4 Percentage of RAP typically used in surface mixes on local roads

Figure B.5 presents the survey results regarding the LPA specifications for RAP processing. About half of the responding LPA agencies do not have any RAP processing requirements. In addition, about one third use ODOT Method 1 for processing RAP. Finally, about 15% of LPAs responding to this survey indicated using ODOT Method 2 for processing RAP. The survey results also indicated that the majority of LPAs do not have any RAP management requirements as well as quality control/ quality assurance specifications for RAP mixes.

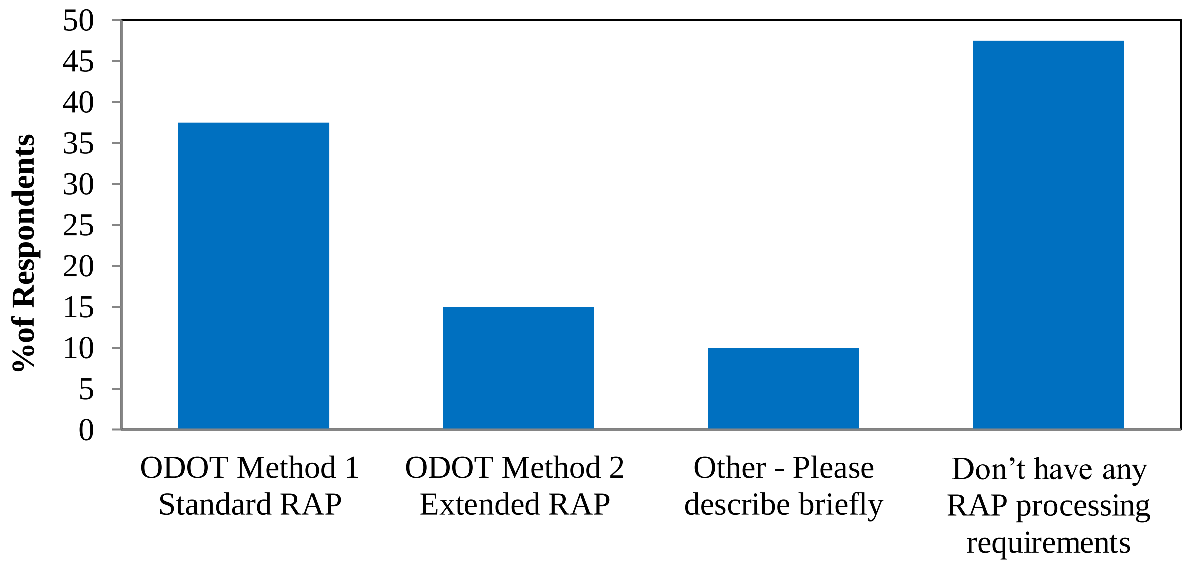

Figure B.5 RAP processing method

Figure B.6 summarizes the response to the question regarding properties contractors are required to provide as part of the agency's mix design approval process. About 70% of LPAs require using the same properties specified in the ODOT CMS book. However, about one quarter of the LPAs do not require any RAP properties to be submitted as part of mix design. It is noted that most of these LPAs do not allow using RAP.

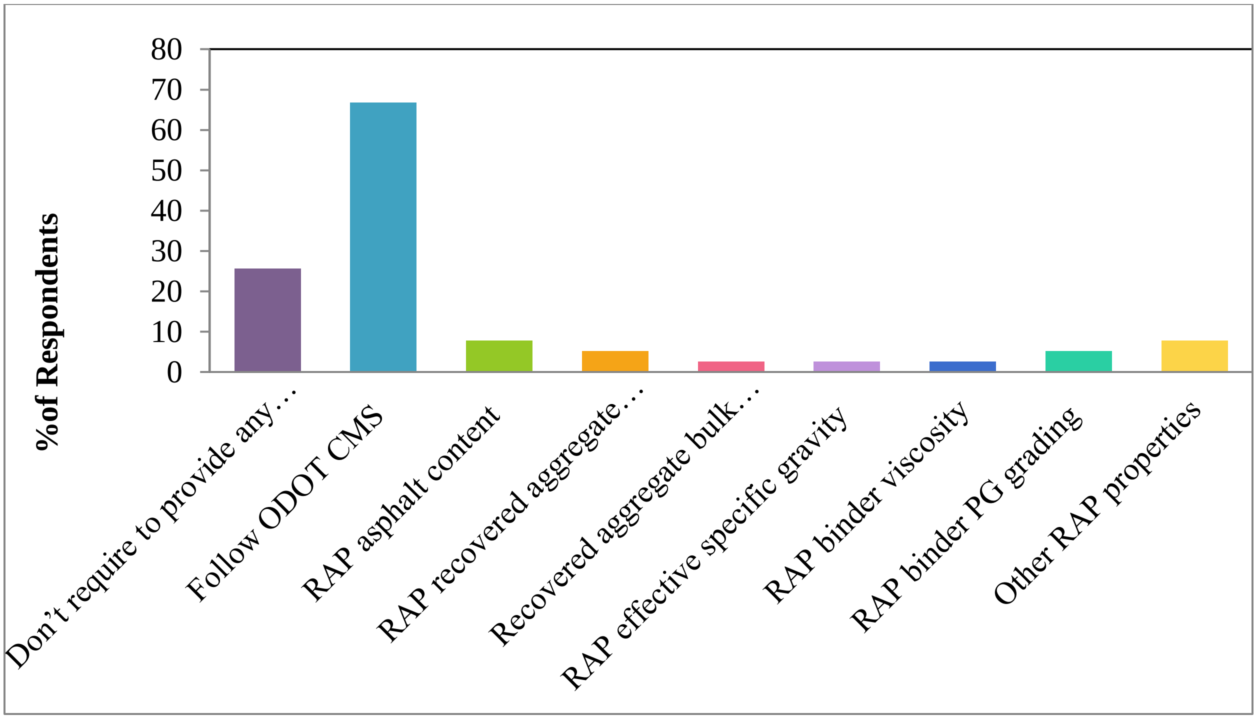

Figure B.6 Properties contractors are required to provide as part of your mix design approval process

Figure B.7 summarizes the responses to the question regarding the main obstacles for using higher percentages of RAP in surface course asphalt mixtures on local roads. About 30% of LPAs believe that currently there is no obstacle stopping LPAs from increasing the allowed RAP percentages on local roads. However, about 40% think that the concerns about poor performance of asphalt mixes with higher RAP contents is currently the main reason for not using more RAP in surface course layers on local roads. The RAP variability as well as the lack of specification for mixes with higher contents are obstacles identified by LPAs for not using asphalt mixes with higher RAP content.

Figure B.8 presents that main type of distresses in surface course layers with RAP mixes identified by the LPAs responding to the survey conducted in this study. About one third of the LPAs indicated that they did not see any premature failure in surface layers with RAP mixes. However, 23% and 37% of LPAs have observed premature thermal cracking and fatigue cracking in surface course layers with RAP mixes, respectively.

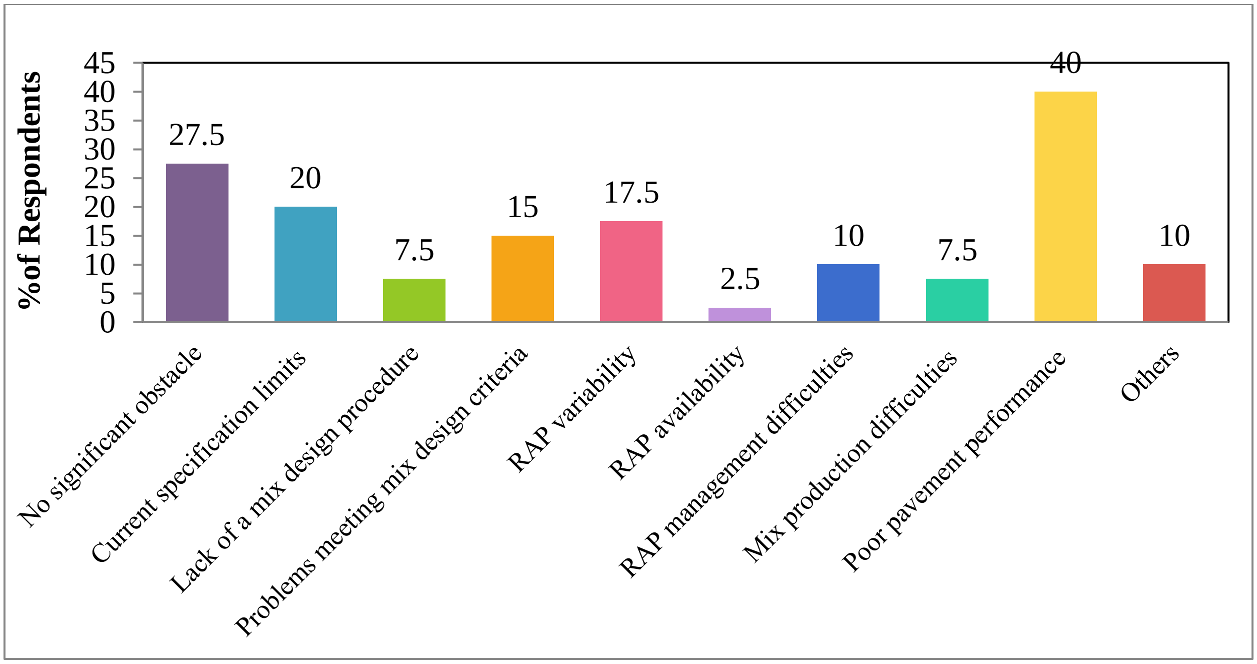

Figure B.7 Main obstacles for not using asphalt mixes with higher RAP contents.

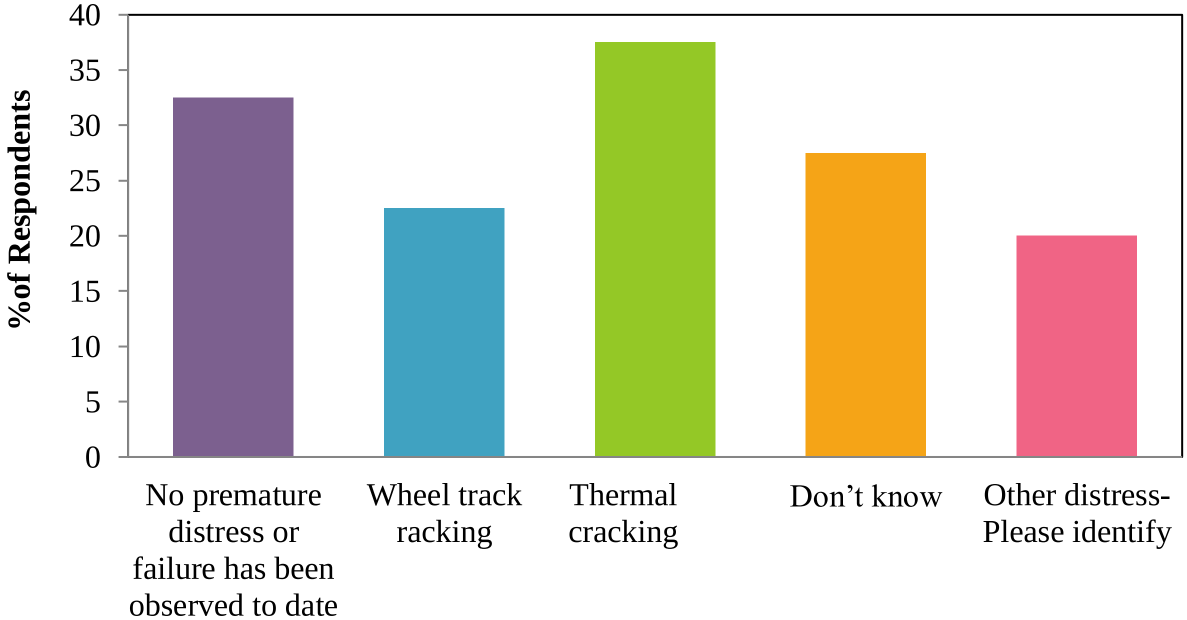

Figure B.8 Distress observed in surface course layers with RAP mixes

Appendix C Testing Program

This appendix provides a description of all the materials that were used in this research study. In addition, it also provides a description of the employed tests and protocols, as well as the preparation procedures developed and used to prepare representative samples for these experiments.

C.1 Materials

C.1.1 Reclaimed Asphalt Pavement (RAP)

RAP materials were obtained from seven different resurfacing projects within Ohio. The binder was extracted and recovered from each of the obtained RAP materials in accordance with AASHTO T164 and AASHTO R59. The performance grade was determined for each of the extracted and recovered RAP binders in accordance with AASHTO M320. Toluene was the solvent used for extraction of all RAP binders. Based on the obtained performance grades, two RAP materials that have binders with different rheological properties were selected in this study: Shelly 2017 Pile RAP-A (hereinafter referred to as RAP-1), and RAP-IR-270 (hereinafter referred to as RAP-2). Table C.1 presents the high- and low-temperature grades for the two RAP binders selected in this study. It is noted that the selected RAP materials were subjected to different aging and environmental conditions through their service life, which resulted in the significant differences in the PG grade of the extracted and recovered binders.

Table C.1 Performance Grade of the RAP Materials

RAP ID	Continuous High Temperature Grade, °C	Continuous Low-Temperature Grade, °C
Shelly 2017 Pile –A RAP-1	93.1	-14.3
IR 270 (RAP 2)	79.9	-21.1

C.1.1 Virgin Asphalt Binder

The target virgin asphalt binder was selected to meet the specifications for PG 64-22 (neat). The PG 64-22 binder is typically used in surface course mixes on local roads with medium traffic. In addition, a softer binder meeting the specifications PG 64-28 (PPA modified) was included in this study. Both binders were obtained from the Shelly Company. All binders were tested in accordance with AASHTO M320. Table C.2 presents the continuous grade and performance grade obtained for each binder.

Table C.2 Performance and Continuous Grade of the Considered Binders

Binder	Continuous Performance Grade	Performance Grade
PG 64-28	CG 64.9-30.6	PG 64-28
PG 64-22	CG 66.7-22.0	PG 64-22

C.1.2 Recycling Agents

Based on results of the literature review conducted in this study and presented in Appendix A, three types of recycling agents (RAs) were selected for evaluation in this study, these included: an aromatic oil (Hydrolene® H90T, hereinafter referred to as Hyrolene), a tall oil (Sylvaroad™ RP1000, hereinafter referred to as Sylvaroad), and a vegetable oil (soybean). Table C.3 presents the properties of each of the three RAs.

Table C.3 Properies of recycling agens used in this study

Property \ RA	Sylvaroad	Hydrolene	Soybean
Viscosity (cm^2/s)	1.008 at 20 °C	0.162 at 100 °C	0.582-0.622
Specific Gravity	Not Available	0.98	0.916-0.922
Engineered or Generic	Generic	Generic	Generic
Petroleum or Organic	Organic	Petroleum	Organic
Price per pound (USD)	1.5	0.2705	0.32
Source	KRATON	HollyFrontier LLC	-

C.2 Optimum Rejuvenator Dosage

The optimum rejuvenator dosage was determined based on the method proposed in National Cooperative Highway Research Program (NCHRP) study 9-50 (*1*). The first step in this method is determining the continuous high and low temperature performance grades for the blends of the RAP binder and virgin asphalt binder that are prepared based on the percentages of these binders in the asphalt mix. The continuous high- and low-temperature grade of these blends with different RA dosages were then determined. Two different dosage levels were used in this study based on the recommended range provided by the manufacturer.

The dynamic shear rheometer test was conducted on unaged and Rolling Thin Film Oven (RTFO) aged samples of the binder blends to determine the continuous high-temperature grading temperatures (PGH). Likewise, the continuous low-temperature grading temperatures (PGL), were determined using the Bending Beam Rheometer test (BBR) conducted on Pressure Aging Vessel (PAV) aged samples of the binder blends. The PGH determined from the DSR tests on RTFO aged and the unaged samples were plotted versus the RA dosage. In addition, the S-controlled PGL and m-controlled PGL are plotted versus RA dosage. A linear regression equation was established for each of the PGH and PGL data obtained. The RA dosage to restore the target binder PGH using the colder PGH regression line was first computed for each rejuvenator. The PGL of the selected RA dosage was then determined using the warmer PGL regression line to verify that it meets the target binder PGL. If the PGL of the selected RA dosage met the target binder PGL, this RA dosage was selected.

C.3 Mixtures

To evaluate the effects of the RAP materials on the pavement performance, a job mix formula (JMF) for an asphalt mixture with RAP that was used in construction of surface course layer in a resurfacing project in the city of Columbus was obtained from the Shelly Company. The asphalt mixture had a 1/2 inch (12.5 mm) nominal maximum aggregate size (NMAS) and was designed to meet ODOT specification for Item 441 for medium traffic surface mixtures. The selected mixture included PG 64-22 asphalt binder. The aggregate blend of the selected mixture consisted of: 47% limestone #8, 16% natural sand, 17% manufactured sand and 20% reclaimed asphalt pavement (RAP) processed according to ODOT Item 401.04 Method 2.

Table C.4 RAP binder blends tested

%RAP in mixture	RAP AC%	RBR	RA Type	RA Dosage
0.0%	0.0%	0.00%	None	0.0%
40.0%	2.1%	32.60%	Sylvaroad	4.0%
40.0%	2.1%	32.60%	Sylvaroad	8.0%
40.0%	2.1%	32.60%	Hydrolene	4.0%
40.0%	2.1%	32.60%	Hydrolene	10.0%
40.0%	2.1%	32.60%	soybean	6.0%
40.0%	2.1%	32.60%	soybean	12.0%

Several asphalt mixes were designed and produced in the lab to evaluate the effects of RAP content and source. These included: a control virgin mixture (no RAP) as well as mixtures with 20% RAP, 30% RAP, 40% RAP, and 50% RAP. Mixtures were designed with RAP-Shelly-2017-PileA (referred hereafter as RAP-1) and RAP-IR 270 (referred hereafter as RAP-2). The aggregate gradation of all mixes were maintained as close as possible to that of the mix in the JMF by adjusting the percentages of the virgin aggregate in the mix. The ratio between the percent manufactured sand and natural sand was also maintained as closely as possible for each mix to eliminate performance variability from sand angularity. Figure C.1 and Figure C.2 demonstrate the 0.45 power chart for RAP-1 and RAP-2 mixes, respectively.

Equation C.1, which was recommended by NCHRP 752, was used to determine the virgin binder performance grade. Based on that, a PG 64-22 binder was used in the control mix, the 20% RAP-1 as well as the 30% RAP-1, 40% RAP-1, and 50% RAP-1 with different recycling agents. In addition, the 30%, 40% and 50% RAP-1 and RAP-2 mixes with no recycling agents were prepared with asphalt binder of PG 64-28.

$$T_{C(\text{virgin})} = \frac{T_{C(\text{need})} - (RBR \times T_{C(\text{RAP binder})})}{1 - RBR} \tag{C.1}$$

where $T_{c(\text{virgin})}$ is the critical temperature (high or low) of the virgin asphalt binder, $T_{c(\text{needed})}$ is the critical temperature (high or low) needed for the climate and pavement layer, and RBR is the RAP to Binder Ratio, which is the ratio of the RAP binder in the mixture divided by the mixture's total binder content, and $T_{c(\text{RAP Binder})}$ is the critical temperature (high or low) of the RAP binder

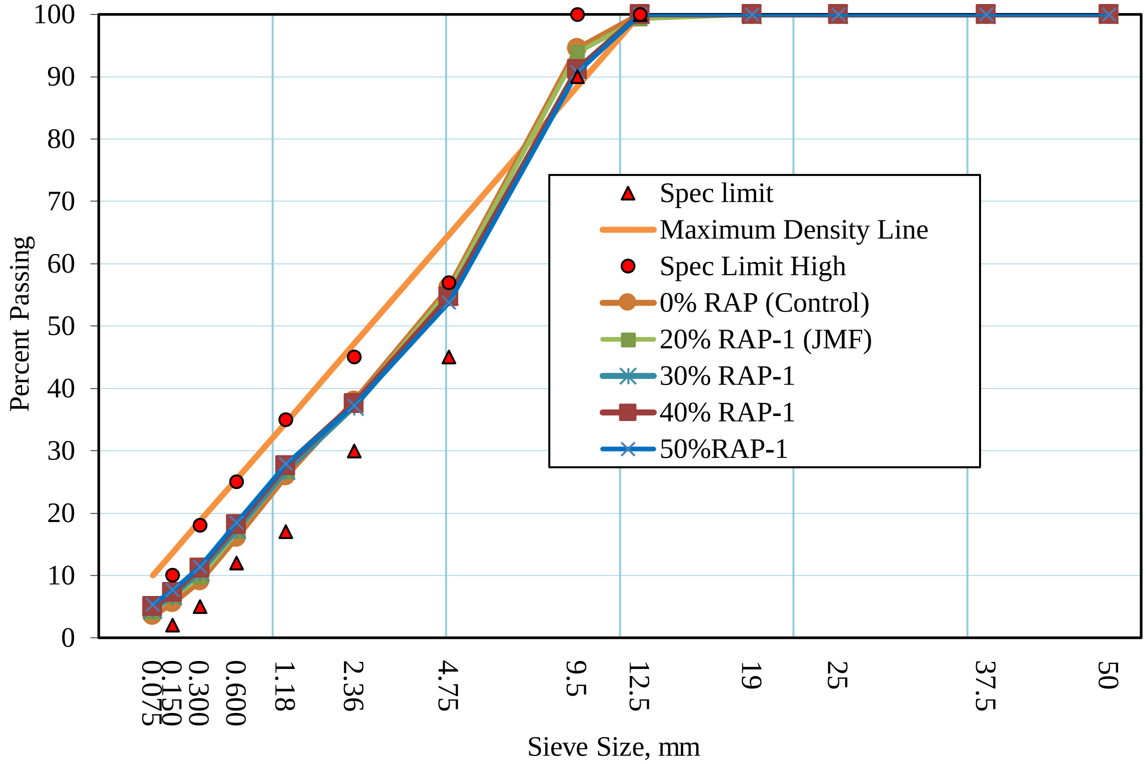

Figure C.1 Gradations of the RAP-1 mixes evaluated in this study

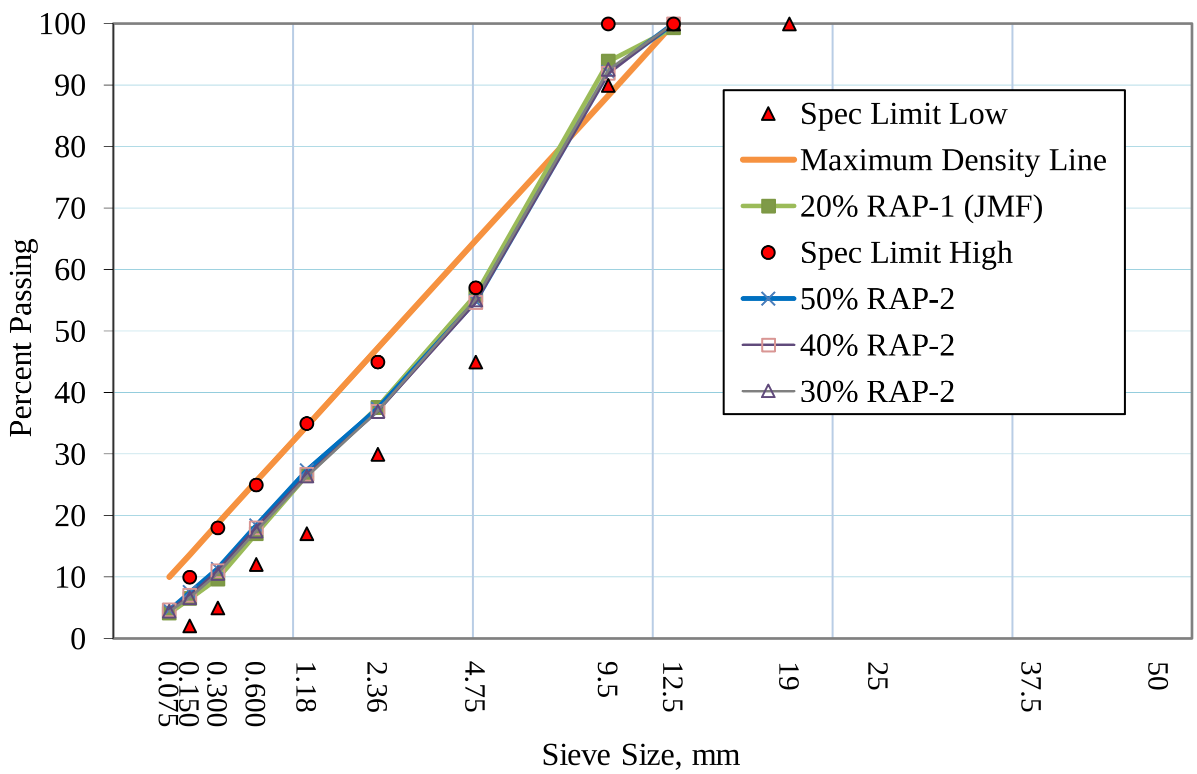

Figure C.2 Gradations of the RAP-2 mixes evaluated in this study

The Marshall mix design method was performed to determine the optimum asphalt content for the different considered mixes. A target air void of 3.5% was used in the mix design. A total of eight mixtures were designed. A summary of the mix design results for the different mixtures is presented in Table C.5. It is noted that the RAP was manually sieved on a ½'' sieve and split to ensure the consistency of the RAP portion in the blend. Once split, the RAP was left to air-dry for 24 hours, then oven-dried at 110 °C for 3 hours .

Table C.5 Tested Mixture Properties

Mix	% RAP	Virgin Binder type	Virgin AC%	RBR	Gmm
Control	0	PG 64-22	6.3	0	2.429
20% RAP-1	20	PG 64-22	5.3	16%	2.428
30% RAP-1	30	PG 64-28	4.8	25%	2.440
40% RAP-1	40	PG 64-28	4.3	33%	2.448
50% RAP-1	50	PG 64-28	3.8	41%	2.455
20% RAP-1	20	PG 64-22	5.3	16%	2.428
30% RAP-1 -Hydrolene RA	30	PG 64-22	4.8	25%	2.439
40% RAP-1 -Hydrolene RA	40	PG 64-22	4.3	33%	2.439
50% RAP-1 -Hydrolene RA	50	PG 64-22	3.8	41%	2.435
30% RAP-1 -Sylvaroad RA	30	PG 64-22	4.8	25%	2.440
40% RAP-1 -Sylvaroad RA	40	PG 64-22	4.3	33%	2.447
50% RAP-1 -Sylvaroad RA	50	PG 64-22	3.8	41%	2.444
30% RAP-1 -Soybean RA	30	PG 64-22	4.8	25%	2.437
40% RAP-1 -Soybean RA	40	PG 64-22	4.3	33%	2.441
50% RAP-1 -Soybean RA	50	PG 64-22	3.8	41%	2.439
30% RAP-2	30	PG 64-28	4.8	25%	2.434
40% RAP-2	40	PG 64-28	4.3	32%	2.433
50% RAP-2	50	PG 64-28	3.8	40%	2.438

C.4 Mixture Testing

Tests were performed on the mixtures to evaluate their resistance to fatigue cracking, moisture damage, low-temperature cracking, and rutting. All samples for these tests were compacted to a target air void of 7± 0.5%.

C.4.1 Semi-Circular Bending (SCB) Test

The SCB test was conducted on each mixture to evaluate the fatigue cracking performance at an intermediate temperature of 25°C. The SCB tests were performed according to the Illinois SCB Test Method (AASHTO TP 124-16: *Determining the Fracture Potential of Asphalt Mixtures Using Semicircular Bend Geometry (SCB) at Intermediate Temperatures)*. In this method, samples with 150-mm diameter were compacted to a height of 150 mm. Each sample was cut in half and the ends trimmed to obtain a thickness of 50 ± 1 mm. Each 50-mm thick sample was then cut in half to create the semi-circular shape. A notch with a depth of 15 mm and a width of 2.5 mm was cut into the center of the sample, as shown in Figure C.3. The SCB test was conducted on at least four long-term aged samples. The long-term aging was conducted according to AASHTO R30 and involved placing the samples in an environmental chamber for 5 days at 85°C. The SCB test was performed by loading the sample monotonically to failure at a constant cross-head deformation rate of 50 mm/min. Load and vertical deformation were recorded until failure. An Instrotek© Auto SCB, Figure C.4, was used to conduct all SCB tests.

Figure C.3 Illinois SCB Sample Preparation and Testing Equipment

Figure C.4 Instrotek© Auto SCB Testing Equipment

The main output of the SCB-IL is a load versus deformation plot, as shown in Figure C.5. From this plot, the Fracture Energy (FE) and the Flexibility Index (FI) are calculated using Equations C.2 and C.3, respectively. The fracture energy represents the energy needed to propagate a crack through the pavement layer, whereas the flexibility index identifies brittle mixes that are prone to pre-mature cracking (*2*). Since the Fracture Energy is a function of the peak load and displacement, Nazzal et al. (*3*) recommended normalizing the fracture energy values based on the peak strength mixture. Therefore, the normalized fracture energy value was used in this study to examine the cracking resistance of the core samples.

$$FE = \frac{W_f}{Area_{lig}} \times 10^6 \quad (C.2)$$

Where:

- FE = fracture energy (Joules/m^2)
- W_f = work of fracture, or area beneath load vs. displacement curve up to peak load (Joules)
- $Area_{lig}$ = ligament area, ligament thickness × length (mm^2)

$$FI = \frac{G_F}{|m|} \times A \quad (C.3)$$

Where:

- $|m|$ = absolute value of slope at inflection point
- A = unit conversion (0.01)

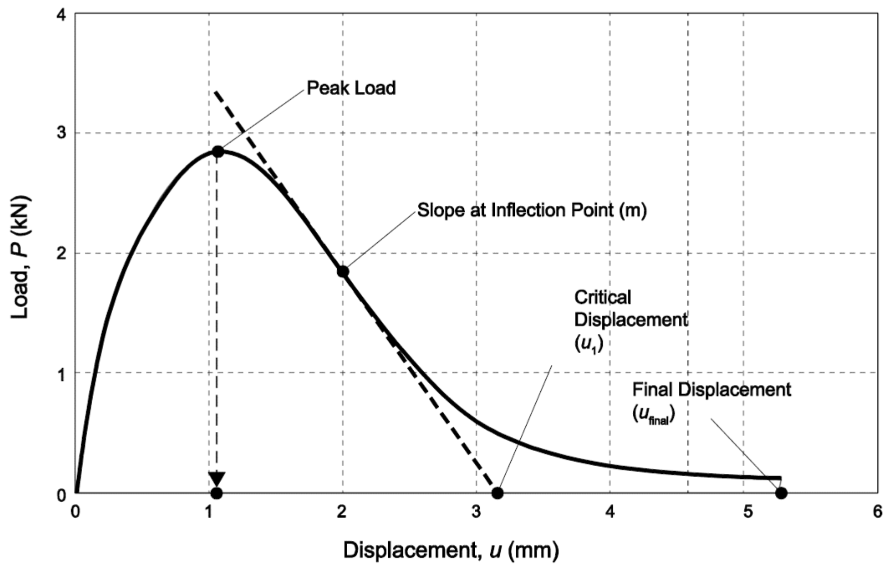

Figure C.5 Plot of Load vs. Displacement Obtained from Illinois SCB Test (*2*)

C.4.2 AASHTO T283

The moisture susceptibility of designed mixtures was evaluated using the AASHTO T283 test procedure modified according to the standard practices implemented in the State of Ohio. At least six samples with 6 inch (150 mm) in diameter and 3.9 inch (95 mm) in height were prepared for each mixture. The samples were then divided into a control group and a moisture-conditioned group. The control samples were wrapped with plastic wrap and stored at room temperature for testing in the dry condition. The second group was moisture conditioned by partially saturating the samples to a level between 70 and 80 percent in a water bath under a 2.9 psi (20 kPa) vacuum pressure for approximately two to three minutes. The partially saturated samples, along with 10 ml of water, were then wrapped and placed in a plastic bag. The samples were then subjected to a freezing cycle by placing them for 16 hours in an environmental chamber at a temperature of 0°F (–18°C). After the freezing cycle, the samples were thawed in a water bath at 140°F (60°C) for about 24 hours. Finally, the samples were conditioned for 2 hours in a water bath at a temperature of 77°F (25°C) before testing.

The IDT test was conducted on both sets of samples in accordance with AASHTO T245 at 25°C. A deformation rate of 50 mm/min was used. The load as well as the vertical and lateral deformations were continuously recorded. The indirect tensile strength is computed using Equation C.4.

$$ITS = \frac{2P}{\pi DT} \quad (C.4)$$

P: is the peak load, lb
D: is the specimen diameter, in
T: is the specimen thickness, in

The tensile strength ratio (TSR) was then computed as the ratio between the average indirect tensile strength of the wet conditioned specimens to the average indirect tensile strength of the dry unconditioned specimens. The TSR ratio is a measure of the resistance of the asphalt mixture to moisture damage. The higher the TSR ratio of an asphalt mixture, the better its resistance to moisture-induced damage.

C.4.3 Asphalt Concrete Cracking Device (ACCD)

This test was conducted to evaluate the low-temperature cracking resistance of mixtures evaluated in this study. In this test, a 22.4-mm (0.88-inch) long-notch was cut at the outer surface of the 60-mm (2.3 inch) diameter, 2-inch thickness (50.8 mm) sample to control the location of the crack. The test specimen and the ACCD ring were heated for 60 minutes at 65°C, and the tapered end of the heated ACCD ring was placed in the center hole of the heated test sample. The sample with the ACCD ring was placed in an environmental chamber (Figure C.6). As the temperature decreased, the contraction of the asphalt mix specimen was restrained by the ACCD ring, developing tensile stress within the test specimen and compressive stress within the ACCD ring. Four samples can be typically tested at the same time. The temperature and strain of each ACCD ring were continuously recorded until failure. The temperature corresponding to the maximum slope of the ACCD strain-temperature curve was considered as the onset on thermal cracking. The point at which the slope of the strain-temperature curve equals to eighty percent of the maximum slope after the onset of cracking is defined as the ACCD cracking temperature. The ACCD was performed on short-term and long-term aged specimens.

Figure C.6 ACCD test setup

C.4.4 Asphalt Pavement Analyzer

The asphalt pavement analyzer (APA) test was conducted according to AASHTO TP 63 (Standard Method of Test for Determining the Rutting Susceptibility of Asphalt Paving Mixtures Using the Asphalt Pavement Analyzer) and ODOT Supplement 1057 (Loaded Wheel Tester Asphalt Mix Rut Testing Method) using the device shown in Figure C.7. This test simulates actual road conditions by rolling a concave-shaped metal wheel at a speed of approximately 23.5 inch/sec (60 cm/sec) over a rubber hose pressurized at 100 psi (689.5 kPa) to 120 psi (827.4 kPa) to generate the effect of high tire pressure (Figure C.8). The hose stays in contact with the sample's surface while the metal wheel rolls back and forth along the length of the hose for 8,000 cycles.

The APA can simultaneously test three beam samples or six cylindrical samples, with each APA sample consisting of two cylindrical samples. Superpave gyratory compacted specimens measuring 6 inch (150 mm) in diameter and 2.95 inch (75 mm) in height were used in this test. The target air void level within these specimens was 7 ± 1%, as specified in ODOT Supplement 1057. A trial and error procedure was followed in determining the weight of mixture required to achieve the target air void level. The loose mixture was short-term aged for a period of 2 hours at the compaction temperature before being prepared in the Superpave gyratory compactor.

Testing was conducted at a temperature of 120^{o}F (49^{o}C). The specimens were conditioned for a minimum of 12 hours at the test temperature prior to loading. During the test, rut depth measurements were obtained at 5, 500, 1000, and 8000 cycles. The total permanent deformation (or rutting) was calculated as the difference between the rut depth readings at the 8000th cycle and the 5th cycle. A total of four rut depth readings were used to calculate the average rut depth value for each APA sample.

Figure C.7 Asphalt Pavement Analyzer

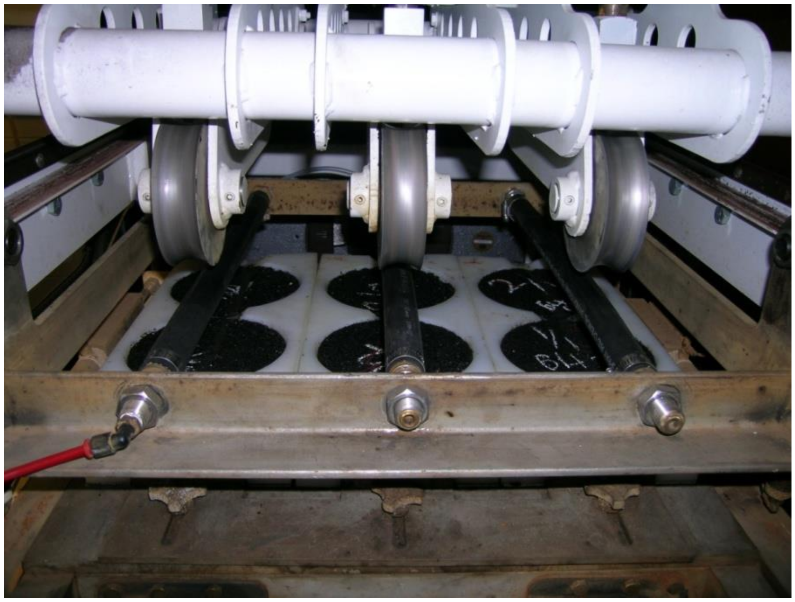
Figure C.8 Repeated Wheel Loading in the APA Device

C.5 Evaluation of IDEAL-CT Test for Quality Control

The SCB test is a simple, practical, and repeatable test to be used as part of the mix design process. Several studies have shown it correlates well with field cracking performance of an asphalt pavement. However, for quality control it is recommended to use tests that do not require any trimming or notching of compacted samples. Zhou et al. (*4*) recently developed a test called IDEAL-CT. This test is similar to the traditional IDT test. However, Zhou et al. (*4*) proposed a new procedure to analyze the IDT load – displacement curve, which was inspired by the laws of crack propagation (*5, 6*). Based on this procedure, a parameter called cracking test index (CTI) is determined using Equation (C.5). It is noted that Zhou et al. (*4*) found that CTI correlates well with the field cracking performance of asphalt mixtures.

$$CTI = \frac{G_f}{|m_{75}|} \times \left(\frac{l_{75}}{D}\right) \tag{C.5}$$

G_f : is the work of fracture which is the total area under load – displacement curve
D: is sample diameter (mm)
l_{75}: is displacement corresponding to the 75 percent of the peak load at the post-peak stage
m_{75}: is slope calculated as shown in Figure E using the following equation

$$|m_{75}| = \left|\frac{P_{85}-P_{65}}{l_{85}-l_{65}}\right| \tag{C.6}$$

P_{85}: is the 85 percent of the peak load at the post-peak stage
P_{65} : is the percent of the peak load at the post-peak stage
l_{85}: is displacement corresponding to the 85 percent of the peak load at the post-peak stage
l_{65}: is the displacement corresponding to the 65 percent of the peak load at the post-peak stage

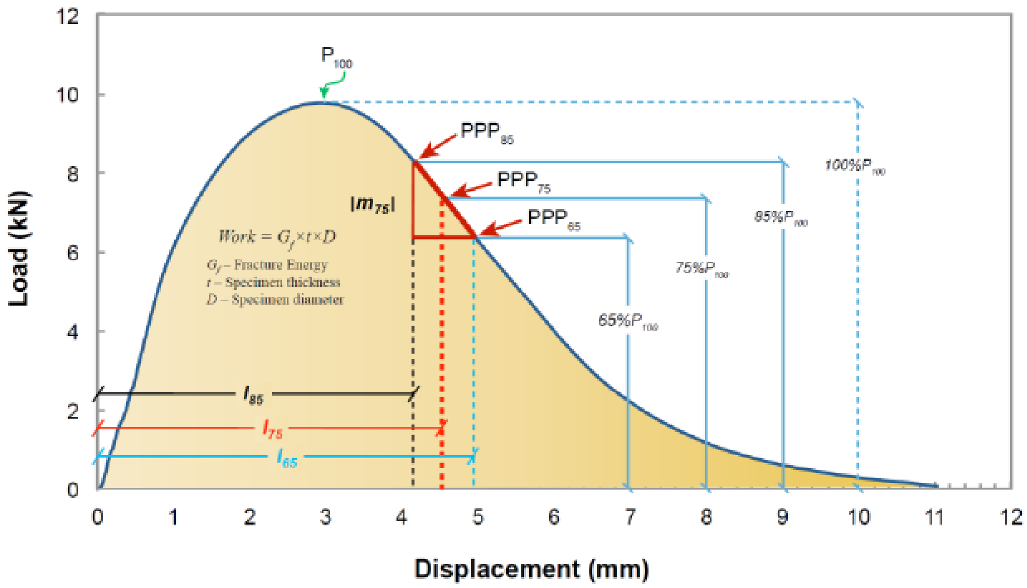

Figure C.9 Illustration of the slope |m75| in CTI calculation(*4*)

C.6 References

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Appendix D Test Results and Data Analysis

This appendix presents the results of the different binder mixtures tests that were conducted in this study. The chapter is divided into several sections. The layout of each section includes the presentation and discussion of the test results.

D.1. Rejuvenator Dosage Selection

The PGH for unaged and RTFO aged samples as well as the S-controlled PGL and m-controlled PGL were obtained for RAP-1 blends with different RA types and dosages. Figures D.1 through D.3 show the variation of PGH and PGL with RA dosages for Sylvaroad, Hydrolene and soybean, respectively. These figures also show the PGH and PGL regression lines equations that were established based on the obtained data. The RA dosage that is needed to restore the PGH to meet the PGH of the target binder of 67.7°C was determined based on these figures for each RA type. The PGL of the RAP blend with the RA dosage was computed based on the warmer PGL equation for each RA and compared to the PGL of the of target binder of 22.2 °C. Table D.1 presents the selected dosage for the different RA types considered in this study.

D.2. Results of Mixture Testing for RAP-1 Mixes

The fatigue cracking of asphalt at intermediate temperature was assessed by the Semi-Circular Bend (SCB) test, and the moisture susceptibility to damage was evaluated through the modified Lottman test. The low-temperature cracking resistance was evaluated using the Asphalt Concrete Cracking Device (ACCD) and the Asphalt Pavement Analyzer (APA) was utilized to examine the resistance of asphalt mixtures to rutting. The results of the performance tests are discussed in this section.

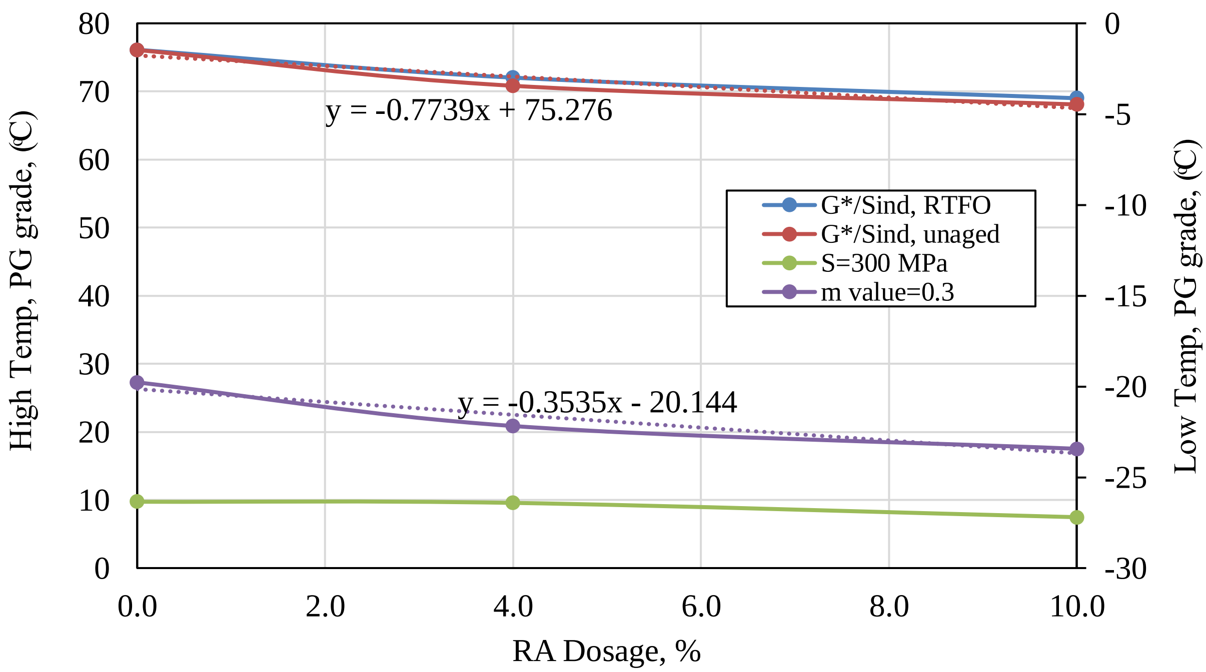

Figure D.1 RA Dosage selection of Sylvaroad-RA blend with PG 64-22 with 40% RAP.

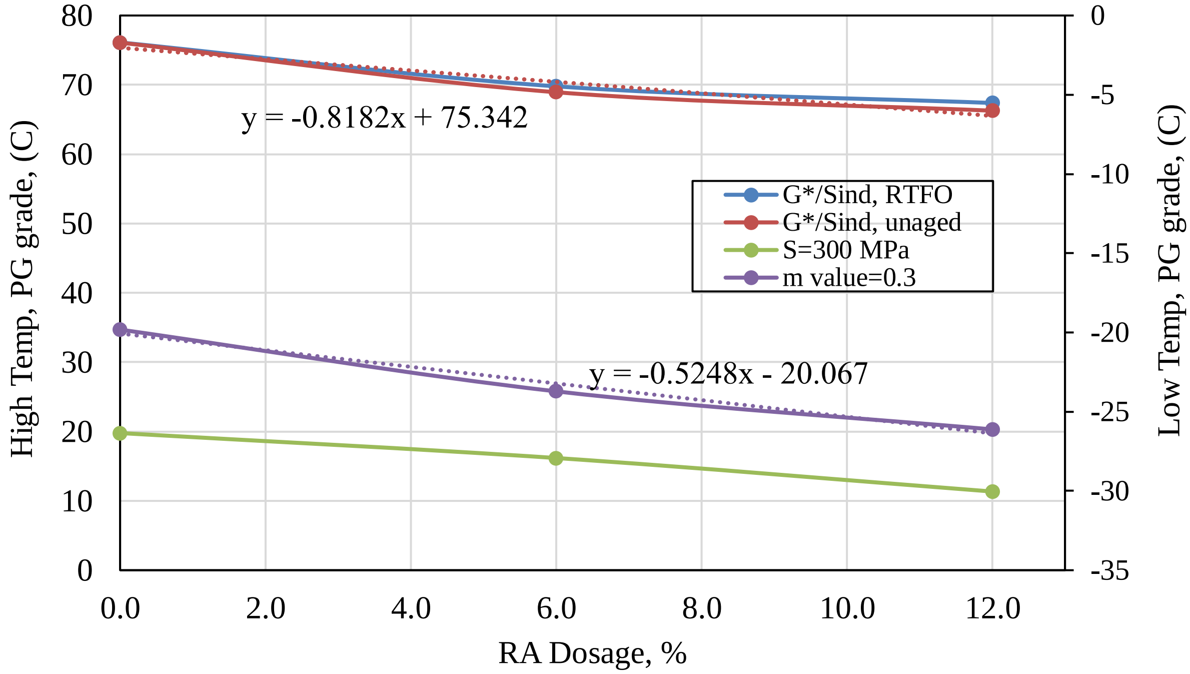

Figure D.2 Dosage selection of Hydrolene-RA blend with PG 64-22 with 40% RAP.

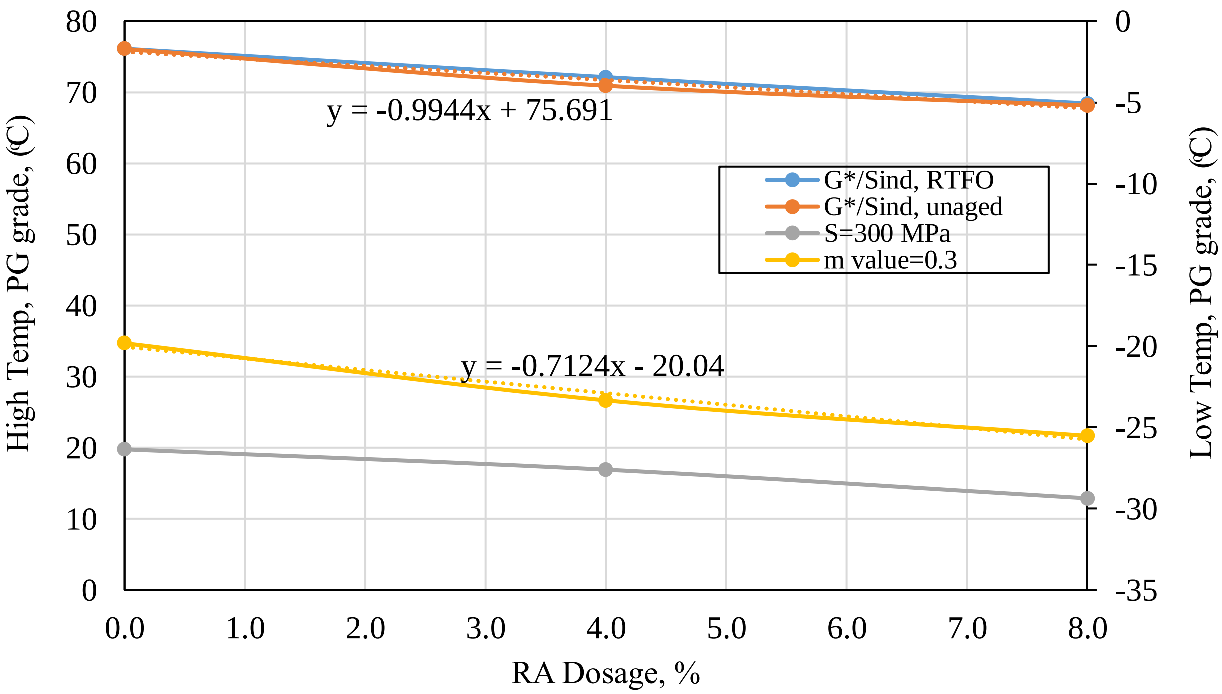

Figure D.3 Dosage selection of soybean-RA blend with PG 64-22 with 40% RAP.

Table D.1 Selected RA dosages

RA	Selected RA Dosage	PGL	PGH
Sylvaroad	8.0%	-25.7	67.7
Hydrolene	10.0%	-23.7	67.5
Soybean	9.5%	-25.1	67.6

D.2.1 SCB Test Results

Figure D.4 presents the average normalized fracture energy (NFE) values of the long-term aged samples of mixtures with RAP-1 tested in this study. It is noted that the NFE for the mixtures with RAP-1 and PG 64-28 binder decreased with an increase in the RAP content. This suggests that the use of softer binder PG 64-28 was not effective in maintaining the fatigue cracking resistance of the RAP-1 mixes when more than 30% RAP was used. Figure D.4 also shows the average NFE values of RAP-1 mixes with the different RA types used in this study. The Sylvaroad and Hydrolene RAs had much higher NFE than RAP-1 mixes with the softer PG 64-28 binder and the soybean RA; particularly for 40% and 50% RAP mixes. This suggests that Sylvaroad and Hydrolene RAs were more effective in improving the fatigue cracking resistance of high RAP mixes.

Figure D.5 shows the averaged Flexibility Index (FI) of long-term aged samples of RAP-1 mixes. The FI is an indication of the asphalt mix cracking resistance; the higher the FI the better the cracking resistance. For the 30% and 40% RAP mixes with Sylvaroad and Hydrolene, the FI values were slightly higher than the FI of the control mix. This indicates that these mixes are less brittle and have a better resistance to fatigue cracking. In addition, the 50% RAP mixes with Sylvaroad and Hydrolene had a similar FI to the 20% RAP mix. In general, the RAP-1 mixes with Hydrolene RA had slightly higher FI than those with Sylvaroad RA. It can be noticed from Figure D.5 that the FI values of the soybean mixes with different RAP percentages are significantly less than those with Sylvaroad and Hydrolene RAP mixes. This suggests that the soybean RA did not considerably improve the brittleness of the RAP mixes.

D.2.2 Modified Lottman Test Results

Figures D.6 and D.7 present the average Indirect Tensile Strength (ITS) values of the dry and wet samples of all RAP-1 mixes, respectively. Note that the 20% RAP-1 mixes with PG 64-22 had higher ITS values than the control virgin mix. However, upon using the softer PG 64-28 binder, the ITS of RAP-1 mixes dropped at 30% and increased with the increase in the RAP content. Mixes with 30%, 40% and 50% RAP-1 with Sylvaroad and Hydrolene RAs have higher ITS values compared to those of the control mix. On the other hand, the ITS values of the soybean mixes had lower ITS values with 30% than the control mix; particularly for 50 % RAP mix. This may indicate that the soybean RA has significantly softened the binder in the RAP mixes.

The Tensile Strength Ratio (TSR) was computed based on ITS of the dry and wet samples of RAP-1 mixes. Figure D.8 shows TSR values of the RAP-1 mixes. In general, the TSR values of the control mix had slightly higher TSR values than mixes with 30%, 40% and 50% RAP. This might be attributed to the higher ITS values of dry RAP mixes. In general, the RA did not have significant effect on TSR values of RAP mixes. All mixes had TSR values higher than 80%, which indicate that all mixtures are able to meet the minimum acceptable TSR value specified by ODOT.

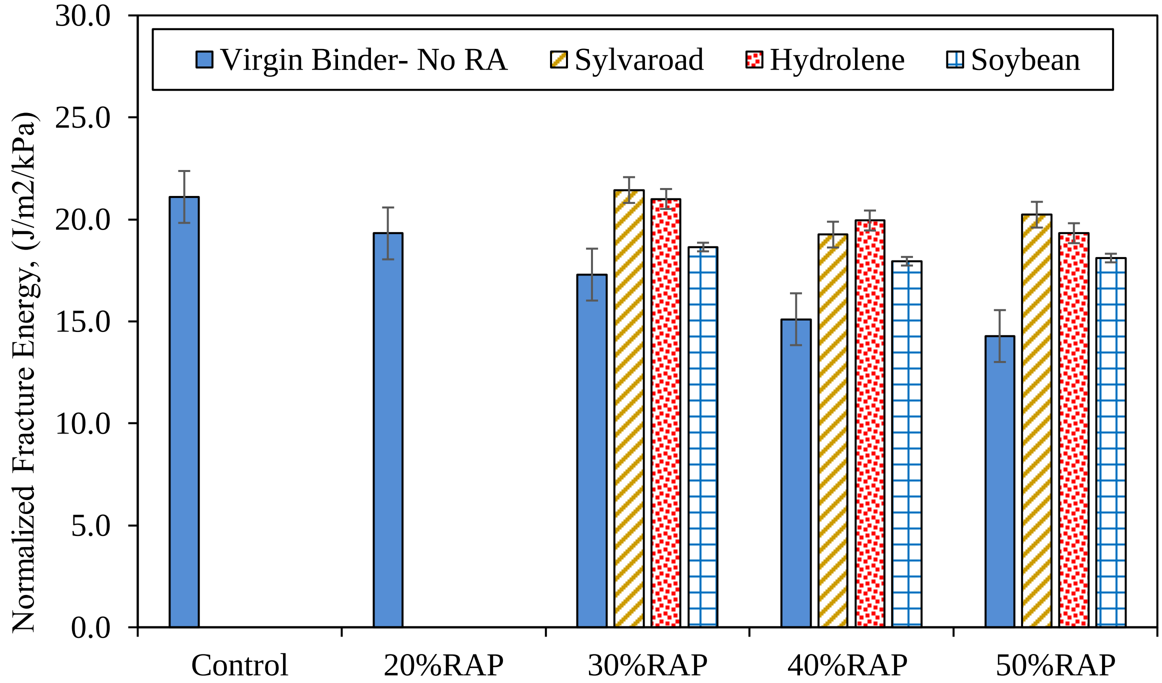

Figure D.4 Normalized Fracture Energy (NFE) for RAP-1 mixes

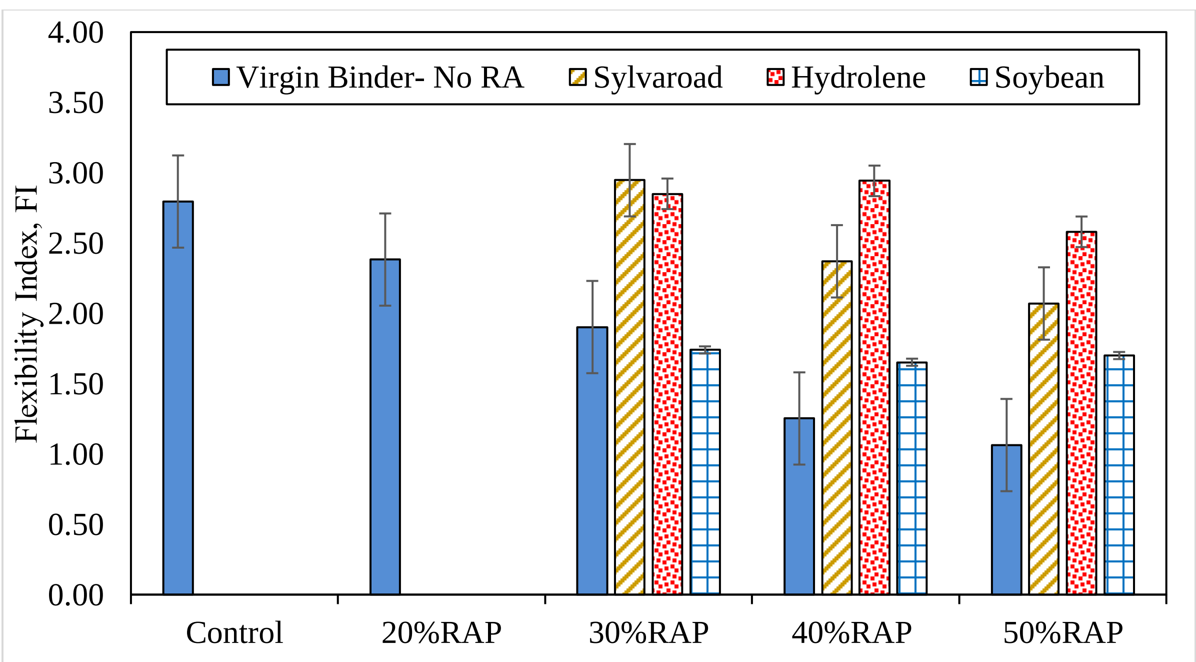

Figure D.5 Flexibility Index (FI) for RAP-1 mixes

D.2.3 Asphalt Concrete Cracking Device (ACCD) Test Results

Figure D.9 presents the average cracking temperature obtained from the ACCD tests performed on the long-term aged samples of the control mix and the RAP-1 mixes prepared with PG 64-28 and different RAs. Note that using the softer binder (PG 64-28) was effective in maintaining the cracking temperature of mixes with different percentages of RAP-1. The RAP mixes with the Sylvaroad, Hydrolene, soybean RA had slightly warmer cracking temperatures than those with softer binder only, but it was, in general, similar to that of the control mix. These results suggest that using a binder with appropriate low-temperature performance grade can help in ensuring satisfactory low-temperature cracking resistance of the RAP mixes.

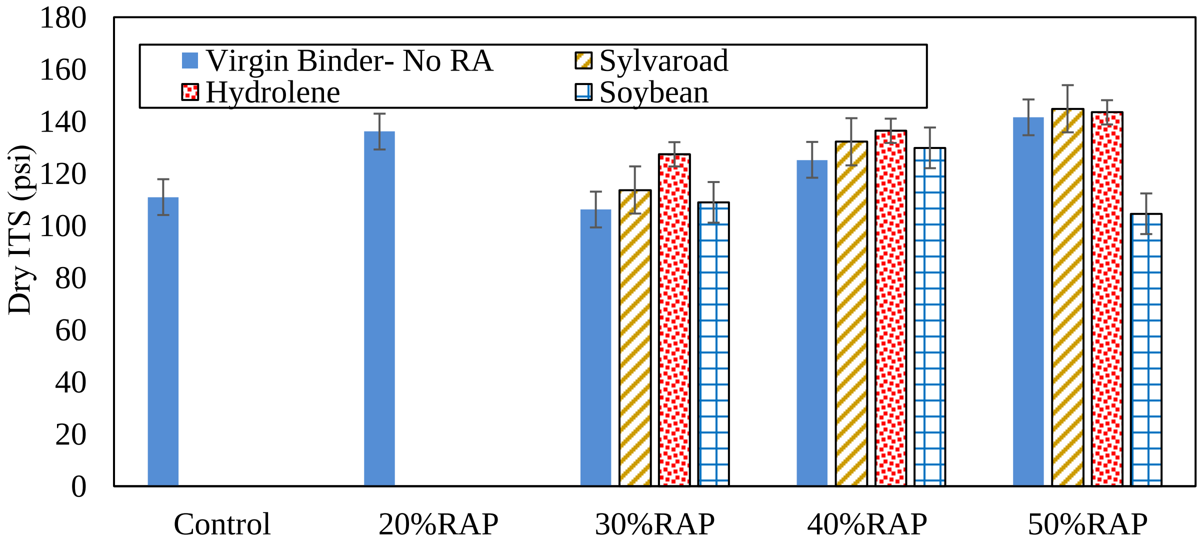

Figure D.6 ITS values of dry samples of RAP-1 mixes

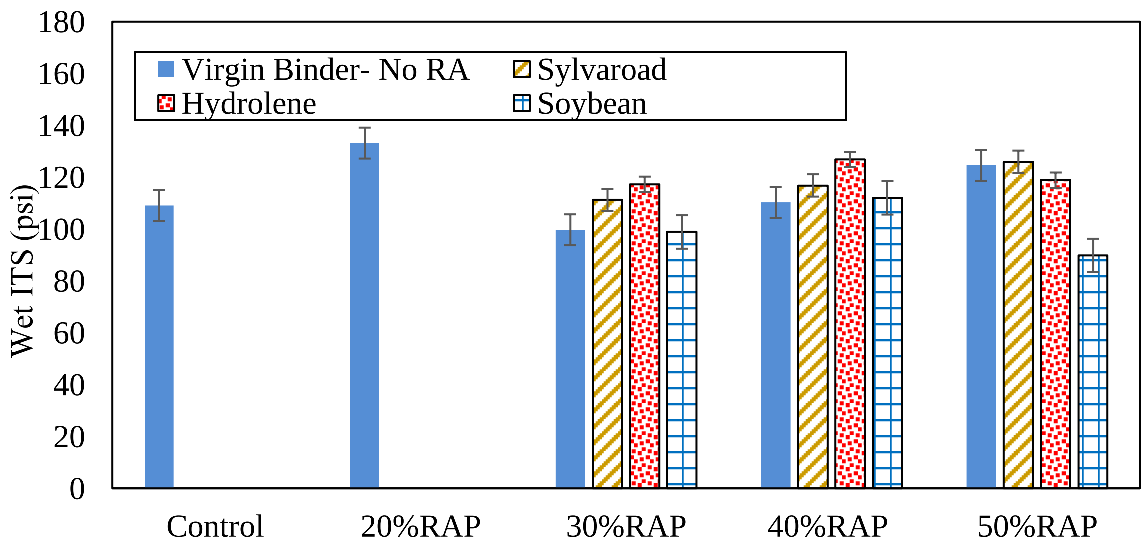

Figure D.7 ITS values of wet conditioned samples of RAP-1 mixes

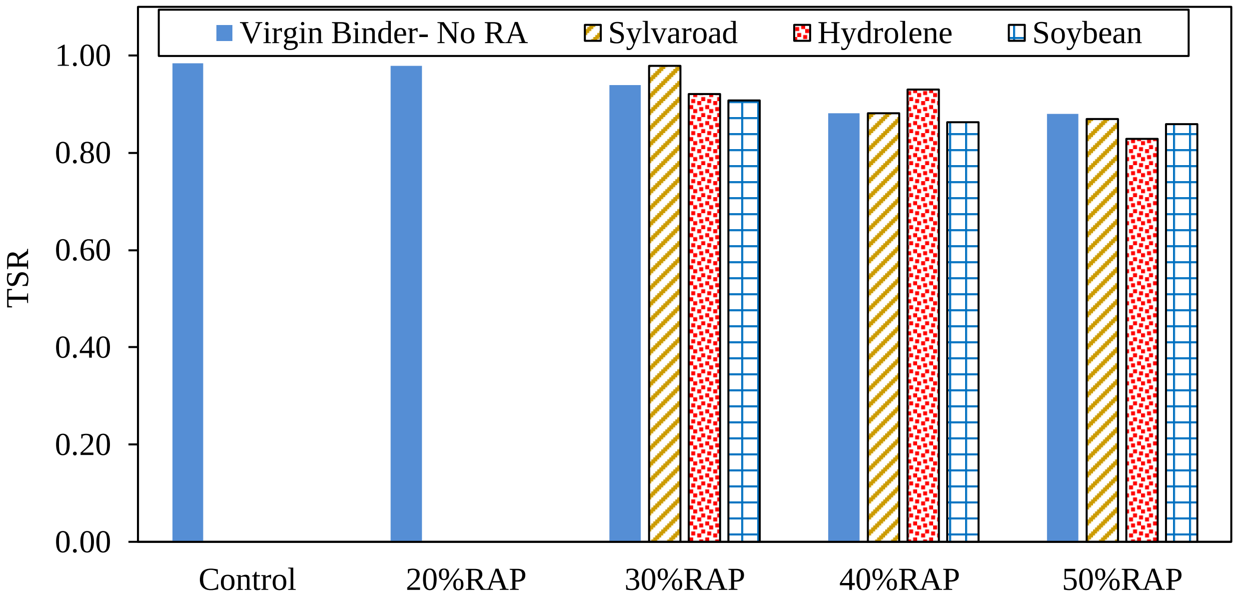

Figure D.8 TSR values of RAP-1 mixes

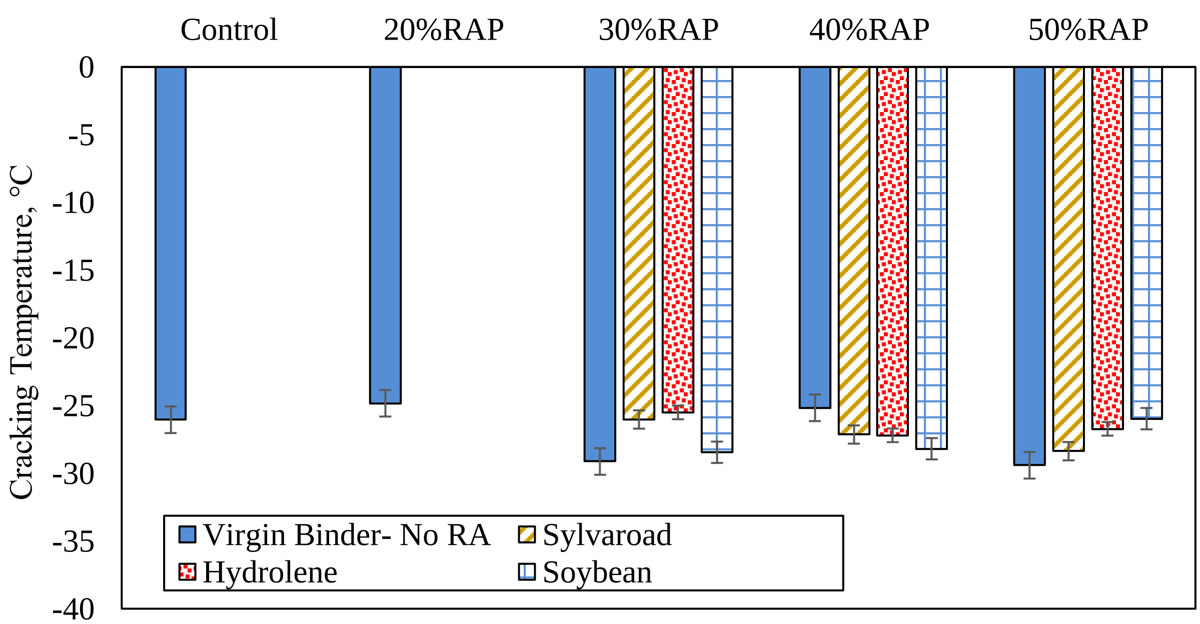

Figure D.9 ACCD cracking temperature for RAP-1 mixes

D.2.4 APA Test Results

Figure D.10 presents the average rutting values obtained in the APA tests conducted on the RAP-1 mixes. The use of the softer PG 64-28 binder resulted in higher rutting in mixes with 30% RAP-1. However, the rutting decreased when increasing the RAP content. In general, the mixes with the three RAs had higher rutting for RAP-1 mixes than the control mix, particularly the 30% RAP-1 mix. The soybean RA mixes had highest rutting, which suggests that this RA has significantly softened the binder. All mixes had rutting values less than the 5 mm, which the maximum rutting value allowed by ODOT for mixes used on roadways with medium traffic. Therefore, all RAP-1 mixes had acceptable APA rutting values.

D.3 Effect of RAP Source

D.3.1 SCB Test Results

Figure D.11 compares the average NFE of long-term aged samples of mixtures with RAP-1 to those with RAP-2. The NFE for the mixtures with both RAP materials and PG 64-28 binder decreased with an increase in the RAP content. However, the NFE values of RAP-2 mixes were higher than those of the RAP-1 mixes. This suggests that the RAP-2 mixtures needed higher energy to crack, which indicates that these mixes have greater resistance to fatigue cracking.

Figure D.12 shows the average FI values of the long-term aged samples of RAP-1 and RAP-2 mixes. Similar to the NFE, the FI values for the mixtures with both RAP materials decreased with the increase in the RAP content. However, the decrease in FI in RAP-1 mixes were more significant than that in the RAP-2 mixes. Note that the use of softer binder PG 64-28 was effective in maintaining the fatigue cracking of the RAP-2 mixes with up to 40% RAP content. The results of SCB tests clearly indicate that the RAP source affects the fatigue cracking resistance of mixes with high RAP content.

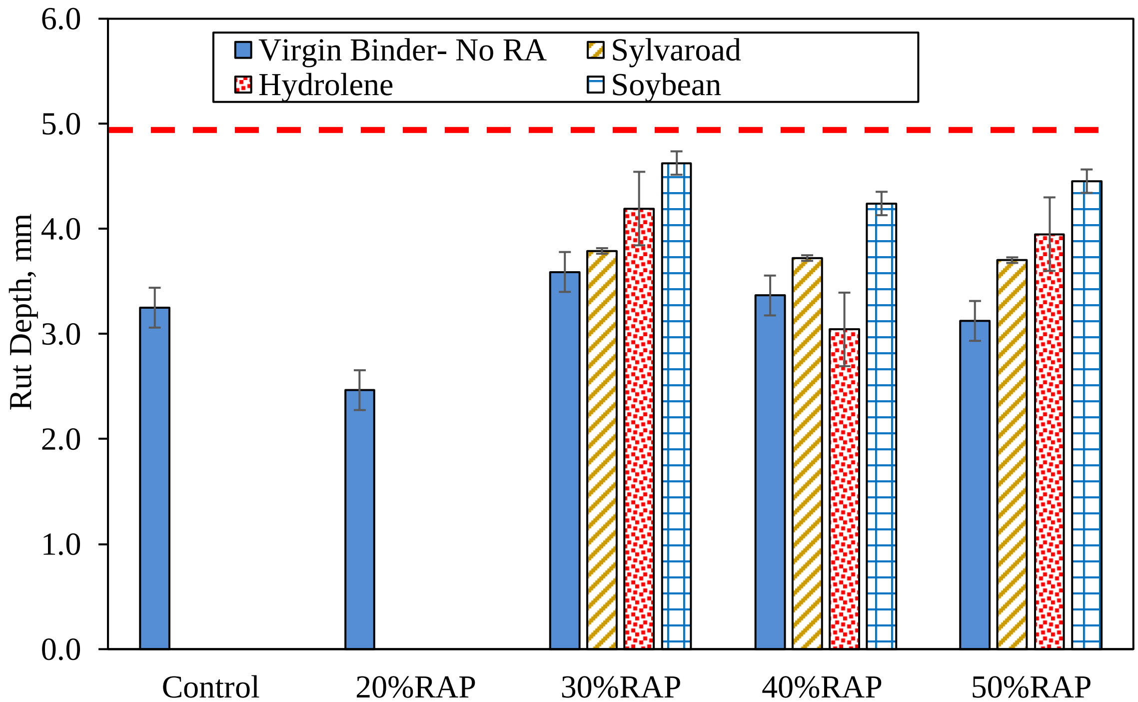

Figure D.9 APA test results for RAP-1 mixes

D.3.2 Modified Lottman Test Results

The average ITS values of the dry conditioned samples of RAP-1 and RAP-2 mixes are shown in Figure D.13. Although the ITS of 20% RAP with PG 64-22 had higher ITS than the control virgin mix, using the softer PG 64-28 binder resulted in lower ITS for RAP-1 and RAP-2 mixes with 30% RAP. However, the ITS increased with the increase of RAP content for 40% and 50% RAP content. The ITS values of RAP-2 mixes were, in general, slightly higher than those of the RAP-1 mixes. This suggests that the RAP-2 mixes have better tensile strength to resist cracking. The ITS of dry samples confirms the SCB test results, further suggesting that the RAP source has an impact on the cracking resistance of high RAP mixes.

Figure D.14 presents the TSR values for RAP-1 and RAP-2 mixes that was computed based on average ITS of the dry and wet samples. In general, the TSR values of control mix were slightly higher than RAP-1 and RAP-2 mixes with 30%, 40%, and 50% RAP. It is clear that RAP-1 and RAP-2 had similar TSR values, which suggests that the RAP source did not affect the moisture susceptibility of high RAP mixes. All RAP-1 and RAP -2 mixes had TSR values higher than 80%, which indicates that all RAP mixtures evaluated in this study met the minimum acceptable TSR value specified by ODOT.

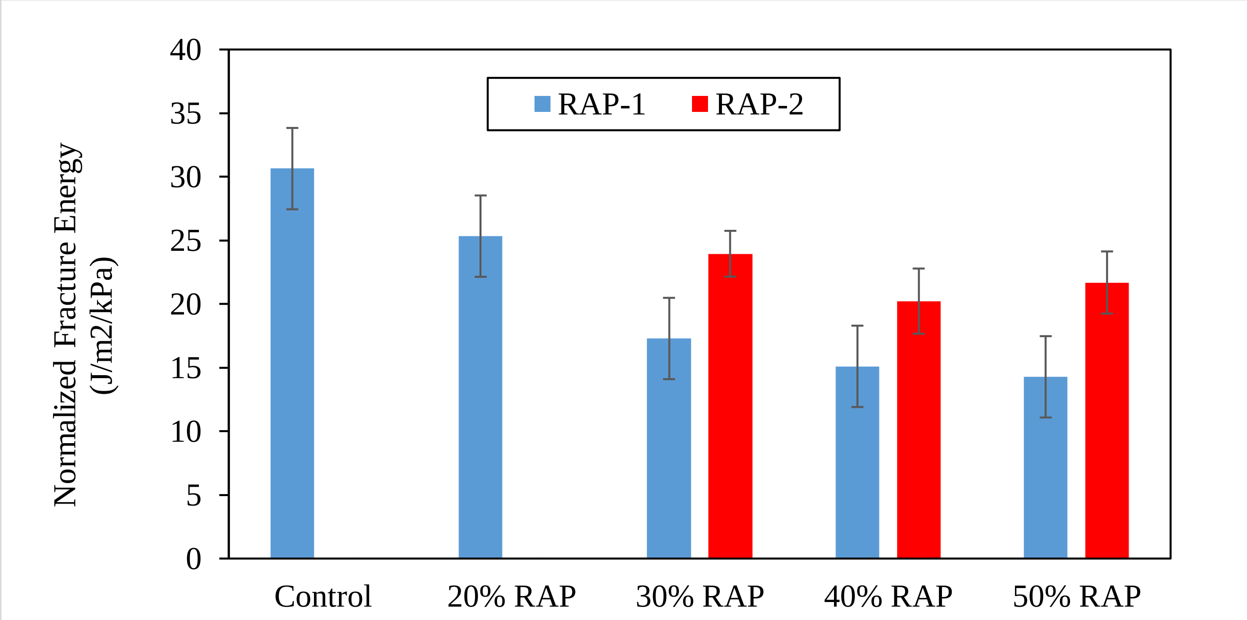

Figure D.11 Normalized Fracture Energy (NFE) for RAP-1 and RAP-2 mixes

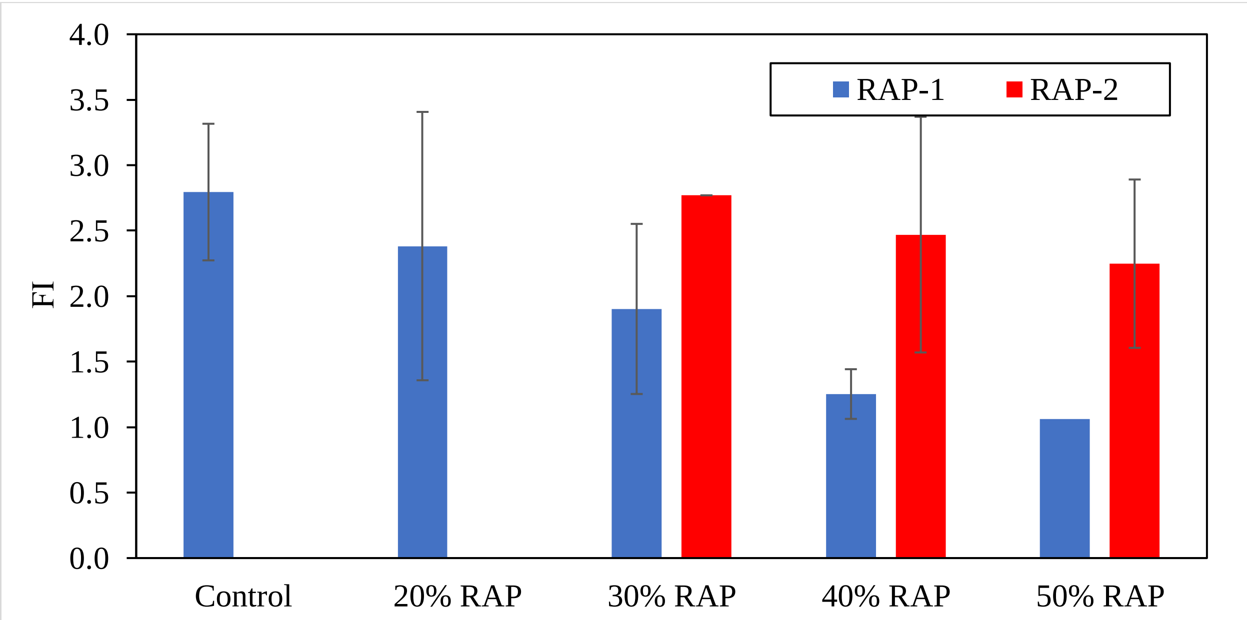

Figure D.12 Flexibility Index (FI) for RAP-1 and RAP-2 mixes

D.3.3 Asphalt Concrete Cracking Device (ACCD) Test Results

Figure D.15 compares the average ACCD cracking temperature of long-term aged samples of mixes prepared with RAP-1 and RAP-2. Note that all RAP-1 and RAP-2 mixes with 30% RAP or more had cracking temperature colder than that of the control mix. This suggests (for mixes with both RAP sources) using the softer binder was effective in improving and maintaining the low-temperature cracking resistance of mixes with high RAP percentages. The results also confirm the previous finding, suggesting that using a binder with appropriate low-temperature performance grade can help ensure satisfactory low-temperature cracking resistance of the high RAP mixes. The RAP-2 mixes had slightly colder cracking temperatures than those of the RAP-1 mixes. This suggests that the RAP source may have an impact on the low-temperature cracking resistance of high RAP mixes.

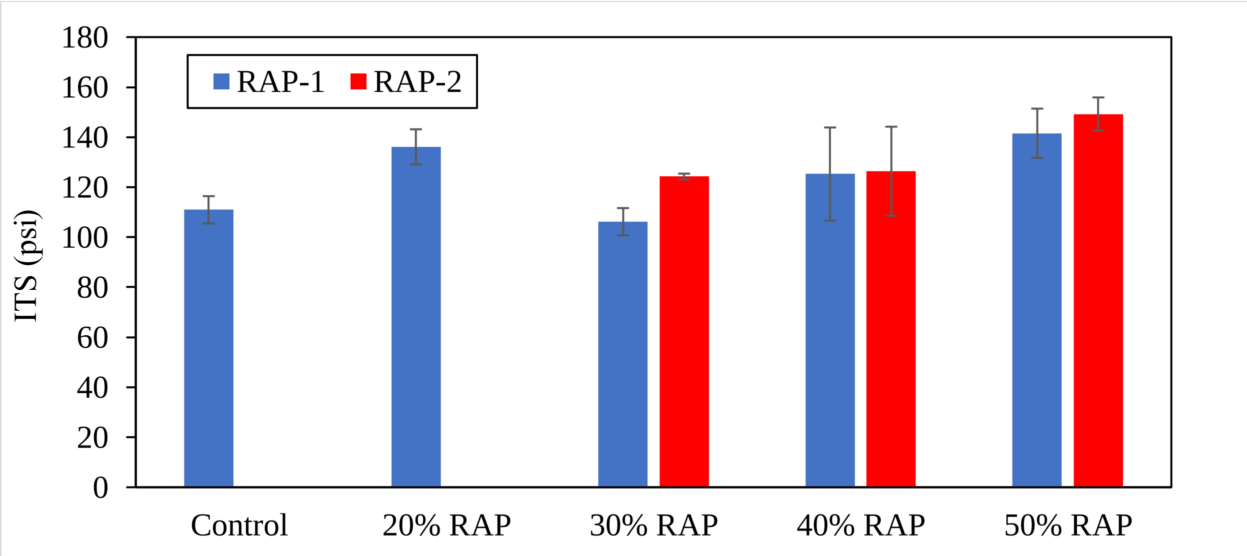

Figure D.13 ITS of dry samples for RAP-1 and RAP-2 mixes

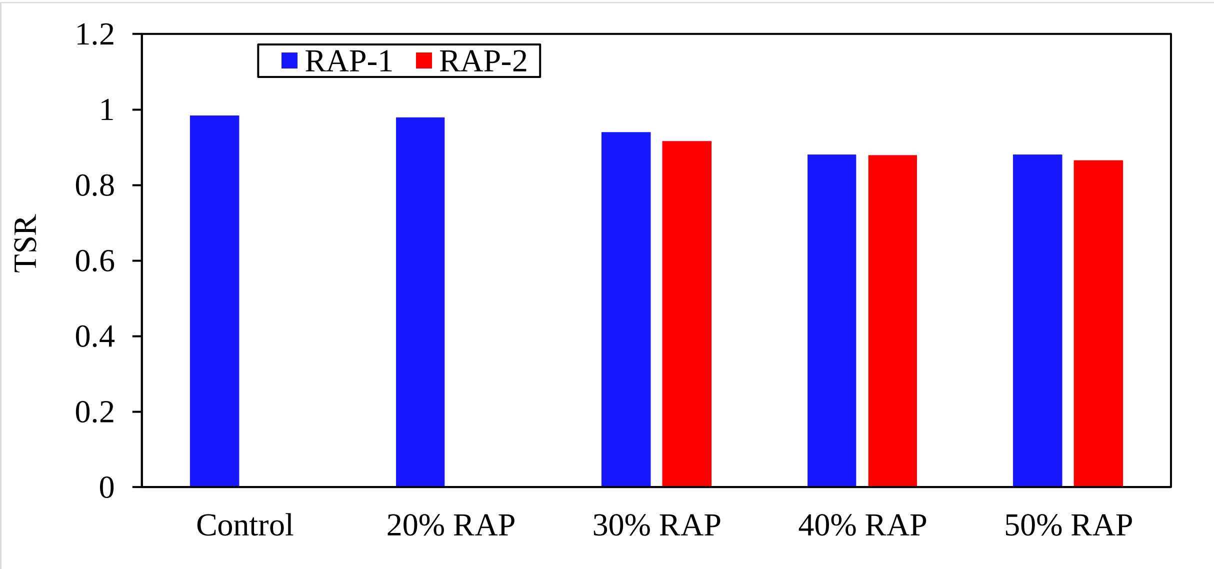

Figure D.13 TSR for RAP-1 and RAP-2 mixes

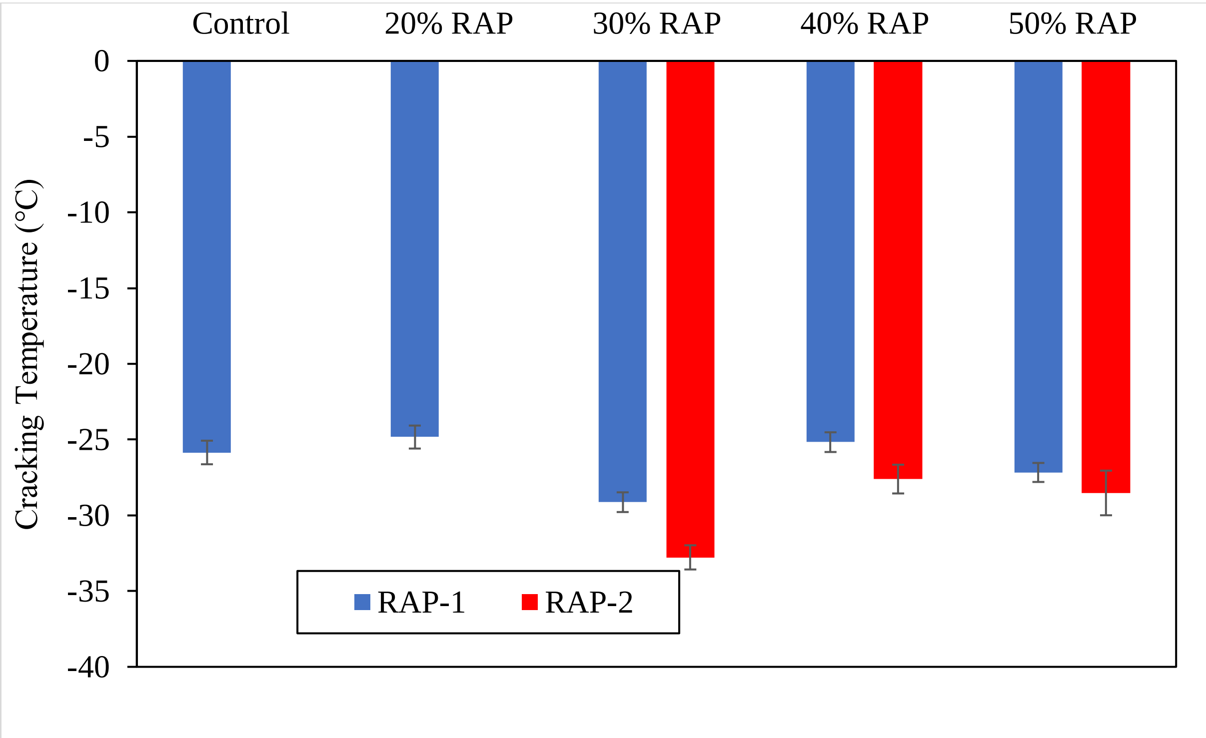

Figure D.13 ACCD cracking temperature for RAP-1 and RAP-2 mixes

D.5 Results of Evaluation of IDEAL-CT Test for Quality Control

The results of IDT tests were re-analyzed to determine CTI for several of the tested RAP mixes. The correlation between the CTI and FI parameters obtained from SCB tests on short-term aged samples was evaluated. Figure D.14 presents this correlation. Note that a relatively good correlation exists between those CTI-IDT and FI-SCB parameters. This suggests that CTI might be a good parameter to be used as part of the quality control procedure for high RAP mixes.

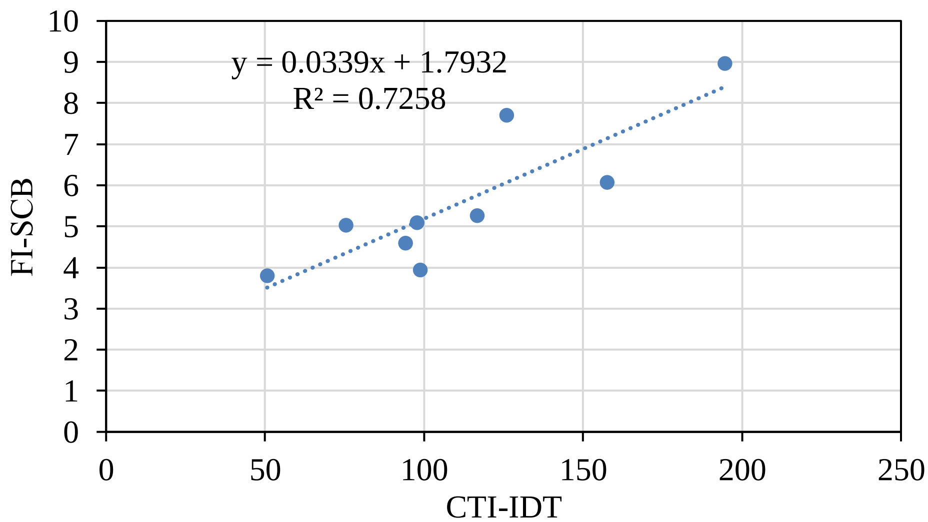

Figure D.14 Correlation of Between CTI and FI

D.4 Cost Analysis Results

The current prices of the PG 64-22 and PG 64-28 asphalt binders, as well as the RAs, are presented in Table D.1. A cost analysis was conducted to determine the prices of the control and RAP mixes with RAs and PG 64-28 and PG 64-22 binders. The results of this analysis are provided in Figure D.15. It is clear that increasing the RAP content reduced the cost of the asphalt mixture. However, this reduction depended on the type of RA used. The RAP mixes with Hydrolene were the least expensive mixes. The costs of the 30%, 40%, and 50% RAP mixes with different types of RAs were compared to that of a virgin mix, as well as a 20% RAP mix. Tables D.2 and D.3 present the cost benefit ratio of the 30%, 40% and 50% RAP mixes in comparison to the control virgin mixture as well as the 20% RAP mix, respectively. Note that using higher RAP content and RAs can reduce the cost of an asphalt mixture by at least 17%. In addition, RAP mixes with Hydrolene have the best cost benefit and can reduce the mix cost by to 38% when 50% RAP is used.

Table D.1 Cost of asphalt binder and recycling agent used

Material	Price ($/ton)*
PG 64-22	$345.83
PG 64-28	$455.83
Sylvaroad	$3,000.00
Hydrolene	$541.00
Soybean	$640.00

**Prices were obtained in February 2018.*

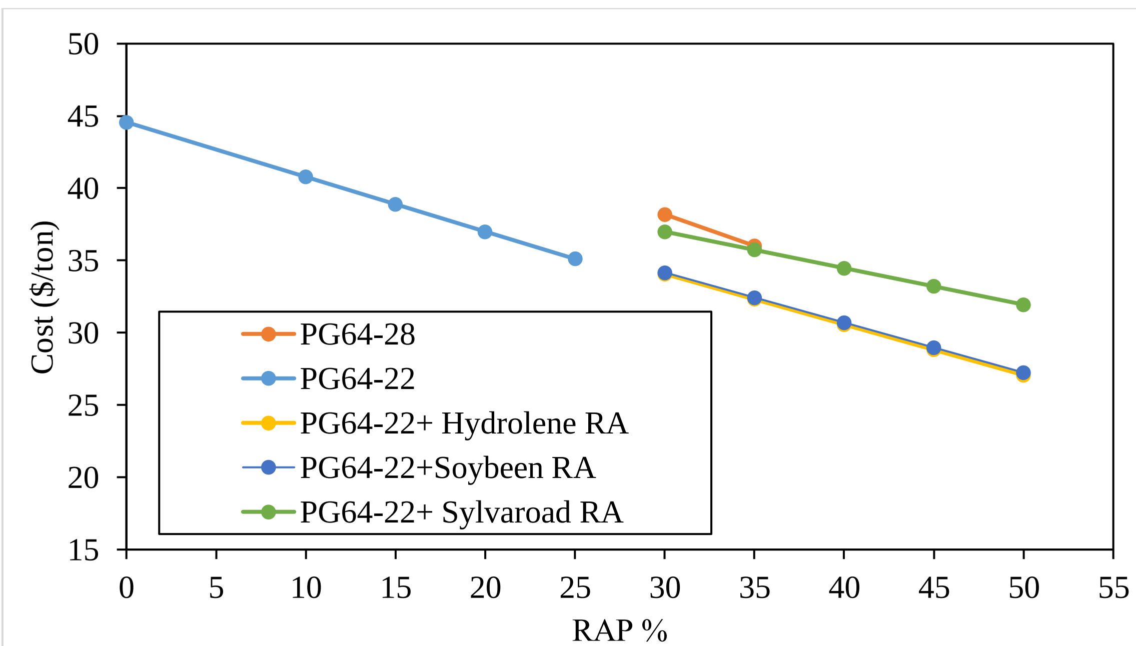

Figure D.15 Cost of RAP mixes with different recycling agents

Table D.2 Cost benefit ratio for RAP mixes with recycling agent to a virgin mix

RAP %	Hydrolene	Soybean	Sylvaroad
30.0%	23.6%	23.3%	17.0%
40.0%	31.4%	31.1%	22.7%
50.0%	39.3%	38.9%	28.3%

Table D.3 Cost benefit ratio for RAP mixes with recycling agent to a 20% RAP mix

RAP%	Hydrolene	Soybean	Sylvaroad
30%	7.9%	7.6%	0.0%
40%	22.1%	21.7%	10.2%
50%	26.8%	26.4%	13.7%

Appendix E Recommendations for Mix Design Specifications and QC Criteria for High-RAP Asphalt Mixtures

E.1 Recommendations for Mix Design Specifications

Figure E.1 provides a flow chart that for recommended method for designing medium traffic surface course mixes with RAP content greater than 20%. The following sections provide details of this method.

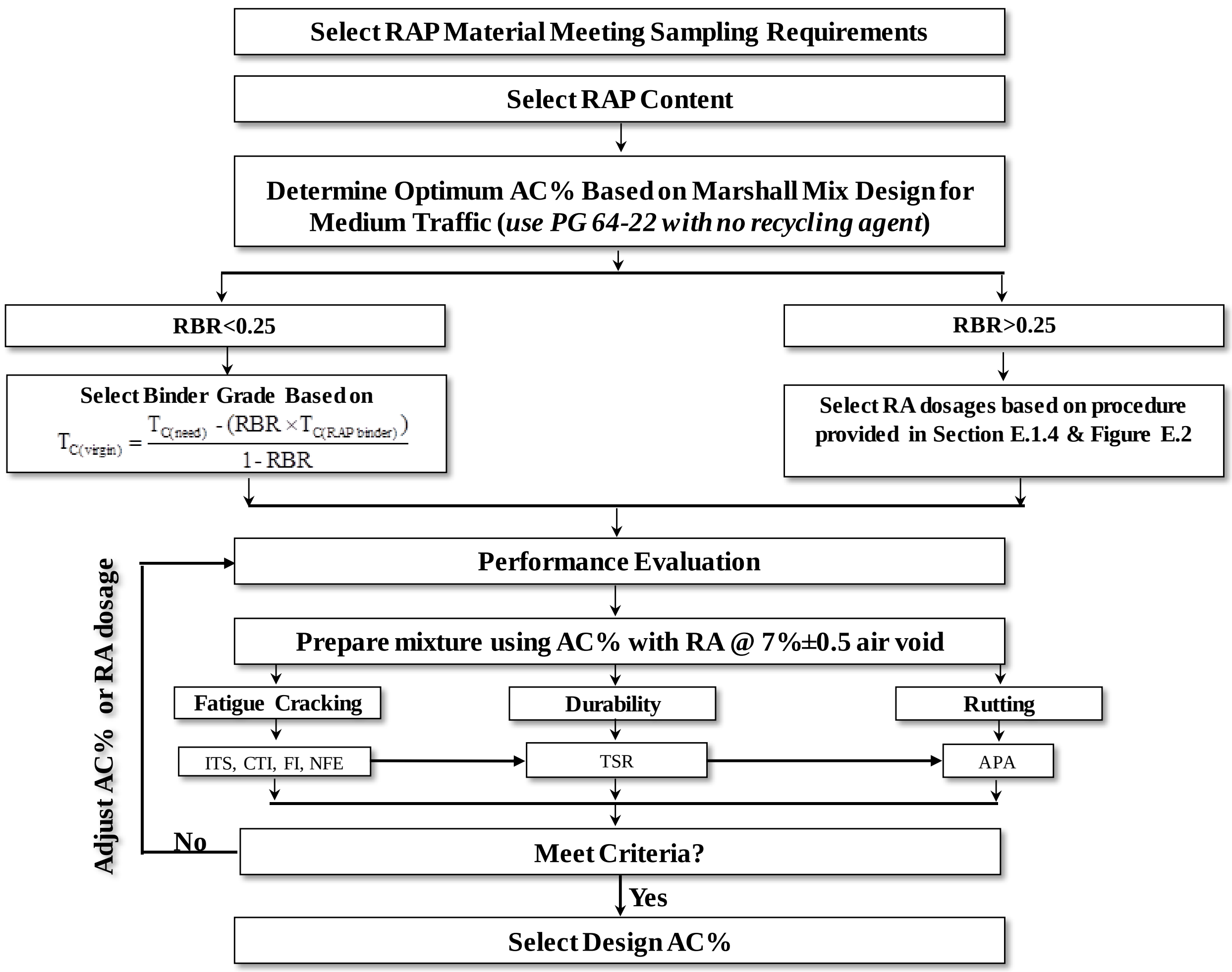

Figure E.1 Recommended method for designing mixes with high RAP contents

E.1.1 RAP Material

RAP materials processed using ODOT Method 2 are only allowed to be used in mixes designed using this specification. The selected RAP materials should be tested according to the recommended sampling and testing frequencies presented in Table E.1 and should meet the maximum standard deviation requirement in this table.

Table E.1 Recommended Sampling and Testing of RAP

Property	Test Method(s)	Frequency	Minimum # Tests per Stockpile	Maximum Standard Deviation
RAP Asphalt Binder Content	AASHTO T 164 or AASHTO T 308	1 per 1,000 tons	10	0.5
RAP Recovered Aggregate Gradation	AASHTO T 30	1 per 1,000 tons	10	5.0 all sieves 1.5 on Sieve No. 200
Recovered Aggregate Bulk Specific Gravity	AASHTO T 84 and T 85	1 per 3,000 tons	3	0.030
Continuous performance grade of extracted and recovered RAP binder*	AASHTO T 319 and AASHTO R 29	1 per 5,000 tons	1	N/A

**RAP binder should be extracted using Toluene solvent.*

E.1.2 Initial Determination of Binder Content

Design the RAP mixture according to the Marshall mix design method. Determine lab mixing and compaction temperatures based on virgin binder grade temperature–viscosity relationship. RAs should not be used in preparing samples.

E.1.3 Selection of Virgin Asphalt Binder

The RAP Binder Ratio (RBR) should be first computed. The RBR is the ratio of the RAP binder in the mixture divided by the mixture's total binder content. If the RBR is less than 0.25, select a virgin binder using Equation E.1 to determine the virgin binder performance grade.

$$T_{C(virgin)} = \frac{T_{C(need)} - (RBR \times T_{C(RAP\ binder)})}{1 - RBR} \tag{E.1}$$

Where:

$T_{c(virgin)}$ is critical temperature (high or low) of the virgin asphalt binder, $T_{c(need)}$ is critical temperature (high or low) needed for the climate and pavement layer, and RBR is RAP Binder Ratio - the ratio of the RAP binder in the mixture divided by the mixture's total binder content.
$T_{c(RAP\ Binder)}$ = Critical temperature (high or low) of the extracted and recovered RAP binder.

E.1.4 Selection of Recycling Agent Type and Dosage

If the RBR is higher than 0.25, select an approved RA (Based on the results of the lab testing program conducted in this study, Hydrolene or Sylvaroad recycling agents should be used). Once the recycling agent is selected, use the following steps (described in the flowchart in Figure E.2) to determine the optimum dosage of the recycling agent to be used with PG 64-22 binder. It is noted that the recycling aged dosage should be based on the RAP binder content in the mixture.

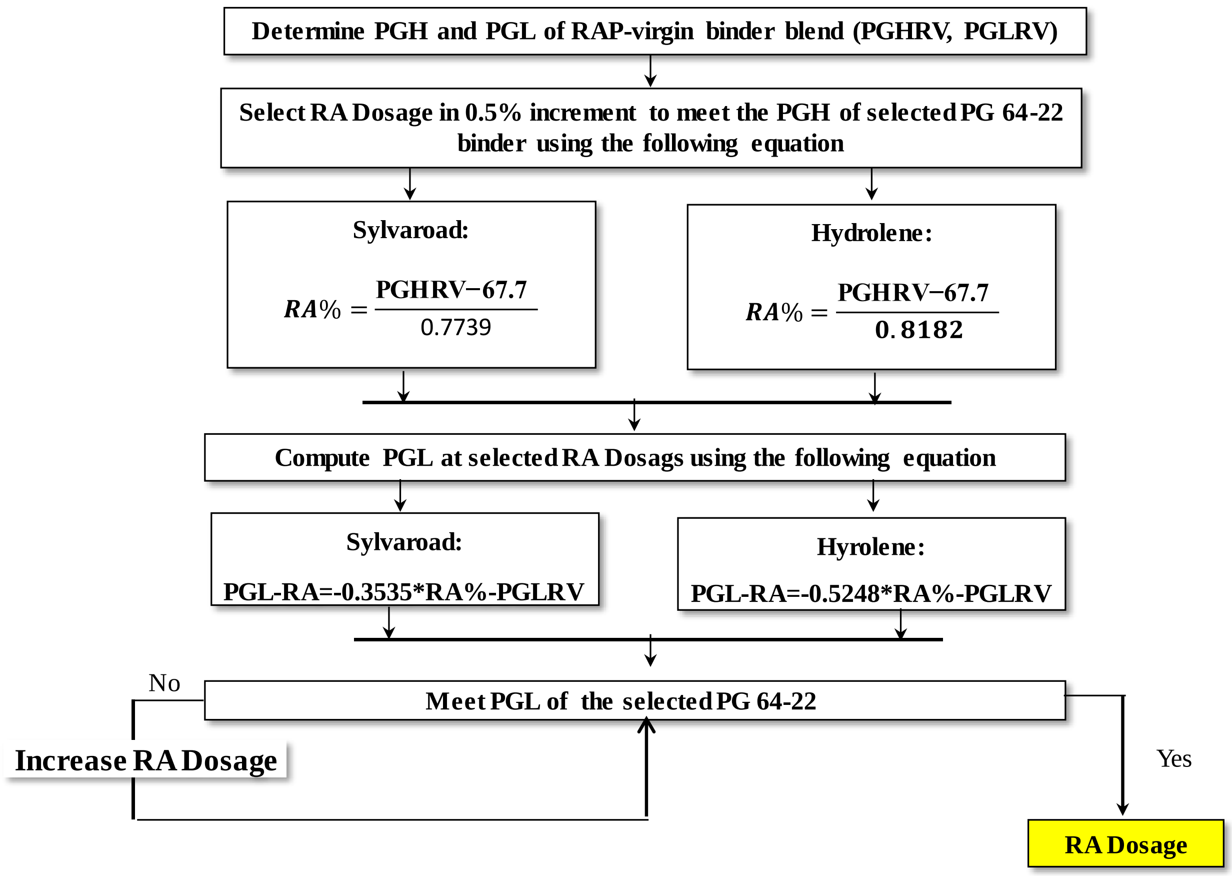

Figure E.2 Recommended method for selecting recycling agent dosage for mixes with high RAP content.

1- Prepare a blend of the extracted and recovered RAP binder and the selected PG 64-22 binder based on the percentages of these binders in the asphalt mix (i.e. percent of RAP in the blend should be equal to the RBR)
2- Conduct dynamic shear rheometer (DSR) tests on unaged and Rolling Thin Film Oven (RTFO) aged samples of the binder blend to determine its continuous high-temperature performance grade (PGH), referred to as PGHRV.
3- Conduct bending beam rheometer test (BBR) on Pressure Aging Vessel (PAV) aged samples to determine the continuous low-temperature performance grade (PGL), referred to as PGLRV.
4- Determine the recycling agent dosage (RA%) to restore the target binder PGH using one of the following equations:

For Hydrolene RA: $RA\% = \frac{\text{PGHRV-67.7}}{0.8182}$

For Sylvaroad RA: $RA\% = \frac{\text{PGHRV-67.7}}{0.7739}$

where

PGHRV: is the continuous high-temperature performance grade temperature for RAP-virgin binder blend.

5- Compute the PGL of the binder blend with the selected recycling agent dosage using one of the following equations:

For Hydrolene RA: PGL-RA=-0.5248*RA%-PGLRV

For Sylvaroad RA: For PGL-RA=-0.3535*RA%-PGLRV

where
PGL-RA: is the continuous low-temperature performance grade of the binder blend at the recycling agent dosage RA%.
PGLRV: is the continuous low-temperature performance grade temperature for RAP-virgin binder blend

6- Compare the PGL-RA computed in previous step to the PGL of the selected PG 64-22. If the PGL-RA meets the PGL of the selected PG 64-22 then the RA dosage found in step 4 should be used. Otherwise, the RA dosage should be increased to meet the PGL of PG 64-22.

It is noted that the selected recycling agent dosage should be added to the asphalt binder prior mixing with the aggregates and RAP material.

E.1.5 Performance Evaluation

Evaluate the following mechanical properties of the mixtures using the selected recycling agent type and dosage and PG 64-22 binder for RBRs greater than 0.25 or the selected virgin binder determined based on Equation E.1, compacted to a target air void of 7±0.5%:

1- Fatigue cracking resistance: conduct SCB tests on at least six long-term aged samples according to the AASHTO TP 124-16. Obtain the flexibility index (FI) and normalized fracture energy (NFE) from the test results. Compare the FI, and NFE to the criteria shown in Table E.2. If the minimum criteria is not met, increase the asphalt binder or the recycling agent dosage to meet that criteria.
2- Moisture damage resistance: evaluate the moisture susceptibility of the designed mixture according to ODOT's Supplement 1051. Determine the tensile strength ratio (TSR) and compare to the criteria shown in Table E.2. If the minimum criteria is not met, increase the asphalt binder or the recycling agent dosage to meet that criterion.
3- Rutting: conduct Asphalt Pavement Analyzer (APA) tests on at least six samples according to AASHTO TP 63 (Standard Method of Test for Determining the Rutting Susceptibility of Asphalt Paving Mixtures Using the Asphalt Pavement Analyzer) and ODOT Supplement 1057 (Loaded Wheel Tester Asphalt Mix Rut Testing Method). Determine the rutting after 8,000 cycles and compare it to the criterion shown in Table E.2. If the minimum criteria is not met decrease the asphalt binder content or the recycling agent dosage to meet that criteria and check if the criteria for other tests in Table E.2 are met.

Table E.2 Criteria for designing high RAP mixes

Parameter	FI (SCB)	NFE (SCB)	TSR (AAHTO T 283)	Rutting (APA)
Criteria	Minimum 2	Minimum 25 $J/m^2/kPa$	Minimum 0.8	Maximum 5 mm

E.2 Recommendations for QC/QA Criteria

Perform quality control tests to control the asphalt concrete mix within the specifications shown in Table E.3. Ensure that these quality control tests measure the asphalt binder content, gradation, air voids, Maximum Specific Gravity (MSG), *Indirect Tensile Strength (ITS),* and *Cracking Test Index (CTI).* Perform each quality control test a minimum of two times per production day or night.

Perform more sampling and testing than the minimum specified at the start of production. Additionally, perform more sampling and testing than the minimum during production when the quality control tests show the asphalt concrete being produced is outside the specifications limits shown in Table E.3. Immediately resolve problems and retest to validate that corrections have returned the materials to within the specifications limits. The contractor may determine the method of testing of the asphalt concrete beyond the minimum specified. Record the results of every test performed. Perform the required quality control tests as follows:

a. **Asphalt Binder Content.** Determine the asphalt binder content of a sample of asphalt concrete by performing an Asphalt Content (AC) Gauge test. Make all printouts available for review by the Monitoring Team at any time. Use solvent extraction when an AC Gauge problem exists and for testing cooled samples that cannot adequately be tested in an AC Gauge test. Determine the moisture content of the asphalt concrete for each AC Gauge test. Maintain the moisture content at 0.8 percent or less.

b. **Gradation.** Perform at least one gradation test each production day on remaining aggregate after removing the asphalt binder using a preapproved asphalt ignition oven.

   The gradation results of all the sieves must be representative of the JMF.

   Calculate the F/A ratio for every ignition oven sample analysis. Maintain the F/A ratio so no F/A ratio is greater than 1.2 for all mixes. Use the asphalt binder content determined by the AC Gauge for calculating the F/A ratio. If the F/A ratio is greater than 1.0, recalculate the F/A ratio using the effective asphalt binder content. If the F/A ratio is greater than 1.0 for ignition oven samples, calculate the F/A ratio using the percent passing the No. 200 (75 µm) sieve from a washed gradation of the ignition oven sample.

c. **Air Voids and MSG.** Determine the air voids of the asphalt concrete by analyzing a set of compacted specimens and a corresponding MSG determination. Ensure that the cure temperature and specimen compaction temperature are the same. Use a 1-hour cure for all mix samples used in voids analysis. The contractor may use a 2-hour cure time if voids are consistently near the low void warning band. In this case, use the 2-hour cure for all voids testing through the remainder of the project. Calculate the Voids in Mineral Aggregate (VMA) value for every set of compacted specimens.

Whenever compacted specimens are to be made and an MSG determination is to be run, take a sample of sufficient size to run a corresponding AC Gauge test. When the air void and MSG test results are recorded reference them to the AC Gauge test of the sample.

Calculate the average of all the MSG determinations performed each production day and report this average. When the range of three consecutive daily average MSG determinations is equal to or less than 0.020, average these three average MSG determinations to determine the Maximum Theoretical Density (MTD). After the MTD is established, compare all individual MSG determinations to the MTD.

d. **IDT.** *Determine ITS and CTI of three specimens compacted to target air void 7±0.5% as well as for three 6-inch core samples obtained from field sections. The indirect tensile strength test can be conducted using Marshall Stability testing frame with a testing jig that can measure and record load and deformation.*

e. **Other Requirements.** Measure the temperature of the mixture and record. Validate the results on the load tickets at least once during each hour of production.
Retain a split sample for each AC Gauge test and MSG test and all compacted specimens for monitoring by the LPA. The contractor may dispose of the AC Gauge test samples after two days and all other split samples after seven days if the LPA does not process the split samples.
The contractor may conduct additional testing of any type. Record such additional testing along with all other quality control records and have these records readily available for the Monitoring Team's review.

Table E.3 Recommended out of specification limits

Mix Characteristic	**Out of Specification Limits**
Asphalt Binder Content[1]	-0.3% to 0.3%
1/2 inch (12.5 mm) sieve[1]	-6.0% to 6.0%
No. 4 (4.75 mm) sieve[1]	-5.0% to 5.0%
No. 8 (2.36 mm) sieve[1]	-4.0% to 4.0%
No. 200 (75 µm) sieve[1]	-2.0% to 2.0%
Air Voids[2]	2.5% to 4.5%
Air Voids[3]	3.0% to 5.0%
MSG[4]	-0.012 to 0.012
ITS	*110 psi (minimum)*
CTI	*100 (minimum)*

[1] deviation from the JMF
[2] for Design Air Voids of 3.5%
[3] for Design Air Voids of 4.0%
[4] deviation from the MTD