Analysis of Ground Tire Rubber (GTR) in Mix Design on Local Roadways in Ohio

Prepared by:
Munir D. Nazzal, Ph.D., P.E.
Sang-Soo Kim, Ph.D., P.E.
Arkan Obaid
Tanvir Iqbal
Department of Civil Engineering
Ohio University

Ala R. Abbas, Ph.D.
Tanvir Quasem
Department of Civil Engineering
The University of Akron

Prepared for:
Ohio's Research Initiative for Locals (ORIL)
The Ohio Department of Transportation,
Office of Statewide Planning &
Research

State Job Number 134989

February 2018

Final Report

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/OH-2018/4		

4. Title and Subtitle	5. Report Date:
Analysis of Ground Tire Rubber (GTR) in Mix Design on Local Roadways in Ohio	**February 2018**
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Munir D. Nazzal, Sang Soo Kim, Ala Abbas, Arkan Obaid, Tanvir Iqbal, and Tanvir Quasem	
9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
Ohio University **Department of Civil Engineering** **Athens, Ohio 45701**	
	11. Contract or Grant No.
	SJN 134989
12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
Ohio Department of Transportation **1980 West Broad Street, MS 3280** **Columbus, Ohio 43223**	**Final Report**
	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

This report summarizes the results of a research project that was conducted to: 1) evaluate the long-term field performance and life cycle cost of Ground Tire Rubber (GTR) modified pavement sections in Ohio and compare them to those obtained for pavement sections constructed using conventionally modified polymer modified asphalt mixtures, and 2) identify and examine new GTR technologies that may reduce the initial cost of GTR mixtures in Ohio. This project was divided into two phases. The results of Phase 1 of this project identified three GTR modified binders that potentially could lower the cost of GTR mixtures. The results of the laboratory tests showed that mixtures prepared with these GTR modified binders had better resistance to low-temperature and fatigue cracking as well as rutting than those prepared using the polymer modified PG 70-22 binder.

Phase 2 of this project involved constructing test sections as part of resurfacing projects in the City of Columbus and the City of Akron. Four test sections were constructed in the City of Columbus. In the first test section (control section), a styrene-butadiene-styrene (SBS) polymer modified PG 70-22M binder was used in the surface course mixture. Furthermore, the surface course mixtures in the other three sections included a PG 64-22 binder modified with 7% MicroDyne™-400, a PG 64-22 binder modified with 6% MicroDyne™-400 GTR and 0.5% Rheopave and a PG 64-22 binder modified with 7% Liberty -30 mesh GTR. Two test sections were constructed in the City of Akron. While the surface course mixtures in first sections included a SBS modified PG 70-22M binder, a PG 64-22 binder modified with 6% MicroDyne™-400 GTR and 0.5% Rheopave was used in the surface mixture of the second section. Cores were obtained at different locations within each test section. Laboratory tests were conducted to evaluate the cracking resistance and durability of the field cores. The results of the laboratory tests showed that the field cores obtained from GTR sections had acceptable resistance to low-temperature and fatigue cracking as well as moisture-induced damage, which were, in general, similar to that of the SBS polymer modified PG 70-22M test section. No distresses were observed in any of the SBS polymer and GTR test sections during the first year of service. Cost analyses conducted in this study indicated the cost of GTR mixes may be lower than that of SBS polymer modified mixes if the GTR mixes become more widely used by local public agencies in Ohio.

17. Keywords	18. Distribution Statement
Ground Tire Rubber, Performance of GTR pavements, LCCA of GTR pavements, Field Test Sections	**No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161**

19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price

Unclassified	**Unclassified**	**112**	

Analysis of Ground Tire Rubber (GTR) in Mix Design on Local Roadways in Ohio

Prepared by:

Munir D. Nazzal, Ph.D., P.E.
Sang Soo Kim, Ph.D., P.E.
Arkan Obaid
Md. Tanvir Iqbal
Department of Civil Engineering
Ohio University
Athens, OH 45701

And

Ala Abbas, Ph.D.
Tanvir Quasem
Department of Civil Engineering
The University of Akron
Akron, OH 44325

February 2018

Prepared in cooperation with the Ohio Department of Transportation, Ohio's Research Initiative for Locals, and the U.S. Department of Transportation, Federal Highway Administration

Acknowledgments

The researchers would like to thank the Ohio Department of Transportation (ODOT), Ohio's Research Initiative for Locals (ORIL), and the Federal Highway Administration (FHWA) for sponsoring this study. The researchers would like also to thank the members of Technical Advisory Committees: Mitch Blackford, JuanPablo Ascarrunz, Mike Huber, Robert Liang, Rui Liu, Mike Teodecki, Perry Ricciardi, and James Young. In addition, the researcher would like to thank the City of Columbus and the City of Akron personnel for all of their effort and help in this project; particularly: Dr. A. Shafi, Daniel Johnson, Ross Kissner, Richie C Dimmerling, and Luke Stevenson. Finally, the researchers would like to express their appreciation to Ms. Vicky Fout for her time and assistance throughout the project.

TABLE OF CONTENTS

Analysis of Ground Tire Rubber (GTR) in Mix Design on Local Roadways in Ohio

Executive Summary

This report summarizes the results of a research project that was conducted to: 1) evaluate the long-term field performance and life cycle cost of Ground Tire Rubber (GTR) modified pavement sections in Ohio and compare them to those obtained for pavement sections constructed using conventionally modified polymer modified asphalt mixtures, and 2) identify and examine new GTR technologies that may reduce the initial cost of GTR mixtures in Ohio. This project was divided into two phases. The results of Phase 1 of this project indicated that previously constructed GTR modified pavement sections had similar performance to polymer modified pavement sections, but they were more expensive. Three GTR modified binders that potentially could lower the cost of GTR mixtures were identified; these included: GTR binders prepared using Liberty GTR, Lehigh GTR, and Lehigh GTR with Rheopave. A laboratory testing program was completed to evaluate the performance of asphalt mixtures prepared using the three GTR modified binders and a control PG 70-22 polymer modified binder with respect to moisture-induced damage, rutting, fatigue cracking, and low-temperature cracking. The results of the laboratory tests showed that the mixtures prepared using GTR modified binders had better resistance to low-temperature and fatigue cracking as well as rutting than those prepared using the polymer modified PG 70-22 binder. In addition, the GTR modified mixes had comparable resistance to moisture-induced damage to those prepared using the PG 70-22 binder.

Phase 2 of this project involved constructing test sections as part of resurfacing projects in the cities of Columbus and Akron. Four test sections were constructed in Columbus. In the first test section (control section), a styrene-butadiene-styrene (SBS) polymer modified PG 70-22M binder was used in the surface course mixture. Furthermore, the surface course mixtures in the other three sections included a PG 64-22 binder modified with 7% MicroDyne™-400, a PG 64-22 binder modified with 6% MicroDyne™-400 GTR and 0.5% Rheopave and a PG 64-22 binder modified with 7% Liberty -30 mesh GTR. Two test sections were constructed in Akron. While the surface course mixture in the first section included an SBS modified PG 70-22M binder, a PG 64-22 binder modified with 6% MicroDyne™-400 GTR and 0.5% Rheopave was used in the surface mixture of the second section. Samples of the GTR modified asphalt binders were obtained and tested in the laboratory using the dynamic shear rheometer and the bending beam rheometer tests. Cores were also obtained at different locations within each test section. Laboratory tests were conducted to evaluate the cracking resistance and durability of the field cores. To this end, semi-circular bending tests and indirect tensile strength tests were conducted on the field cores to examine their fatigue cracking resistance. In addition, AASHTO T283 and asphalt concrete cracking device tests were performed to evaluate resistance to low-temperature moisture and cracking damage of the field cores, 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 polymer and GTR modified test sections.

The results of the laboratory tests showed that the field cores obtained from the GTR sections had acceptable resistance to low-temperature and fatigue cracking as well as to moisture-induced damage, which was in general similar to that of the polymer modified PG 70-22M test section. No distresses were observed in any of the polymer and GTR test sections during first year of service.

The cost of the GTR mixes was higher than that of the SBS polymer modified PG 70-22M mix used in this study. This should be attributed to producing small quantities of these GTR mixes on one project and not being able to use them in other paving projects. However, based on cost analyses conducted in this study, the estimated cost of GTR mixes is expected to be lower than that of polymer modified mixes if the GTR mixes become more widely used by local public agencies in Ohio. GTR modifiers can be purchased cheaper than SBS modifiers, at this present time. Based on the findings of this study, it is recommended to use mixes produced using GTR modified binders meeting the specifications developed in this study. The wide use of GTR mixes on local roadways will help reduce their cost and make them more affordable than conventionally-modified polymer mixes.

1. Project Background

Ground tire rubber (GTR), also known as crumb rubber, has been incorporated in asphalt mixtures since the 1960s to enhance the performance and service life of pavements. In more recent years, GTR has also gained interest due to its potential for reducing highway-related traffic noise (Associated Construction Publication, 2015). One of the main benefits of GTR is its positive impact on the environment through the reuse of tires that might otherwise be discarded and would take up space in landfills, where they would pose a fire hazard and provide a breeding ground for rodents and insects. Tires at landfills can also cause other problems due to their tendency to settle unevenly and to rise to the surface of the landfills, where they may cause damage to the landfill cover (Associated Construction Publication, 2015).

While a number of states with milder climates – including Arizona, California, Florida, Texas, South Carolina, Nevada, and New Mexico – have been using GTR in asphalt for roadway construction, it has not yet seen wide adoption in northern regions of the United States. In Ohio, GTR has been used on approximately 33 local roads and 3 state highways since 2005. Although the use of GTR may be beneficial for pavement quality and the environment, the high initial cost for incorporating it into asphalt mixtures is likely the main reason for not using it more extensively within the state. Therefore, research was needed to evaluate the long-term field performance of GTR asphalt mixtures produced using the wet process on Ohio roads. Further, research was needed to perform a life cycle cost benefit analysis of these asphalt mixtures to determine if they are more cost-effective than traditional asphalt mixtures that do not contain GTR. In addition, there is a need to examine recent advances and technologies in GTR production methods that can help reducing the initial cost of GTR mixtures produced using the wet process and make these mixtures more affordable.

The Ohio Department of Transportation (ODOT) has various specifications concerning asphalt mix designs that include GTR asphalt mixtures produced using the wet process, such as ODOT Supplement Specification 887. These specifications address the use of GTR materials on interstates and highways, but they may not be appropriate for local roads. Because traffic volume, traffic type, and traffic patterns (e.g., intersections) are different for local roads, the GTR may influence the performance in a different manner, with current ODOT specifications resulting in over or under-designed mixtures for local roads. Therefore, research was needed to evaluate the current ODOT mix design specifications and the supplemental quality control/quality assurance (QC/QA) testing and acceptance criteria to determine their applicability for GTR asphalt mixtures produced using the wet process that are used on local roads. This research is also be needed to provide ODOT with clear guidance for developing specifications on the use of GTR for asphalt pavements on local roads.

2. Research Context

The main objectives of this study are:

- Evaluate the field performance of GTR modified asphalt mixes in Ohio.
- Compare the life-cycle cost of GTR modified asphalt mixes with traditional polymer asphalt mixtures.
- Develop draft GTR mix design specifications to be used for local roads.
- Provide recommendations regarding quality control/quality assurance (QC/QA) criteria for testing and acceptance of GTR asphalt mixtures.
- Examine recent advances in GTR production methods and assess their potential in reducing the initial cost of this material.

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

Phase 1: Synthesis Study on the Use of GTR
Task 1: Conduct Literature Review
Task 2: Collect Information on Previously Constructed GTR Projects in Ohio
Task 3: Analyze Data Collected from Previously Constructed GTR Projects in Ohio
Task 4: Conduct Life-Cycle Cost Analysis
Task 5: Conduct Laboratory Testing
Task 6: Develop Draft Mix Design Specifications and QC/QA Criteria to be used for GTR Asphalt Mixtures on Local Roads
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 Field Evaluation and Testing Methodology
Task 9: Construction of GTR Pavement Test Section
Task 10: Evaluation of GTR Pavement Test Section
Task 11: Prepare Final Report and Present Findings

3. Research Approach

The results of Phase 1 of this study indicated that previously constructed GTR modified pavement sections had similar performance to polymer modified pavement sections. However, the life cycle cost analysis indicated that the GTR modified pavement sections had slightly higher life cycle costs than those constructed with polymer modified mixtures. This was attributed to the slightly higher initial cost for GTR modified asphalt mixtures. Based on the cost analysis conducted in Phase 1, the three least expensive GTR modified binders were selected for further evaluation. These included GTR modified binders prepared using 10% Liberty GTR, 10% Lehigh MicroDyne™-400 GTR, and 7% Lehigh MicroDyne™-400 GTR mixed with 0.5% Rheopave. The modifier rates used were based upon the manufacturer's recommendations. The cost of these GTR modified binders was at least $47 per ton less than the estimated cost of a typical PG 70-22 SBS polymer modified binder. A laboratory testing program was conducted to evaluate the performance of asphalt mixtures prepared using the selected GTR modified binders and a PG 70-22 SBS polymer modified binder with respect to moisture-induced damage, rutting, fatigue cracking, and low temperature cracking. The results of the laboratory tests showed that mixtures prepared with Lehigh and Liberty GTR modified binders had better resistance to low-temperature and fatigue cracking as well as rutting than those prepared using the SBS polymer modified PG 70-22 binder. In addition, the GTR modified mixes had comparable resistance to moisture-induced damage to those prepared using the SBS polymer modified PG 70-22 binder. Based on the outcome of Phase 1 of this project, it was recommended to evaluate the performance of asphalt mixtures with GTR binders prepared using 10% Liberty GTR, 10% Lehigh GTR, or 7% Lehigh GTR mixed with 0.5% Rheopave in the field as part of Phase 2. Appendix D provides details about Phase 1 of this study. 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

Four test sections were constructed in the City of Columbus and two test sections were constructed in the City of Akron as part of resurfacing projects to evaluate the performance of the GTR modified mixes identified in Phase 1 of this study and compare them to that of the control SBS polymer modified mix. The Columbus test sections were located on Kenny Road between West Lane Avenue and Ackerman Road. Each section was divided into two subsections, one on the curb lane and another on the through lane. In these test sections, a 1½-in asphalt concrete surface course was placed. The surface course asphalt mixtures were Marshall mixes and had the same aggregate blend. However, the binders used in those mixtures were different. In the first test section (control section), a styrene-butadiene-styrene (SBS) polymer modified PG 70-22M binder was used in the surface mixture. The surface mixtures in the other three sections included a PG 64-22 binder modified with 7% MicroDyne™-400 (LEH), a PG 64-22 binder modified with 6% MicroDyne™-400 GTR with 0.5% Rheopave (LEH+RH), and a PG 64-22 binder modified with 7% Liberty -30 mesh GTR (LIB).

The two test sections in the City of Akron were located on State Route (SR) 59 extended between North Summit Street and State Route 8. The surface course asphalt mixtures were Superpave mixtures and had the same aggregate blend. While, a SBS polymer modified PG 70-22M binder was used in the surface mixture of the first test section, the second test section included a PG 64-22 binder modified with 6% MicroDyne™-400 GTR and 0.5% Rheopave (LE-RH). It is noted that the GTR modifiers percentages were selected based on binder testing done by the contractor.

3.1.2 Field Test Section Construction

A meeting with the city personnel as well as representatives of the asphalt paving contractor was held prior to construction of each test section 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 marked on the curb to avoid distressed areas. Videos and pictures were taken after milling the existing pavement. The research team monitored the placement and compaction of the control and GTR test sections in the projects in the City of Columbus and the City of Akron. 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 Binder Testing

The dynamic shear rheometer (DSR) and the bending beam rheometer (BBR) tests were completed on the GTR and polymer modified binder samples obtained from the production line at the asphalt plant to determine their performance grade (PG) in accordance with AASHTO M320 "Standard Specification for Performance-Graded Asphalt Binder". Additional DSR tests were completed on samples of GTR binders obtained at the asphalt terminal after mixing to evaluate the tendency of the GTR particles to separate from the GTR modified binders.

3.1.4 Laboratory Testing of Cores Samples

Cores were obtained at different locations within the test sections in Columbus and Akron. In addition, samples of loose asphalt mixture were obtained for each of the control and GTR mixtures at the asphalt plant. Laboratory tests were conducted to evaluate the cracking resistance and durability of the core samples. To this end, the propensity of the asphalt mixtures to fatigue cracking was evaluated using the semi-circular bend (SCB) and the indirect tensile strength (IDT) tests. The low-temperature cracking potential of the obtained core samples was assessed using the asphalt concrete cracking device (ACCD). Finally, AASHTO T283 was used to evaluate the moisture damage susceptibility of the cores. A detailed description of each of those 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 polymer and GTR modified test sections. Details of that methodology is 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. Training workshops were organized to discuss the details of the field evaluation methodology with the cities personnel involved in this project.

The developed field methodology included evaluating the performance of polymer and GTR modified test sections by the research team and designated city personnel during the study duration. In addition, it included annual evaluations performed by the city personnel for the first five years after construction. All field evaluations included 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

A cost analysis was performed to compare the costs of the GTR and polymer modified test sections. 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 was obtained from the contracts provided by the City of Columbus and the City of Akron. An analysis considering the additional costs incurred due to producing the GTR mixtures for this project only was performed; which included the costs of: 1) the amount GTR modified binders wasted, 2) the amount GTR mixtures wasted, and 3) cleaning the storage tanks at the terminal. Based on that analysis, an estimated cost of the GTR mixes was determined upon the wide use of these mixes by local public agencies in Ohio.

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 subsections provide a summary of the main findings and conclusions that were made based on the results obtained in Phase 2 of this study.

- The DSR tests conducted on GTR binder samples obtained at the asphalt terminal and from the production line at the asphalt plant indicated that there was more separation in the Liberty GTR modified binder than the Lehigh GTR modified binders. This can be attributed to the coarser gradation of the Liberty GTR particles.
- The addition of Rheopave, an anti-settling agent, did not seem to affect the Lehigh GTR separation in the binder.
- No distresses were observed in either the SBS polymer modified binder or the GTR modified binder test sections during the first year of service.
- The results of the laboratory tests showed that the field cores obtained from the GTR test sections had resistance to low-temperature and fatigue cracking similar to those obtained from the SBS polymer modified PG 70-22M test section.
- The laboratory test results indicated that the GTR mixes have slightly better resistance to moisture damage than the polymer modified mix.
- The cost of GTR mixes was higher than the cost of the SBS polymer modified PG 70-22M mix used in this study. This was attributed to the bidding risk associated with producing new, unfamiliar asphalt binders and mixes. Based on a cost analysis done in this study, the cost of GTR mixes is expected to be lower than the polymer modified mixes if and once the GTR mixes become more widely used by local public agencies in Ohio.

5. Recommendations for Implementation

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

- The initial performance of the GTR 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 GTR mixes for local roads.
- GTR modified binders/mixture specifications and quality control/assurance criteria were developed in this study. It is recommended that local public agencies use these specifications to implement the use of GTR mixes on local roads. The wide use of GTR mixes by local agencies will provide these agencies with a more cost-effective alternative to conventional polymer modified mixes.

6. References

Associated Construction Publications - Silence Please." Associated Construction Publications - Silence Please. Accessed October 16, 2015. http://web.archive.org/web/20060319143533/http://www.acppubs.com/article/CA6279032.html

ODOT (2016). Ground Tire Rubber Modified Asphalt Binder Materials and Construction Requirements. Supplement Specification 887. Ohio Department of Transportation, Columbus, Ohio. October, 2016.

Appendix A Testing Program

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

A.1 Test Sections Description and Construction

Tests sections were constructed in the City of Columbus and the City of Akron. The follwoing sections provide details about constructed sections.

A.1.1 City of Columbus Test Sections

Four test sections were constructed as part of a resurfacing project on Kenny Road in Columbus, Ohio, to evaluate the performance of the identified GTR modified mixes and compare them to that of a conventional polymer modified mix. Figure A.1 presents a map of the test section location. As shown in this figure, the test sections were located on Kenny Road, a four-lane highway, between West Lane Avenue and Ackerman Road. Each test section was divided in two subsections, one on the curb lane and another on the through lane. Table A.1 shows the exact locations of each test subsection.

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 47% limestone #8, 16% natural sand, 17% manufactured sand and 20% RAP. However, the binders used in these mixtures were different. In the first test section (control section), a styrene-butadiene-styrene (SBS) polymer modified PG 70-22M binder was used in the surface mixture. The surface mixtures in the other three sections included a PG 64-22 binder modified with 7% MicroDyne™-400 (LEH), a PG 64-22 binder modified with 6% MicroDyne™-400 GTR and 0.5% Rheopave (LEH+RH), and a PG 64-22 binder modified with 7% Liberty -30 mesh GTR (LIB). A summary of the properties of the four surface course mixtures evaluated in this study is presented in Table A.2.

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 June of 2016 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 control and GTR sections started on 08/25/2016 and was completed on 08/30/2016. One day was allocated for each test section. The research team monitored the placement and compaction of control and GTR test sections. This included measuring the mat temperature and recoding 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.

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

For all GTR mixtures, compaction was as easy as the control SBS polymer modified binder mixture. For the GTR modified binder mixture, the roller operators used more water due to higher mix temperature (305°F versus 295°F). The paving crew indicated that mixtures with Lehigh GTR modified binder was stickier than the Liberty GTR modified mixture as they had to spend more time to scrap off mixtures from their tools. There were two occasions that a large chunk of RAP stuck at the paver screed and left a long streak of empty mat.

Table A.1 Locations of Test Sections On Kenny Road

Section Name	Direction	Start Station	End Station
Control (SBS)	NB (Through)	54+42	78+06
Control (SBS)	SB (Curb)	31+82	54+39
Lehigh GTR	NB (Curb)	31+82	54+40
Lehigh GTR	SB (Through)	54+54	78+06
Lehigh GTR+ Rheopave	NB (Curb)	54+40	78+06
Lehigh GTR+ Rheopave	SB (Through)	31+82	54+54
Liberty GTR	NB (Through)	31+82	54+42
Liberty GTR	SB (Curb)	54+39	78+06

Table A.2 Summary of Mix Design Parameters

Mixture	Control (SBS)	Lehigh GTR	Lehigh GTR+ Rheopave	Liberty GTR
Total Asphalt Content	6.2%	6.4%	6.4%	6.4%
Virgin Asphalt Content	5.2%	5.4%	5.4%	5.4%
RAP Content	20%	20%	20%	20%
Design Blow	50	50	50	50
Design Air Void	3.5%	3.5%	3.5%	3.5%
G_{mm}	2.410	2.408	2.412	2.417
Mixing Temp	315°F	350°F	350°F	350°F
Compaction Temp.	295°F	305°F	305°F	305°F
Tensile Strength Ration (TSR)	87.1%	84.7%	84.2%	86.6%

A.1.2 City of Akron Test Sections

Two test sections were also constructed as part of a rehabilitation project on State Route (SR) 59, a four-lane highway, in the Akron, Ohio. Figure A.3 presents a map of the test sections. The test sections extended between North Summit Street and SR 8 on SR 59. While the GTR test section was located on the curb and through lanes of the east bound of the SR 59, the SBS polymer modified test section was located on the west bound lanes of SR 59. In both test sections, a 1-½ in asphalt concrete surface course was placed. The surface course asphalt mixtures were Superpave mixtures with a 12.5 mm NMAS and had the same aggregate blend, which consisted of 45% limestone #8, 7% limestone #9, 18% manufactured sand, 15% natural sand, and 15% RAP. Different binders were used in these mixtures. In the first test section (control section), a SBS polymer modified PG 70-22M binder was used in the surface mixture. The surface mixtures in the other test sections included a PG 64-22 binder modified with 6% MicroDyne™-400 GTR and 0.5% Rheopave (LEH+RH). A summary of the properties of the two surface course mixtures used in the City of Akron project is presented in Table A.3.

A meeting with the City of Akron 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 May of 2017 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. The test sections on SR 59 were evaluated prior to construction to identify highly distressed areas. Coring locations were identified after milling and marked on the curb to avoid identified areas. Videos and pictures were taken after milling of the existing pavement. The GTR and control test sections were constructed 10/10/2017 and 10/12/2017, respectively. The research team monitored the placement and compaction of control and GTR test sections. This included measuring the mat temperature and recoding the density at core locations. Field density was measured using a nuclear density gauge. Photos were collected and videos of the test sections were recorded during and after construction. Figure A.4 presents some of the photos taken. It is worth noting that at the beginning of construction of the GTR test section, the asphalt mix was tender. This resulted in some difficulties in compaction of the asphalt mix. The contractor slightly adjusted the binder content of the mix, and the issue was resolved. The asphalt binder content before and after this adjustment was within the acceptable specifications.

Table A.3 Summary of Mix Design Parameters for Mixes in The City of Akron project

Mixture	Control (SBS)	Lehigh GTR+ Rheopave
Total Asphalt Content	5.8%	6.2%
Virgin Asphalt Content	5.1%	5.5%
RAP Content	15%	15%
Design Number of Gyration	50	50
Design Air Void	4%	4%
Gmm	2.492	2.488
Mixing Temp	320°F	320°F
Tensile Strength Ration (TSR)	83.8%	86.0%

A.2 Binder Testing

For all GTR test sections, samples of the GTR modified asphalt binders were obtained for the following cases:

A. At the terminal, directly after mixing the GTR
B. From the storage tank at the terminal after 24 hours of mixing
C. At the terminal, immediately prior to transporting the GTR modified binder to the asphalt plant
D. From the storage tank at the asphalt plant
E. From the production line at the asphalt plant

Figure A.3 Location Test Sections in the City of Akron.

Figure A.4 Pictures Taken during Constriction of Test Sections in the City of Akron.

The dynamic shear rheometer (DSR) tests and the bending beam rheometer (BBR) tests were conducted on the GTR and polymer modified binders samples obtained from the production line at the asphalt plant to determine their performance grade (PG) in accordance with AASHTO M320 "Standard Specification for Performance-Graded Asphalt Binder". The DSR test procedure was modified as suggested in ODOT Supplement Specification 887 to accommodate the presence of the GTR particles in the asphalt binder. Additonal DSR tests were conducted on samples of GTR binders obtained at the asphalt temrinal after mixing to evulate the separation tendency of the GTR particles from the GTR modified binders. A testing temperature of 70° C was used.

A.3 Laboratory Testing of Cores Samples

While twelve 6-inch cores were obtained at different locations within each of the four test sections in the City of Columbus, ten 6-inch cores and ten 4-inch cores were obtained at different locations within the two test section in in the City of Akron. It is noted that cores were obtained along the wheel path as well as along the lane centerline. For test section in both cities, samples of loose asphalt mixture were obtained for each of the control and GTR mixtures at the asphalt plant. The air voids of the cores were calculated. Laboratory tests were conducted to evaluate the cracking resistance and durability of the obtained core samples. To this end, the propensity of the asphalt mixtures to fatigue cracking was evaluated using the semi-circular bend (SCB) and indirect tensile strength (IDT) tests. Low-temperature cracking potential of obtained core samples was assessed using the asphalt concrete cracking device (ACCD) test. Finally, AASHTO T283 test was used to evaluate the moisture damage susceptibility of obtained cores. A detailed description of each of those tests is provided below.

A.3.1 Semi-Circular Bending (SCB) Test

The SCB test was conducted on each mixture to evaluate 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. A cutting jig was used to cut each sample in half and trim the ends 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.5. The SCB test was conducted on at least four core samples. 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 A.6, was used to conduct all SCB tests.

The main output of the SCB-IL is a load versus deformation plot, as shown in Figure A.7. From this plot, the Fracture Energy (FE) and the Flexibility Index (FI) are calculated using the Equations A.1 and A.2, 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 (Al-Qadi et al. 2015). Since the Fracture Energy is a function of the peak load and displacement, Nazzal et al. (2017) 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.

$$FE = \frac{W_f}{Area_{lig}} \text{ x } 10^6 \quad \text{(A.1)}$$

Where:

- G_F = 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)

$$FI = \frac{G_F}{|m|} \text{ x } A \quad \text{(A.2)}$$

Where:

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

Figure A.5 Illinois SCB Sample Preparation and Testing Equipment

Figure A.6 Instrotek© Auto SCB Testing Equipment

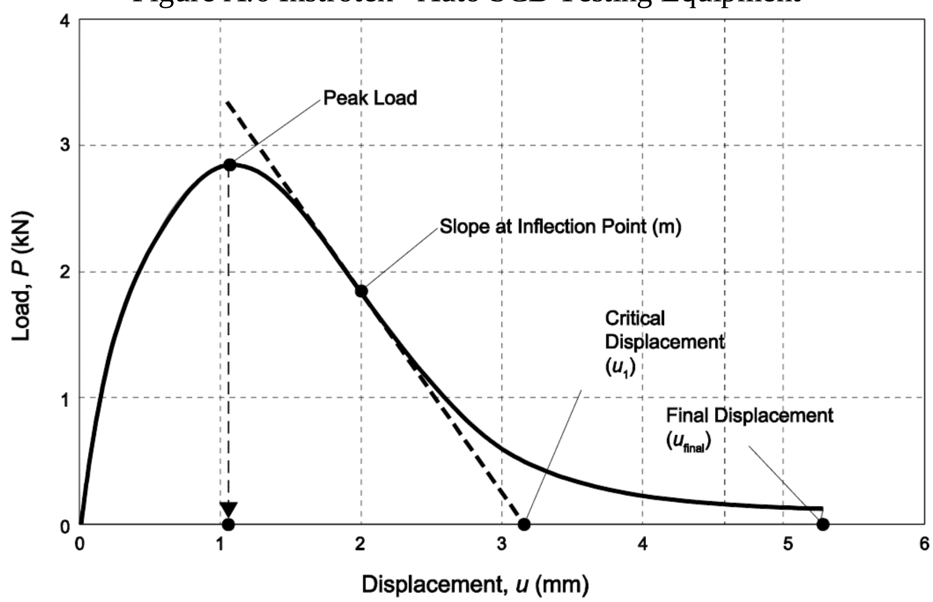

Figure A.7 Plot of Load vs. Displacement Obtained from Illinois SCB Test (Al-Qadi et al. 2015)

A.3.2 AASHTO T283

The moisture susceptibility of the core samples was evaluated using the AASHTO T283 test procedure modified according to the standard practices implemented in the State of Ohio. At least four samples 4-inch (100-mm) core samples were tested. The samples were then divided into two groups. The first group, control samples, was wrapped with plastic wrap and stored at room temperature for testing in the dry condition, whereas the second group was conditioned. The conditioning procedure involved partially saturating the samples to a level between 70 to 80 percent saturation in a water bath under a 2.9 psi (20 kPa) vacuum pressure for approximately two to three minutes. The partially saturated samples were then wrapped and placed in a plastic bag, and 10 ml of water was added to the 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 indirect tensile strength test was conducted on the dry and conditioned wet samples. The tensile strength ratio (TSR) was then computed as the ratio between the average indirect tensile strength of the wet conditioned specimens to 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.

A.3.3 Asphalt Concrete Cracking Device (ACCD)

The asphalt concrete cracking (ACCD) test was conducted to evaluate the low-temperature cracking resistance of the core samples. In this test, a 60-mm (2.3-inch) diameter inner core of the 6-inch (150-mm) core specimen was obtained. A 22.4-mm (0.88-inch) long-notch was then introduced at the outer surface of the 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 A.8). 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 equivalent 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 A.8 ACCD Test Setup

A.5 Cost Analysis

Cost analysis was performed to compare the associated costs with the construction of the GTR and polymer modified test sections in the City of Columbus and the City of Akron. 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 were provided by the two cities. An analysis considering the additional costs incurred due to producing the GTR mixtures for this project only was performed; which included the costs of: 1) the amount GTR modified binders wasted, 2) the amount GTR mixtures wasted, and 3) cleaning of the storage tanks at the terminal. Based on that analysis, an estimated cost of GTR mixes was determined upon the wide use of these mixes by local public agencies in Ohio.

A.6 Field Evaluation of Constructed Test Sections

A field and laboratory testing methodology was developed to evaluate the performance of the polymer and GTR modified test sections in Columbus and Akron. Details of the developed methodology is 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 graphical user interface incorporated user-friendly screens to enter the data and generate the reports. Training workshops were organized to discuss the details of the field evaluation methodology with the city personnel involved in this project. During these workshops, the research team also trained the cities personnel on the use of the developed interactive database.

The developed field methodology included evaluating the performance of polymer and GTR modified test sections by the research team and designated cities personnel during the project duration. In addition, it included annual evaluations performed by the city personnel for the first five years after construction. All field evaluations included examining the severity and extent of the distresses developed in these sections. In addition, 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.7 References

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.

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).

Appendix B Test Results and Data Analyses

This appendix presents a summary of test results obtained in Phase 2 of this study. It also provides analyses of the obtained data.

B.1 Binder Test Results for Columbus Test Sections

Figure B.1 presents the continuous high-temperature grade that was determined based on the test results for binder obtained from the plant production line during construction of test sections in the City of Columbus. All GTR binders had a continuous high temperature PG grade greater than 70°C. It is noted that the Lehigh GTR binders had higher continuous high-temperature grade than the conventionally polymer modified and Liberty GTR modified binders. This is consistent with the results of the laboratory tests conducted in Phase 1 of this study.

Figure B.2 presents the continuous low-temperature grade of GTR binders, based on the BBR test results. All GTR binders had a continuous low-temperature grade colder than -22°C, meeting the performance grade of 70-22. The low-temperature grade obtained based on asphalt binder cracking device (ABCD) test results are presented in Figure B.2. The ABCD low-temperture grade was slighlty colder than those obtained in the BBR test.

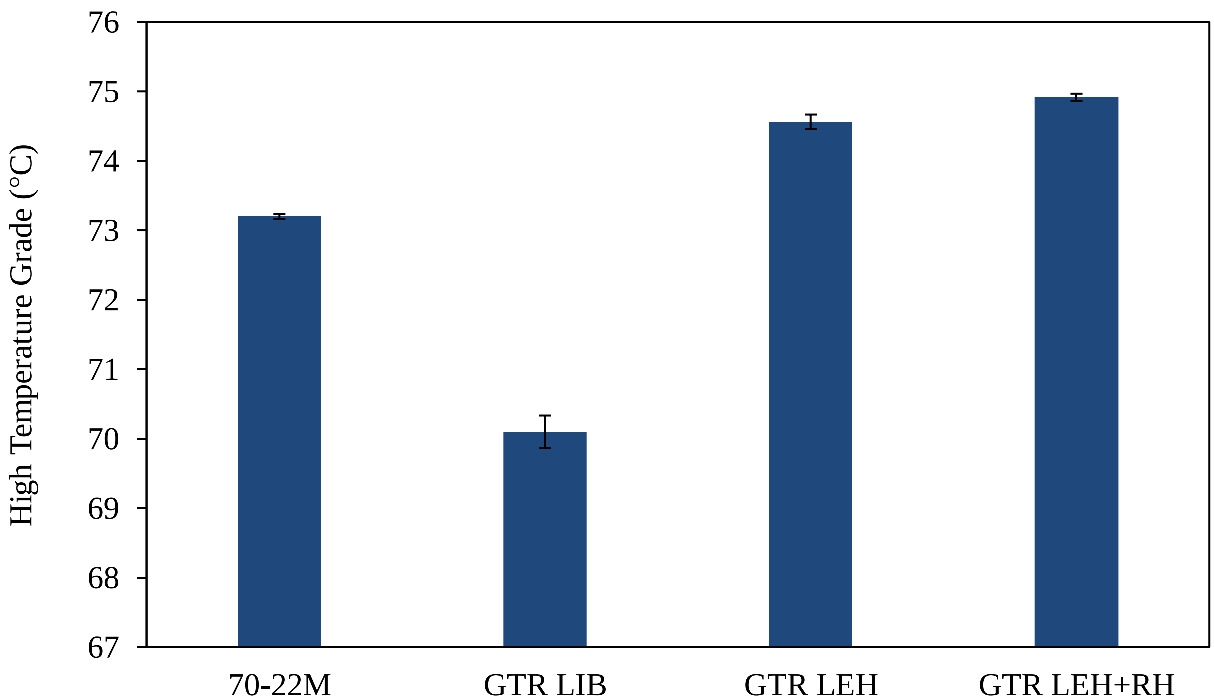

Figure B.1 Continuous High Temperature Grade for Binder in Columbus Test Sections

Additional DSR tests were also conducted on samples of GTR binders obtained at the asphalt terminal right after mixing to evaluate the separation tendency of the GTR particles from the GTR modified binders. Figure B.3 compares the average ratio of complex shear modulus (G*) to the sine of phase angle (δ) of binder samples obtained from the production line to those obtained after mixing at the asphalt terminal. The Lehigh GTR binders showed small differences in the G*/sin (δ) between samples obtained at the terminal directly after mixing (Case A) and those obtained from the production line at the asphalt plant (Case E). Higher differences were observed with Liberty GTR binder, which indicates a higher degree of separation in the Liberty GTR binder. This can be attributed to the coarser gradation and the larger particle size of the Liberty GTR compared to the Lehigh GTR particles.

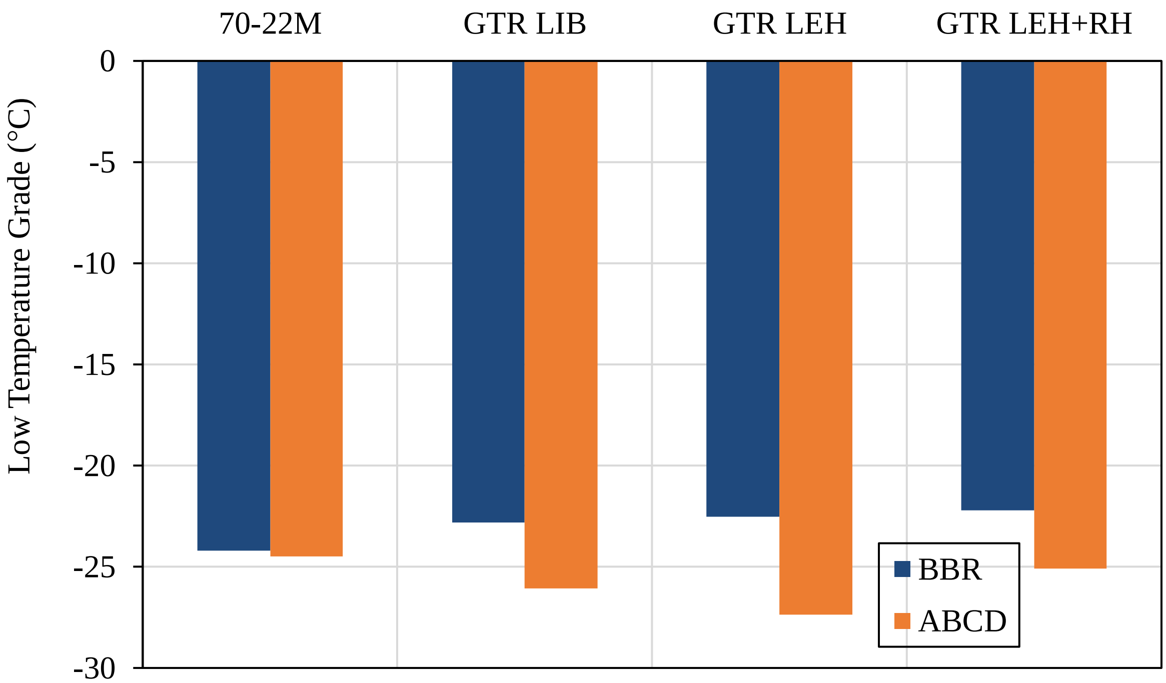

Figure B.2 Continuous Low Temperature Grade Based on BBR and ABCD Test for Binders in Columbus Test Sections

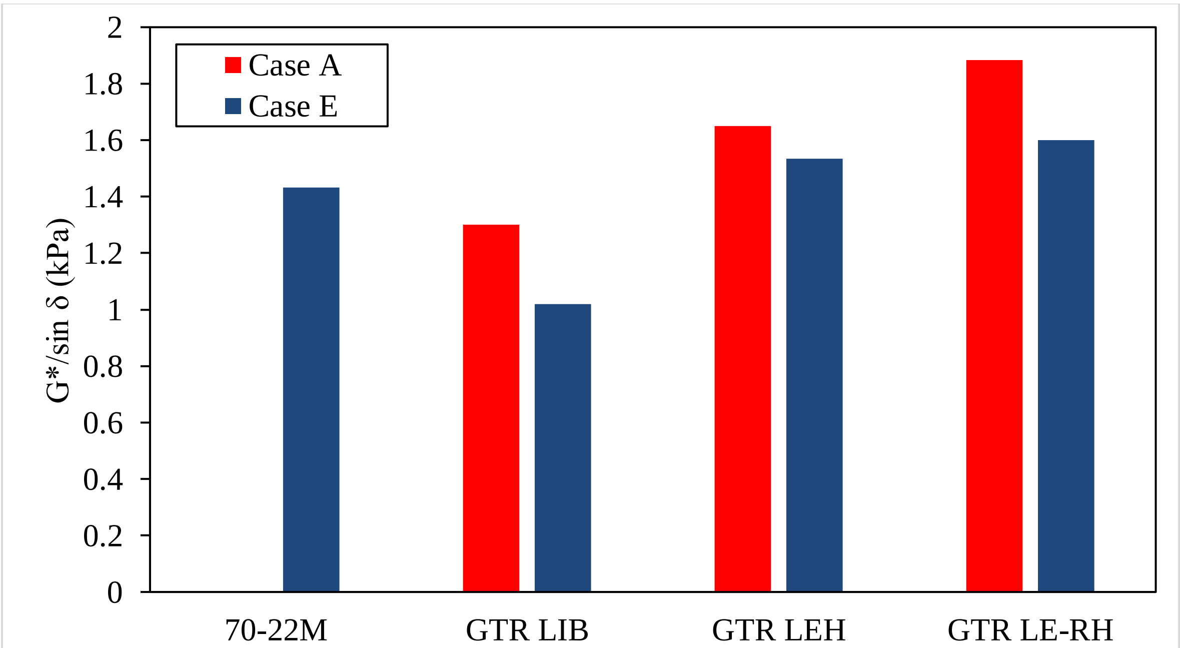

Figure B.3 DSR Tests at 70 °C for GTR Binders at Different Cases for GTR Binders in Columbus Test Sections

B.2 Binder Test Results for Akron Test Sections

Figure B.4 shows the continuous high-temperature grade for the GTR and SBS polymer modified binders obtained from the production line at the asphalt plant during construction of test sections in the City of Akron. The GTR and SBS polymer modified binders GTR binders had a continuous high temperature PG grade greater than 70°C. However, the GTR LEH+RH modified binder had slightly greater continuous high temperature PG grade than that of the SBS polymer modified binder.

Figure B.5 presents the continuous low-temperature grade of GTR and SBS polymer modified binders, based on the BBR test results. The GTR and SBS polymer modified binders had a continuous low-temperature grade of -21.8°C and -25.9°C, respectively. It is noted that GTR polymer modified binder had an m-value of 0.296, which is close but less than the minimum m-value of 0.3. The low temperature grade obtained based on asphalt binder cracking device (ABCD) test results are also presented in Figure B.5. The GTR had a colder continuous low-temperature grade of -26.2°C in the ABCD test as compared to the SBS polymer modified binder (-25.9°C). Previous studies have shown that the low temperature performance of modified asphalt binders cannot be accurately determined by BBR test results alone. In the BBR method, the low temperature performance of asphalt binder is determined by stiffness (S) or relaxation behavior (m-value). The BBR performance criteria were originally developed from studies that used only unmodified asphalt binders, assuming all asphalt binders possess a similar strength at low temperature. However, when asphalt binders are modified with polymers, GTR, and/or other additives, not only the rheological properties (such as BBR S and m-value) but also the binder strength are often affected (Bouldin et al., 2000).

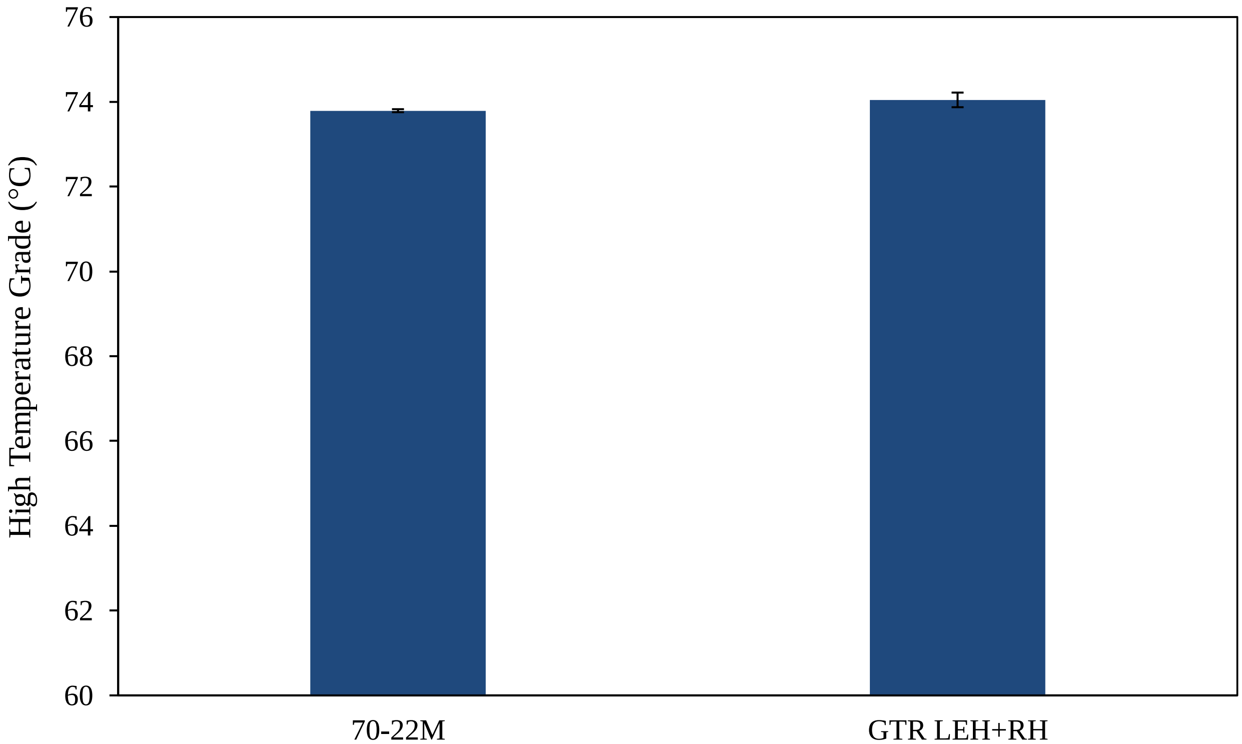

Figure B.4 Continuous High Temperature Grade for Binders in Akron Test Sections

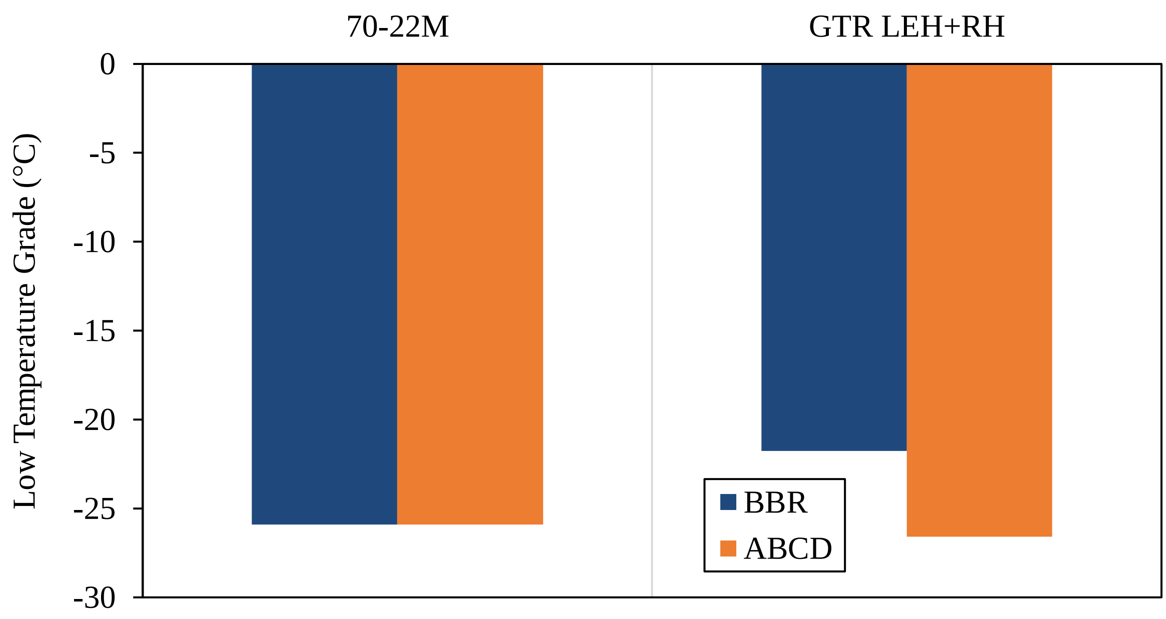

Figure B.5 Continuous Low Temperature Grade for Binders in Akron Test Sections

Figure B.6 compares the average G*/sin (δ) of the GTR binder sample obtained at the asphalt terminal right after mixing to those obtained from the production line at the asphalt terminal. Small differences in the G*/sin (δ) of the binder samples obtained in the two cases (Case A and Case E). This may indicate the small amount of GTR particles separation.

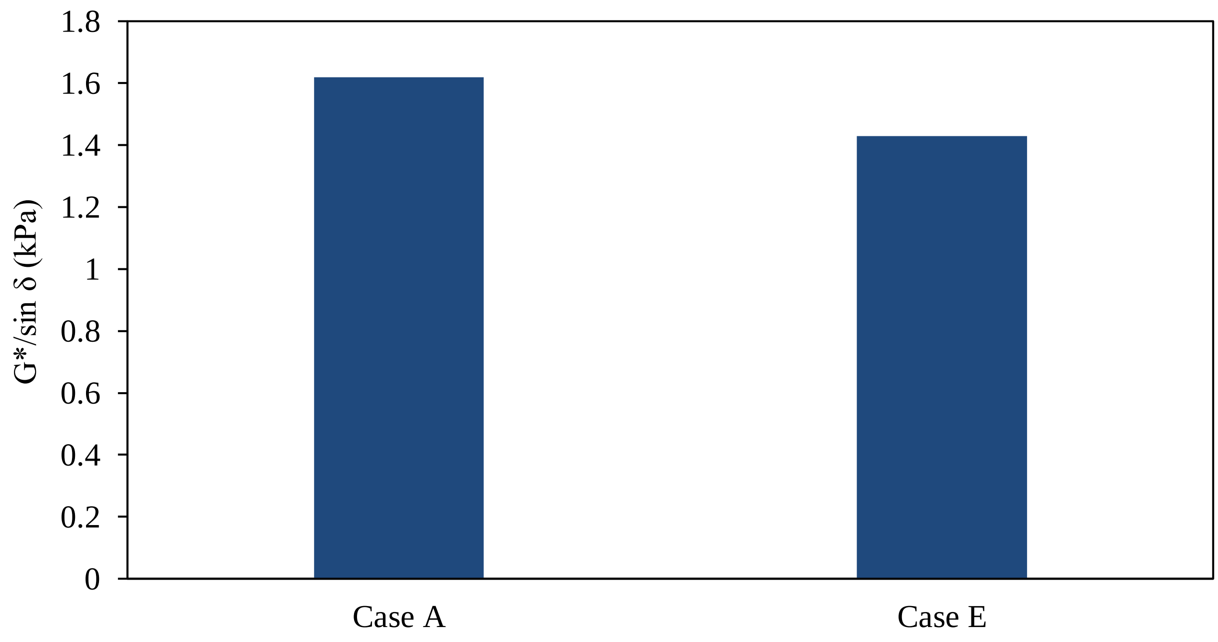

Figure B.6 DSR Tests at 70 °C for GTR Binders at Different Cases for GTR Binders in Akron Test Sections

B.3 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.7. In general, the control and GTR test subsections had similar average relative densities of about 94%, which indicates that the target density of 93%±1% was achieved. The Lehigh GTR northbound (NB) test section and Lehigh Rheopave GTR southbound (SB) 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.7.

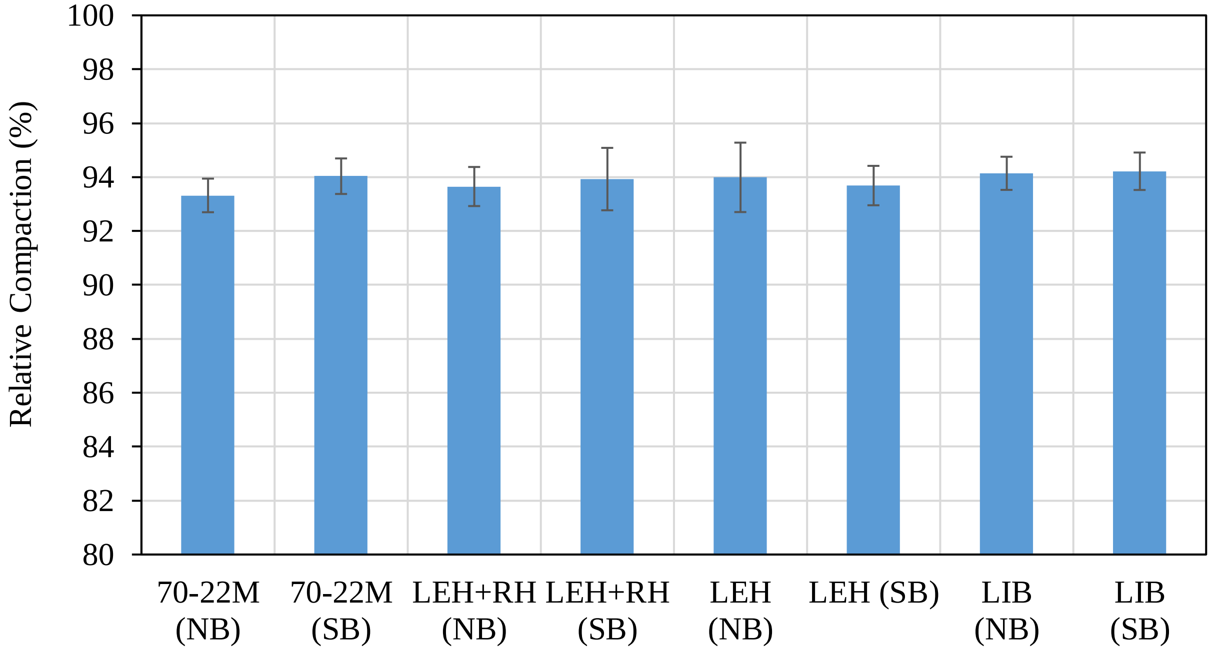

Figure B.7 Average Relative Compaction of City of Columbus Test Sections

B.4 Field Density Measurements for Akron Test Section

Figure B.8 presents the average relative density obtained for the test sections in the City of Akron using nuclear density gauge. The Lehigh Rheopave GTR test section had slightly higher average relative densities than the control test section. However, the target density of 93%±1% was achieved for both test sections. The GTR test sections had similar variability in the in-place density as compared to polymer sections, as indicated by the error bar in Figure B.8.

B.5 Mixture Test Results

The following sections present the results of the tests conducted on the core samples obtianed from the GTR and SBS polymer modifed binder test sections constructed in the City of Columbus and the City of Akron.

B.5.1 SCB Test Results for Columbus Cores

The flexibility index (FI) and normalized fracture energy values were calculated based on the results obtained from the SCB tests performed on core samples obtained from the conventional polymer and GTR modified test sections in the City of Columbus. Figure B.9 shows the average normalized fracture energy for the different mixes. In general, the GTR modified mixes had lower normalized fracture energy values to the control SBS polymer modified mixes. The Liberty GTR mix had slightly higher fracture energy than Lehigh GTR mixes. Figure B.10 presents the average flexibility index values for the SBS polymer and GTR modified binder mixes. All GTR mixtures had FI values higher than 10, which is the minimum acceptable value set for surface mixes in a recent Illinois Department of Transportation study (Al-Qadi et al., 2015). The GTR mixes had lower FI values than the control polymer modified mix. The Liberty GTR had slightly higher FI values than the Lehigh mixes. However, the results were variable as indicated by the relatively high error bars.

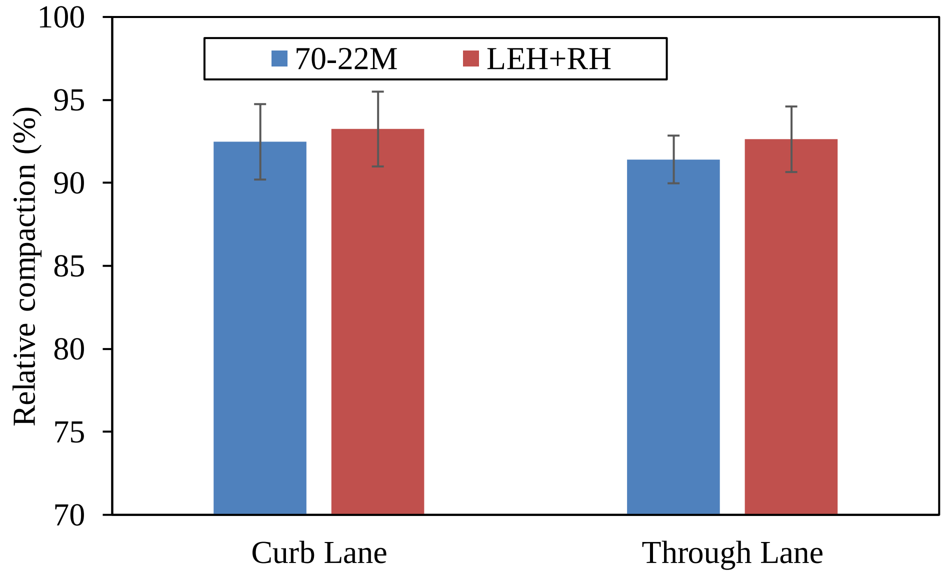

Figure B.8 Average Relative Compaction of City of Akron Test Sections

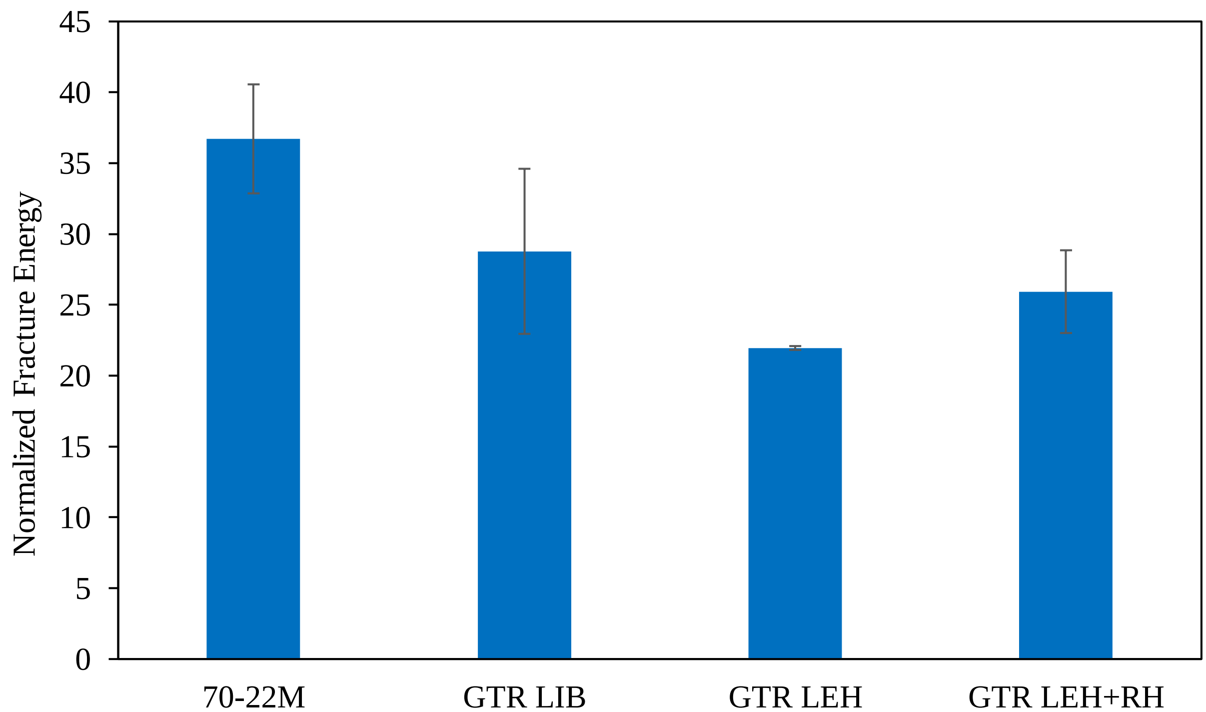

Figure B.9 Fracture Energy Values for Columbus Test Sections Cores

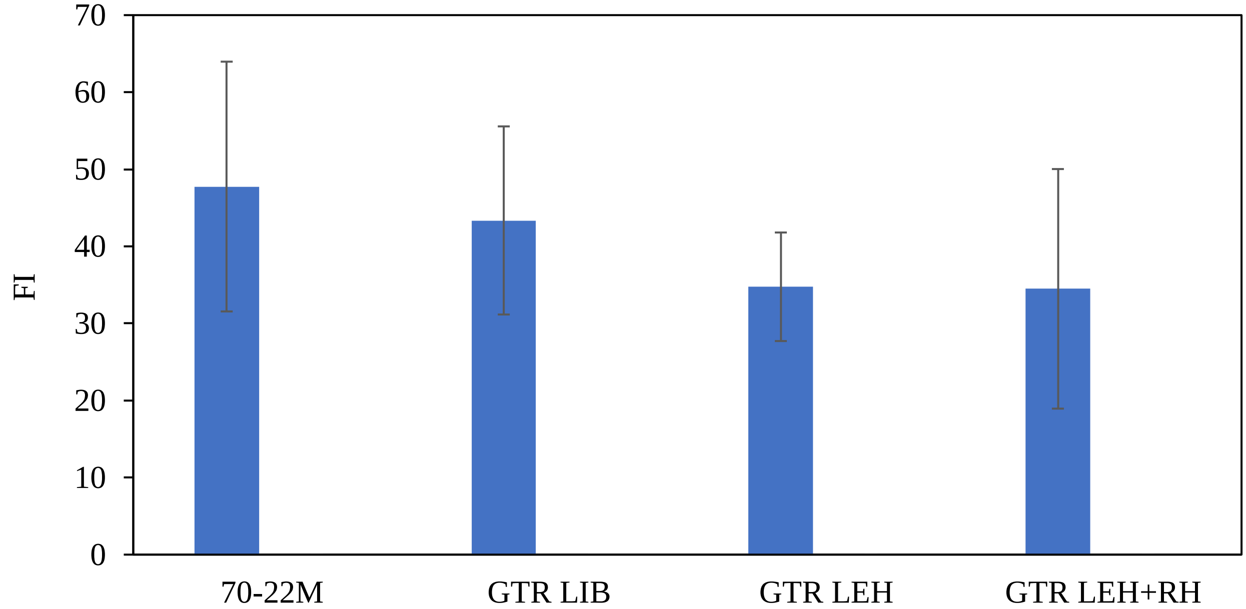

Figure B.10 Flexibility Index Results for Columbus Test Sections Cores

B.5.2 SCB Test Results for Akron Cores

The FI and normalized fracture energy values were calculated based on the results obtained from the SCB tests performed on core samples obtained from the Akron test sections. Figure B.11 and B.12 presents the average FI and normalized fracture energy values obtained, respectively. The control SBS polymer modified mix had a slightly higher normalized fracture energy than Lehigh Rheopave GTR mix. However, the SBS polymer and GTR modified mixes had similar FI values, which were higher than 10; the minimum value recommended for surface mixes (Al-Qadi et al., 2015). This indicates that the GTR modified mixes have acceptable resistance to cracking, similar to the SBS polymer modified mixes considered in this study.

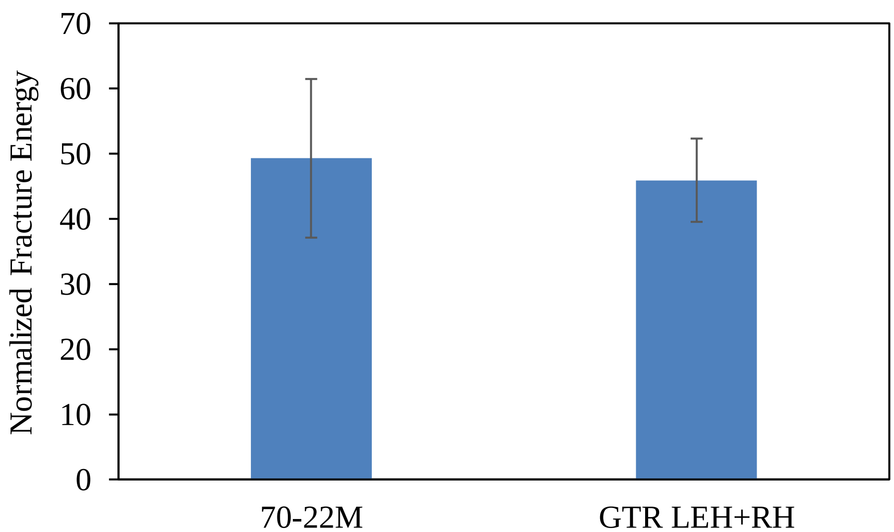

Figure B.11 Normalized Fracture Energy Values for Akron Test Sections Cores

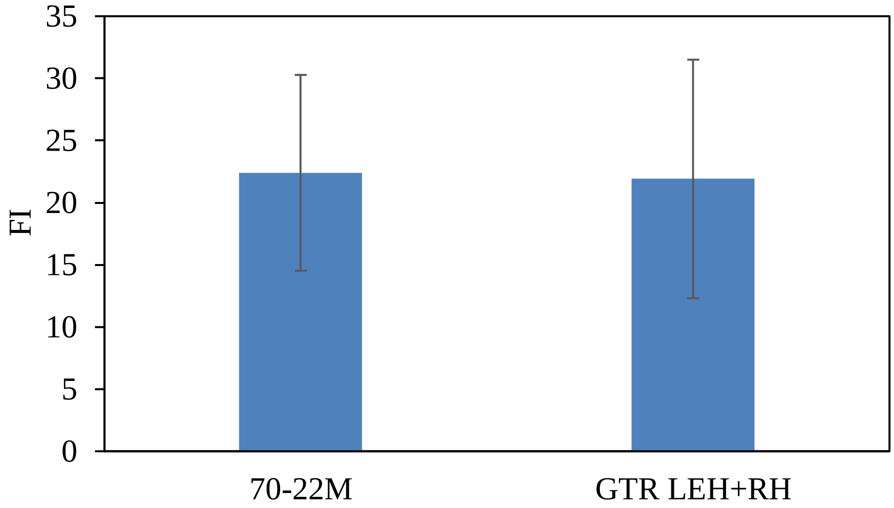

Figure B.12 Flexibility Index Results for Akron Test Sections Cores

B.5.3 AASHTO T283 Test Results for Columbus Cores

Figure B.13 compares the average indirect tensile strength (ITS) values of dry and wet conditioned samples for the Columbus project. The average ITS values of dry GTR mixes were higher than the minimum acceptable ITS values of 110 psi discussed in the draft specification developed in Phase 1 of this study. The ITS values of dry GTR mixes were similar to the SBS polymer modified mix. Upon conditioning, the ITS of all mixtures dropped; however, the largest decrease in the ITS testing was observed for the SBS polymer modified mix. Figure B.14 presents the tensile strength ratio obtained in the AASHTO T283. All mixes had higher a TSR value than the required minimum TSR value of 80%. However, the GTR mixes had higher TSR values than the mix with a polymer modified binder. This suggests that the GTR mixes are more resistant to moisture damage than the SBS polymer modified mix.

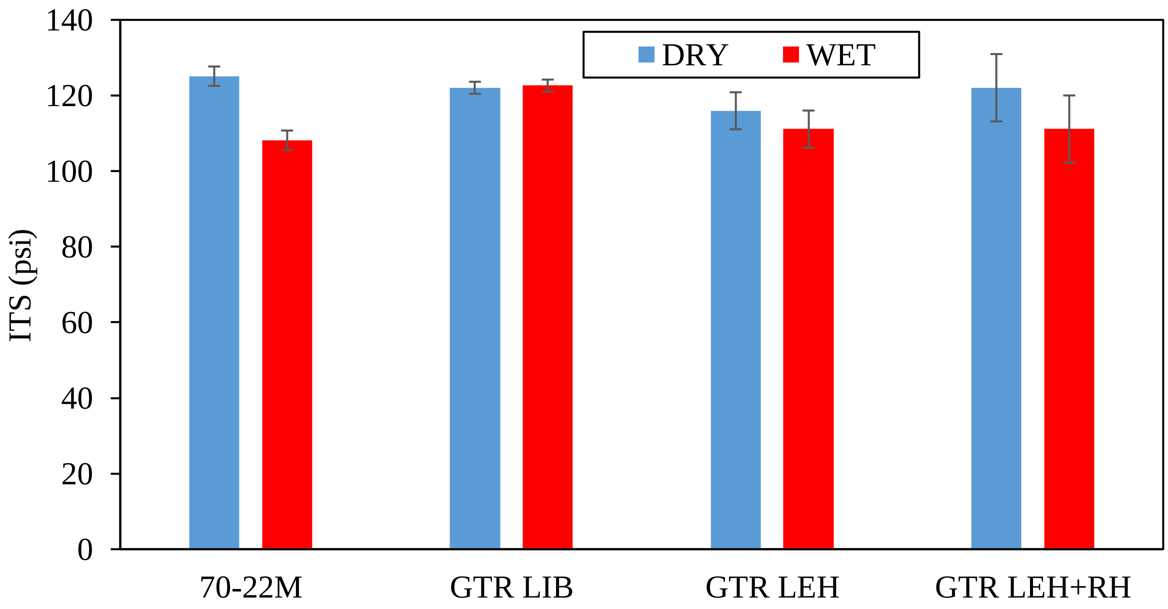

Figure B.13 ITS Results for Columbus Test Sections Cores

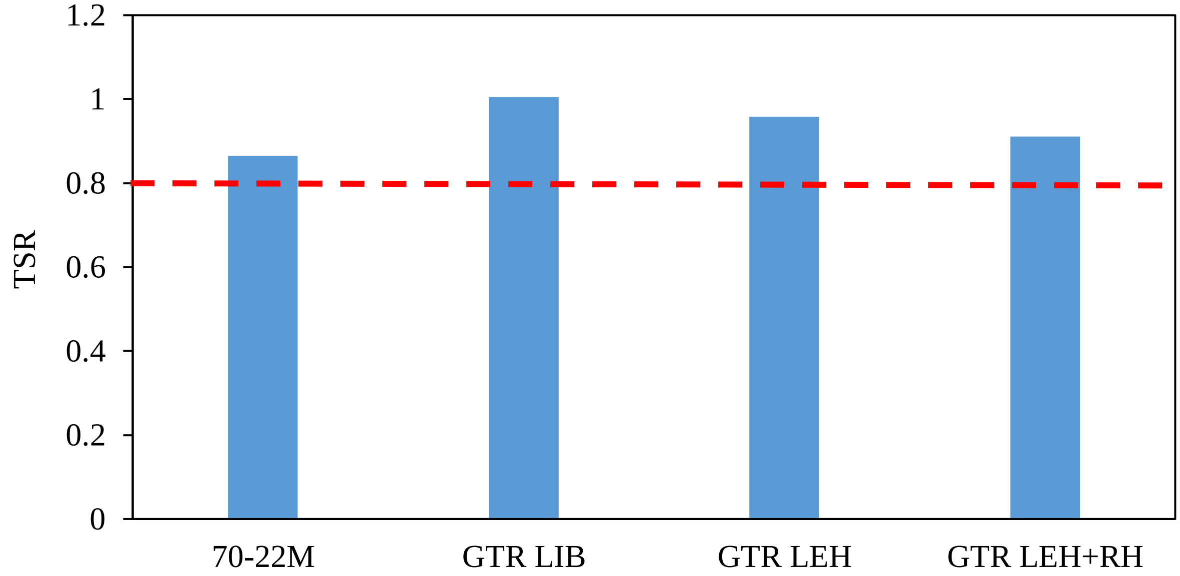

Figure B.14 Tensile Strength Ratio Results for Columbus Test Sections Cores

B.5.4 AASHTO T283 Test Results for Akron Cores

Figure B.15 compares the average ITS values of dry and wet conditioned samples for cores obtained from Akron test sections. The ITS values of dry SBS polymer modified core samples were slightly higher than those of the dry GTR core samples ; however, both dry GTR and SBS polymer modified mixes had higher ITS values than the minimum acceptable value of 110 psi recommended in Phase 1 of this project. Upon conditioning, the ITS values of all mixes dropped; however, the SBS polymer modified mix was lower. Figure B.16 presents the TSR values. All mixes had a higher TSR value than the required minimum TSR value of 80%. The GTR mixes had slightly higher TSR values than the mix with the polymer modified binder, which suggests that the GTR mix is more resistant to moisture damage than the SBS polymer modified mix.

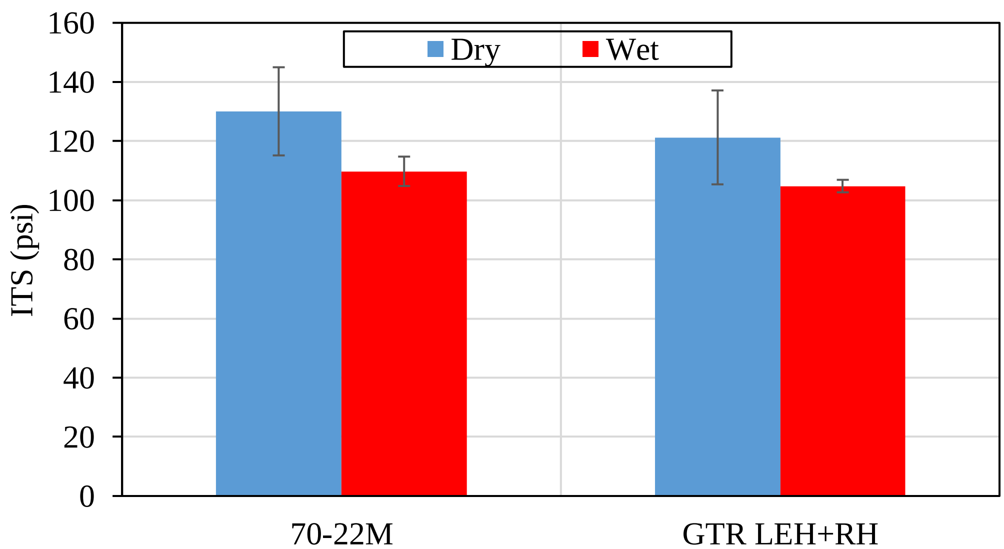

Figure B.15 ITS Results for Akron Test Sections Cores

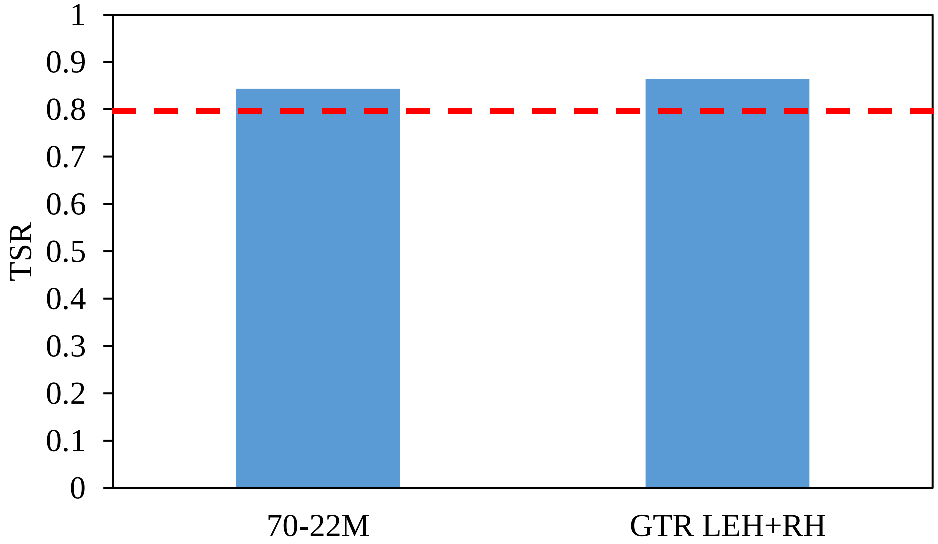

Figure B.16 Tensile Strength Ratio Results for Akron Test Sections Cores

B.5.5 ACCD Test Results for Columbus Cores

Figure B.17 presents the cracking temperature obtained from the ACCD tests that were conducted on field cores obtained from Columbus test sections. In general, all GTR mixes had similar average cracking temperatures, which were similar to the temperature of well performing surface mixes with PG 70-22M binder reported in previous studies. The GTR mixes had slightly warmer cracking temperature than that of the SBS polymer modified mix used in this study, which might indicate that they had a slightly lower resistance to low-temperature cracking.

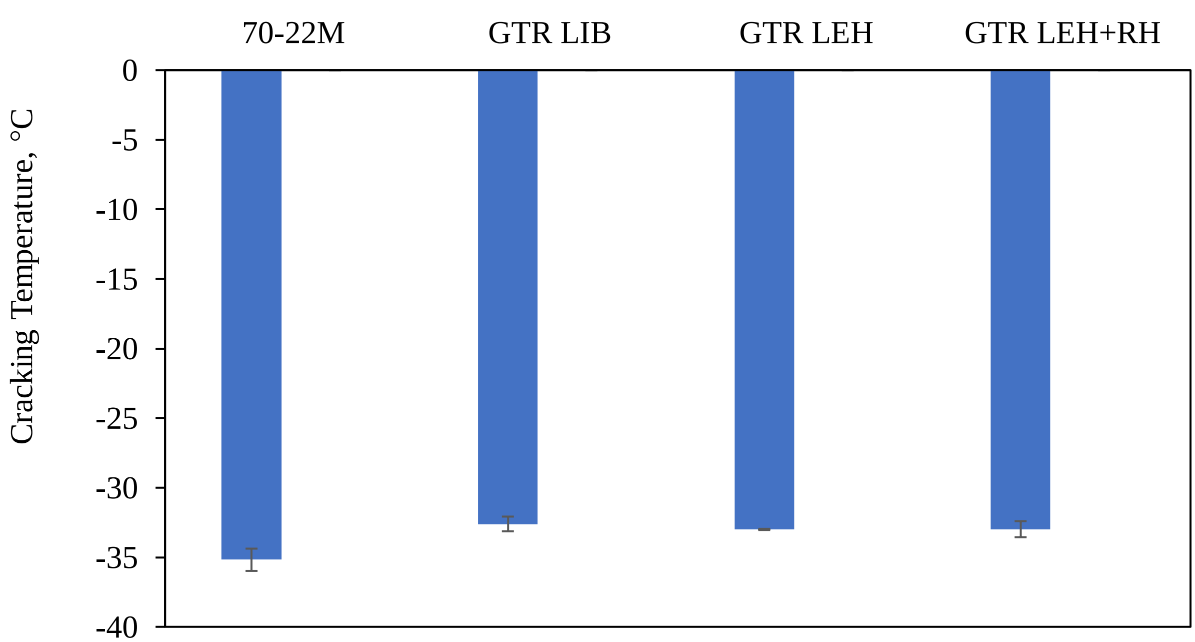

Figure B.17 Cracking Temperature for Columbus Test Sections Cores

B.5.6 ACCD Test Results for Akron Cores

Figure B.18 presents the cracking temperature obtained from the ACCD tests that were conducted on cores obtained from the City of Akron test sections. The GTR mix had slightly colder cracking temperature than that of the SBS polymer modified mix. The GTR mix used in the City Akron test sections had substantially colder average cracking temperatures than that of the GTR mixes used in the City of Columbus test section.

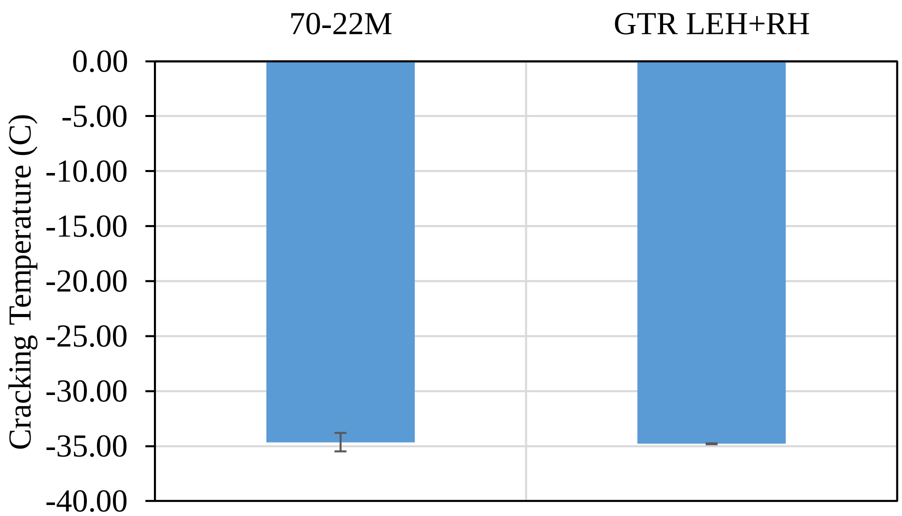

Figure B.18 Cracking Temperature for Akron Test Sections Cores

B.6 Results of Field Evaluation of Columbus Test Sections

Performance data were collected 2, 5, and 8 months after the construction of the test sections. Figures B.19 through B.21 depict pictures of the polymer modified and GTR test sections taken 2, 5, and 8 months after construction, respectively. It is noted that there was no observed distresses in the test sections after eight months of construction.

B.7 Results of Field Evaluation of Akron Test Sections

The test sections in the city of Akron were evlauated two months after the construction. Figure B.22 depicts some of the pictures of the polymer modified and GTR test sections taken during the evaluation. It is noted that there was no observed distresses in the test sections after two months of construction.

B.8 Cost Analysis Results

Table B.1 presents the initial price of the GTR and polymer modified mixes used in the construction of Columbus and Akron test sections, which was obtained from the contracts provided by the two cities. The initial cost of the GTR mixes was higher than the cost of the SBS polymer modified PG 70-22M mix used in this study, even though the cost of the raw materials used in the production of the GTR binders was less than those used in the production of the conventional polymer modified binder (please see referrer Chapter 4 in Appendix D for the raw material cost analysis validating the current competitive advantage of GTR binders). However, this is explained by:

Figure B.19 Pictures of Columbus Test Sections after Two Months of Construction: a) Control polymer Test Section, b) Lehigh GTR Section, c) Lehigh Rheopave GTR Section, and d)Liberty GTR Section

1- Bid risks associated with a new, unfamiliar product (i.e., GTR mixes).
2- Small production quantities: In the both projects only 500 tons of each GTR mix was produced.
3- Binder waste: The amount of GTR binders at the asphalt terminal produced was more than that used in this project and the left-over GTR binders cannot be used in other paving projects. For the city of Columbus project, about 27 tons of GTR binder was produced but only 25 tons were used. This resulted in about 8% increase in the price of the GTR binders to account for the waste binder material. Similarly, the City of Akron project wasted about 18 tons of GTR binder. This resulted in increasing in the price of the GTR binder by 35%.
4- Mix waste: In both projects, the amount of GTR mixes produced was more than that used in the project and the left-over GTR mixes cannot be used in other paving projects. The wasted GTR mixes resulted in an increase of about 10% and 4% in the price of GTR mixes in the City of Columbus and the City of Akron projects, respectively. Also, about 20 tons of GTR mix was wasted during plant startup. By comparison, it must be noted that a very limited amount of SBS polymer modified binder and mix is wasted as an SBS polymer modified mixture can be used in other projects.
5- Binder tank cleaning: For the City of Columbus project, an additional cost of $15,000 was incurred for cleaning the GTR binder storage tanks. Cleaning was necessary, as the tanks

are typically used for SBS polymer modified binder only. The total cost of all mixes was about $149,092. The cost of cleaning added about 10% to the cost of producing the GTR mixes.

6- Higher Asphalt binder content: The GTR mixes had 0.2% and 0.4% higher optimum asphalt binder contents than the polymer modified mix in the City of Columbus and the City of Akron projects, respectively. The higher binder content resulted in an increase of 3.1% and 4.7% in the price of GTR mixes.

Figure B.20 Pictures of Columbus Test Sections after Five Months of Construction: a) Control polymer Test Section, b) Lehigh GTR Section, c) Lehigh Rheopave GTR Section, and d)Liberty GTR Section

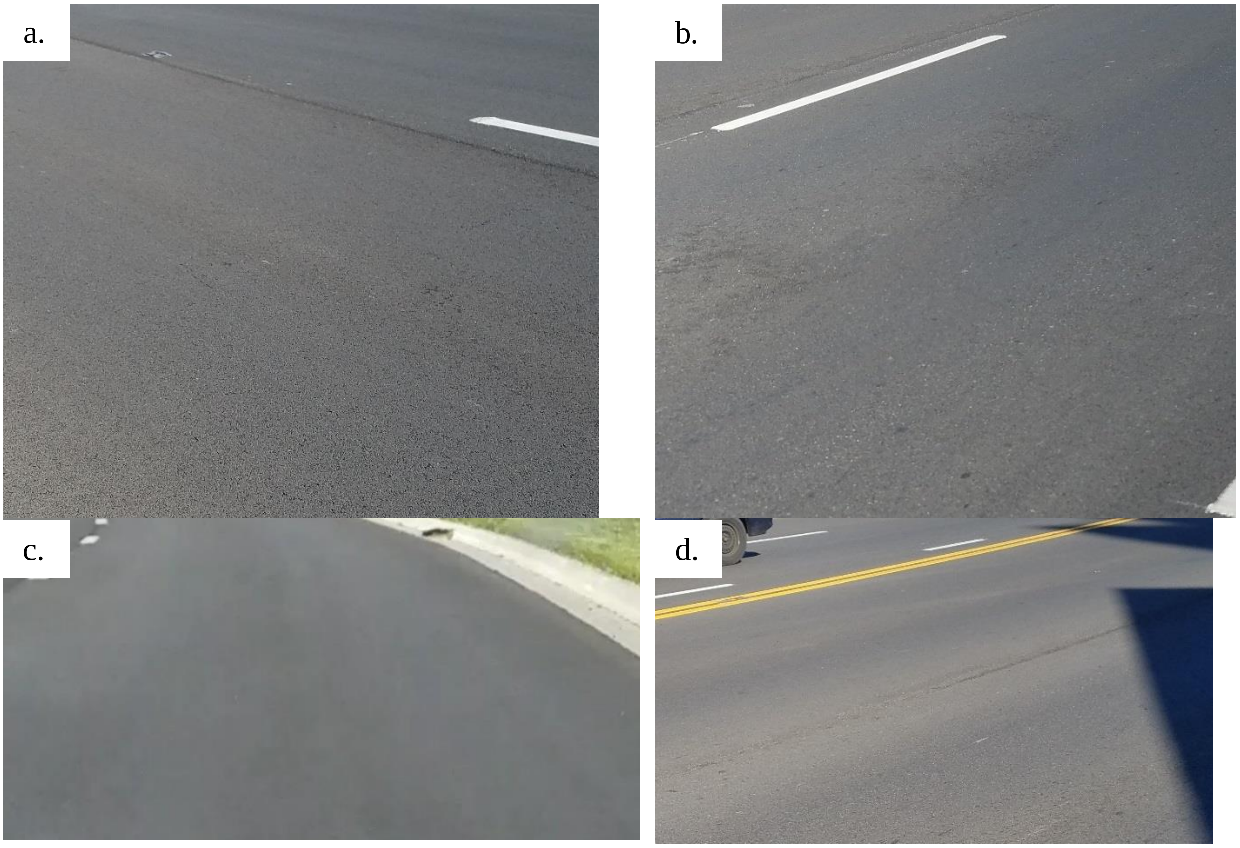

Figure B.21 Pictures of Columbus Test Sections after Eight Months of Construction: a) Control polymer Section, b) Lehigh GTR Section, c) Lehigh Rheopave GTR Section, and d) Liberty GTR Section

Figure B.22 Pictures of Akron Test Sections after Two Months of Construction: a) Control polymer Section, b) Lehigh Rheopave GTR Section

The additional costs associated with producing GTR mixes can be significantly reduced if these mixes become widely used in Ohio since:

1- A limited amount, if any, of GTR binder will be wasted.
2- Cleaning will occur once during the construction season. Therefore, the cleaning cost will be minimal, as a much larger amount of GTR mixture will be produced during the season as compared to cleaning tanks after producing GTR mixture for a single project.

Therefore, the costs of GTR modified mixes is expected to be comparable to or less than conventional polymer modified mixes.

Table B.1 Cost of Polymer Modified and GTR mixes

Mix	City of Columbus Project		City of Akron Project	
	Cost per Cubic Yard	Cost per Ton	Cost per Cubic Yard	Cost per Ton
Polymer Modified	$161.00	$80.50	$180.00	$90.00
Lehigh GTR+ Rheopave	$193.00	$96.50	$210.00	$105.00
Lehigh GTR	$193.00	$96.50	-	-
Liberty GTR	$193.00	$96.50	-	-

B.9 References

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.

Bouldin, M.G. Dongre, R. Rowe, G.M. , Sharrock, M.J. and Anderson, D.A. (2000). “Predicting Thermal Cracking of Pavements from Binder Properties: Theoretical Basis and Field Validation.” Journal of Association of Asphalt Paving Technologists, vol. 69, pp. 455-496.

Appendix C Field Evaluation Methodology

The construction of the polymer and GTR modified test sections in the City of Columbus and the City of Akron was completed on 08/30/2016 and 10/12/2017, respectively. Field evaluations were performed 2, 5, and 8 months after construction of test and section in the City of Columbus. In addition, the City of Akron test section were evaluated 2 and 4 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 entirely inspected visually 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 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 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 of pavement condition rating, based on ODOT method, with time.

The evaluation conducted 1, 3, and 5 years after construction should also include obtaining three 6-inch core samples. The core samples should be obtained about 3 feet away from the locations of cores that were obtained along the wheel path during construction. Tables C.1 and C.2 provides the sampling locations for cores obtained along the wheel path in the test sections in the City of Columbus and the City of Akron, respectively. 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)*.

Table C.1 Locations of Cores Obtained along Wheel Path in Columbus Test Sections

Section	**Direction**	**Lane**	**Station**
Control	SB	Curb	40+88
Control	SB	Curb	42+43
Control	SB	Curb	45+69
Control	NB	Through	64+47
Control	NB	Through	68+57
Control	NB	Through	71+18
LE	NB	Curb	41+00
LE	NB	Curb	44+28
LE	NB	Curb	47+17
LE	SB	Through	60+42
LE	SB	Through	66+32
LE	SB	Through	70+01
LE-RH	SB	Through	40+88
LE-RH	SB	Through	42+43
LE-RH	SB	Through	45+69
LE-RH	NB	Curb	64+17
LE-RH	NB	Curb	68+57
LE-RH	NB	Curb	71+18
LI	NB	Through	41+00
LI	NB	Through	44+28
LI	NB	Through	47+17
LI	SB	Curb	60+42
LI	SB	Curb	67+32
LI	SB	Curb	70+01

Table C.2 Locations of Cores Obtained along Wheel Path in Akron Test Sections

Section	Direction	Lane	Station
Control	WB	Through	25+50
Control	WB	Curb	32+50
Control	WB	Curb	25+50
Control	WB	Through	29+50
Control	WB	Through	19+50
Control	WB	Through	71+18
LE-RH	EB	Curb	19+50
LE-RH	EB	Through	24+50
LE-RH	EB	Curb	25+50
LE-RH	EB	Curb	29+50
LE-RH	EB	Through	30+50
LE-RH	EB	Through	38+50

ASPHALT SURFACE LOCAL ROAD

Section: Columbus_Kenny Road_CTRL_NB (Thru)_54+42_78+06

Construction Date:

City: **Road:**

Binder Type: **Direction:** **Evaluation Date:**

Start Station: **End Station:** **Rated By:**

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%	8.0
BLEEDING	5	Yes	No	Not Rated	Bitumen and Aggregate Visible	Black Surface	< 10%	10% - 30%	> 30%	3.0
PATCHING	5	Yes	No	< 1 ft sq.	< 1 yd sq.	> 1 yd sq.	< 10/mile	10 - 20/mile	> 20/mile	3.0
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	5.0
RUTTING	10	Yes	No	1/8" - 3/8"	3/8" - 3/4"	> 3/4"	< 20%	20% - 50%	> 50%	2.4
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%	1.0
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	7.0
SETTLEMENTS	5	Yes	No	Noticeable Effect on Ride	Some Discomfort	Poor Ride	< 2/mile	2 - 4/mile	> 4/mile	2.8
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'	5.0
WHEEL TRACK CRACKING	15	Yes	No	Single/Multiple Cracks < 1/4"	Multiple Cracks > 1/4"	Alligator > 1/4" Spalling	< 20%	20 - 50%	> 50%	7.5
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'	1.2
EDGE CRACKING	5	Yes	No	Tight, < 1/4"	> 1/4", Some Spalling	> 1/4", Moderate Spalling	< 20%	20 - 50%	> 50%	1.8
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	2.5
CRACK SEALING DEFIC.	5	Yes	No		Not Considered		< 50%	> 50%	No Sealant	0.0

Total Deduct = 50.2

PCR = 49.9

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

Comments:

Figure C.1 Performance Evaluation Form

Appendix D Phase 1 Interim Report

Analysis of Ground Tire Rubber (GTR) in Mix Design on Local Roadways in Ohio-Phase 1

Prepared by:
Munir D. Nazzal, Ph.D., P.E.
Sang-Soo Kim, Ph.D., P.E.
Tanvir Iqbal
Department of Civil Engineering
Ohio University

Ala R. Abbas, Ph.D.
Tanvir Quasem
Department of Civil Engineering
The University of Akron

Prepared for:
Ohio's Research Initiative for Locals (ORIL)
The Ohio Department of Transportation,
Office of Statewide Planning & Research

State Job Number 134989

September 2015

Interim Report

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NA		
4. Title and Subtitle		5. Report Date:
Analysis of Ground Tire Rubber (GTR) in Mix Design on Local Roadways in Ohio-Phase 1		**September 2015**
		6. Performing Organization Code
7. Author(s)		8. Performing Organization Report No.
Munir D. Nazzal, Sang-Soo Kim, Ala R. Abbas, Tanvir Iqbal, and Tanvir Quasem		
9. Performing Organization Name and Address		10. Work Unit No. (TRAIS)
Ohio University Department of Civil Engineering Athens, Ohio 45701		
		11. Contract or Grant No.
		SJN 134989
12. Sponsoring Agency Name and Address		13. Type of Report and Period Covered
Ohio Department of Transportation 1980 West Broad Street, MS 3280 Columbus, Ohio 43223		**Interim Report**
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

This report summarizes Phase 1 research work that was completed to: 1) evaluate the long-term field performance and life cycle cost of Ground Tire Rubber (GTR) modified pavement sections in Ohio and compare them to those obtained for pavement sections constructed using polymer modified asphalt mixtures, and 2) identify and examine new GTR technologies that can reduce the initial cost of GTR mixtures in Ohio. To achieve the first objective, all available information for previously constructed GTR projects in Ohio was collected. In addition, the field performance of several GTR pavement sections was evaluated, and field cores were obtained from four GTR projects for further testing in the laboratory. Two of these projects included a polymer modified pavement section and a GTR modified pavement that were constructed for side by side comparison. Relatively good performance was obtained for the GTR modified pavement sections, even after 10 years of service. Comparable results were also obtained for the polymer modified pavement sections. The field cores from the GTR modified pavement sections exhibited similar fatigue cracking resistance to those obtained from the polymer modified pavement sections, but slightly better resistance to low-temperature cracking and moisture-induced damage. The life cycle cost analysis indicated that the GTR modified pavement sections had slightly higher life cycle costs than those constructed with polymer modified mixtures. This was attributed to the slightly higher initial cost for GTR modified asphalt mixtures.

This phase also evaluated the potential use of alternative GTR technologies that may reduce the cost of GTR mixtures in Ohio. Although various GTR technologies were identified, the GTR binders prepared using 10% Liberty GTR, 10% Lehigh GTR, and 7% Lehigh GTR mixed with 0.5% Rheopave were the least expensive. The cost of these GTR modified binders was at least $47 less per ton than the estimated cost of a typical PG 70-22 polymer modified binder. A laboratory testing program was completed to evaluate the performance of asphalt mixtures prepared using the selected GTR modified binders and a PG 70-22 polymer modified binder with respect to moisture-induced damage, rutting, fatigue cracking, and low temperature cracking. The results of the laboratory tests showed that mixtures prepared with Lehigh and Liberty GTR modified binders had better resistance to low-temperature and fatigue cracking as well as rutting than those prepared using the polymer modified PG 70-22 binder. In addition, the GTR modified mixes had comparable resistance to moisture damage to those prepared using the PG 70-22 binder. Based on the outcome of Phase 1 of this project, it is recommended to evaluate the performance of asphalt mixtures with GTR binders prepared using 10% Liberty GTR, 10% Lehigh GTR, or 7% Lehigh GTR mixed with 0.5% Rheopave in the field as part of Phase 2. The GTR modified asphalt binders and mixtures shall satisfy the requirements outlined in ODOT supplement specification 887 with the recommended modifications presented in this report.

17. Keywords		18. Distribution Statement	
Ground Tire Rubber, Performance of GTR pavements, LCC of GTR pavements		**No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161**	
19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price
Unclassified	**Unclassified**	**46**	

Analysis of Ground Tire Rubber (GTR) in Mix Design on Local Roadways in Ohio-Phase 1

Prepared by:

Munir D. Nazzal, Ph.D., P.E.
Department of Civil Engineering
Ohio University
Athens, OH 45701
nazzal@ohio.edu

Sang-Soo Kim, Ph.D., P.E.
Department of Civil Engineering
Ohio University
Athens, OH 45701

Ala R. Abbas, Ph.D.
Department of Civil Engineering
The University of Akron
Akron, OH 44325

Tanvir Iqbal
Department of Civil Engineering
Ohio University
Athens, OH 45701
&
Tanvir Quasem
Department of Civil Engineering
The University of Akron
Akron, OH 44325

September 2015

Prepared in cooperation with the Ohio Department of Transportation,
Ohio's Research Initiative for Locals, and the U.S. Department of Transportation,
Federal Highway Administration

Acknowledgments

The researchers would like to thank the Ohio Department of Transportation (ODOT), Ohio's Research Initiative for Locals, and the Federal Highway Administration (FHWA) for sponsoring this study. The researchers would like also to thank the members of Technical Advisory Committees: Mitch Blackford, JuanPablo Ascarrunz, Mike Huber, Robert Liang, Rui Liu, Mike Teodecki, Perry Ricciardi, and Hassan Zahran. Finally, the researchers would like to express their appreciation to Ms. Vicky Fout for her time and assistance.

TABLE OF CONTENTS

List of Figures

List of Tables

Abstract

This report summarizes Phase 1 research work that was completed to: 1) evaluate the long-term field performance and life cycle cost of Ground Tire Rubber (GTR) modified pavement sections in Ohio and compare them to those obtained for pavement sections constructed using polymer modified asphalt mixtures, and 2) identify and examine new GTR technologies that can reduce the initial cost of GTR mixtures in Ohio. To achieve the first objective, all available information for previously constructed GTR projects in Ohio was collected. In addition, the field performance of several GTR pavement sections was evaluated, and field cores were obtained from four GTR projects for further testing in the laboratory. Two of these projects included a polymer modified pavement section and a GTR modified pavement that were constructed for side-by-side comparison. Relatively good performance was obtained for the GTR modified pavement sections, even after 10 years of service. Comparable results were also obtained for the polymer modified pavement sections. The field cores from the GTR modified pavement sections exhibited similar fatigue cracking resistance to those obtained from the polymer modified pavement sections, but slightly better resistance to low-temperature cracking and moisture-induced damage. The life cycle cost analysis indicated that the GTR modified pavement sections had slightly higher life cycle costs than those constructed with polymer modified mixtures. This was attributed to the slightly higher initial cost for GTR modified asphalt mixtures.

This phase also evaluated the potential use of alternative GTR technologies that may reduce the cost of GTR mixtures in Ohio. Although various GTR technologies were identified, the GTR binders prepared using 10% Liberty GTR, 10% Lehigh GTR, and 7% Lehigh GTR mixed with 0.5% Rheopave were the least expensive. The cost of these GTR modified binders was at least $47 less per ton than the estimated cost of a typical PG 70-22 polymer modified binder. A laboratory

testing program was completed to evaluate the performance of asphalt mixtures prepared using the selected GTR modified binders and a PG 70-22 polymer modified binder with respect to moisture-induced damage, rutting, fatigue cracking, and low temperature cracking. The results of the laboratory tests showed that mixtures prepared with Lehigh and Liberty GTR modified binders had better resistance to low-temperature and fatigue cracking as well as rutting than those prepared using the polymer modified PG 70-22 binder. In addition, the GTR modified mixes had comparable resistance to moisture-induced damage to those prepared using the PG 70-22 binder. Based on the outcome of Phase 1 of this project, it is recommended to evaluate the performance of asphalt mixtures with GTR binders prepared using 10% Liberty GTR, 10% Lehigh GTR, or 7% Lehigh GTR mixed with 0.5% Rheopave in the field as part of Phase 2. The GTR modified asphalt binders and mixtures shall satisfy the requirements outlined in ODOT supplement specification 887 with the recommended modifications presented in this report.

Chapter 1: Introduction

1.1 Problem Statement

Ground tire rubber (GTR), also known as crumb rubber, has been incorporated in asphalt mixtures since the 1960s to enhance the performance and service life of pavements. In more recent years, GTR has also gained interest due to its potential for reducing highway-related traffic noise (*1*). One of the main benefits of GTR is its positive impact on the environment through the reuse of tires that might otherwise be discarded and would take up space in landfills, where they would pose a fire hazard and provide a breeding ground for rodents and insects. Tires at landfills can also cause other problems due to their tendency to settle unevenly and to rise to the surface of the landfills, where they might cause damage to the landfill cover (*1*).

While a number of states with milder climates – including Arizona, California, Florida, Texas, South Carolina, Nevada, and New Mexico – have been using GTR in asphalt for roadway construction, it has not yet seen wide adoption in northern regions of the United States. In Ohio, GTR has been used on approximately 33 local roads and 3 state highways since 2005. Although the use of GTR may be beneficial for pavement quality and the environment, the high initial cost for incorporating it into asphalt mixtures is likely the main reason for not using it more extensively within the state. Therefore, research is needed to evaluate the long-term field performance of GTR asphalt mixtures produced using the wet process on Ohio roads and to perform a life cycle cost benefit analysis of these asphalt mixtures in order to determine if they are more cost-effective than traditional asphalt mixtures that do not contain GTR.

The Ohio Department of Transportation (ODOT) has various specifications concerning asphalt mix designs (e.g., Items 446 and 448) that include GTR asphalt mixtures produced using the wet process, such as ODOT Supplement Specification 887 (*2*). These specifications address the use of GTR materials on interstates and highways, but they may not be appropriate for local roads. Because traffic volume, traffic type, and traffic patterns (e.g., intersections) are different for local roads, the GTR may influence the performance in a different manner, with current ODOT specifications resulting in over or under-designed mixtures for local roads. Therefore, research is needed to evaluate the current ODOT mix design specifications and the supplemental quality control/quality assurance (QC/QA) testing and acceptance criteria to determine their applicability for GTR asphalt mixtures produced using the wet process that are used on local roads. In addition, there is a need to examine recent advances and technologies in GTR production methods that can help reducing the initial cost of GTR mixtures produced using the wet process and make these mixtures more affordable. This will also be needed to provide ODOT with clear guidance for developing specifications on the use of GTR for asphalt pavements on local roads.

1.2 Study Objectives

The main objectives of Phase 1 of this study are to:

- Evaluate the long-term field performance of GTR in Ohio.
- Compare the life-cycle cost of GTR to traditional asphalt mixtures.
- Develop draft GTR mix design specifications to be used for local roads.
- Provide recommendations regarding quality control/quality assurance (QC/QA) criteria for testing and acceptance of GTR asphalt mixtures.
- Examine recent advances in GTR production methods and assess their potential in reducing the initial cost of this material.

1.3 Report Organization

This report is organized into six chapters. Chapter 2 presents a literature review of pertinent studies on GTR asphalt binders and mixtures produced using the terminal blend wet process. It provides an overview of the results of studies that evaluated the factors that affect the performance and durability of GTR asphalt mixtures. Chapter 3 presents the results of the field evaluation and analyses that were completed to examine the performance and life cycle costs of GTR pavements sections in Ohio. Chapter 4 presents the results of work done to evaluate new GTR technologies that can reduce the initial cost of GTR mixtures. Chapter 5 presents the recommended specifications for GTR modified binders and mixtures as well as tests to control the quality of these binders and mixtures. Finally, Chapter 6 presents the main conclusions and recommendations of Phase 1 of this project.

Chapter 2: Literature Review

2.1 Background

Ground tire rubber (GTR), also known as crumb rubber, has been used in asphalt mixtures for more than 50 years (*3*). GTR has been incorporated in asphalt mixtures using two different processes, namely the dry process and the wet process. In the wet process, the GTR is blended with the asphalt binder before being mixed with the aggregate. This process is expected to provide better blending between the GTR particles and the asphalt binder, resulting in better performance for the GTR asphalt mixtures (*4*).

In the United States, the wet process has been achieved using two methods. The first method involves adding graded GTR particles to the asphalt binder and agitating the blend in a specialized unit at elevated temperatures to promote chemical and physical bonding between the two materials. The agitation is required due to the relatively large size and amount of GTR used in this method. The second method involves adding finer GTR particles (typically passing Sieve No. 30) to the asphalt binder at a refinery or at an asphalt binder storage/distribution terminal before being transported to an asphalt mix plant. The GTR obtained using this method is commonly referred to as pre-blended GTR or terminal blend GTR. The main advantage of this method is that it eliminates the need for the specialized blending equipment at the job site, resulting in lower production costs. The amount of GTR used in this method varies between 5% and 15% of the asphalt binder by weight, depending on the specifying agency.

2.2 Summary of Previous Work

During the past decade several studies have been completed to evaluate the behavior and performance of GTR asphalt binders and mixtures produced using terminal blend wet process (e.g., *5-13*). Hicks et al. (*5*) conducted a national survey to document the experience of state highway agencies with GTR asphalt mixture produced using terminal blend wet process. In general, these mixtures were found to perform well in the field. Some problems were encountered when the GTR was not handled properly (e.g., settlement in asphalt storage tank and inadequate reaction time). In some instances, the terminal blend GTR lost color quickly and turned grey. In addition to the national survey, Hicks et al. (*6*) summarized the findings of various field and laboratory studies conducted in the state of California to evaluate the performance of the GTR asphalt mixture produced using terminal blend wet process. Based on this review, it was reported that terminal blend GTR asphalt mixtures had better performance than conventional asphalt mixtures, and that the use of GTR may help in preventing reflective and fatigue cracking.

Some studies compared the performance of GTR modified binders to those modified with polymer. Willis et al. (*7*) reported the results of a study that was conducted to compare the performance of plant-produced GTR and polymer modified asphalt mixtures. The results of their study showed the GTR modified mixtures had good rutting performance and resistance to moisture damage that were similar to those of polymer modified mixes. In addition, the GTR modified mixture exhibited better fatigue cracking resistance than the polymer modified mixture. Sebaaly et al. (*8, 9)* compared the laboratory performance of GTR modified mixtures produced using terminal blend wet process to polymer-modified asphalt mixtures. Two types of GTR and styrene-butadiene-styrene (SBS) polymer modified binders were considered, namely PG 64-28 and PG 76-22. The rubber modified binder contained 10% ground tire rubber. It was reported that GTR and polymer modified mixtures exhibited similar good resistance to moisture-induced damage, rutting, and thermal cracking. However, it was found that the polymer-modified PG 76-22 asphalt mixtures had in general better resistance to fatigue cracking than the GTR PG 76-22 asphalt mixtures. This was attributed to the higher modulus and stiffness the GTR mixtures exhibited at the intermediate temperature (21.1°C). Blankenship (*10*) evaluated the laboratory performance of field-produced asphalt mixtures prepared using PG 64-28 terminal blend GTR and PG 64-28 polymer-modified asphalt binder. It was reported that the GTR asphalt mixture produced using terminal blend wet process had slightly better rutting resistance than the polymer-modified asphalt mixture. It was also reported that the fatigue life of the GTR asphalt mixture was 4 to 18 times more than that of the polymer-modified asphalt mixture in the flexural beam fatigue test. As a result, it was suggested that the GTR asphalt mixture produced using terminal blend wet process might require less maintenance in the field and hence is more cost effective than the polymer-modified asphalt mixture.

Different factors were found to affect the performance of GTR modified asphalt binders and mixtures. The influence of the GTR on binder properties is dependent on the interaction between the rubber particles and the asphalt binder, which depends on several factors (*11, 12*), including:

1- Mixing variables: temperature, time and device (applied shear stress).
2- GTR properties: source, processing methods, particle size and content.
3- Base binder properties: bitumen source and eventual use of oil extenders.

The two main interaction mechanisms that control the GTR modified binder properties during mixing are rubber particle swelling and degradation (devulcanization and depolymerization). As rubber particles react with the asphalt binder at high temperatures (160–220°C) they absorb the asphalt oily fraction and swell to two to three times their original volume forming a gel-like material. This swelling increases the stiffness of the binder as it reduces the inter-particle distances and removes the lighter oily fractions from the liquid phase of the binder. At the same time, depolymerization and devulcanization of rubber particle occurs, which crack the polymer networking. At some point at the elevated temperature, depolymerization starts releasing rubber components back to the liquid phase, causing a decrease in the binder stiffness. The swelling and depolymerization mechanisms are function of mixing temperature. As the temperature increases, the rate of swelling increases but the extent of swelling decreases. Thus, the mixing temperature affects the process by controlling the stage at which depolymerization overcomes swelling. Thus, very high temperatures (>240 °C) reduces the benefits of matrix buildup as the GTR materials depolymerize.

The developed properties of GTR modified asphalt binders are also function of the mixing time. Abdelrahman & Carpenter (*12*) and Attia & Abdelrahman (*13*) indicated that if the temperature is high enough most of the binder modifications due to GTR occurs within the first 30 to 40 minutes of mixing while it will take few hours for the properties to stabilize.

The rubber particle size, production method (type), and surface area can also affect the interaction between the GTR and the binder, as it controls the swelling mechanism over time (*12*). There are two main types of GTR based on the production method, namely ambient and cryogenic. For the ambient GTR, the scrap tire is processed at or above room temperature. Ambient processing typically provides irregularly shaped, torn particles with relatively large surface areas to improve the interaction with the asphalt binder (*11*). On the other hand, for cryogenic GTR liquid nitrogen is used to freeze the scrap tire typically to a temperature between -87 to -198 °C until it becomes brittle, and then uses a hammer mill to shatter the frozen rubber into smooth particles.

Buckly and Berger (*14*) suggested that the time required for swelling of GTR increases proportionally with the square of the particle radius. Shen et al. (*15*) studied the effect of the particle size and surface area of GTR on the high temperature properties of GTR modified asphalt binders. Two base binders (PG 64-22 and PG 52-28) and two types of GTR (ambient and cryogenic) with three different sizes were considered. The binders were mixed with GTR at a mixing temperature of 176°C for 15, 30 and 45 minutes using a high shear mixer at 700 rpm. The results of this study showed that the larger the GTR particle size is, the more improvement in the elastic properties of the GTR modified binder. In addition, the stiffness of the GTR modified binder increased with the rubber particle size and decreased with its surface area. However, the effect of the particle size was more dominant than the surface area. For the same particle size, the ambient GTR modified asphalt binder was stiffer than the cryogenic GTR modified binder.

Willis et al. (*16*) studied the effect of the GTR loading rate as well as the rubber particle size, surface area, and production method on the performance grade of GTR modified binders. Based on the binder test results, it was concluded that the GTR loading rate, and particle size had the most influence on increasing the high and low-temperature grade of the modified binder. In addition, the surface area had significant effect on the high temperature properties only. However, the GTR processing method had little to no influence on the modified binders due to relatively higher surface area of the cryogenic GTR materials used in their study. GTR with larger particle sizes showed greater indication of rubber separation.

In regards to the asphalt binder source, Abdelrahman (*17*) concluded that all asphalt sources have similar interactions with GTR, but with different degrees of compatibility. Willis (*16*) examined the effect of incorporating polymers into a GTR modified binder. Their results showed that the polymer helped in increasing the stiffness of the GTR modified binder but it did not prevent the settling of rubber particles.

Previous research studies have also suggested that the inclusion of GTR may require some changes to the standard mix design procedure that is commonly used for conventional asphalt mixtures (7, *18-19*). GTR mixtures typically require a higher binder content that will result in a thicker binder film to coat the aggregate (*7*). This will help in better absorbing elastic stress; however, it may cause flushing and reduced air void (*18*).

Chapter 3: Analysis of Data and Field Evaluation of GTR Pavements In Ohio

3.1 Information on Previously Constructed GTR Projects in Ohio

All available information for GTR projects constructed in Ohio were collected. The collected information included: pavement structure (pavement layer thicknesses), traffic data, mixture information (Construction and Material Specification (C&MS) Item No., Job Mix Formula (JMF), GTR asphalt mixtures properties (e.g., aggregate type, aggregate gradation, asphalt binder content, etc.), name of contractor, mixture costs, QC/QA data, any problems encountered during construction, pavement condition data, dates and costs of maintenance/repair activities. The collected data were analyzed to identify any inconsistencies. Table A.1 in Appendix A summarizes all the collected information and analyzed data for previously constructed GTR sections. Based on the results presented in this table the following conclusions are made:

- All GTR asphalt mixtures used in previously constructed GTR sections in Ohio were produced using Seneca Petroleum company GTR binder. The Seneca GTR binder were dual graded to meet specifications for PG 70-22 and PG76-22 binders.
- In general, all GTR modified mixtures used in previous sections were dense graded surface mixes with a nominal maximum aggregate size of 9.5 mm (3/8'').
- More than half of the GTR modified mixtures used limestone aggregates while the others had gravel aggregates. In addition, the percentage of Recycled Asphalt Pavement (RAP) used in the GTR mixtures ranged between 0% and 25%. At least half of the mixtures used in previous GTR sections had only 10% RAP.
- In the previous GTR projects in Ohio, the use of GTR binder in place of a polymer modified PG 76-22M binder resulted in increasing the mixtures price by 10-15%. This can be

attributed to the additional cost that an asphalt contractor encounters when using a binder purchased from a supplier rather than made at his own terminal. In addition, using GTR binders had resulted in increasing the required asphalt binder content by 0.2-0.5% as compared to a typical SBS polymer modified binder. This increase in the required asphalt content contributed to higher prices of GTR mixtures in Ohio.

- The higher initial cost of GTR asphalt mixtures is the main reason for not using them extensively within the state.
- In general, GTR sections have performed well to date similar to sections with polymer modified mixtures.

3.2 Field Evaluation of Selected GTR Pavement sections

Field evaluation was performed by the research team in 2015 on pavement sections in four GTR projects. Two of the evaluated projects included polymer modified and GTR modified sections that were constructed for side-by-side comparison. Figure 3.1 shows the location of the evaluated sections. Table 3.1 summarizes the traffic and weather information for the evaluated sections. The field evaluation included examining the severity and extent of the distresses developed in these sections as well as obtaining at least four 4 inch and two 6 inch core samples from these sections. The results of previous performance evaluations of the GTR and polymer modified sections conducted by Local Public Agencies (LPAs) and ODOT were also obtained. The following sections provide a description of each of GTR projects and the main results of the field evaluations.

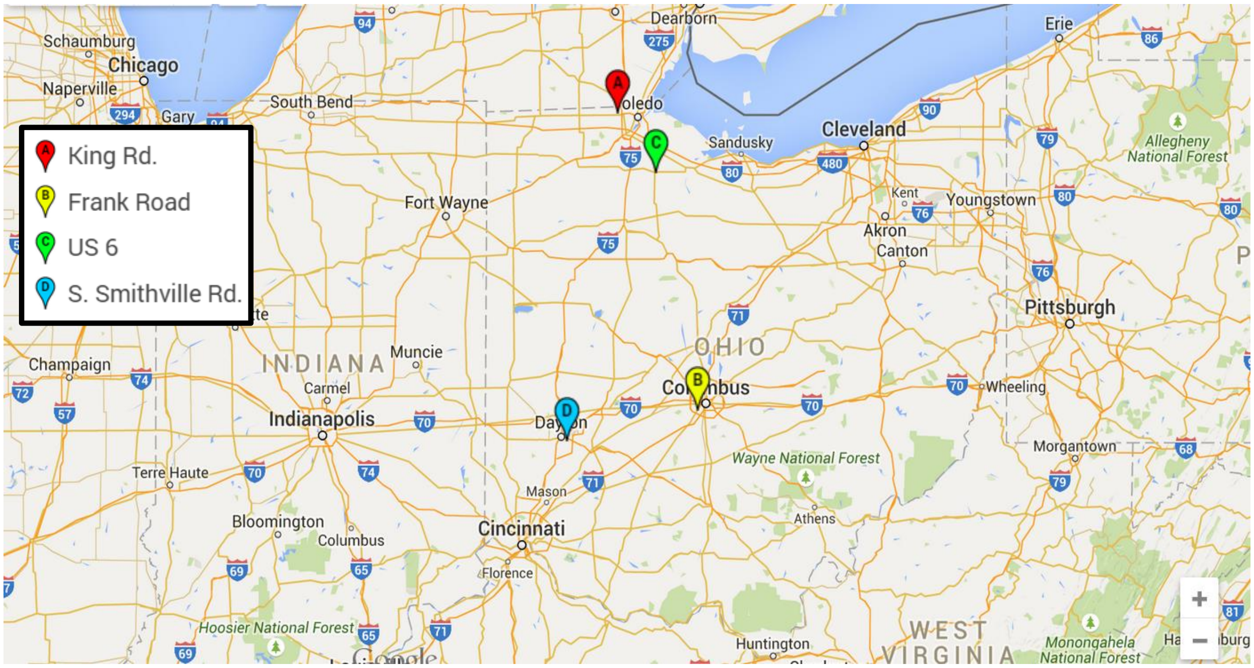

Figure 3.1 Location of Testing Sites

Table 3.1 Summery of traffic and Weather Information for Evaluated Projects

Project	Date of Construction	ADT	ADTT	Mean Annual Lowest/Highest Temperature °F	Highest Annual Difference Temperature°F
King Rd.	2005	7120	142	22/87	16
Frank Road	2007	19698	1241	20/85	19
US 6	2009	6039	1420	18/85	20
S. Smithville Rd.	2012	8372	167	20/85	18

ADT: Average Daily Traffic, ADTT: Average Daily Truck Traffic

3.2.1 King Road Project

This project involved the placement of a 1-inch thin overlay layer in 2005 on an existing flexible pavement located on King Road in the City of Sylvania. The pavement section length was one mile. In this project, control and GTR mixtures containing polymer and GTR modified asphalt binders meeting PG 76-22 were used to pave the northbound and southbound lanes of the roadway, respectively. Both mixtures were designed to meet ODOT specifications for fine graded polymer asphalt mixes (Item 424 type B). Table 3.2 summarizes the main properties of the GTR and polymer modified mixtures used in this project.

Table 3.2 Properties of Mixtures used in Evaluated Field Sections

Roadway	King Rd		Frank Rd	US 6		Smithville Rd
Section	GTR	Polymer	GTR	GTR	Polymer	GTR
Usage	Surface /Medium traffic	Surface /Medium traffic	Surface / Heavy traffic	Surface / Heavy traffic	Surface / Heavy traffic	Surface /Medium traffic
Mix type	424-Type B	424	448 T-1	442-Type A	442-Type A	404
Binder PG	76-22	76-22	76-22	70-22	70-22M	76-22
AC content (total)	7.3%	6.8%	6.7%	6.7%	6.3%	5.8%
AC content (Virgin)	7.3%	6.8%	6.7%	6.3%	5.9%	5.2%
RAP%	0%	0%	0%	10%	10%	10%
Aggregate Type	Limestone	Limestone	Limestone	Limestone	Limestone	Gravel
Aggregate Gradation						
Sieve size	% Passing					
2"	100	100	100	100	100	100
1 1/2"	100	100	100	100	100	100
1"	100	100	100	100	100	100
3/4"	100	100	100	100	100	100
1/2"	100	100	100	100	100	100
3/8"	99	99	90	96	96	98
#4	86	86	59	56	56	64
#8	56	56	30	35	35	51
#16	41	41	17	20	20	36
#30	31	31	12	13	13	23
#50	16	16	5	8	8	10
#100	7	7	2	6	6	6
#200	4.8	4.8	2	4.6	4.6	4.2

The control and GTR pavement sections performance and distresses were recorded for 10 years of service, and the pavement condition rating (PCR) was determined based on the ODOT pavement rating method. Figure 3.2 presents the PCR rating for these sections. It is worth noting that both control and GTR pavement sections had the same PCR rating in all years. Figure 3.3 depicts pictures taken of the GTR and polymer modified sections after 10 years of service. Both sections have performed well to date. In both sections, transverse cracks developed after two years of service. In addition, non-wheel track longitudinal cracks developed after 4 years. The intensity and severity of both types of cracks increased with time and this required applying crack sealant after 4 years of service. It is noted that PCR value was 87% after four years of service; this value did not significantly change after that.

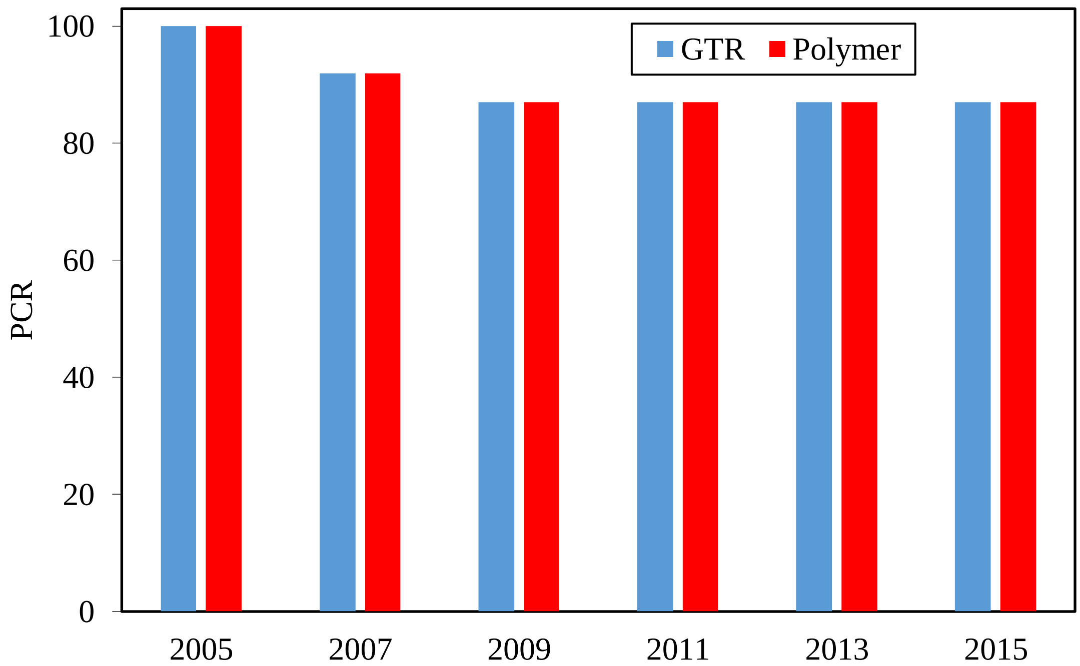

Figure 3.2 PCR Values of GTR and Polymer Modified Pavement sections at King Road

Figure 3.3 Pictures of GTR and Polymer Modified Pavement Sections at King Road After 10 Years Of Service

3.2.2 Frank Road Project

This project involved the placement of a 1.5-inch overlay layer on an existing flexible pavement on Frank road in Columbus, Oh in 2007. As shown in Table 3.2, the GTR modified mixture used in this project was a surface Marshall mix with a 3/8 inch (9.5 mm) nominal maximum aggregate size. Figure 3.4 presents the PCR values for this section that were obtained based on the field evaluation conducted during its eight years of service. Low temperature transverse crack as well as non-wheel load longitudinal cracking developed within the first two years of service, which reduced the PCR value to 85%. After the second year, the width and extent of these cracks increased and alligator fatigue cracking developed, which subsequently resulted in a significant deterioration in the pavement condition. Cracks were sealed after the fourth year; this has helped in controlling the existing cracks, but other cracks still developed especially at the edge of the pavement section yielding a slight drop in the PCR value that was obtained in the sixth year of service. After eight years of service, the GTR section had a PCR of 68%, which is close to the limiting PCR value requiring a new overlay of 65%.

3.2.3 US Highway 6 Project

This project involved the placement of a 1.5-inch overlay layer on a flexible pavement on US highway 6 between mile posts 0 and 6.2. A control surface mixture containing polymer modified asphalt binder meeting specifications for PG 76-22 was used for the first 2.5 miles of the project. In addition, a mixture with the same aggregate gradation but containing a GTR binder meeting the same performance grade of PG 76-22 was used for the rest of the project (mile posts 2.5 to 6.2). The GTR and polymer modified mixtures had 9.5 mm nominal maximum aggregate size and were designed to meet ODOT specification for Item 442 (Superpave)-Type A for heavy traffic roads. Both mixes contained 10% RAP. Table 3.2 summarizes the main properties of the GTR and polymer modified mixtures used in the US highway 6 project.

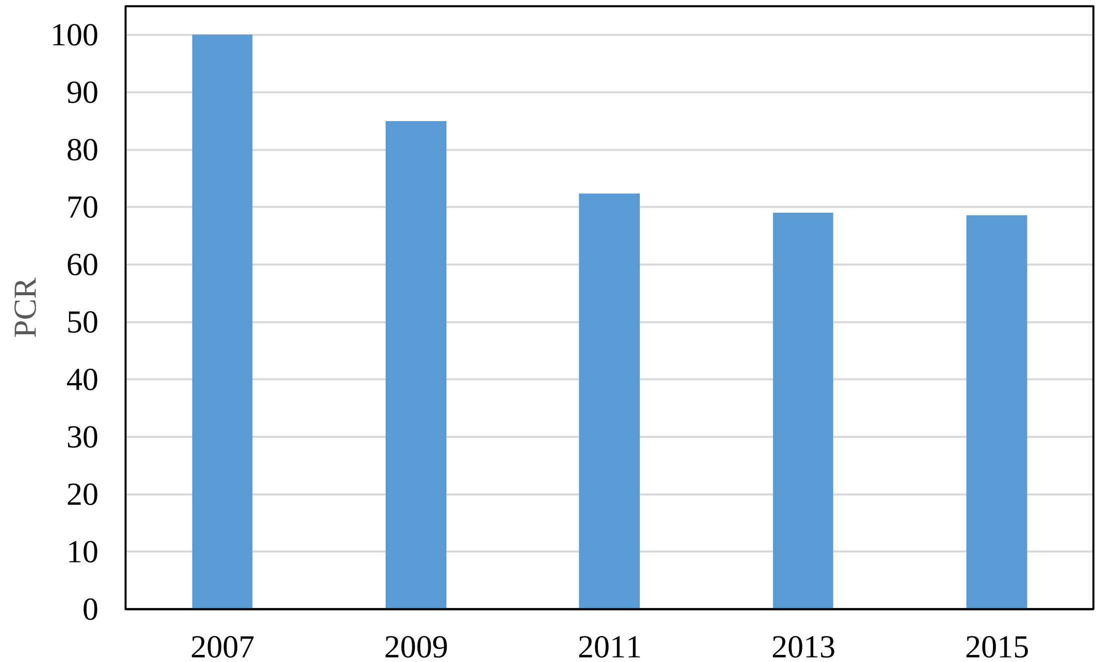

Figure 3.4 PCR Values of GTR Modified Pavement Sections Frank Road

Each section was evaluated annually during the first six years of service. Figure 3.5 presents the obtained PCR rating for the GTR and polymer modified pavement sections. The GTR and polymer modified pavement sections exhibited similar PCR rating. Low temperature transverse and longitudinal cracks developed after four years of service in both sections. These cracks were very narrow and widely spaced. However, the intensity and severity of these cracks increased but at a very slow rate as crack sealant was applied after fourth year of the service. As shown in Figure 3.6, the GTR and polymer modified sections are performing well after 6 years of service with a PCR value higher than 90%.

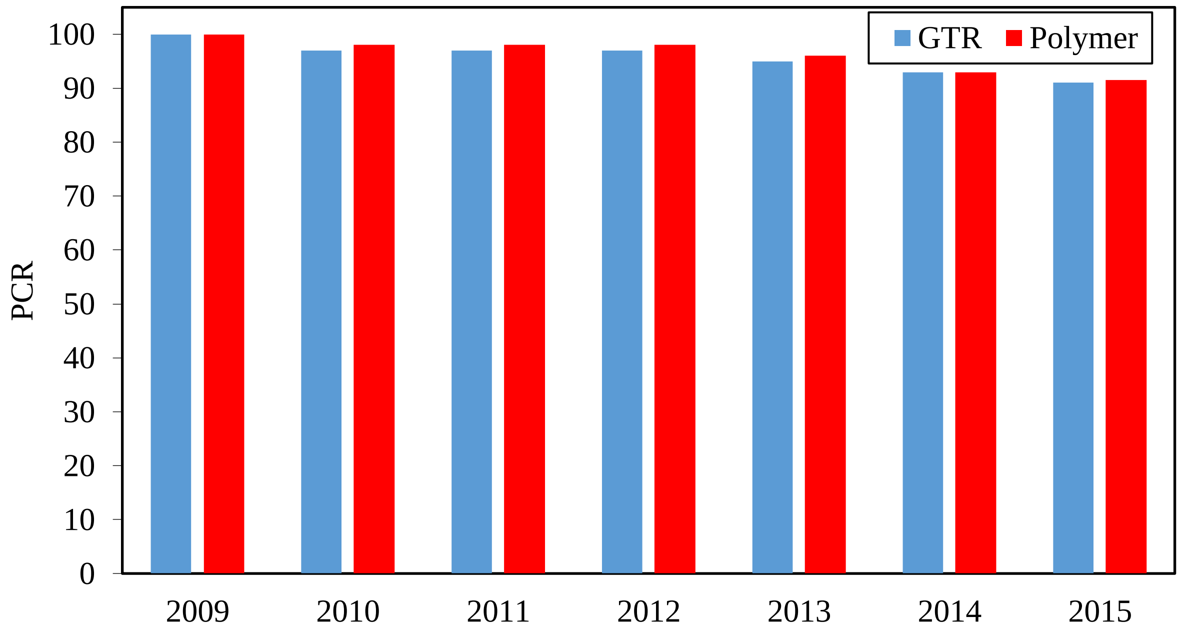

Figure 3.5 PCR Values of GTR and Polymer Modified Pavement Sections at US Highway 6

Figure 3.6 Pictures of GTR and Polymer Modified Pavement Sections at US 6 After 6 Years of Service

3.2.4 Smithville Road Project

In this project, a 1.5-inch overlay layer was placed in 2012 on an existing rigid pavement on Smithville road in the City of Dayton. The mixture used in the overlay layer was a 9.5 surface course mix with a GTR modified asphalt binder meeting specification for PG 76-22. Table 3.2

summarizes the main properties of the asphalt mixtures used in this project. Field evaluation of this section conducted after two and a half years of service indicated that low severity reflective and longitudinal joint cracks randomly developed. This resulted in a PCR value 95%. Figure 3.7 presents pictures of the developed distress that were obtained during the field evaluation.

Figure 3.7 Pictures of GTR Modified Pavement Sections on Smithville Road after 2.5 Years of Service

3.3 Labortary Testing of Cores Samples

As the main distresses that developed in all of the evaluated GTR and polymer sections were fatigue and low-temperature cracking, laboratory tests were conducted to evaluate the cracking resistance of the obtained core samples. To this end, indirect tensile strength (IDT) test and asphalt concrete cracking device (ACCD) test were conducted to examine the propensity of the GTR and polymer modified mixtures to fatigue cracking and the low-temperature cracking, respectively. A detailed description of the IDT and ACCD tests is provided in Appendix B.

3.3.1 IDT Test Results

Figure 3.8 presents the average Indirect Tensile Strength (ITS) values computed from the results of the IDT test conducted on at least two 4 inch core samples obtained from each of the evaluated GTR and polymer sections. In general, the samples obtained from GTR sections had slightly higher ITS values than those obtained from control polymer sections. This might be explained by the higher initial ITS values of the GTR mixes. Figure 3.9 presents the toughness index (TI) values for the obtained core samples. The TI value represents the amount of energy absorbed by the mixture under tensile strain; lower TI indicates more brittle behavior of the mixture. All field mixtures except that obtained from Frank Road exhibited TI greater than 0.75, which is the minimum value observed for fatigue resistant mixtures in previous studies (*20*). The Frank Road GTR mix had the lowest TI index value. The low TI index values and the high ITS values may indicate that the GTR mix in Frank Road had encountered more aging than mixtures in other sections. It is worth noting, that the GTR mix on King Road had the highest TI values although it was the longest time in service (10 years). However, King Road had much lower truck traffic as compared to the other sections. This may indicate that the aging of mixtures is affected by the environmental and traffic loading conditions of the pavement. For the same project, the GTR mixes had in general similar TI values to those of control polymer modified mixes. The IDT test results suggest that the GTR and polymer modified field mixes on King Road and US Highway 6 have good and have similar resistance to fatigue cracking. This is in agreement with the field performance recorded for the GTR and polymer modified sections used in King Road and US highway 6 evaluated after 10 and 6 years of service, respectively.

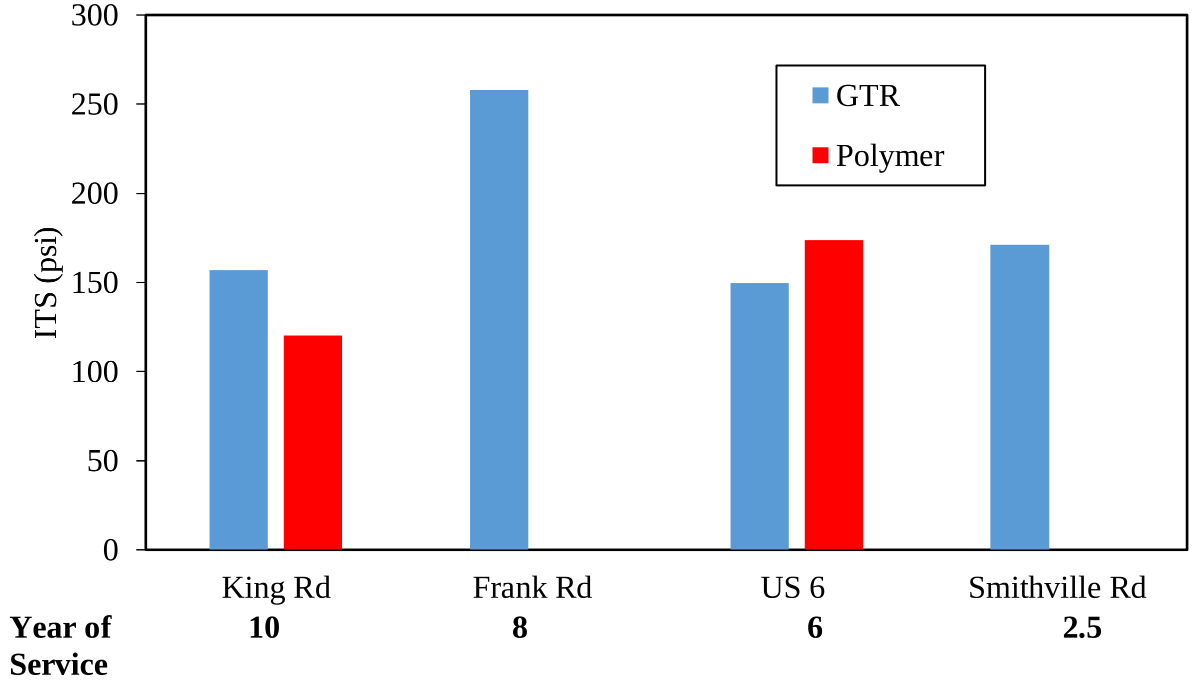

Figure 3.8 Average ITS Values of Field Core Samples

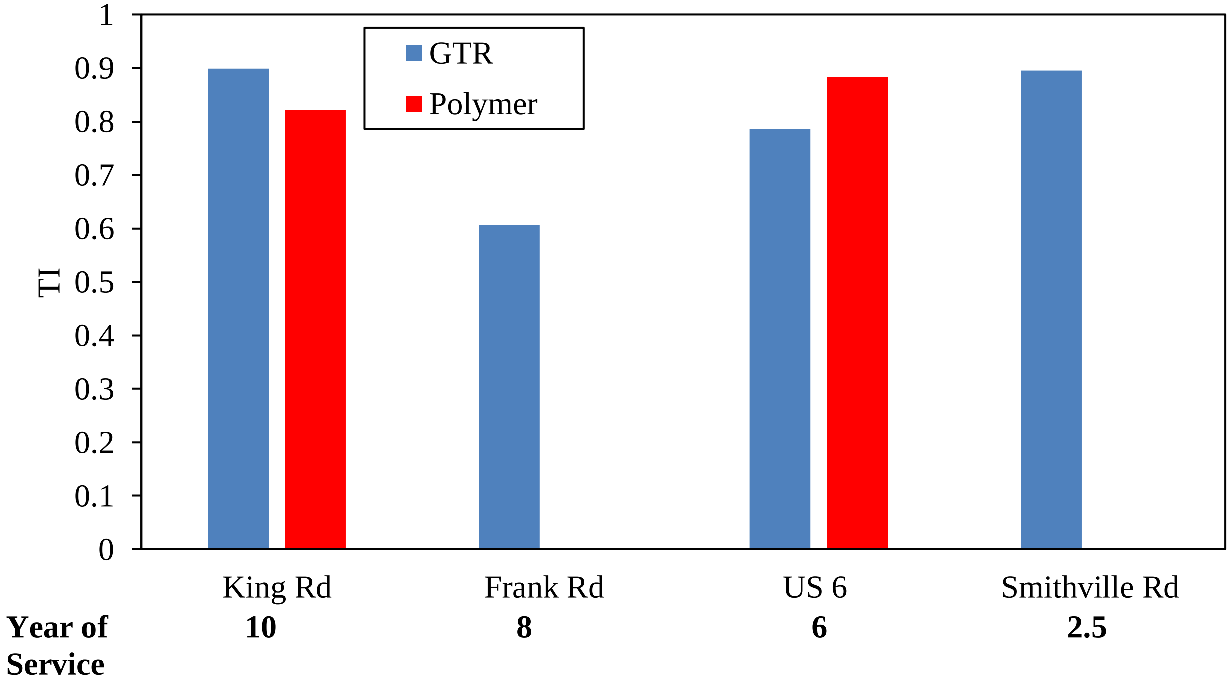

Figure 3.9 Average TI Values Of Field Core Samples

3.3.2 ACCD Test Results

Figure 3.10 presents the cracking temperature obtained from ACCD tests that were conducted on field cores. The GTR mix obtained from Frank Road had the warmest cracking temperature indicating that it had the least resistance to low temperature cracking. This might explain the more severe and extensive low temperature cracking observed in this section as compared to the other sections evaluated in this study. In addition, the GTR mix at Smithville road had much colder cracking temperatures than mixes from the other section, which is explained by the shorter service time and thus less aging that this GTR mix encountered. It is worth noting that no low temperature cracking was observed in this section. The GTR mixes had slightly colder cracking temperature than the control polymer mixes. These results suggest that GTR mixtures have better resistance to low temperature cracking.

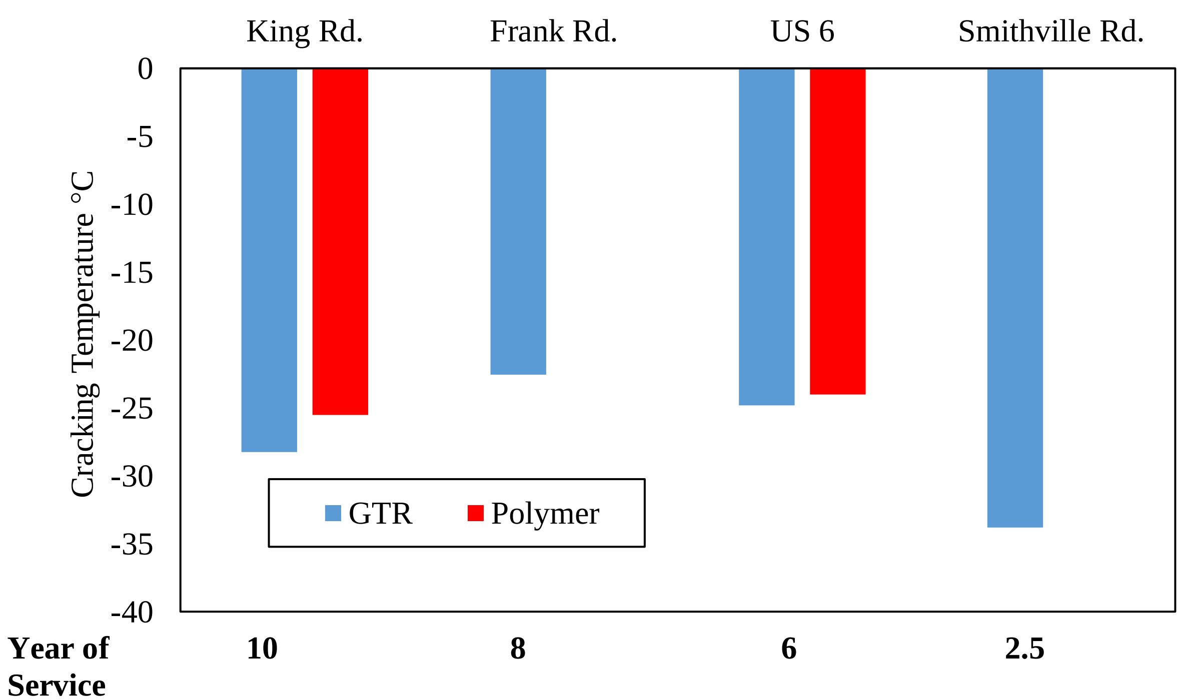

Figure 3.10 Cracking Temperature Obtained in ACCD Test

3.4 Life Cycle Cost Analysis

Life cycle cost analysis of existing GTR and polymer modified sections on King Road and US Highway 6 were performed. The analysis was conducted according to Ohio DOT Pavement Design Manual guidelines and using RealCost Version 2.5, a life cycle cost analysis software developed by the Federal Highway Administration (FHWA). An analysis period of 10 years was used. The initial as well as the maintenance and repair costs for these sections were obtained and used in the analysis. Figure 3.11 presents the life cycle costs for one mile of the GTR and polymer modified sections on King Road and US Highway 6. Although the GTR and polymer modified sections had very similar performance and maintenance costs, the GTR modified sections had 10 to 15% higher life cycle costs. This is explained by the higher initial cost of the GTR sections. The GTR modified mixes were more expensive than those with polymer modified due to the higher cost of Seneca GTR modified binder and to the increase in required asphalt content when using this binder. It is worth noting that for the same aggregate gradations about 0.2-0.5% higher asphalt content was needed when using Seneca GTR modified binder.

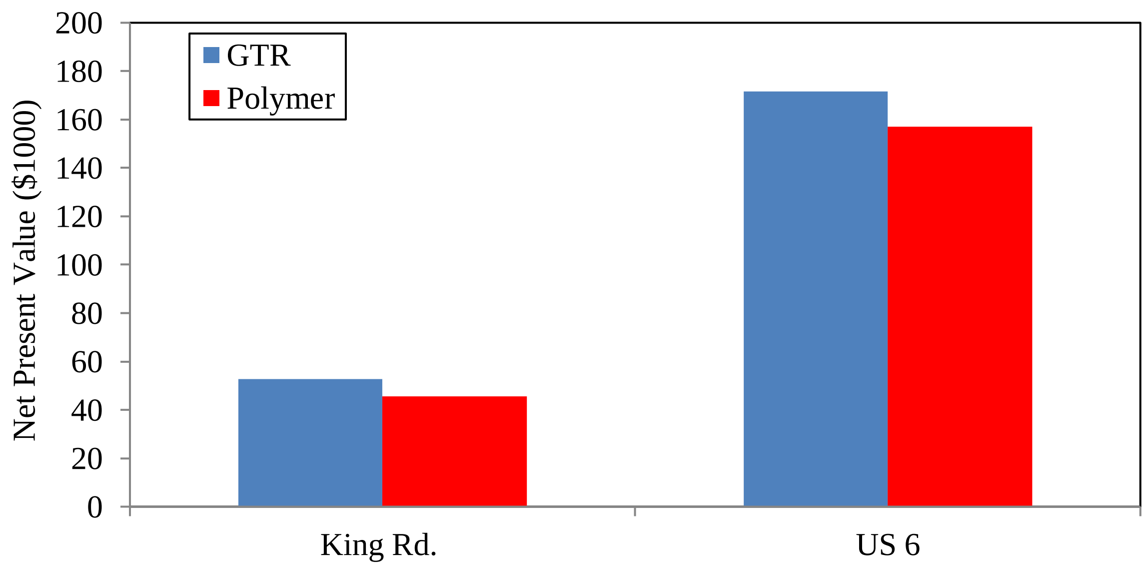

Figure 3.11 Life Cycle Cost Results

Chapter 4: Evaluation of New GTR Technologies

4.1 Introduction

The multi-stage procedure shown in Figure 4.1 was pursued to select the GTR technologies that can reduce the initial cost and yet can be used to produce a PG 70-22 that has a similar performance to that of a polymer modified binder.

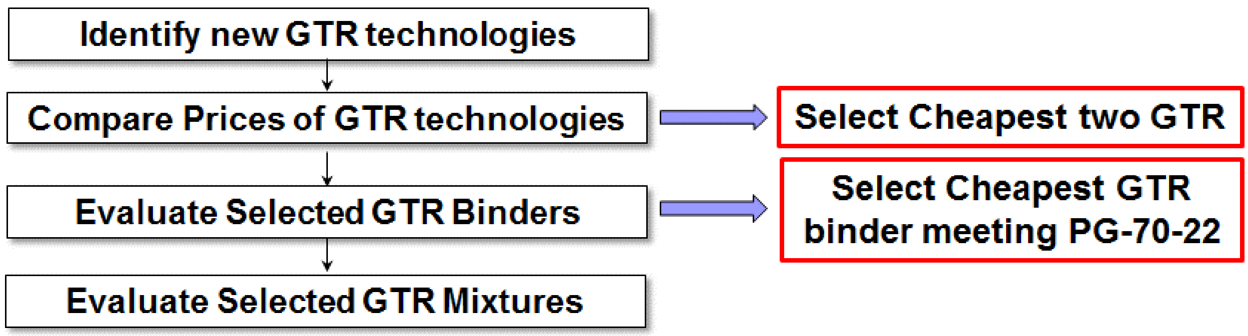

Figure 4.1 Flow Chart of Approach Pursued To Identify New GTR Technologies

The following are the main terminal blend GTR products and technologies that have been used in the United States:

1- Seneca Petroleum GTR Modified Asphalt Binder: This GTR binder is produced at the Seneca company terminal and shipped to the asphalt contractor. Seneca GTR binder is dual graded; it can meet PG 70-22 and PG 76-22. All GTR projects in Ohio were constructed using Seneca GTR modified asphalt binder.

2- Wright's Tire Rubber Modified Asphalt Cement (TRMAC™) Technology: The GTR modified binder in this technology is produced using an absorption process that completely digests and incorporates recycled, whole scrap ground tire rubber into asphalt binder. The GTR in this case is 99% soluble. The TRMAC™ binder has to be produced at the Wright asphalt company terminal in Houston, Texas and shipped to contractors in Ohio. The Wright GTR binder is dual graded and meets PG 70-22 and PG 76-22. Pavement sections have been constructed using the Wright GTR modified asphalt binder in other states but not in Ohio. There are some concerns about the TRMAC™ technology as it may burn the GTR eliminating some of its benefits.

3- Ecorphalt: This product is devulcanized tire rubber pellets developed by Quantum Polymer. Ecorphalt can be added at the terminal to the neat asphalt binder along with SBS and another additive called Eco-Cure. The loading rates of the different additives needed to produce GTR binders to meet PG 70-22 and PG 76-22 is provided in Table 4.1. This product has been evaluated by few researchers. There are not much data about the field performance of mixes produced using this product.

Table 4.1 Required Additives to Produce GTR Binder Using Ecorphalt

Material	PG 70-22	PG 76-22
Ecorphalt	4%	6%
SBS	1%	1%
Eco-Cure	0.4%	0.4%

4- **MicroDyne 400-GTR**: this product is developed by Lehigh Technologies. This is a -40 mesh GTR produced using cryonic method. This GTR can be added at the terminal to neat asphalt binder (PG64-22) and mixed to make PG 70-22 or PG 76-22. The recommended loading rate is 10%. Lehigh Technologies also recommends the use of Rheopave XP10 (an anti-settling agent) for stabilizing GTR in asphalt binders. Based on limited tests conducted on a neat binder used in Ohio, Lehigh recommended using 7% MD400TR and 0.5% RHEO XP10 to produce a dual graded binder meeting PG 70-22 and PG 76-22. The prices for the MD400-TR and Rheopave XP10 including shipping to Ohio is $0.21/lb and $2.9/lb, respectively. The GTR modified binder produced using this product has been previously evaluated by several researchers including the National Center for Asphalt Technologies (NCAT) (*e.g. 5,6, 16*).

5- **Liberty GTR Product:** This GTR is a -30 mesh GTR produced using ambient method and pre-treated with a Sonneborn warm mix technology. The Liberty GTR is a dry powder that can be added to neat asphalt binders and mixed at the terminal. Liberty recommends adding 10% of this GTR to a PG 64-22 to produce a dual graded binder meeting PG 70-22 and PG 76-22 grade. The price for this GTR product is $0.30/lb. The Liberty GTR modified binder has been evaluated by NCAT as well as other researchers (*e.g. 5,6, 16*).

The price for a GTR modified asphalt binder meeting PG 70-22 and PG76-22 was computed based on the price information collected from producers of the different GTR binders/products,. Table 4.2 compares the prices of the different GTR modified asphalt binders meeting PG 70-22 and PG76-22 to those of polymer modified asphalt binders. It is noted that the binders produced by the Lehigh and Liberty GTR have lowest prices. These binders are at least $47/ton cheaper than polymer modified asphalt binders.

Table 4.2 Price of Different GTR and Polymer Modified Asphalt Binders

Asphalt Binder	**Price $/Liquid Ton***	
	PG 70-22	**PG 76-22**
Seneca Petroleum-GTR asphalt	$660	$660
Wright-GTR asphalt	$675	$675
Quantum Polymer –GTR	$628.20	$642.70
7% MD400-TR+Rheopave	$582.1	$582.1
10% MD400-TR	$550.50	$550.50
10% Liberty GTR	$561.6	$561.6
ODOT Price Index	$665.00	$695.80
SBS-Polymer modified Binder (Estimated Contactor cost)	$629.70	$652.00

* Based on ODOT asphalt binder price index for October 2014.

4.2 GTR Binders Preparation

The laboratory testing program included evaluating the least expensive GTR modified asphalt binders meeting PG 70-22, namely Lehigh and Liberty. Figure 4.2 shows the gradation for both GTR types used along with the upper and lower limits specified by ODOT. GTR binders were prepared by heating the PG 64-22 asphalt binder to 190°C (375 °F) and adding GTR materials. The GTR and binder were then blended using a high shear mixer at 3600 RPM for 50 minutes. A heating mantle was used to ensure that the binder's temperature remained constant at 190 °C (375 °F) during mixing. For the Lehigh GTR, two GTR modified binders were prepared: one using 10% of the MicroDyne™-400 GTR, and another using 7% of the MicroDyne™-400 GTR and Rheopave. The Rheopave is the anti-settling agent recommended by Lehigh Technologies to ensure that the GTR is properly bonded to the asphalt binder. All binders were placed in the oven at 177 °C (350 °F) for 24 hours to allow for the interaction between the GTR and the asphalt binder and ensure the stability of the GTR modified binder.

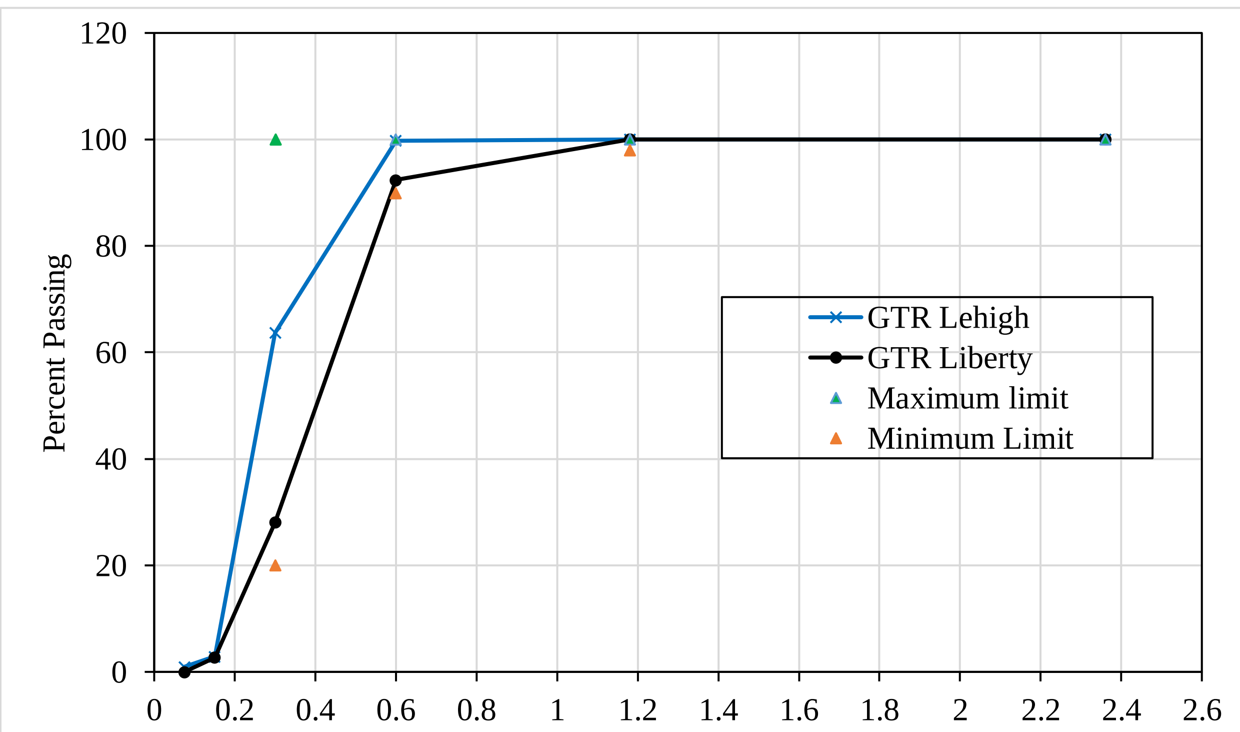

Figure 4.2 Gradation of GTR Materials

4.3 Performance Grade Testing

The Dynamic shear rheometer (DSR) tests and bending beam rheometer (BBR) tests were conducted on the GTR and polymer modified binders to determine their performance grade (PG) in accordance with AASHTO M320 "Standard Specification for Performance-Graded Asphalt Binder". DSR test procedure was modified as suggested in ODOT Supplement Specification 887 to accommodate the presence of the GTR particles in the asphalt binder. Tests were performed on GTR binders directly after mixing as well as after placing them in the oven for 24 hours. Figure 4.3 presents the continuous high temperature obtained based on the DSR test results. All GTR binders had a continuous high temperature PG grade greater than 76 °C directly after 50 minute of mixing and after being placing in the oven for 24 hours. While the liberty GTR binder's high grade slightly dropped after the 24 hours oven placement, the Lehigh GTR binders' high grade slightly increased.

Figure 4.4 presents the continuous low PG grade of GTR binders obtained based on the BBR test results. It is noted that all GTR binders had a continuous low temperature PG grade less than -22 °C. All GTR had colder low temperature grade upon placement for 24-hours in the oven; particularly those with Lehigh GTR. This indicates that all GTR binders had performance grade of 76-22. The low temperature grade obtained based on asphalt binder cracking device (ABCD) test results are presented in Figure 4.5. The ABCD low temperture cracking was in general the same as those obtained in the BBR test. The ABCD test results are also confirming those obtained in the BBR tests, such that low temperature grade became slighlty colder after the 24-hours placement in the oven. This may be attributed to the interactions between the GTR and asphalt binder constiuents that ocurred during the 24 hours after mixing. Based on that it recomndded that the GTR binder grading should be done after placing it in the oven for 24 hours.

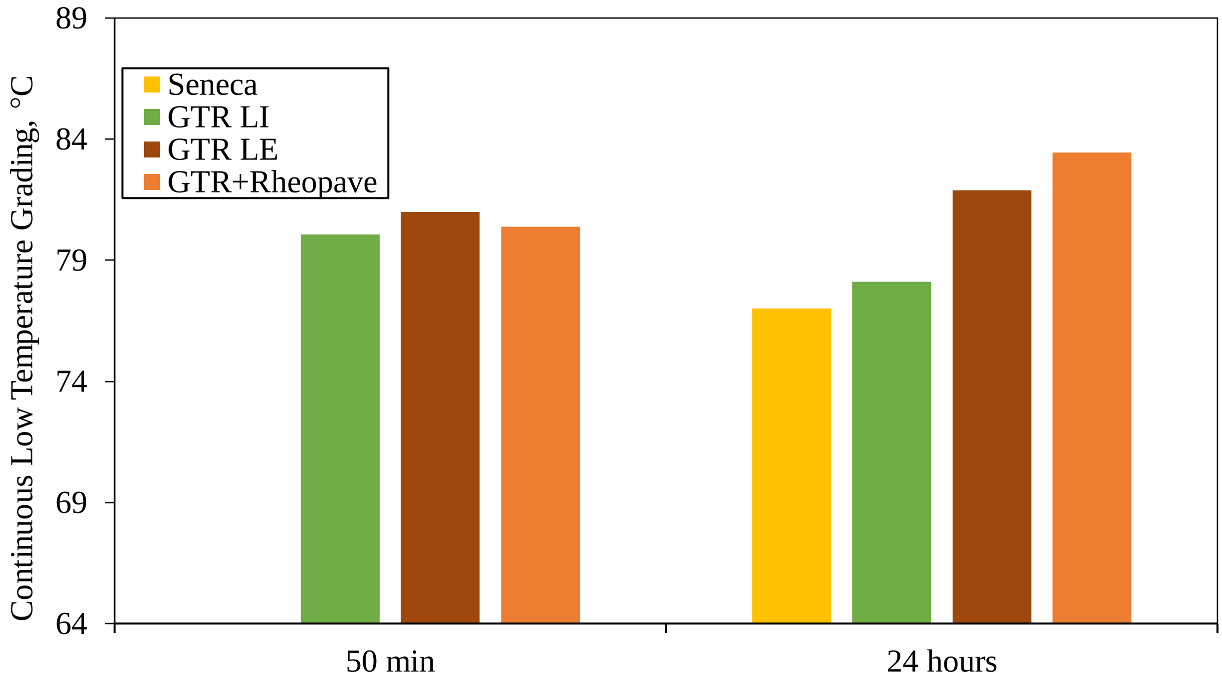

Figure 4.3 Continuous High Temperature Grade

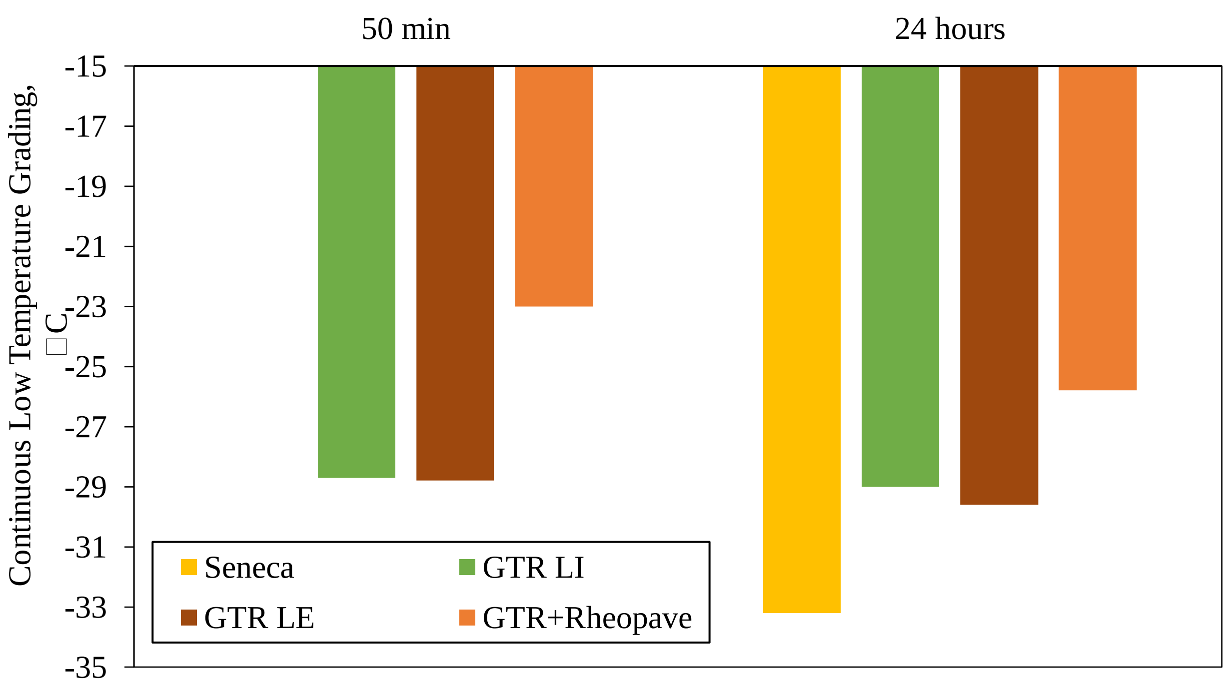

Figure 4.4 Continuous Low Temperature Grade Based on BBR Test

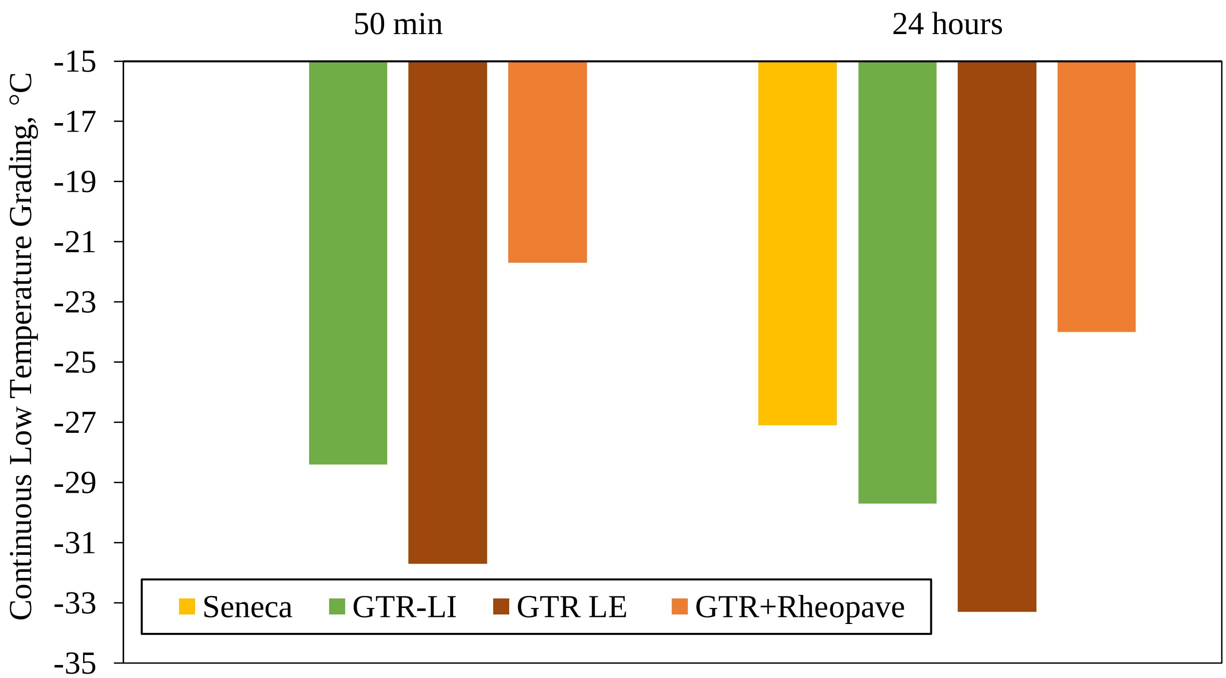

Figure 4.5 Continuous Low Temperature Grade Based on ABCD Test

4.4 Seperation Test

Separation tendency of the GTR particles from the rubberized binder was determined using cigar tube test (CTT). Detailed procedure for the test is provided in ASTM D 7173 "Standard Practice for Determining the Separation Tendency of Polymer from Polymer Modified Asphalt". For this test, aluminium cigar tubes were filled with rubberized asphalt binder. Tubes were then sealed, and allowed to stand vertically at 163° C for 48 hours. They were then placed in a freezer at -10° C for four hours before being cut in three equal parts. The middle part was discarded and the softening point was determined for the top and bottom parts. Figure 4.6 compares the softening points for the bottom and top parts for each of the considered GTR binders. The Lehigh GTR binders showed small differences in the softening point (<3 °F) between the top and bottom. Higher difference was observed in the case of the Liberty GTR binder. However, this difference was less than the limiting value specified by ODOT of 10 °F. The greater the difference in softening point between the bottom and top part of the Liberty GTR indicate that higher degree of separation between the GTR and binder, which might be attributed to the coarse gradation and larger particle of the Liberty GTR as compared to the Lehigh GTR.

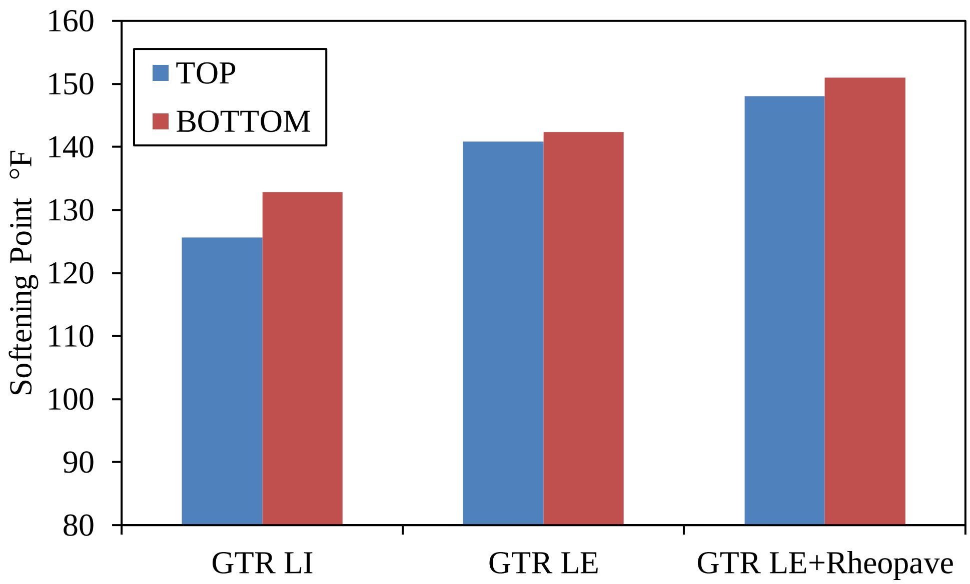

Figure 4.6 Results of Separation Tests

4.5 Mixtures Design

To select the aggregate gradation of the mixture to be evaluated in this study, the gradations of aggregates of GTR and polymer modified mixtures previously used in local roadways in Ohio shown in Figure 4.7 were examined. Based on that, the selected asphalt mixture had a 3/8 inch (9.5 mm) nominal maximum aggregate size (NMAS) and was designed to meet ODOT specification for Item 441 for medium traffic surface mixtures. Figure 4.8 shows the 0.45-power chart for the selected aggregate gradations as well as the coarsest (Dayton 2013) and finest (Erie County 2011) aggregate gradations of GTR mixtures previously used in construction pavement section in Ohio are shown. It is noted that three aggregate types (47% limestone #8, 16% natural sand, 17% manufactured sand and 20% reclaimed asphalt pavement (RAP) were blended to produce the required gradation. The job mix formula for the asphalt mixture was obtained from the Shelly Company. Mix design was performed using the SBS polymer modified binder specification for PG 70-22 to verify the optimum asphalt content for the selected aggregate gradation provided by the asphalt contractor. Verification of the mix design with the GTR binders was also performed using the same aggregate gradation and a target air void of 3.5%. Figure 4.9 compares the obtained optimum binder content for the different GTR binders. All GTR binders required slightly higher (0.1-0.2%) asphalt binder content. This may be attributed to the percent of the base PG 64-22 binder replaced by the GTR material in GTR binders. It is noted that mixtures with finer GTR material required lower asphalt binder content as compared to those with coarse GTR.

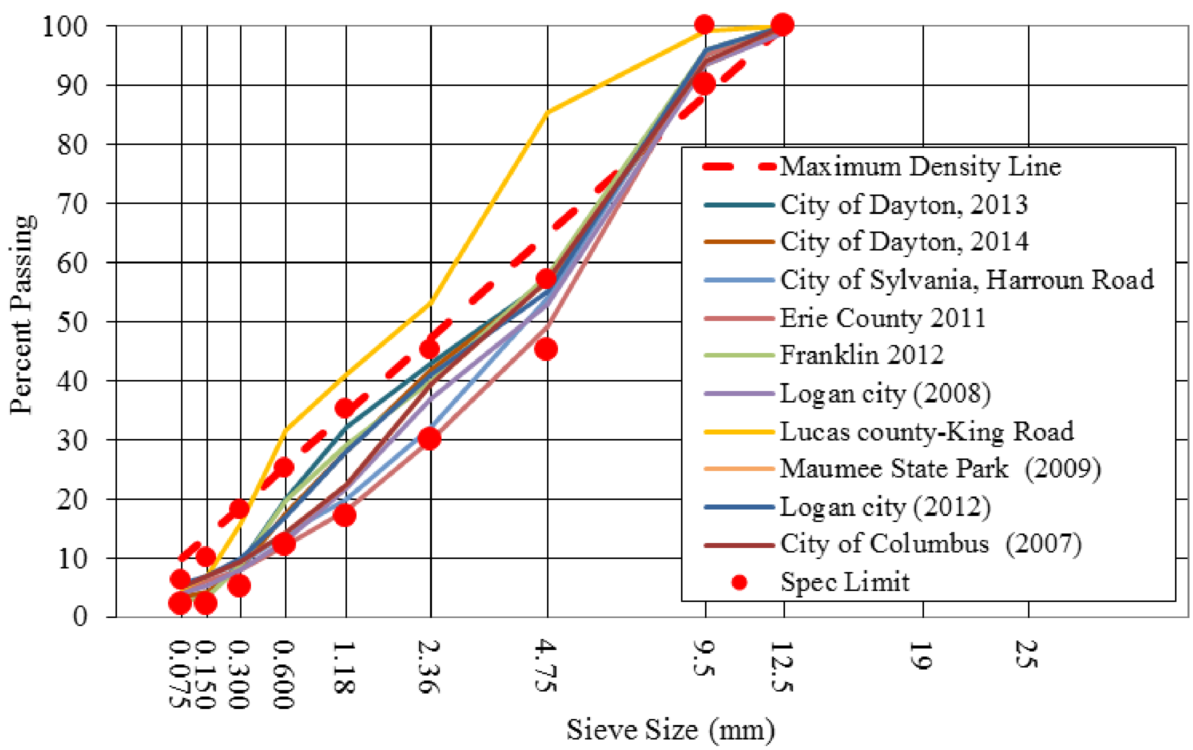

Figure 4.7 Aggregate Gradations of GTR Mixtures Used in Ohio

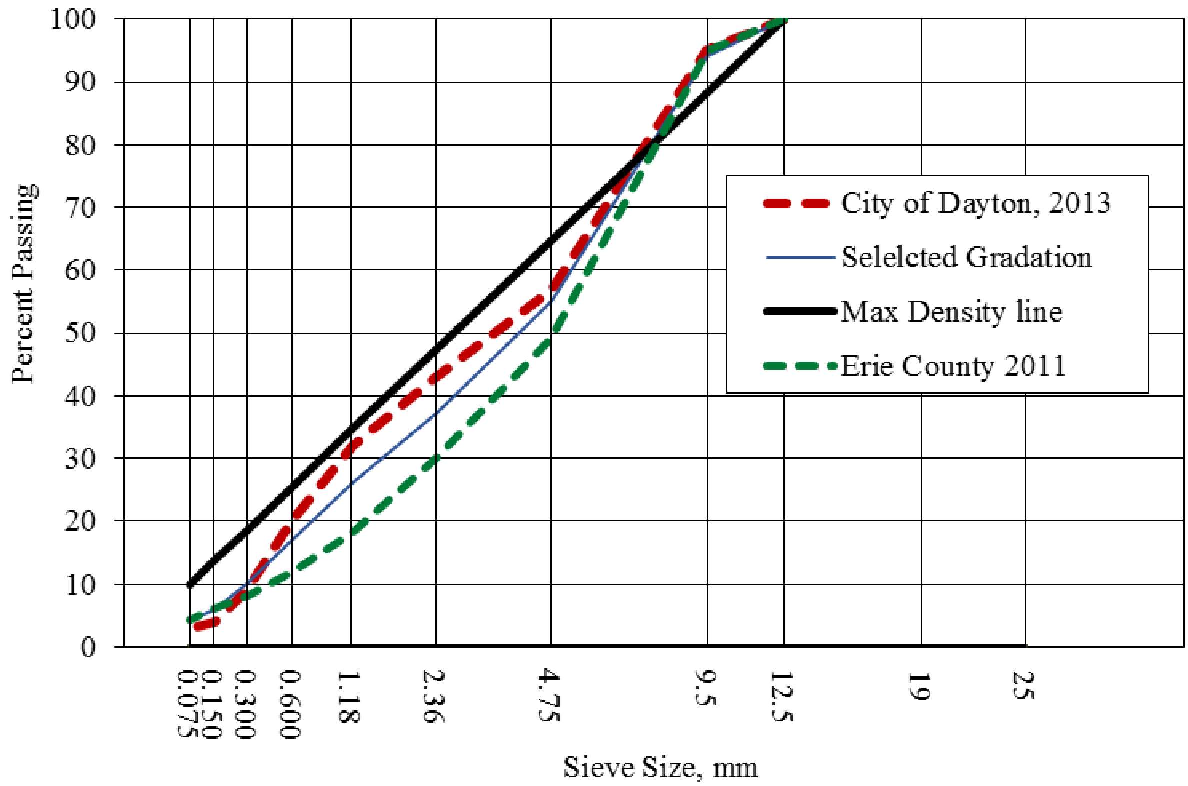

Figure 4.8 Selected Aggregate Gradations of GTR Mixtures in This Study

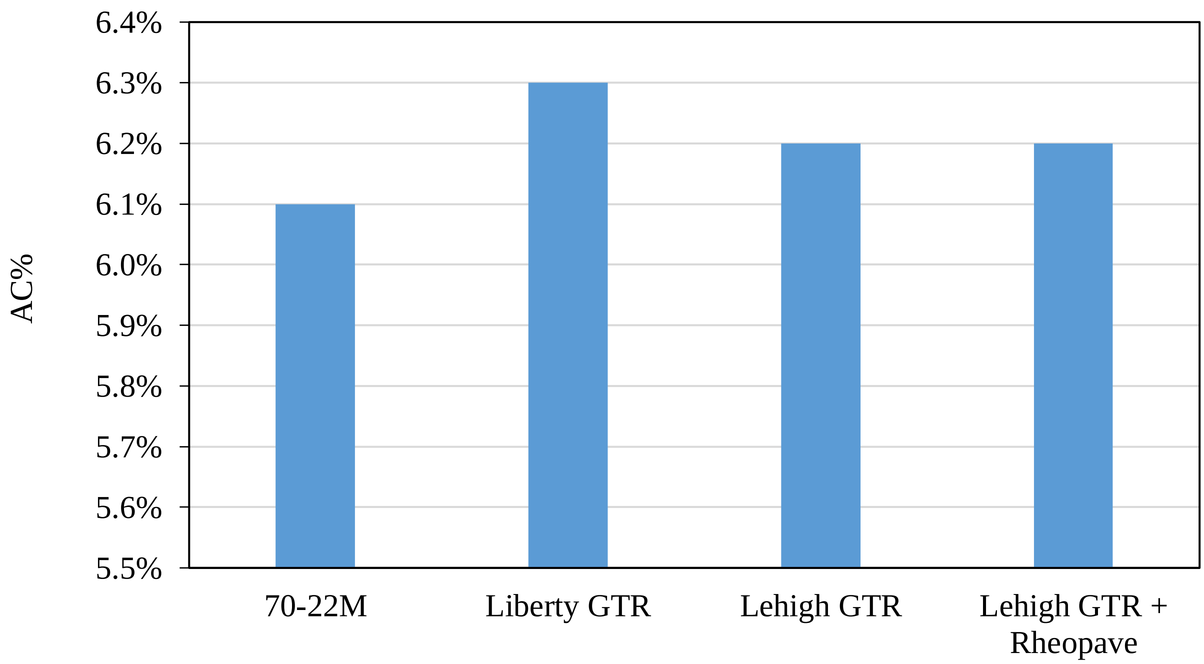

Figure 4.9 Optimum Asphalt Content of GTR Mixtures

4.6 MixtureTesting

A laboratory testing program was performed to evaluate the performance of the control SBS polymer modified asphalt mixture and the GTR modified mixtures with respect to moisture-induced damage (or durability), permanent deformation (or rutting), fatigue cracking, and low temperature cracking. The susceptibility of the asphalt mixtures to moisture-induced damage was evaluated using the modified Lottman test, the rutting performance of the mixtures was evaluated using the Asphalt Pavement Analyzer (APA) test, the propensity of the asphalt mixtures to fatigue cracking was evaluated using the IDT test, and the low-temperature cracking potential was assessed using the ACCD. A description of the performed tests and details of procedure followed are provided in Appendix B.

4.6.1 Indirect Tensile Strength (IDT) Test Results

IDT test was conducted in accordance with AASHTO T245 on at least three samples for each evaluated mixture. A loading rate of 2 in/min was used. Figure 4.10 presents the mean and standard deviation of the ITS values for the considered mixtures at 25ºC. Higher ITS values are desirable as they correspond to a strong and durable mixture. In general, GTR mixtures had slightly higher ITS values than the polymer modified 70-22 mixture; however, mixes with Liberty GTR binder had the highest ITS value.

4.6.2 Modified Lottman (AASHTO T283) Test Results

AASHTO T283 tests were performed to evaluate the moisture susceptibility of GTR and polymer modified mixtures. The test was conducted on dry and wet conditioned samples, and the indirect tensile strength was determined for those samples. The tensile strength ratio (TSR) was also computed by dividing the average ITS value of the wet conditioned samples by that of the dry samples. Figure 4.11 compares the average ITS values for the dry and wet conditioned samples evaluated in this study. The conditioning of the all mixtures has resulted in reducing their average ITS values. The conditioned mixtures exhibited lower ITS values as compared to the unconditioned dry mixes but still had in general the same rankings. The Lehigh GTR mix had slightly higher reduction in the ITS values upon conditioning as compared to the other types of GTR mixtures as well as the polymer modified mixture. This can be also noticed in Figure 4.12, which presents the TSR values for the different mixtures. However, all mixtures had TSR values higher then 0.8, which is the minimum TSR value specified by ODOT as well as other state and local agencies.

Multi-factor Analysis of Variance (ANOVA) and post ANOVA Least Square Mean (LSM) analyses were conducted using Statistical Analysis Software (SAS) (*21*) to statistically evaluate the results in Figure 4.11. A linear Completely Random Design (CRD) model was used. The results of this analyses showed that at 95% confidence level, the effects of the binder and conditioning were significant. Table 4.3 presents the results of the grouping of the different mixtures that was determined using the post ANOVA LSM analysis. In this table, the groups are listed in descending order with the letter “A” assigned to the highest mean followed by the other letters in appropriate order. In addition, groups with same letter next to them are not significantly different. It is noted that the Liberty GTR had significantly higher ITS value than the other GTR mixtures as well as the PG-70-22 mix.

4.6.3 APA Test Results

APA test was conducted on at least three samples for each evaluated mixture. Figure 4.13 presents the APA test results for the evaluated GTR and polymer modified mixtures. The GTR mixtures had lower rut depths than the PG 70-22M mixture. This indicates that GTR mixtures had better rut resistance than mixture with the PG 70-22M binder. This result is consistent with the DSR test results, which showed that all GTR binders had continuous high grade greater than 76 °C. It is noted that the mixture with Lehigh GTR and had slightly higher rut depth than that with Liberty GTR. However, the addition of Rheopave resulted in stiffening the Lehigh GTR binder and significantly lowering the mixture rut depth.

The results of the ANOVA analyses that were conducted on APA test results showed that at 95% confidence level, the binder type used in the mixture significantly affected the rut depth. Table 4.4 presents the grouping of the different mixtures that was determined using the post ANOVA LSM analysis. The polymer modified PG 70-22 mixture had significantly higher rut depth than the GTR modified mixtures. In addition, the mixture with Lehigh GTR and Rheopave had significantly lower rutting than the other GTR modified mixes.

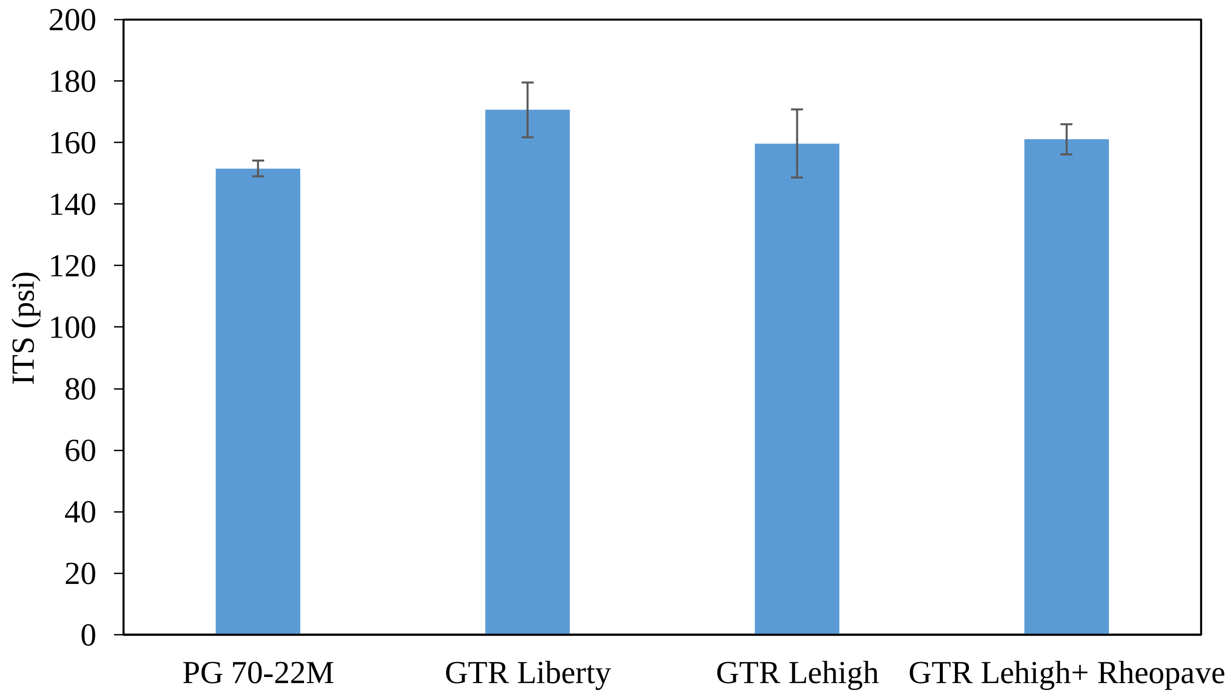

Figure 4.10 Results of IDT Tests on Dry samples

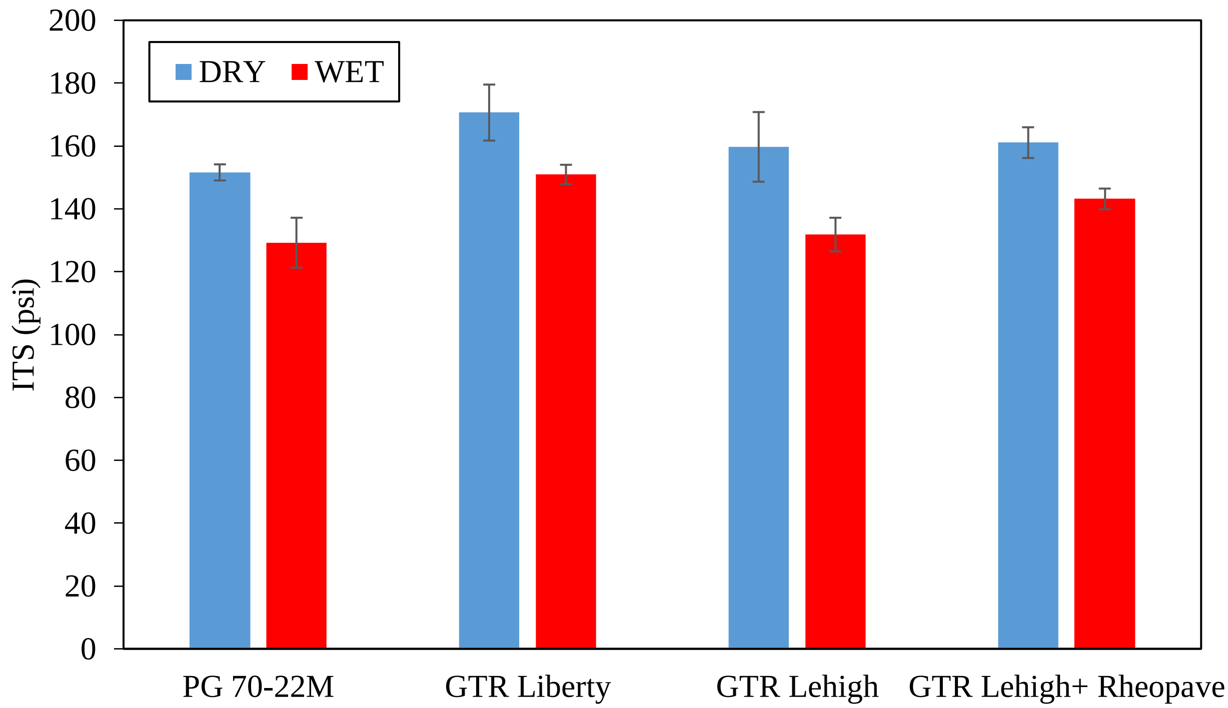

Figure 4.11 Average ITS values for Dry and Wet Conditioned Samples

Figure 4.12 TSR Values for the Evaluated Mixtures

Table 4.3 Results of Post ANOVA LSM on AASHTO 283 Test Results

Binder	Average ITS (psi)	Letter Group
Liberty	164.00	A
Lehigh+ Rheopave	146.86	B
Lehigh	144.80	B
PG 70-22	142.30	B

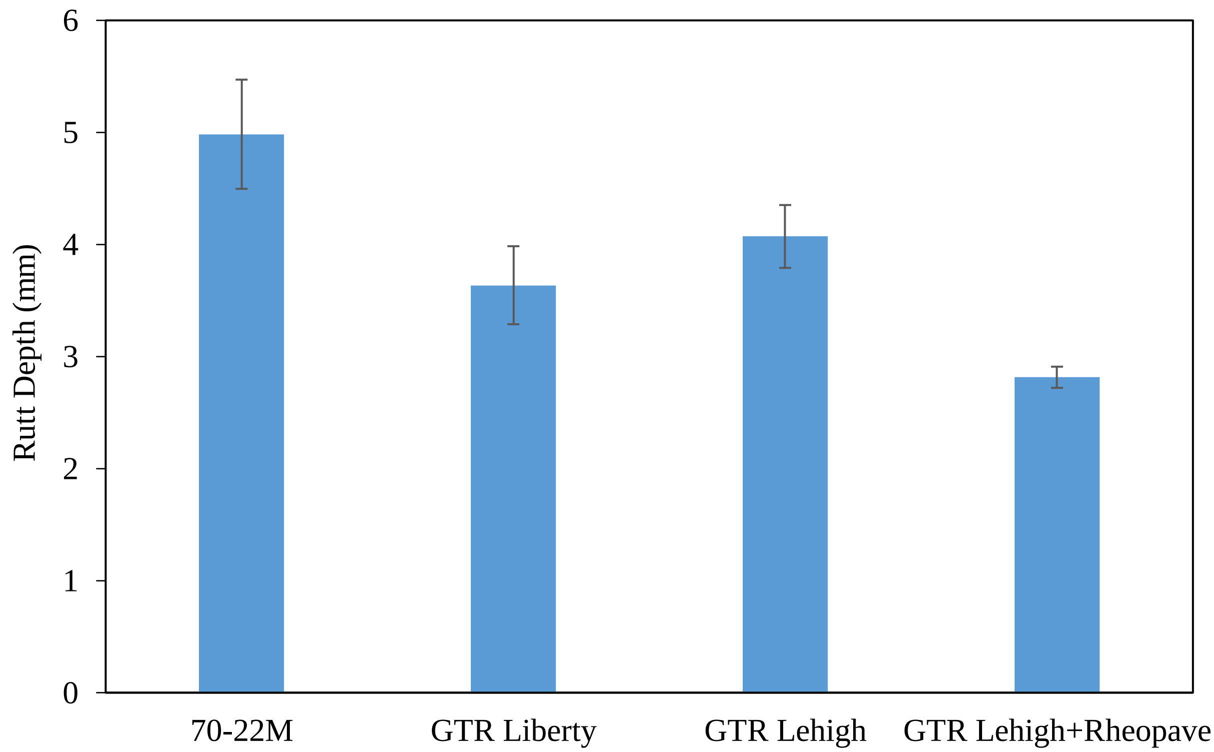

Figure 4.13 APA Test Results

Table 4.4 Results of Post ANOVA LSM results on APA Test Results

Binder	Average Rut (mm)	Letter Group
PG 70-22	4.98	A
Lehigh	3.83	B
Liberty	3.64	BC
Lehigh+ Rheopave	2.82	C

4.6.4 ACCD

The ACCD was performed on short-term and long-term aged specimens. The short-term aged specimens were prepared by placing the loose asphalt mixture in an air draft oven at the compaction temperature for 4 hours prior to compaction. Long term aging of compacted mix was performed according AASHTO R 30 procedure after the compacted specimens were cut. AASHTO R 30 involves placing compacted asphalt mixtures in an oven at 85°C for 5 days to simulate the aging that takes place in the field after approximately 10 years of service. Figure 4.14 presents the average ACCD cracking temperature for the short-term and long-term aged samples tested in this study. For the short-term aged samples, the GTR mixes had similar cracking temperature, which was at about 3°C colder than that of the PG 70-22M mix. The long-term aging reduced the cracking temperature of all mixes. However, the PG 70-22M mixture exhibited more reduction due to long-term aging as compared to the GTR mixes. Such that the GTR mixes cracking temperature was about 5°C colder than that of the PG 70-22 mixture. The results of ACCD test indicate the GTR mixtures had better resistance to low temperature cracking as compared to the mixture with polymer modified PG 70-22M binder. This result may suggest that the GTR helps reduce the adverse effect of aging on the low temperature performance of asphalt binders and mixtures.

The analysis of variance (ANOVA) that was conducted to evaluate the results of ACCD tests indicated that at 95% confidence level the type of binder used in the mixtures and their aging conditions affected their cracking temperature. Table 4.5 presents the results of the post ANOVA LSM analyses. All GTR mixtures had significantly colder cracking temperature than the polymer modified PG 70-22. In addition, the cracking temperatures of the GTR mixtures were statistically indistinguishable from each other.

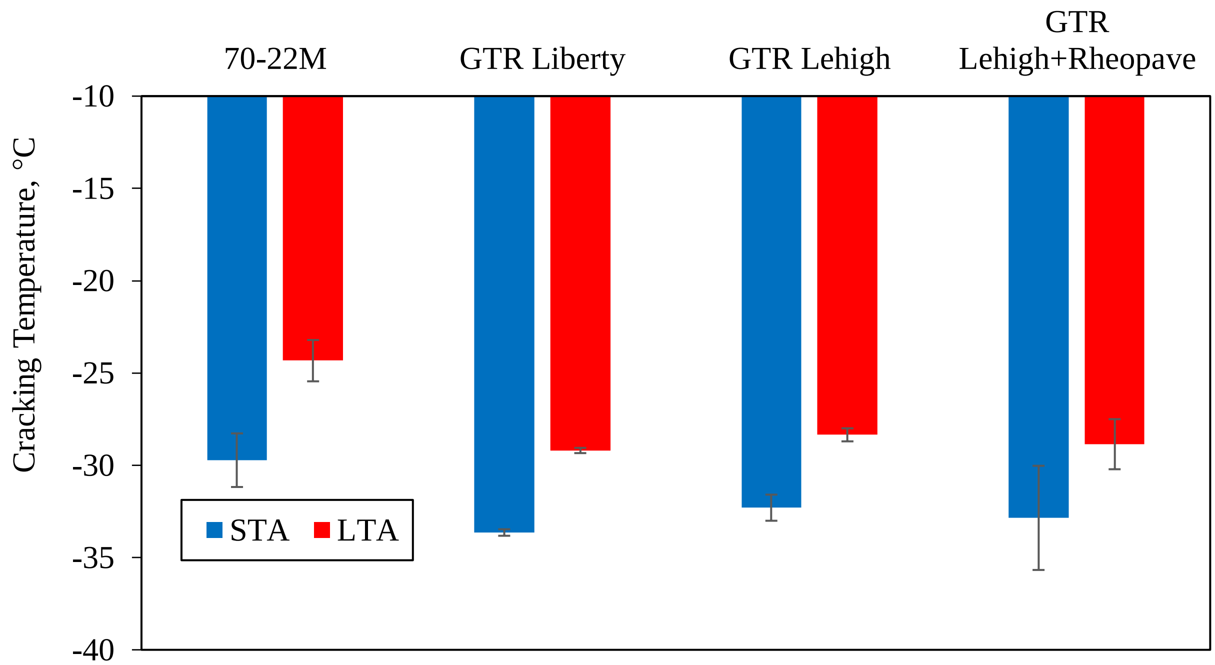

Figure 4.14 Cracking Temperature Obtained from ACCD test

Table 4.5 Results of Post ANOVA LSM Analyses on ACCD Test Results

Binder	Average Cracking Temperature °C	Letter Group
PG 70-22	-27.03	A
Lehigh	-30.36	B
Lehigh+ Rheopave	-30.86	B
Liberty	-31.43	B

Chapter 5: Recommendations for GTR Modified Binders/Mixtures Specifications and QC/QA Criteria

5.1 Recommendation for GTR Modified Binders Specifications

All the requirements specified in ODOT supplement specification 887 applies but with the following modifications:

1. Materials Requirements for GTR Modified Asphalt Binder

a- In Table 887.02-01, the minimum required GTR for PG 70-22 is 7% instead of 10%.

b- GTR can be produced from processing automobile and/or truck tires by the ambient grinding method. If GTR is produced using cryogenic grinding method, then the surface area of used GTR materials should be at least 0.075 m^2/g.

c- GTR gradation should conform to the gradation limits in Table 5.1. GTR gradation should be determined according to ASTM D5644.

Table 5.1 Recommended GTR Gradation Specifications

Sieve Size	GTR Ambient Method		GTR Cryogenic Method	
	Maximum Limit	Minimum Limit	Maximum Limit	Minimum Limit
No. 8	100	100	100	100
No. 16	100	98	100	98
No. 30	100	90	100	90
No.50	100	25	100	50

2. Blending of GTR Modified Asphalt Binder

Only blend GTR modified asphalt binder at a terminal. Asphalt plant blending is not allowed. Use a separate heated, agitated tank with continuous mixing. React the GTR modified asphalt binder at 365 °F to 383 ºF (185 ºC to 195 ºC) at a minimum mixing rate of

3500 rpm for at least 50 minutes to give a blend having GTR chemically bonded to asphalt binder resulting in only minor separation upon loss of circulation. The GTR and asphalt binder will be considered properly bonded if the binder is not agitated for four hours and is then easily re-blended thru transport and pumping. Store GTR modified asphalt binder at 329 °F to 383 ºF (160 °C to 195 ºC) with continuous mixing and/or recirculation for a minimum of 24 hours. Softening point and DSR tests should be conducted on the GTR modified binder at the terminal and upon delivery to asphalt plants.

3. Asphalt Plant Requirements

Do not store the GTR modified asphalt binder at the asphalt plant for more than two days. Softening point and DSR tests should be determined daily and compared to the value obtained at the terminal as described below.

5.2 Recommendations for Mix Design Specfications for GTR Modified Mixtures

It is recommended that mixtures prepared using GTR binders are designed using the same specifications and requirements as those with polymer modified binders. Moisture damage potential test should be conducted according to ODOT Supplement 1051 as part of the design process and the results should be reported in the JMF submittal. It is recommended to use a minimum tensile strength ratio (TSR) of 0.8 for GTR modified asphalt mixtures.

5.3 Recommendations for QC/QA Criteria

The following sections describe the recommended tests to control the quality of GTR modified binders and mixtures.

5.3.1 Binders

- Supply proper containers and take two 1 quart (1 liter) samples of the GTR modified asphalt as follows:
  a. At the terminal, directly after mixing the GTR and the asphalt binder
  b. From storage tank at the terminal after 24 hours of mixing the GTR and the asphalt binder
  c. At the terminal, immediately prior to transporting GTR modified binder to the asphalt plant
  d. At the asphalt plant, from the transport truck load before incorporation into the storage tank
  e. At the asphalt plant, prior to GTR modified asphalt mixture production

- Properly label the samples with supplier, project number and date and retain them in the plant laboratory for future reference. Discard the samples at end of the project, if not taken by the Monitoring Team.

- Monitor the separation of GTR by:

1- Determining the softening point of GTR modified binder samples obtained in the above cases. The maximum allowable difference in the softening points measured in case “b”, “c”, “d”, and “e” and that in case “a” is 10 °F.

2- Conducting DSR tests at 70 °C and determining the complex shear modulus (G*) and phase of angle (δ) of the GTR modified binder samples obtained in above cases. The percent separation should be computed for case “b”, “c”, “d”, and “e” as follows:

$$Sepration(\%)_{case\ x} = \frac{(G^*/sin\delta)_{case\ x} - (G^*/sin\delta)_{case\ a}}{(G^*/sin\delta)_{case\ a}}$$

Where:

G^* = complex shear modulus

δ = phase angle

$Separation(\%)_{case\ x}$: is separation at given case; x can be b, c, d, or e

The percent separation in any case should be less than 10%.

5.3.2 Mixtures

Perform quality control tests to control the asphalt concrete mix within the specifications shown in Table 5.2. Ensure that these quality control tests measure the asphalt binder content, gradation, air voids, and Maximum Specific Gravity (MSG), Indirect Tensile Strength (ITS). 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 5.2. Immediately resolve problems indicated by any out of outside the specifications limits test and immediately retest to validate corrections have returned the materials to within the outside 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 aggregate remaining 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. **ITS.** Determine ITS of three specimens compacted to target air void 7±0.5 as well as for three 4-inch core samples obtained from field sections. The indirect tensile strength test can be conducted using Marshall Stability testing frame.

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 5.2 Recommended Out of Specification Limits

Mix Characteristic	**Out of Specification Limits**
Asphalt Binder Content[1]	-0.5% to 0.5%
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)

[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

Chapter 6: Conclusions and Recommendations

6.1 Summary and Conclusions

In Phase 1 of this project, the long-term field performance and life cycle costs of pavements sections constructed with GTR modified mixtures were evaluated and compared to those constructed using polymer modified asphalt mixtures. In addition, new GTR technologies that can reduce the initial cost of GTR mixtures were identified and examined through a comprehensive laboratory testing program. Finally, this phase assessed the current ODOT mix design specifications and the supplemental quality control/quality assurance (QC/QA) testing and acceptance criteria to determine their applicability for GTR asphalt mixtures produced using the terminal blend method that are used on local roads. The following sections provide the main conclusions drawn based on the results of Phase 1.

6.1.1 Analysis of Data and Field Evaluation of GTR Pavements in Ohio

- All GTR asphalt mixtures used in previously constructed GTR sections in Ohio were produced using Seneca Petroleum company GTR binder.
- In all previous GTR projects in Ohio, the use of GTR binder in place of SBS polymer modified PG 76-22M binder resulted in increasing the mixtures price by 10-15%. This can be attributed to the additional cost that the asphalt contractor encountered when using a binder purchased from a supplier (e.g. Seneca Petroleum) rather than prepared at his own terminal. In addition, using Seneca GTR binders had resulted in increasing the required asphalt binder content by 0.1-0.5% as compared to a SBS polymer modified binder. This increase in the required asphalt content yielded higher prices of GTR mixtures in Ohio.

- The higher initial cost for GTR asphalt mixtures is the main reason for not using them widely within Ohio.
- The field evaluation of sections constructed using terminal blend GTR modified mixes showed that they had good performance after 10 years of service which was similar to the sections in which polymer modified mixes were used.
- Thermal and fatigue cracking were the main distresses developed in the GTR and polymer modified pavement sections. Those distresses developed at the same time and in the same pattern in both section. No rutting problems were observed in any of the sections.
- The laboratory tests conducted on the core samples obtained from the evaluated sections indicated that the GTR modified field mixtures had similar fatigue cracking resistance to the polymer modified mixes, but slightly better resistance to low- temperature cracking and moisture induced damage.
- There was good agreement between IDT test results parameters (i.e. toughness index and indirect tensile strength) and the fatigue cracking field performance of the GTR and polymer modified mixture.
- Although the GTR and polymer modified sections had very similar performance and maintenance costs, the GTR modified sections had 10-15% higher life cycle costs. This was attributed to the higher initial price of GTR modified asphalt mixes.

6.1.2 Evaluation of New GTR Technologies

- Different GTR technologies were identified. The GTR binders prepared using 10% Liberty GTR, 10% Lehigh GTR, or 7% Lehigh GTR and 0.5% Rheopave were the least expensive.

The prices of these GTR modified binders were at least $47 per ton less than the estimated price of SBS polymer modified PG 70-22 binder.

- The GTR binders prepared using 10% Liberty GTR, 10% Lehigh GTR, or 7% Lehigh GTR and Rheopave had a continuous high PG grade higher than 76 °C and a low temperature PG grade lower than -22 °C. Thus, these binders had a performance grade meeting PG 76-22.
- Mixtures prepared with Lehigh and Liberty GTR modified binders had better resistance to low temperature cracking than those prepared using PG 70-22 polymer modified binder as indicated by the ACCD test results. This was more pronounced in samples subjected to long-term aging.
- In terms of rutting, all GTR mixes had lower rutting in APA test and is expected to have better rutting performance than PG 70-22 polymer mixes.
- GTR mixes had slightly higher indirect tensile strength values than those prepared using PG 70-22M polymer modified binder. This suggests that GTR mixes have better or similar fatigue cracking to polymer modified 70-22M mixes.
- The results of the modified Lottman (AASHTO T283) indicated that GTR modified mixes had similar moisture damage resistance to those prepared using polymer modified binder meeting PG 70-22M.

6.2 Recommendations for Implementation

Based on the results of the cost analyses and the labrotrary testing program conducted in this study, the mixtures prepared using 10% Liberty GTR, 10% Lehigh GTR, and 7% Lehigh GTR or 0.5% Rheopave modified binders evaluated in Phase 1 should be further examined in the field as part of Phase 2 of this project. All GTR modified asphalt binders and mixtures should satisfy the requirements specified in ODOT supplement specification 887 with the recommended modifications presented in Chapter 5.

References

1- Associated Construction Publications - Silence Please." Associated Construction Publications - Silence Please. Accessed October 16, 2015. http://web.archive.org/web/20060319143533/http://www.acppubs.com/article/CA6279032.html

2- ODOT (2014). Ground Tire Rubber Modified Asphalt Binder Materials and Construction Requirements. Supplement Specification 887. Ohio Department of Transportation, Columbus, Ohio. January 17, 2014.

3- USEPA (2014). "Scrap Tires." United States Environmental Protection Agency, Washington, D.C. Available at http://www.epa.gov/wastes/conserve/materials/tires/basic.htm. Accessed on March 19, 2014.

4- Heitzman, M. (1992). "State of the Practice – Design and Construction of Asphalt Paving Materials with Crumb Rubber Modifier," Research Report No. FHWA-SA-92-022, Federal Highway Administration, Washington, D.C., May 1992.

5- Myhre, M., and D.A. MacKillop (2002). "Rubber Recycling." *Rubber Chemistry and Technology*. Vol. 75, No. 3, pp. 429-474. http://dx.doi.org/10.5254/1.3547678

6- Hicks, R.G., D. Cheng, and T. Duffy. (2010). "Evaluation of Terminal Blend Rubberized Asphalt in Paving Applications," Report No CP2C-2010-102TM, California Pavement Preservation Center, May 2010. Available at http://www.paramountasphalt.com/_blog/Paramount_Asphalt_News/post/Evaluation_of_Terminal_Blend_Rubberized_Asphalt_in_Paving_Applications/. Accessed on April 27, 2015.

7- Hicks, G. (2009). “Differences between asphalt rubber and terminal blend modified asphalts.” *CP2 Center News*, Chico, California, October 2009.

8- Willis, J. R., Plemons, C., & Mitchell, T. (2013). Effect of Ground Tire Rubber Particles On Open-Graded Mixture Performance. NCAT Report 13-11, National Center for Asphalt Technology Auburn University, Auburn, Alabama.

9- Sebaaly, H. K., E. Y. Hajj, P. E. Sebaaly, D. Weitzel, and E. Hitti. (2008). “Laboratory Evaluation of HMA Mixes Using Tire Modified Binders,” International Journal of Pavements, Vol. 7, #1-2-3, 2008, pp. 64-75.

10- Sebaaly, P.E., H. Sebaaly, and E. Hajj, (2009). “Properties of HMA Mixtures Produced with Polymer-Modified and Tire Rubber-Modified Asphalt Binders,” Proceedings of Asphalt Rubber Conference, Nanjing, China, Nov. 2-9, 2009, pp. 831-846.

11- Blankenship, P. B. (2009). “Summary report for Paramount Petroleum.” Asphalt Institute, Lexington, Kentucky, October 26, 2009.

12- Presti, Davide Lo. "Recycled Tyre Rubber Modified Bitumen for Road Asphalt Mixtures: A Literature Review." *Construction and Building Materials* 49 (2013): 863-881.

13- Abdelrahman MA, Carpenter SH. The mechanism of the interaction of asphalt cement with crumb rubber modifier (CRM). Transport Res Rec 1999;1661: 106–13.

14- Attia, Mohamed, and Magdy Abdelrahman. "Enhancing the performance of crumb rubber-modified binders through varying the interaction conditions." International Journal of Pavement Engineering 10, no. 6 (2009): 423-434.

15- Buckly, D., and M. Berger. The Swelling of Polymer System in Solvents.*Journal of Polymer Science,* Vol. 56, 1962

16- Shen, Junan, Serji Amirkhanian, Feipeng Xiao, and Boming Tang. "Influence Of Surface Area And Size Of Crumb Rubber On High Temperature Properties Of Crumb Rubber Modified Binders." *Construction and Building Materials* 23, no. 1 (2009): 304-310.

17- Willis, J. Richard, Clayton Plemons, Pamela Turner, Carolina Rodezno, and Tyler Mitchell. "Effect Of Ground Tire Rubber Particle Size And Grinding Method On Asphalt Binder Properties." *National Center for Asphalt Technology. NCAT Report* (2012): 12-09.

18- Abdelrahman, M. A. *Engineering Characterization of the Interaction of Asphalt with Crumb Rubber Modifier (CRM).* Ph.D. thesis. University of Illinois at Urbana-Champaign, May 1996.

19- Glover, C.J., R.R. Davison, J.A. Bullin, C.K. Estakhri, S.A. Williamson, T.C. Billiter, J.F. Chipps, J.S. Chun, P. Juristyarini, S.E. Leicht, and P. Wattanachai. (2000). "A comprehensive laboratory and field study of high cure crumb rubber modified asphalt materials." Texas Transportation Institute, Texas A&M University, Report 1460-1, January 2000. Available at http://d2dtl5nnlpfr0r.cloudfront.net/tti.tamu.edu/documents/1460-1.pdf. Accessed on March 27, 2014

20- Troy, K., Sebaaly, P., and Epps, J., (1996) Evaluation Systems for Crumb Rubber Modified Binders and Mixtures. Transportation Research Record, No. 1530, TRB, National Research Council, Washington, D.C.

21- Mohammad, L.N., Nazzal, M., and Austin, A., 2013 "Development of a design Methodology for Asphalt Treated Base." Final report, Federal Highway Administration/

Louisiana Department of Transportation and Development Report No. 453, Baton Rouge, 2013.

22- SAS Institute Inc. 2004. SAS OnlineDoc® 9.1.2. Cary, NC, SAS Institute Inc.

Appendix A

Table A.1. Summary of Data Collected from GTR Sections in Ohio

Year	County or City	Location	ADT	Pavement Layer Type & Thickness	Mixture Type	Aggregate Type	RAP %	Cost of GTR Mix $ per Ton	Cost of Original Mix $ per Ton	PCR
2009	Champaign/Clark	SR 235	4216	1.5" surface course	448-1	Gravel	20	69	-	82
2012	City of Dayton	W. Third St.	9626	2" surface course	404	Gravel	10	77	-	96.8
2012	City of Dayton	Wyoming Ave	8977	2" surface course	409	Gravel	10	77	-	98.1
2012	City of Dayton	Shroyer Rd.	8969	2" surface course	410	Gravel	10	77	-	97.2
2012	City of Dayton	S. Smithville Rd.	8963	2" surface course	411	Gravel	10	77	-	95
2013	City of Dayton	E. Third St.	8864	2" surface course	448-1	Gravel	25	80	-	99.6
2013	City of Dayton	Waterville	5418	2" surface course	448-1	Gravel	25	80	-	98.5
2013	City of Dayton	Riverside Dr.	15947	2" surface course	448-1	Gravel	25	80	-	98.4
2014	City of Dayton	Edwin C. Moses	11324	2" surface course	442-1A	Limestone	15	90		100
2010	City of Sylvania	Haroun Rd.	10015	1.5" surface course & 0.5 intermediate course	448-1	Limestone	10	85.5	-	-
2011	City of Sylvania	Main St.	-	1.5" surface course & 0.75 intermediate course	448-1	Limestone	20	85.5	-	-
2007	Columbus	21st St.	Residential	1.25" surface course	416-3	Limestone	20	70		64
2011	Erie County	Patten Track Rd.	2469	1.25" surface course& 1.25" intermediate course	448-1	Limestone	20	72	$63.5 (PG 64-22)	NA*
2007	Franklin County	Frank Rd.	19698	1.5" surface course	448-1-H	Limestone	0	66	-	68.5
2011	Franklin County	Trabue Rd.	-	1.25" surface course	448-1-H	Limestone	10	80	-	93
2011	Franklin County	Hague Ave	3185	1.25" surface course	448-1-H	Limestone	10	80	-	91
2012	Franklin County	Spiegel Dr.	9094	3.0" surface course	448-1	Limestone	10	85	-	95
2009	Hardin	SR 53/37	1990	1.5" surface course	441-1	Limestone	25	66.5	-	

Year	County or City	Road Name	ADT	Pavement Layer Type & Thickness	Mixture Type	Aggregate Type	RAP %	Cost of GTR Mix $ per Ton	Cost of Original Mix $ per Ton	PCR
2010	Holmes County	CR 201	1818	1.5" surface course	448-2	Limestone		$72	$55.3 (PG 64-22)	-
2010	Knox County	Mclarnan Rd.	398	1.25" surface course	448-1	Limestone	15	69.92	-	-
2011	Lake County	Bacon Rd. & Blackbrook Rd.		2" surface course	448-1	Limestone		79.5	-	-
2008	Logan County	CR 48	154	1.5" surface course	448-1	Gravel	10	66.75	-	NA*
2008	Logan County	CR 10	1465	1.5" surface course	448-1	Gravel	10	66.75	-	NA
2008	Logan County	CR 142	1223	1.25" surface course	448-1	Gravel	10	64.75	-	NA
2012	Logan County	CR 20	249	1.5" surface course	448-1	Limestone	17	74	-	95
2012	Logan County	CR 26	451	1.5" surface course	448-1	Limestone	17	80.5	-	95
2012	Logan County	CR 50	306	1.5" surface course	448-1	Limestone	17	76	-	95
2012	Logan County	CR 142	421	1.5" surface course	448-1	Limestone	17	75.25	-	95
2005	Lucas County	King Rd.	7120	1" surface course	424-B	Limestone	0	55.46	$49.9(PG 76-22)	87
2011	Mahoning County (Berlin township)	Heiser Rd.	low volume	1" surface course & 1" intermediate course	448-1	Limestone	-	71.5	-	-
2010	Maumee Bay State park	Parking Lot	NA	1.5" surface course	448-1	Limestone	10	-	-	NA
2009	Maumee State Park	Parking Lot	NA	1.5" surface course	448-1	Limestone	10	-	-	NA
2009	Sandusky	US 6	6039	1.5" surface course	442-1	Limestone	10	72	$66 (PG 76-22)	91
2006	Wood	Entrance to wood county landfill	-	1.5" surface course & 0.75 intermediate course	-	Limestone	-	73	-	NA

*Roadway was repaved or a chip seal was applied.

Appendix B

Indirect Tensile Strength (IDT) Test

The test was conducted in accordance with AASHTO T245 at 25 °C on at least three 100 mm x 62.5 mm cylindrical samples compacted to target air void of 7 ± 0.5%. A deformation rate of 2 in/min was used. The load as well as the vertical and lateral deformations were continuously recorded as shown in Figure B.1. The indirect tensile strength is computed Equation 1. In addition, the toughness index (TI), which is a parameter that describes the toughening characteristics in the post-peak region was also calculated using Equation 2.

$$ITS = \frac{2P}{2\pi DT} \tag{1}$$

P: is the peak load, lb
D: is the specimen diameter, in
T: is the specimen thickness, in
H_t: is horizontal deformation at peak load, in

$$TI = \frac{A_{3\%-P}}{(3\% - \varepsilon_p) * Stress_{peak}} \tag{2}$$

Where:
$A_{3\%-p}$: is the area under stress-strain curve between the peak lateral strain and a lateral strain value of 3%
ε_p: is the lateral strain at peak stress in %
$Stress_{peak}$: maximum stress value obtained.

AASHTO T283 Test

The moisture susceptibility was evaluated using the AASHTO T283 test procedure modified according to the standard practices implemented in the State of Ohio. At least six samples were prepared for each mixture evaluated in this study. The target air void level within these specimens was 7 ± 0.5%.The samples were then divided into two groups. The first group, control samples, was wrapped with Saran-Wrap and stored at room temperature for testing in the dry condition. In addition, the second group was conditioned. The conditioning procedure involved partially saturating the samples to a level between 70 to 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 were then wrapped and placed in a plastic bag, and 10 ml of water was added to the bag. The samples were then subjected to a freezing cycle by placing them for 16 hours in an environmental chamber set at a temperature of 0°F (–18°C). After the freezing cycle, the samples are 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.

Figure B.1. Indirect Tensile Strength Test Setup

Asphalt Concrete Cracking Device (ACCD)

ACCD was originally developed as a simplified version of Thermal Stress Restrained Specimen Test (TSRST). In this test, a sample with 150 mm diameter and compacted to target air void of 7 ± 0.5% is cut into two 50-60 mm thick slices. Then, the 60 mm diameter inner core of the specimen was cored out. A 22.4 mm long-notch is introduced at the outer surface of the sample to control the location of crack. The test sample and the ACCD ring were heated for 60 minutes at 60 °C (65-70°C for long term aged specimen) and the tapered end of the heated ACCD ring slid through the center hole of the heated test sample. The sample with the ACCD ring fitted inside was placed in the environmental chamber. As temperature decreases, the contraction of the asphalt mix specimen is restrained by the ACCD ring which has near zero CTE, developing tensile stress within the test specimen. Four samples were tested at the same time as shown in Figure B.2. Cooling rate of 10°C/hr was used throughout the study.

Figure B.2. ACCD Test Setup

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 B.3. 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 B.4). 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 study. 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. Averaged rut depth values for three APA samples are reported in this study.

Figure B.3. Asphalt Pavement Analyzer

Figure B.4. Repeated Wheel Loading in the APA Device