Analysis of Aramid Synthetic Fibers in Asphalt Mixes on Local Roads

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16. Abstract

This report summarizes the results of a research project that was conducted to evaluate the cracking resistance of aramid fiber-reinforced asphalt mixes used for resurfacing applications on local roads and compare it to that of polymer-modified asphalt mixes. This project was divided into two phases. Based on the results of laboratory study in Phase 1, fifteen test sections were constructed during 2020 construction season as part of five projects in the City of Columbus, Fayette County, and the City of Kettering. Two aramid fiber types, one with 0.75 in. (Fiber B) and the other 1.5 in. length (Fiber A) from different sources, were used for this project. During the construction of the test sections, loose asphalt mixtures and field cores were collected for evaluation in the laboratory using semi-circular bend (SCB), indirect tensile asphalt cracking test (IDEAL-CT), and asphalt concrete cracking device (ACCD). The results of laboratory tests conducted on field cores and field-produced laboratory compacted samples indicated that the effects of addition of aramid fiber to asphalt mixture vary depending on binder grade, binder type, and mix type. In general, Fiber A and Fiber B improved the cracking resistance of mixes with PG 64-22. Mixes with PG 64-22 binder and aramid fibers had similar cracking resistance to those with PG 70-22M asphalt mix. Fiber A improved the cracking resistance for mixes with PG 58-28 binder. In addition, Fiber B improved the indirect tensile strength for mixes with PG 58-28 and had similar cracking resistance as those with PG 64-22. The fibers did not improve the low-temperature cracking resistance of asphalt mixes. The statistical analysis of the test results indicated that the properties related to the cracking resistance of the fiber mixes did not significantly change during the different production days.

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Executive Summary

This report summarizes the results of a research project that was conducted to evaluate fiber-reinforced asphalt mixes used for resurfacing applications on local roads and compare it to that of polymer-modified asphalt mixes. This project was divided into two phases. The results of laboratory tests conducted in Phase 1 of this project indicated that, for short length (0.75 in.) aramid fibers, unmodified PG 64-22 Type 1 surface mix meeting the City of Columbus specifications for Item 441 for medium traffic with Fiber B (a blend of aramid and polyolefin fibers) showed much higher cracking resistance as measured by SCB, IDEAL-CT, and Overlay Tester than mixes with unmodified PG 64-22 binder, polymer modified 70-22M binder, and unmodified PG 64-22 binder with Fiber A (wax treated aramid fiber). In addition, for long length (1.5 in.) aramid fibers, unmodified PG 64-22 asphalt mixes with Fiber A showed much higher cracking resistance as measured by SCB, IDEAL-CT, and Overlay Tester than mixes with unmodified PG 64-22 binder, polymer modified 70-22M binder, and unmodified PG 64-22 binder with aramid Fiber B. Doubling the recommended dosage by the fiber suppliers resulted in, in many cases, asphalt mixes with significantly reduced cracking resistance. All aramid fiber reinforced unmodified PG 64-22 mixes showed satisfactory resistance to rutting and moisture damage in HWT tests. Phase 1 results indicated that the optimum aramid fiber formulation for cracking resistant asphalt mixes for Fiber A was 1.5 in. length and the supplier recommended dosage. In addition, the optimum formulation for Fiber B was 0.75 in. length and the supplier recommended dosage.

Based on the results of Phase 1, Phase 2 of this project involved constructing fifteen test sections as part of five projects in the City of Columbus, Fayette County, and the City of Kettering. During the construction of the test sections, loose asphalt mixtures and field cores were collected for evaluation in the laboratory using semi-circular bend (SCB), indirect tensile asphalt cracking test (IDEAL-CT), and asphalt concrete cracking device (ACCD). The results of laboratory tests conducted on field cores and field-produced laboratory compacted samples indicated that the effects of addition of aramid fiber to asphalt mixture vary depending on binder grade, binder type, and mix type. In general, Fiber A and Fiber B improved the cracking resistance of mixes with PG 64-22. Mixes with PG 64-22 binder and aramid fibers had similar cracking resistance to those with PG 70-22M asphalt mix. Fiber A improved the cracking resistance for mixes with PG 58-28 binder. In addition, Fiber B improved the indirect tensile strength for mixes with PG 58-28 and had similar cracking resistance as those with PG 64-22. The results of the ACCD tests indicated that both fibers did not improve the low-temperature cracking resistance of asphalt mixes. The statistical analysis of the test results indicated that the properties related to the cracking resistance of the fiber mixes did not significantly change during the different production days.

1. Project Background

Over the past three decades, polymer-modified asphalt binders have been used in the United States to enhance the performance and service life of asphalt pavements and overlays. Polymer-modified binders have higher stiffness and elasticity as well as better adhesion to the aggregate particles than unmodified binders (*1*). Therefore, polymer-modified binders can enhance the resistance of asphalt mixtures to rutting, cracking, and moisture-induced damage. Previous studies have shown that the use of polymer-modified asphalt mixes instead of unmodified asphalt mixes can improve the performance and subsequently increase the service life of asphalt overlays by up to 6 years (*1*). Although polymer-modified asphalt mixes have several advantages, they are more expensive than those produced with unmodified (neat) asphalt binders. In addition, local public agencies (LPAs) typically requires that the pavement surface and the air temperature are at least 50°F for placing a surface course with a polymer-modified asphalt binder. Most LPAs as well as the Ohio Department of Transportation (ODOT) do not allow paving with polymer-modified asphalt mixes after November 1 (*2*). These requirements limit the time polymer asphalt mixes can be used in the construction season resulting in an increased unpredictability to construction schedules, which can result in additional costs to bid items associated with polymer-modified asphalt placement. Therefore, the use of polymer-modified asphalt mixes by LPAs is typically limited to roads with relatively high truck traffic volumes and/or heavy loads.

Asphalt overlay is a common technique used by transportation agencies in Ohio for rehabilitation of structurally or functionally deteriorated roads. One of the main types of distresses that develop in overlays is reflection cracking. This type of cracking develops in an asphalt overlay over an existing crack or joint. Several types of treatments have been proposed and used to control or delay reflection cracking (*3, 4*). One of the most common approaches used by LPAs in Ohio is to install a stress-absorbing membrane interlayer (SAMI) between the existing old pavement and the new overlay. SAMI consists of a highly polymerized asphalt emulsion and a quality crushed aggregate that is installed much like a chip seal. SAMI is used to reduce the tensile stress in the overlay in the vicinity of a crack in the underlying old layer (*4*). The use of SAMI results in an increase in a project cost and duration as it requires more time for its application and curing. Furthermore, the SAMI's effectiveness is still not well quantified to date (*4*).

Different technologies have been developed and used to enhance the resistance of asphalt mixes to different types of distresses in new flexible pavements and overlays. One of these technologies is the use of fibers. ODOT has Supplemental Specification 826 for the use of fibers in asphalt mixes *(*5*)*. This specification allows the use of different types of fibers in asphalt mixes: polyester, polypropylene, and aramid. The aramid fibers are heat-resistant fibers that have a much higher tensile strength than the other two types of fibers. They are mixed with fibrillated polyolefin fibers or wax coated to ensure proper distribution within the mix. Over the last decade, there has been an increased interest in using aramid fibers to enhance the performance of asphalt mixes as they have been shown to enhance the rutting and cracking resistance of the asphalt mixtures (e.g.6-8*)*. In addition, aramid fibers can help in absorbing the tensile stresses in an asphalt overlay. Therefore, they can potentially be used to control and/or delay the development of reflection cracking in an overlay; thus, eliminating the need for the SAMI. This can reduce the cost of resurfacing projects in LPAs that use SAMI. One of the advantages of non-polymer modified aramid fiber-reinforced asphalt mixes is that they can be placed at temperatures as low as 40ºF (instead of 50ºF for polymer-modified asphalt mixes). In addition, fibers can be easily included in an asphalt mixture during production in both batch and drum plants without the need to modify the binder at the terminal as in the case with some polymer modified asphalt binders.

Despite the potential benefits for the use of aramid fibers in asphalt mixes, limited information is available on the field performance of aramid fiber-reinforced asphalt mixes as overlays on local roads. Furthermore, no research has been conducted to compare their effectiveness in reducing the reflection cracking to that of the SAMI. Therefore, research is needed to evaluate the cost-effectiveness of using non-polymer modified aramid fiber-reinforced asphalt mixes on local roads. The proposed projects to assess the performance of non-polymer-modified aramid fiber-reinforced asphalt mixes used on local roads and compare it to that of polymer-modified asphalt mixes. Furthermore, this project is also to compare the performance and life cycle costs of overlays constructed using non-polymer-modified fiber-reinforced asphalt mixes without a SAMI to those constructed with non-fiber-reinforced mixes (both polymer-modified and non-polymer-modified) with the use of a SAMI. In addition, the proposed project is to develop recommendations for designing a cost-effective non-polymer-modified aramid fiber-reinforced asphalt mixes that can reduce cracking and rutting on local roads.

2. Research Context

The main goal of this study is to evaluate the rutting and cracking resistance of non-polymer-modified aramid fiber-reinforced asphalt mixes used for resurfacing applications on local roads and compare it to that of polymer-modified asphalt mixes. Another objective of this study is to compare the performance of non-polymer-modified fiber-reinforced asphalt mixes without the use of SAMI to non-fiber-reinforced mixes (both polymer-modified and non-polymer-modified) with the use of SAMI to control reflection cracking. The specific objectives of this project include:

- Identify the optimal aramid fiber dosage for use in non-polymer-modified mixes to reduce the rutting and cracking of surface course layers on local roads.
- Provide recommendations for designing cost-effective non-polymer-modified aramid fiber-reinforced asphalt mixes that can reduce cracking and rutting on local roadways.

Phase 1 and 2 of this study included conducting the following tasks to achieve the outlined objectives:

Phase 1
Task 1. Perform Literature Review
Task 2: Develop Laboratory Testing Plan
Task 3: Evaluate Previously Constructed Test Section with Fiber-Reinforced Asphalt Mix Projects in Columbus
Task 4: Conduct Laboratory Testing Plan
Task 5: Conduct Cost-Benefit Analysis
Task 6. Design a Study for Field and Laboratory Testing in Phase 2
Task 7. Prepare and Submit Interim Report

Phase 2
Task 8. Construction of Pavement Test Sections
Task 9. Lab Testing of Field Samples
Task 10. Perform a Field Evaluation of Test Sections
Task 11. Prepare a Final Report and present Findings

3. Research Approach

A laboratory testing program was conducted in Phase 1 to evaluate the rutting and cracking resistance of non-polymer-modified aramid fiber-reinforced Type 1 surface mixes used for resurfacing applications on local roads and compare them to that of polymer-modified asphalt mixes. To determine the factors affecting the performance of aramid fiber reinforced asphalt mixes, a laboratory test plan was developed. The test plan included two types of aramid fibers (Fiber A: wax treated aramid fibers and Fiber B: a blend of aramid and polyolefin fibers), two fiber lengths (0.75 in. and 1.5 in.), and two dosage levels (one time and two times of suppliers' recommended dosage). This 2 x 2 x 2 laboratory factorial design was performed using PG 64-22 unmodified binder and an asphalt mix design commonly used by LPA. Additional tests were performed using PG 70-22M polymer modified and PG 58-28 binders with few selected aramid fiber length and dosage. Cracking resistance of asphalt mixes were evaluated using semi-circular bend (SCB) test, IDEAL-CT, and Overlay Tester. Rutting resistance and moisture resistance were evaluated using Hamburg Wheel Tracking (HWT) test. The asphalt concrete cracking device (ACCD) was used to determine the low temperature cracking resistance.

The results of laboratory test conducted in Phase 1 indicated that, for short length (0.75 in.) aramid fibers, unmodified PG 64-22 asphalt mixes with Fiber B (a blend of aramid and polyolefin fibers) showed much higher cracking resistance as measured by SCB, IDEAL-CT, and Overlay Tester than mixes with unmodified PG 64-22 binder, polymer modified 70-22M binder, and unmodified PG 64-22 binder with Fiber A (wax treated aramid fiber). In addition, for long length (1.5 in.) aramid fibers, unmodified PG 64-22 asphalt mixes with Fiber A showed much higher cracking resistance as measured by SCB, IDEAL-CT, and Overlay Tester than mixes with unmodified PG 64-22 binder, polymer modified 70-22M binder, and unmodified PG 64-22 binder with aramid Fiber B. Doubling the recommended dosage by the fiber suppliers resulted in, in many cases, asphalt mixes with significantly reduced cracking resistance. All aramid fiber reinforced unmodified PG 64-22 mixes showed satisfactory resistance to rutting and moisture damage in HWT tests. PG 58-28 binder mixes with or without aramid fibers showed the highest cracking resistance among mixes tested. However, their resistance to rutting and moisture damage were significantly lower than other mixes. The optimum aramid fiber formulation for cracking resistant asphalt mixes for Type A aramid fiber was 1.5 in. length and the supplier recommended dosage. The optimum formulation for Type B aramid fiber was 0.75 in. length and the supplier recommended dosage.

The fatigue life of unmodified PG 64-22 mixes that was estimated based on the laboratory tests was found to be improved due to the addition of Fiber A and Fiber B. In addition, the life cycle cost analysis based on the estimated fatigue life of the overlay showed that the unmodified PG 64-22 mix with Fiber A and Fiber B could be less expensive than the unmodified PG 64-22 mix and the polymer modified PG 70-22M mix.

Based on the results of Phase 1, it was recommended to conduct a field study aimed at comparing the performance of the recommended non-polymer mixtures reinforced with Fiber A with length of 1.5 in. and non-polymer mixtures reinforced with Fiber B with length of 0.75 in. An aramid fiber dosage of 2.1 oz per ton of mix should be used for both types, i.e. 4.2 oz. total weight of Fiber A per ton of mix and 16 oz Fiber B per ton of mix. The field study should also compare the performance of non-polymer aramid fiber reinforced mixtures to those with polymer modified PG 70-22M binder. In addition, Phase 2 should compare the field performance under different conditions of existing pavement of sections with non-polymer aramid fiber reinforced mixture to those with SAMI and asphalt mixes with non-polymer and polymer modified binders.

3.1 Testing Program

3.1.1 Description of Field Test Sections

Fifteen test sections were constructed in five resurfacing projects: three projects were in the City of Columbus, one project in Fayette County, and the last project in the City of Kettering as part of a resurfacing project to evaluate the performance of the mixes with different synthetic aramid fiber sources designed based on the method recommended in Phase 1 of this study. First project involved constructing an asphalt overlay on arterial road. The test sections for this project were located on W North Broadway Street between Kenny Road and Olentangy River Road. For test sections in this project, a 2-in Type 1 surface mix meeting the City of Columbus specifications for Item 441 for medium traffic was placed after milling 2-inches of the existing pavement, and the construction was done in July 2020. The second project involved constructing an asphalt overlay on top of concrete pavement with one of the sections having Stress Absorbing Membrane Interlayer (SAMI). This project was located northside Columbus area. For the test sections in this project, a 1½-in. asphalt Type 1 surface course mix was placed and the construction was done in September 2020. The third project involved constructing an asphalt overlay on top of brick road with one of the sections having (SAMI) layer. This project was located in Columbus downtown area. For the test sections in this project, a 1½-in asphalt concrete surface course was placed and the construction was completed early November 2020.

The fourth project was located in the Fayette County on Bloomingburg New Holland Road NW (CR 27) between CR 25 and SR 38. For test sections in this project, a 1-in. asphalt concrete surface course was placed after milling 1 inch of the existing pavement and the construction was done in August 2020.

The fifth project was located in the City of Kettering on Wilmington Pike between E Stroop Road and Arrowhead Drive. The surface course asphalt mixtures were Marshall mixes and had a similar aggregate blend and the two aramid fiber types. For test sections in this project, 2 inches of existing pavement were milled and replaced by a 2-in asphalt concrete surface course and the construction was completed in September 2020.

In the first Columbus project, similar aggregate blend was selected for all test sections. The control mix did not contain fiber and produced with a stiffer polymer modified binder (PG 70-22M). The two other mixes were produced with Fiber A and Fiber B using a softer binder (PG 64-22). In the second and third Columbus projects, similar aggregate blend was used for all test sections with one asphalt binder (PG 64-22). The control mix in each project did not have fiber but SAMI layers were placed on the old Portland Cement Concrete or old brick road before placing the asphalt overlays. The two other mixes were produced with Fiber A and Fiber B and placed as companion sections.

In the fourth project at Fayette County, similar aggregate blend was used for all three mixes with soft asphalt binder (PG 58-22). The control mix did not contain fiber and the other two mixes were produced with Fiber A and Fiber B. It is noted that the asphalt mixture used in this project met specifications for 404-low volume traffic mixes.

In the fifth project at City of Kettering, similar aggregate blend was used for all asphalt mixes. The control mix was produced with a stiffer polymer modified binder (PG 70-22M) without fiber. The other two mixes were produced with Fiber A and Fiber B separately using a soft binder (PG 64-22). It is noted that the asphalt mixture used in this project met the City of Kettering specifications for Item 441 for medium traffic.

3.1.2 Field Test Section Construction

A meeting with the LPA personnel and representatives of the asphalt paving contractors for each project was held prior to the construction of the test sections to coordinate the construction activities. The existing pavements within the test sections were evaluated prior to construction to identify distressed or repaired areas. Coring locations were identified after milling and were marked to avoid collecting field cores from the distressed areas. Videos and pictures were taken after milling of the existing pavements. The research team also monitored the placement and compaction of the test sections in all project locations. This included measuring the mat temperature and recording the density at core locations. Photos were taken and videos of the test sections were recorded during and after the construction.

3.1.3 Laboratory Testing of Cores Samples

Cores were obtained at different locations within the test sections in Columbus arterial project and the city of Kettering project. In addition, loose asphalt mixture samples were obtained at the asphalt plant for each mixture used in the test sections in each project. Specimens of the loose mixtures were compacted in the laboratory using Superpave Gyratory Compactor to achieve target air voids of 7.0 ± 0.5%. Laboratory tests were conducted on the core and lab-compacted specimens. To this end, the propensity of the cores and lab-compacted specimens to fatigue cracking was evaluated using the semi-circular bend (SCB) and the indirect tensile asphalt cracking test (IDEAL-CT) tests. In addition, the low-temperature cracking potential was assessed using the asphalt concrete cracking device (ACCD). A detailed description of each of the tests is provided in Appendix A.

3.2 Field Evaluation of Constructed Test Sections

The performance of each of constructed test sections was evaluated every three months for the first six months after construction. The periodic field evaluations included an assessment of the pavement condition with regard to the various pavement distresses encountered during the evaluations and the corresponding extent and severity level for each distress. Photographs were also taken during the periodic field evaluations to document the presence, extent, and severity of the pavement distresses

4. Research Findings and Conclusions

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

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

- The results of laboratory tests conducted on field-produced laboratory compacted samples indicated that Fiber A and Fiber B improved the cracking resistance of mixes with PG 64-22.
- The results of SCB tests on field-produced laboratory compacted samples indicated that mixes with PG 64-22 binder and aramid fibers had lower cracking resistance as compared to those with PG 70-22M binder used in the City Columbus test sections. However, mixes with PG 64-22 binder and aramid fibers had similar or higher cracking resistance as compared to those with PG 70-22M binder used in the City of Kettering test sections.

- The results of IDEAL-CT tests on field-produced laboratory compacted samples indicated that mixes with PG 64-22 binder and aramid fibers had similar or higher cracking resistance as compared to those with PG 70-22M binder.
- The results of laboratory tests indicated that Fiber A improved the cracking resistance for mixes with PG 58-28. In addition, Fiber B improved the indirect tensile strength for mixes with PG 58-28 and had similar cracking resistance as those with PG 64-22.
- The results of ACCD tests indicated that the fibers did not improve the low-temperature cracking resistance of asphalt mixes. The low-temperature cracking resistance appears to be mostly affected by the base binder.
- The results from laboratory tests and statistical analysis indicated that the properties related to the cracking resistance of the fiber mixes did not significantly change during the different production days. This may suggest that aramid fibers had the same distribution in the mix during production.
- The overlay test was used to evaluate the reflective cracking of core samples obtained from test sections with fiber mixes and compare them to those obtained from a section with SAMI. However, no conclusion can be made as the crack prorogated during the test laterally rather than vertically, which typically does not occur in the overlay tester. This might be attributed to the weak plane that developed at the interface between the concrete and overlay layers. Field evaluation of the test sections constructed in this study should be used to make the final conclusions about the effectiveness of fiber mixes to control reflective cracking as compared to the SAMI layer.

5. Recommendations for Implementation

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

- The initial performance of the all test sections was evaluated and documented in this report; however, it is recommended to monitor the long-term performance of these sections. To this end, it is recommended that the sections be evaluated annually for a minimum of five years after construction. The long-term evaluation data should be used to make final conclusions about the cost-effectiveness of fiber mixes for local roads and to validate the results of the laboratory tests conducted in this study.
- Future research is needed to develop a laboratory testing procedure to evaluate the effectiveness of using a SAMI layer between the existing old pavement and the new overlay.
- The results of laboratory tests conducted in this study indicated that the addition of aramid fibers (Fiber A and Fiber B) improved the cracking resistance of mixes with PG 64-22 binder compared to a PG 64-22 mix without the fibers. Therefore, it is recommended that local public agencies conduct pilot studies to further investigate the use of aramid fibers in asphalt mixes on local roads and validate the results of this study.

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Appendix A Testing Program

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

A.1 Test Sections Description

Fifteen test sections were constructed in five resurfacing projects in Ohio to evaluate the performance of the mixes with different synthetic aramid fiber sources designed based on the method recommended in Phase 1 of this study. Three projects were located in the City of Columbus, one project in Fayette County, and the last project in the City of Kettering. The locations of those projects are shown in Figure A.1.

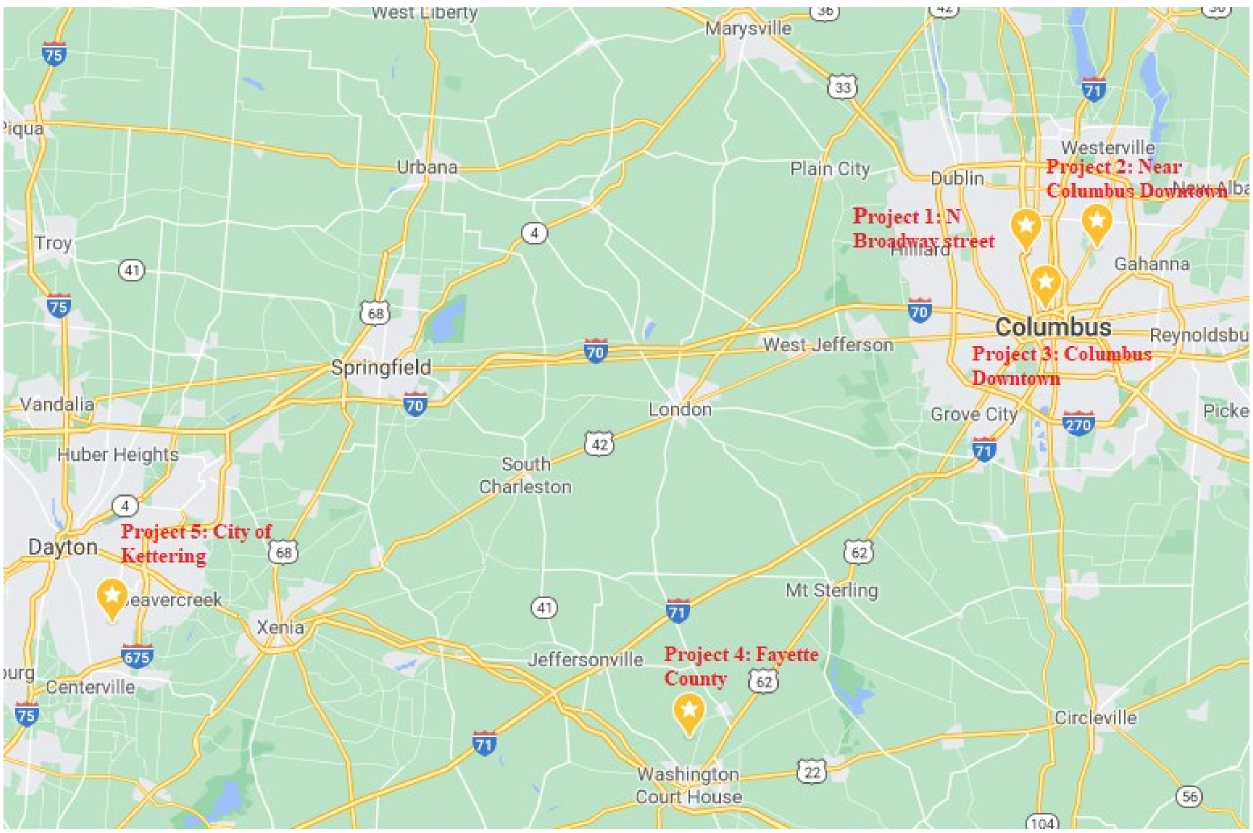

Figure A.1: Location of each resurfacing project considered in this study (Google Maps, 2021).

A.1.1 City of Columbus Projects

Figures A.2 to A.4 present a map of the test sections location in each project constructed in Columbus, Ohio. As shown in Figure A.2, the test sections for the first project were located in Columbus on W North Broadway street between Kenny Road and Olentangy River Road. Table A.1 shows the exact locations of each test section. In all test sections, a 2 in. asphalt concrete surface course was placed. The surface course asphalt mixtures were Marshall mixtures with a 12.5 mm nominal maximum aggregate size (NMAS) and had the same aggregate blend, which consisted of No. 8 gravel/limestone aggregates, natural sand, limestone sand and 20% RAP. The control mix did not include aramid fiber and was produced with a stiff polymer modified binder (PG 70-22M). The other two mixes for companion test sections were produced with a neat binder PG 64-22 using one of two types of aramid fibers; Fiber A (wax treated aramid fibers) and Fiber B (a blend of aramid and polyolefin fibers). The length and dose of the aramid fibers were based on recommendations of Phase 1 of this study.

As shown in Figure A.3, the test sections of the second Columbus project were located northeast part of Columbus. Table A.2 shows the exact locations of each test section. In all test sections, a 1-½ in asphalt concrete surface course was placed. The surface course asphalt mixtures were Marshall mixtures with a 12.5 mm NMAS and had the same aggregate blend, which consisted of No. 8 gravel/limestone aggregates, natural sand, limestone sand and 20% RAP. One asphalt binder grade (PG 64-22) was used for all sections. The control mix did not contain aramid fiber and was placed on SAMI layer constructed on the old Portland cement concrete road. The two other mixes were produced with Fiber A or Fiber B using PG 64-22 binder and were placed without SAMI. Figure A.4 shows the test sections of the third Columbus project located in the Columbus downtown area. Table A.3 shows the locations of each test section. In all test sections, a 1-½ in asphalt concrete surface course was placed. The surface course asphalt mixtures were Marshall mixtures with a 12.5 mm nominal maximum aggregate size (NMAS) and had the same aggregate blend, which consisted of No. 8 gravel/limestone aggregates, natural sand, limestone sand and 20% RAP. One asphalt binder grade (PG 64-22) was used. The control mix did not contain aramid fiber and was placed on SAMI layer constructed on the old brick road. The two other mixes were produced with aramid Fiber A or aramid Fiber B using PG 64-22 binder were placed without SAMI.

A.1.2 Fayette County Test Sections

As shown in Figure A.5, the test sections for this project were located in Fayette county on Bloomingburg New Holland Road NW (CR 27) between CR 25 and old SR 38. Table A.4 shows the exact locations of each test section. In all test sections, a 1 in. asphalt concrete surface course was placed. The surface course asphalt mixtures were 404-Low Volume Traffic (LVT) mixes and had the same aggregate blend, which consisted of No. 8 limestone aggregates, natural sand, and 10% RAP. One soft asphalt binder (PG 58-22) was used for all sections. The control mix did not contain aramid fiber. The two other mixes were produced with Fiber A or Fiber B. The length and dose of these fibers were based on recommendations of Phase 1 of this study.

A.1.3 City of Kettering Test Sections

As shown in Figure A.6, the test sections for this project were located in the City of Kettering on Wilmington Pike between E Stroop Road and Arrowhead Drive. Table A.5 shows the exact locations of each test section. In all test sections, a 1.5 in. asphalt concrete surface course was placed. The surface course asphalt mixtures were Marshall mixtures with a 9.5 mm NMAS and had the same aggregate blend, which consisted of No. 8 gravel aggregates, natural sand, limestone sand and 10% RAP. The control mix was produced without aramid fiber using a stiffer polymer modified binder (PG 70-22M). The two other mixes were produced with Fiber A or Fiber B using a softer binder (PG 64-22). It is noted that the length and dose of the two fibers were based on recommendations of Phase 1 of this study.

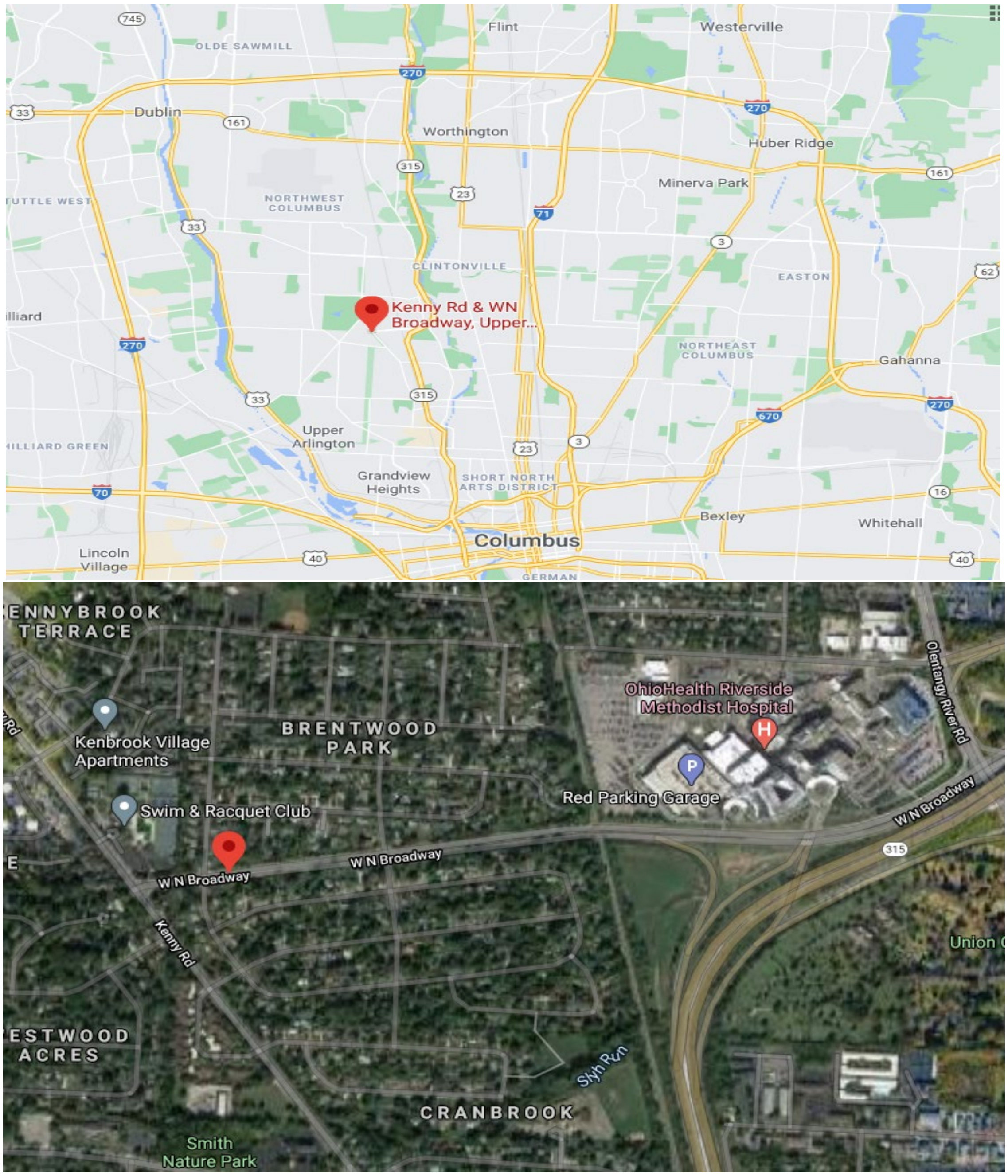

Figure A.2 Location of Test Sections in the City of Columbus – Project 1 (Google Maps, 2021).

Table A.1 Location of Test Sections in the City of Columbus – W North Broadway Street

Section	**Start**	**End**	**Lane**
Control (PG 70-22M)	Kenny Road	Olentangy River Road	Inner lane
Control (PG 70-22M)	Olentangy River Road	Kenny Road	Inner lane
Fiber A (PG 64-22)	Olentangy River Road	Kenny Road	Outer lane
Fiber B (PG 64-22)	Kenny Road	Olentangy River Road	Outer lane

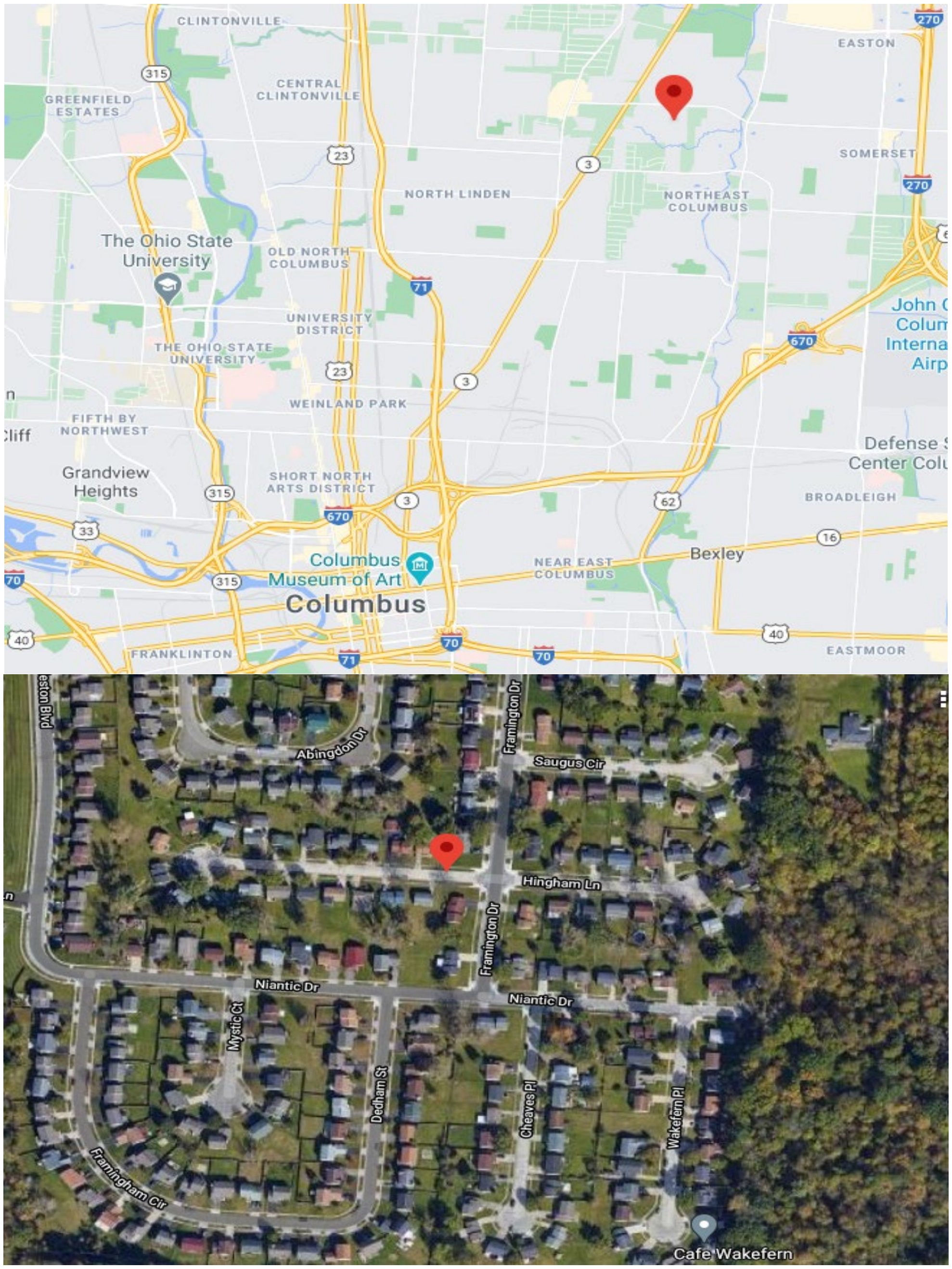

Figure A.3 Location of Test Sections in the City of Columbus – Project 2 (Google Maps, 2021).

Table A.2 Location of Test Sections in Columbus

Section	**Street Name**	**Direction**
Control (PG 64-22)	Hingham Lane	Both lanes (Westside)
Fiber A (PG 64-22)	Wakefern place	Both lanes
Fiber B (PG 64-22)	Cheaves place	Both lanes

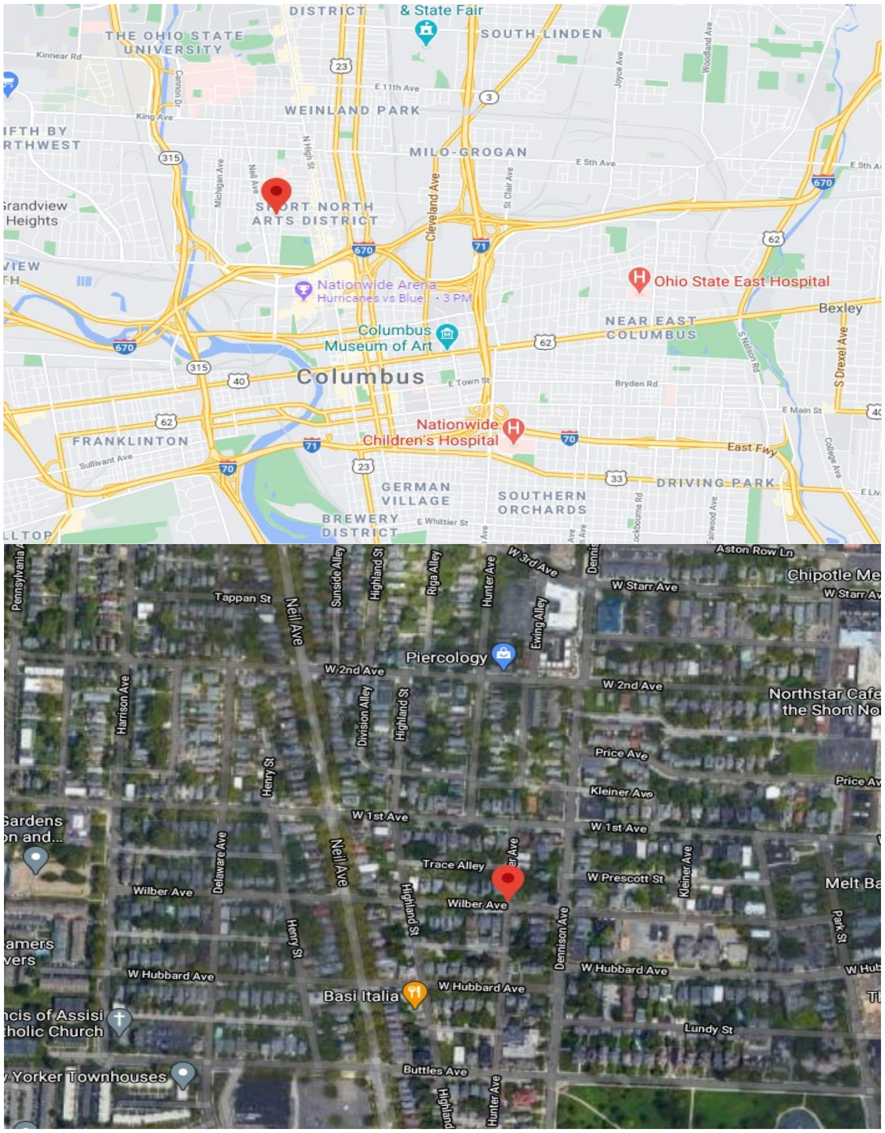

Figure A.4 Location of Test Sections in the City of Columbus – Project 3 (Google Maps, 2021).

Table A.3 Location of Test Sections in Columbus Project 3

Section	Street Name	Start	End
Control (PG 64-22)	Wilber Avenue	Dennison Avenue	Harrison Avenue
Control (PG 64-22)	W. Hubbard Avenue	High St.	Dennison Avenue
Control (PG 64-22)	2nd Avenue	High St.	Neil Avenue
Fiber A (PG 64-22)	2nd Avenue	Dennison Avenue	High St.
Fiber A (PG 64-22)	W. Hubbard Avenue	Dennison Avenue	High St.
Fiber A (PG 64-22)	Dennison Avenue	2nd Avenue	Aston Row Ln.
Fiber A (PG 64-22)	3rd Avenue	Aston Row Ln.	High St.
Fiber B (PG 64-22)	Wilber Avenue	Harrison Avenue	Dennison Avenue
Fiber B (PG 64-22)	Dennison Avenue	Buttles Avenue	2nd Avenue
Fiber B (PG 64-22)	2nd Avenue	Neil Avenue	Dennison Avenue

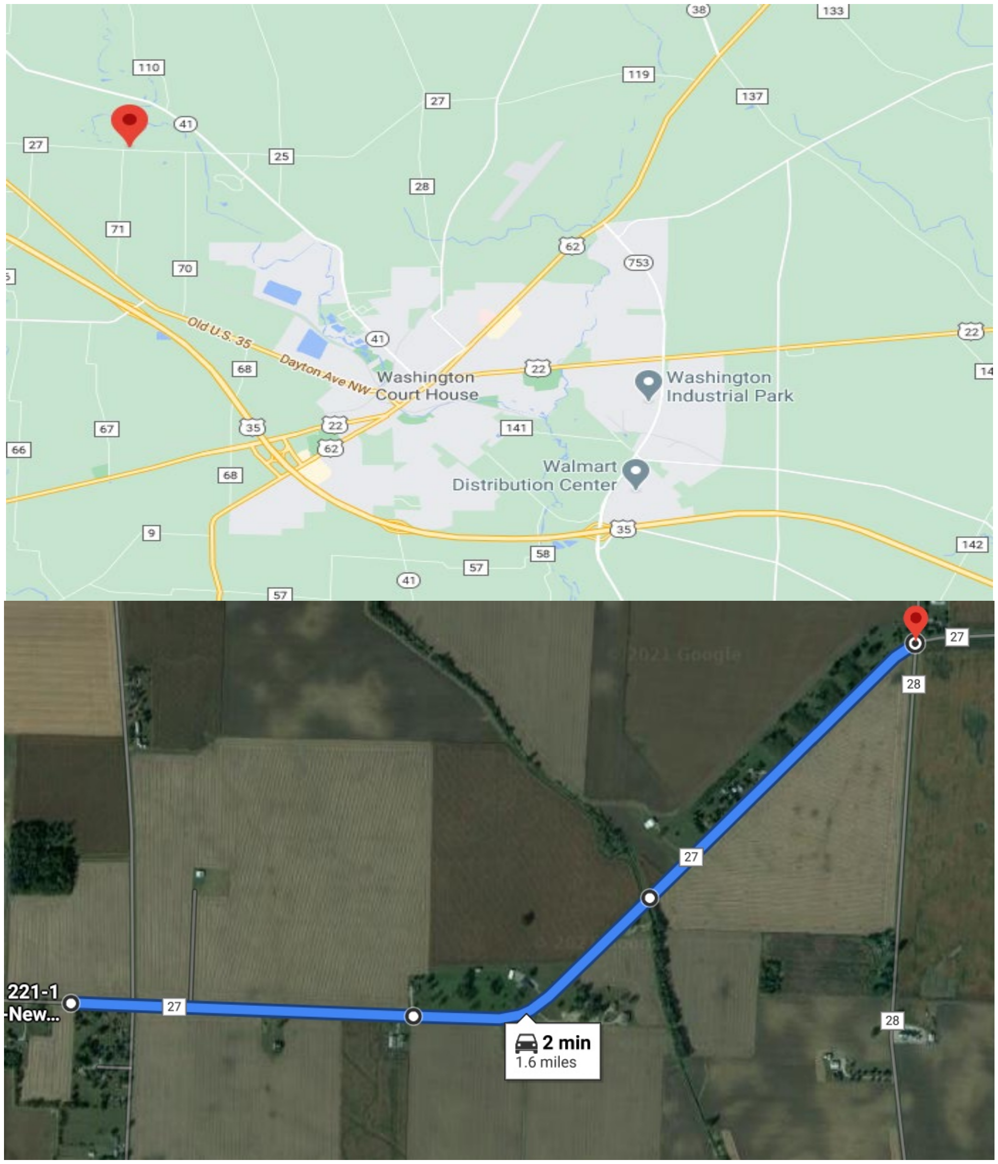

Figure A.5 Location of Test Sections in Fayette County (Google Maps, 2021).

Table A.4 Location of Test Sections in Fayette county

Section	**Start**	**End**	**Direction**
Control (PG 58-28)	200 ft West of CR 25	2700 ft East of CR 25	Both Lanes
Fiber A (PG 58-28)	2700 ft East of CR 25	5300 ft East of CR 25	Both Lanes
Fiber B (PG 58-28)	5300 ft East of CR 25	CR 28	Both Lanes

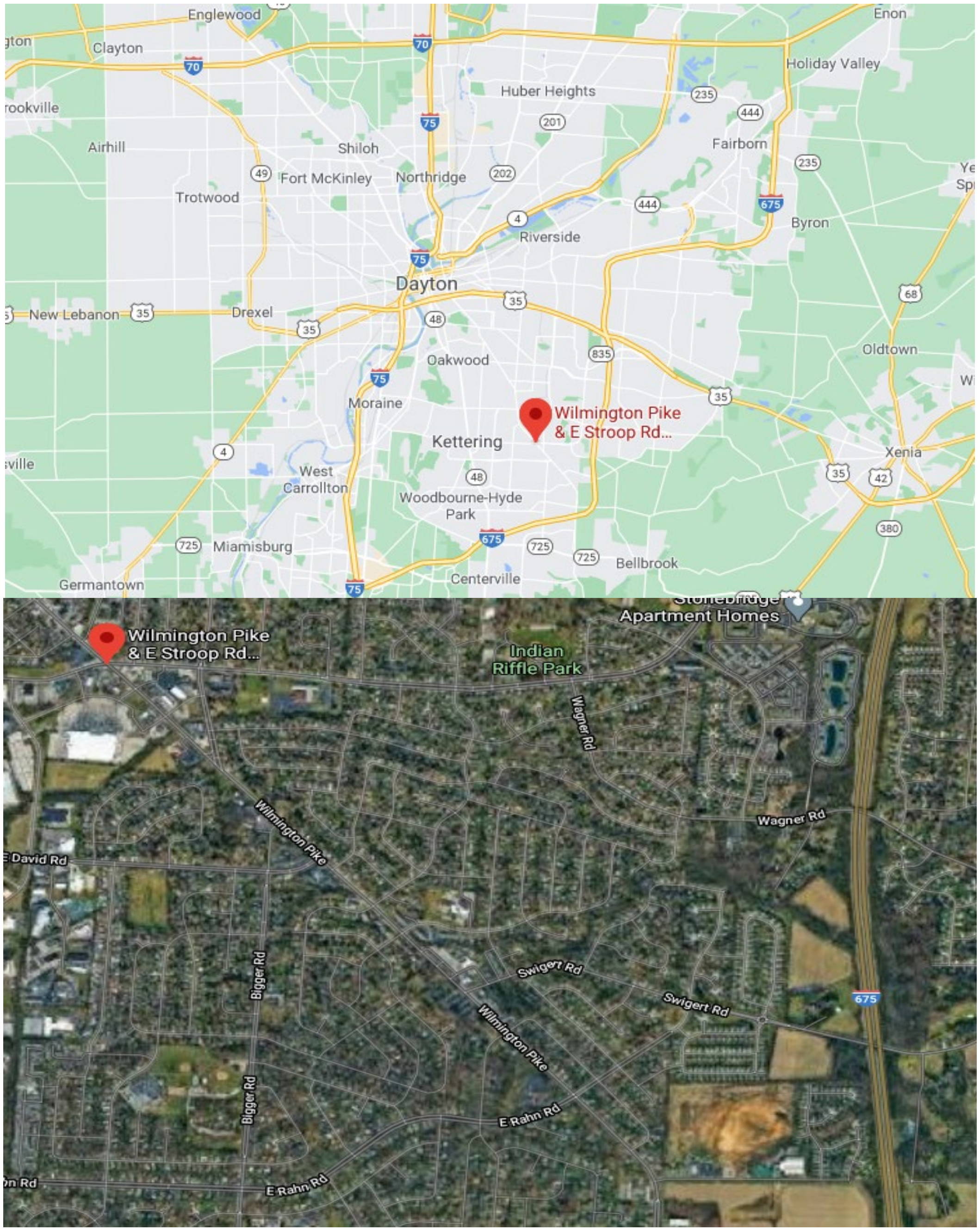

Figure A.6 Location of Test Sections in The City of Kettering (Google Maps, 2021).

Table A.5 Location of Test Sections in the city of Kettering – Wilmington Pike

Section	**Start**	**End**	**Lane**
Control (PG 70-22M)	Arrowhead Drive	Woodman Drive	Outer lane (curb lane)
Fiber A (PG 64-22)	Glenheath Drive	Arrowhead Drive	Outer lane (curb lane)
Fiber B (PG 64-22)	E Stroop Road	Glenheath Drive	Outer lane (curb lane)

A.2 Test Sections Construction

A meeting with LPA personnel and representatives of the asphalt paving contractors for each project was held prior to the construction of the test sections to coordinate the construction activities. During each meeting, an overview of the project was provided and the onsite sampling and laboratory testing plans were discussed. In addition, the anticipated start date for paving of the test sections was set.

The existing pavements within the test sections were evaluated prior to construction to identify distressed or repaired areas. Coring locations were identified after milling and were marked to avoid collecting cores from the distressed areas. Videos and pictures were taken after milling the existing pavements. The research team also monitored the placement and compaction of the test sections at all project locations. 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.

A.3.1 Columbus projects construction

Construction of test sections at three locations was completed in July 2020, September 2020, early November 2020, respectively. The research team monitored the placement and compaction of the all test sections. This included measuring the mat temperature and recording the density at core locations. Field density was measured using a PQI 380 asphalt density gauge. Photos were collected and videos of the test sections were recorded during and after construction. Figures A.7-A.9 present some of the photos taken during construction in each project.

A.3.1 Fayette County project construction

The test sections were constructed during August 2020. The research team monitored the placement and compaction of the test sections. This included measuring the mat temperature and recording the field density every 250 ft along each test section after construction. 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.10 presents some of the photos taken during the construction.

A.3.1 City of Kettering project construction

Construction of test sections was completed in September 2020. It should be noted that prior to the construction of surface course, a leveling course was placed at all test sections. The research team monitored the placement and compaction of the test sections. This included measuring the mat temperature and recording the density at core locations. Field density was measured using a PQI 380 asphalt density gauge. Photos were collected and videos of the test sections were recorded during and after construction. Figure A.11 presents some of the photos taken during construction.

Figure A.7 Pictures Taken during Construction of Test Sections in the Columbus Project 1.

Figure A.8 Pictures Taken during Construction of Test Sections in Columbus Project 2.

Figure A.9 Pictures Taken during Construction of Test Sections in Columbus Project 3.

Figure A.10 Pictures Taken during Construction of Test Sections in Fayette County (Project No. 4).

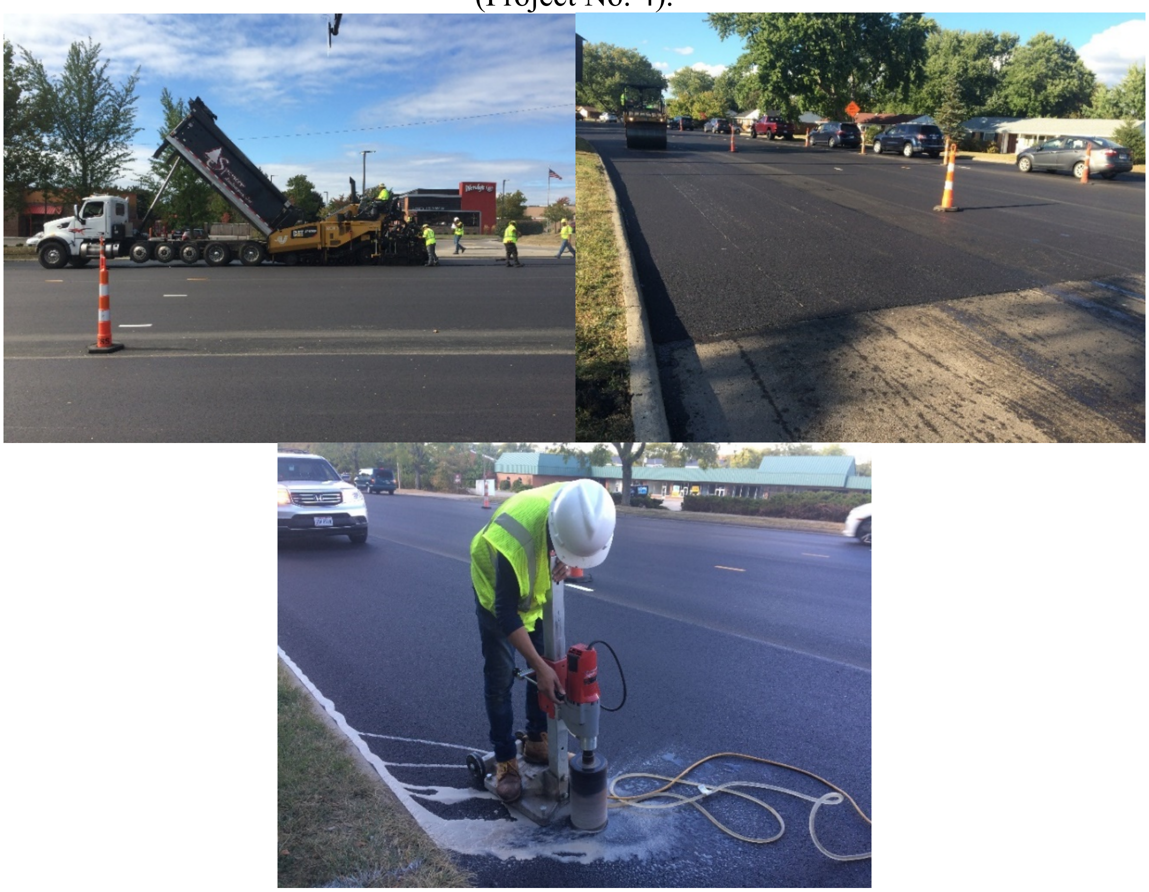

Figure A.11 Pictures Taken during Construction of Test Sections in the City of Kettering (Project No. 5).

A.3 Laborary Testing Program

Cores were obtained at different locations within the test sections. In addition, loose asphalt mixture samples were obtained at the asphalt plant for each mixture used in the test sections. Specimens of the loose mixtures were compacted using a Superpave Gyratory Compactor in the laboratory with target air voids of 7±0.5%. Laboratory tests were conducted on the core and lab-compacted specimens. To this end, the propensity of the cores and lab-compacted specimens to fatigue cracking was evaluated using the semi-circular bend (SCB) and the indirect tensile asphalt cracking test (IDEAL-CT). In addition, the low-temperature cracking potential was assessed using the asphalt concrete cracking device (ACCD). 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 the fatigue cracking performance at an intermediate temperature of 25ºC. The SCB tests were performed according to the Illinois SCB Test Method (AASHTO TP 124-18: *Determining the Fracture Potential of Asphalt Mixtures Using the Illinois Flexibility Index Test (I-FIT)*). In this method, samples with a 150 mm diameter were compacted to a height of 160 mm. Each sample was cut in half and the ends trimmed to obtain a thickness of 50 ± 1 mm. Each 50-mm-thick sample was then cut in half to create the semi-circular shape. A notch with a depth of 15 mm and a width of 2.25 mm was cut into the center of the sample, as shown in Figure A.7. The SCB test was conducted on at least four replicate samples. The SCB test was performed by loading the sample monotonically to failure at a constant crosshead deformation rate of 50 mm/min. All tests were conducted at a temperature of 25 °C. Load and vertical deformation were recorded until failure. An Instrotek© Auto SCB, Figure A.8, was used to conduct all SCB tests.

Figure A.7 Illinois SCB Sample Preparation and Testing Equipment

Figure A.8 Instrotek© Auto SCB Test Equipment

The main output of the SCB is a load versus deformation plot, as shown in Figure A.9. From this plot, the Fracture Energy (FE) and the Flexibility Index (FI) are calculated using 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 premature cracking (*2*). Since the Fracture Energy is a function of the peak load and displacement, Nazzal et al. (*3*) recommended normalizing the fracture energy values based on the peak strength of the mixture. Therefore, the normalized fracture energy (NFE) value (Equation A.3) was used in this study to examine the cracking resistance of the core samples.

$$G_F = \frac{\mathrm{W_f}}{\mathrm{Area_{lig}}} \ \mathrm{x}10^6 \tag{A.1}$$

$$\mathrm{FI} = \frac{\mathrm{G_F}}{|\mathrm{m}|} \ \mathrm{x\,A} \tag{A.2}$$

$$NFE = \frac{G_F}{\sigma_{peak}} \tag{A.3}$$

Where,

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

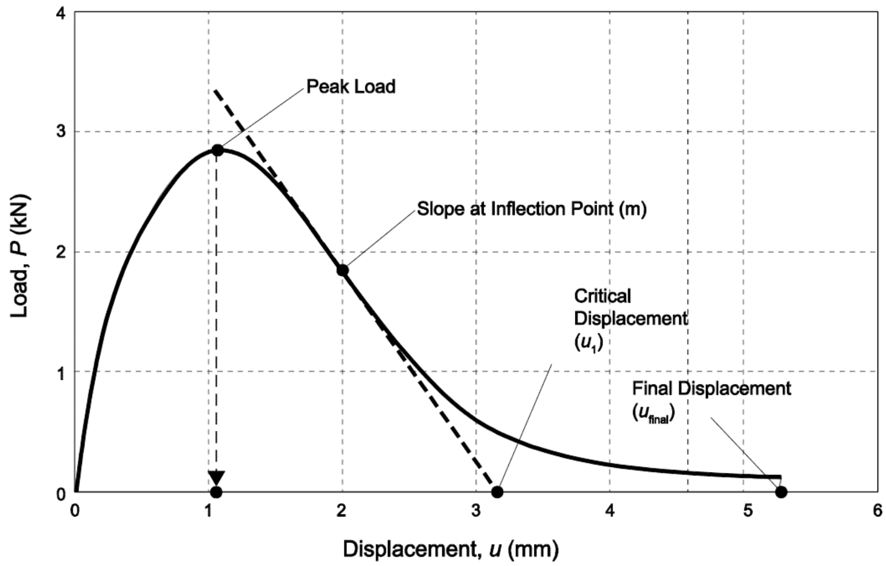

Figure A.9 Plot of Load vs. Displacement Obtained from Illinois SCB Test (*2*)

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

The IDEAL-CT test was developed by Zhou et al. (4). This test is similar to the conventional indirect tensile strength test but with a new procedure proposed by Zhou et al. (4) to analyze the load-displacement curve (Figure A.10) with inspiration from crack propagation laws proposed by Paris and Erdogan (5) and Bazant and Prat (6). Based on this procedure, Equation A.3 can be used to calculate the cracking test index (CTI) which was found to correlate well with the cracking performance of asphalt mixtures in the field.

$$\mathrm{CTI} = \frac{\mathrm{G_f}}{|\mathrm{m_{75}}|} \times \left(\frac{\mathrm{l_{75}}}{\mathrm{D}}\right) \tag{A.4}$$

Where,
G_f: is the work of fracture which is the total area under load – displacement curve
D: is sample diameter (mm).
l_{75}: is displacement corresponding to the 75 percent of the peak load at the post-peak stage.
m_{75}: is slope calculated as shown in Figure A.6 using the following equation:

$$m_{75} = \frac{\mathrm{P_{85}} - \mathrm{P_{65}}}{\mathrm{l_{85}} - \mathrm{l_{65}}} \tag{A.5}$$

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

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

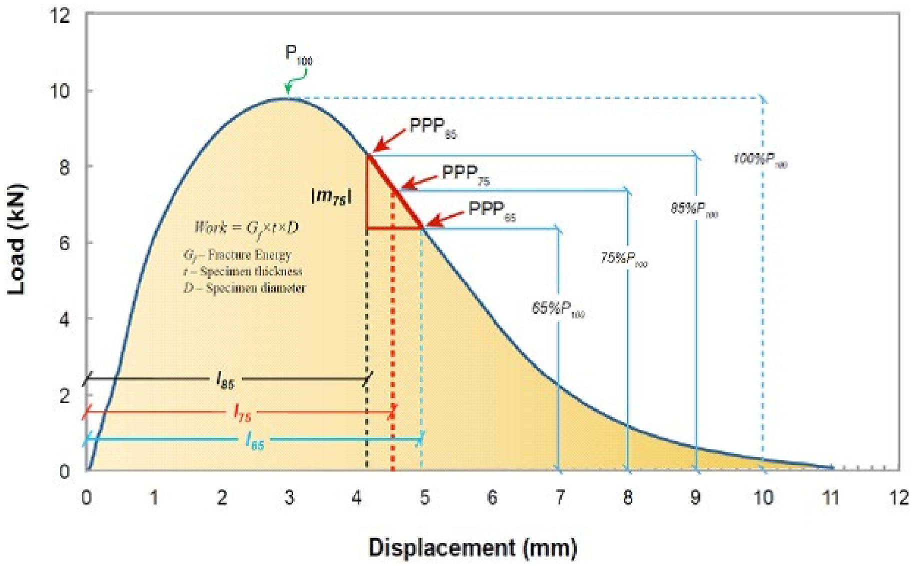

Figure A.10 Illustration of the Slope m_{75} in CTI Calculation *(4)*

A.3.3 Asphalt Concrete Cracking Device (ACCD)

This test was conducted to evaluate the low-temperature cracking resistance of mixtures evaluated in this study. In this test, a 22.4-mm (0.88-inch) long-notch was cut at the outer surface of a 60-mm (2.3-inch) diameter, 2-inch thick (50.8 mm) specimen to control the location of the crack. The test specimen and the ACCD ring were heated for 60 minutes at 65°C, and the tapered end of the heated ACCD ring was placed in the center hole of the heated test sample. The sample with the ACCD ring was placed in an environmental chamber (Figure A.11). As the temperature decreased, the contraction of the asphalt mix specimen was restrained by the ACCD ring, developing tensile stress within the test specimen and compressive stress within the ACCD ring. The temperature and strain of each ACCD ring were continuously recorded until failure. The temperature corresponding to the maximum slope of the ACCD strain-temperature curve was considered as the onset on thermal cracking. The point at which the slope of the strain-temperature curve is equal to eighty percent of the maximum slope after the onset of cracking is defined as the ACCD cracking temperature. The ACCD test was performed on short-term and long-term aged specimens.

Figure A.11 ACCD Test Setup

A.3.3 Overlay Tester (OT)

Overlay tester was initially developed to evaluate the reflection crack resistance of hot mix asphalt (HMA) overlay and also was proposed for characterization of fatigue crack resistance (6). In this study, the overlayer tester was conducted on core samples that were obtained from the City of Columbus project where an asphalt overlay was placed with and without SAMI layer on top of a concrete pavement. As shown in Figure A.12, the core samples included the overlay as well as part of concrete slab below it. In order to test the reflection crack resistance of the samples with and without the SAMI the following steps were pursued:

1. The cores samples were trimmed to produce samples that include the overlay and 1/3 inch of the old concrete pavement.
2. A notch was carefully made at the middle until black SAMI is visible at the cutting surface
3. The concrete surface was glued on OT metal plates.

Figure A.13 pictures of prepared overlay tester sample. As the OT test was conducted at a constant temperature of 25°C. The test involved moving the plate horizontally in a cyclic triangular wave form to a constant displacement of 0.6 mm (0.025 in.). One cycle of OT loading was defined as the sliding block reaches the maximum displacement and returns to its initial position in 10 seconds. The test continues up to 1,000 cycles or the load to when the maximum displacement reduced by 93% in comparison to the maximum load recorded for the first opening cycle.

Figure A.12 Picture of Core Obtained from the City of Columbus Project with an Overlay Placed on Concrete Pavement

Figure A.13 Prepared Overlay Tester Sample.

A.4 Field Evaluation of Constructed Test Sections

The performance of each of constructed test sections was evaluated every three months for the first six months after construction. The periodic field evaluations included an assessment of the pavement condition with regard to the various pavement distresses encountered during the evaluations and the corresponding extent and severity level for each distress. Photographs were also taken during the periodic field evaluations to document the presence, extent, and severity of the pavement distresses

A.5 References

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2- 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.

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

4- Zhou, F., S. Im, L. Sun, and T. Scullion, 2017, "Development of an IDEAL Cracking Test 23 for Asphalt Mix Design and QC/QA", Journal of the Association of Asphalt Paving 24 Technologists (AAPT), Volume

5- Paris, P. and F. Erdogan, 1963, "A Critical Analysis of Crack Propagation Laws", *Journal of* 27 *Basic Engineering, Transactions of the American Society of Mechanical Engineers*, p. 528 – 28 534. 29

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Appendix B Test Results and Data Analysis

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

B.1. Field Density Measurements for Columbus Test Sections

The average relative density for each of the test sections in each project location was measured using the PQI 380 density gauge as presented in Figures B.1 to B.3. For Columbus projects, in general, the control and the other test sections had similar average relative densities of about 92.5% to 93.6%, which indicates that the target density of 93%±1% was achieved. Fiber A test section had slightly higher in-place density values as compared to other sections, as shown in Figure B.1. Similarly, the control and the aramid fiber test sections had similar average relative densities of about 92.5% to 93.6% for Fayette County test sections, which indicates that the target density of 93%±1% was achieved. Fiber A test section had slightly higher in-place density values as compared to other sections, as shown in Figure B.2. City of Kettering field mixes had also acceptable values of in-place density achieving the target density of 93%±1%, Fiber B test section had slightly lower value of in-place density compared to other sections, as shown in Figure B.3.

B.2. Results of Core Sample Testing

The fatigue cracking resistance of core samples obtained from Columbus arterial project and the city of Kettering project at intermediate temperature was assessed by the Semi-Circular Bend (SCB) and/or IDEAL-CT tests. The results of the performance tests are discussed in this section.

B.2.1 SCB Test Results

Cracking resistance of asphalt mixtures were evaluated using two SCB test outcomes; the normalized fracture energy (NFE) and the flexibility index (FI). The higher the NFE or FI value is, the more crack-resistant the mix is.

Figures B.4 and B.5 present the average normalized fracture energy (NFE) and the flexibility index (FI) values of the core samples obtained from test sections in Columbus Project 1 (North Broadway Street) constructed for this study. It is noted that the control mix with polymer modified stiffer binder (PG 70-22M) had significantly higher NFE and FI values as compared to those in the fiber mixes that have softer binder (PG 64-22). However, the difference of NFE and FI values between Fiber A and Fiber B mixes are small and similar. In addition, the general trend depends on the SCB parameters. Fiber B mix had slightly higher NFE value than Fiber A mix. This suggests that Fiber B tends to be more effective in improving the fatigue cracking resistance of the mix with PG 64-22 binder than Fiber A when compared with NFE values. However, Fiber A mix had slightly higher FI value than Fiber B mix. This suggests that Fiber A is slightly more effective in improving the fatigue cracking resistance of the mix than Fiber B, when compared with FI value. All tested mixes had FI values higher than 10, which is the minimum FI value suggested by Al-Qadi et al. (2) for surface mixes to ensure adequate resistance to fatigue cracking.

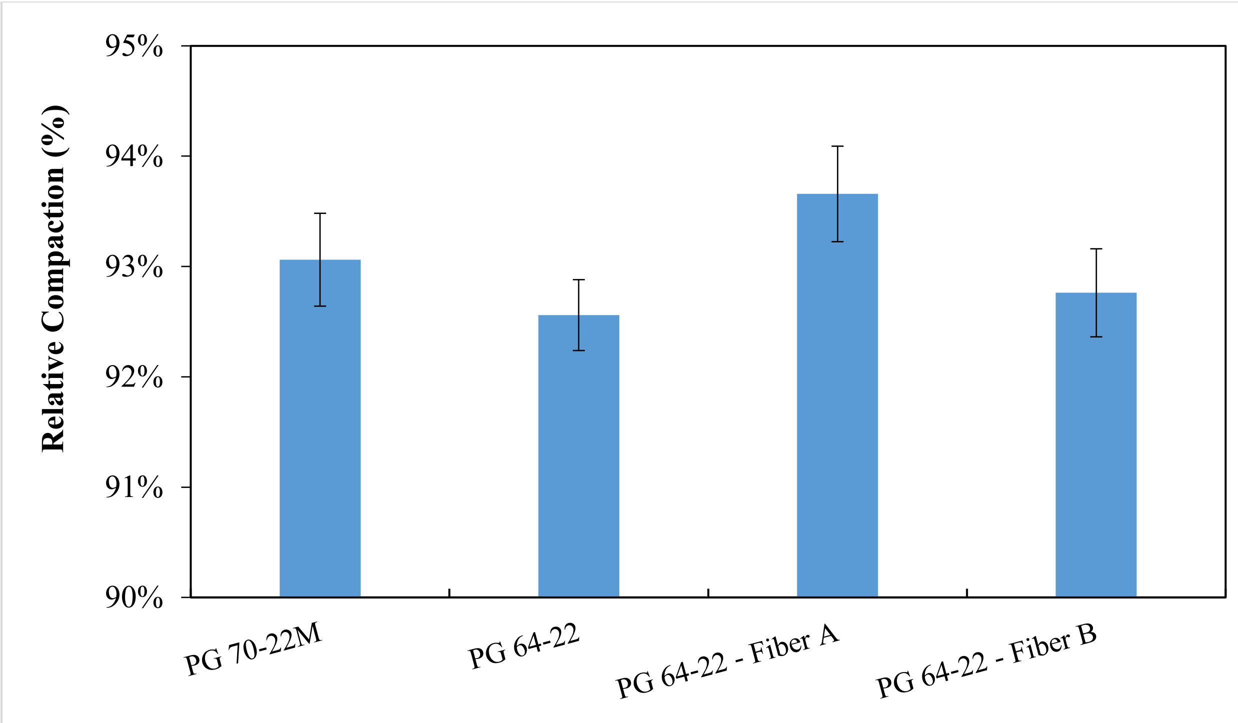


Figure B.1 Average Relative Compaction for City of Columbus Test Sections at Three Locations

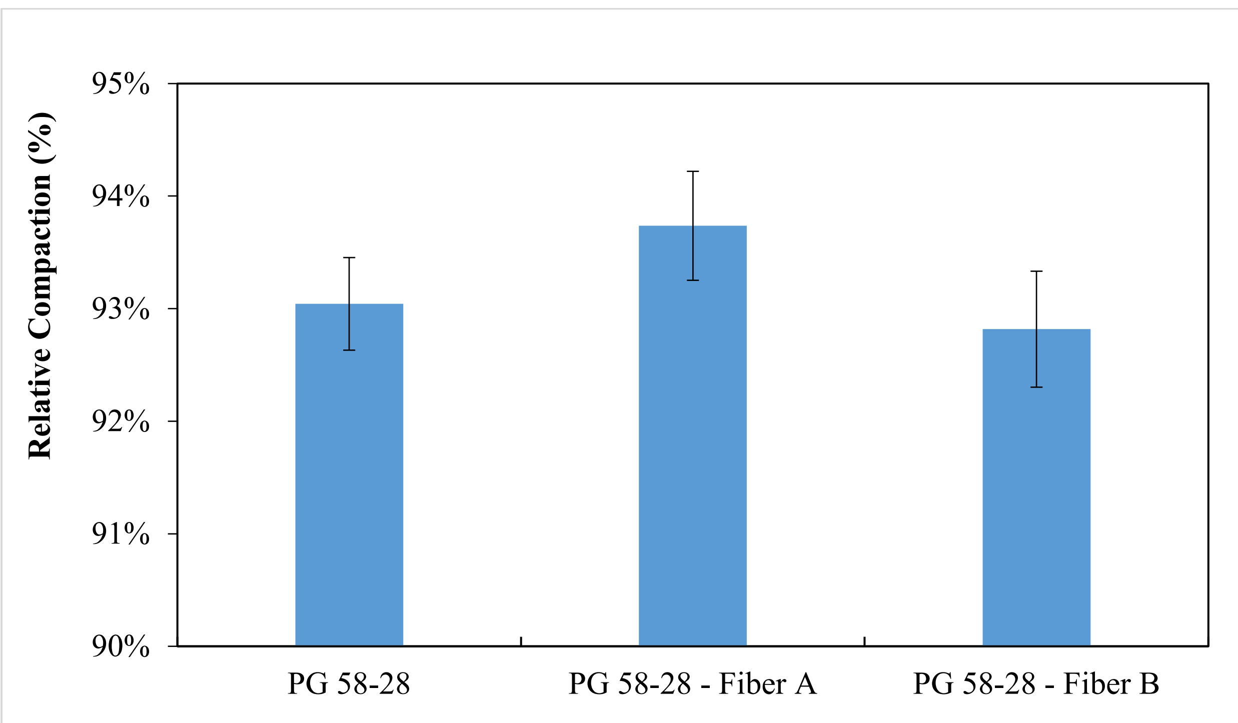


Figure B.2 Average Relative Compaction for Fayette County Test Sections

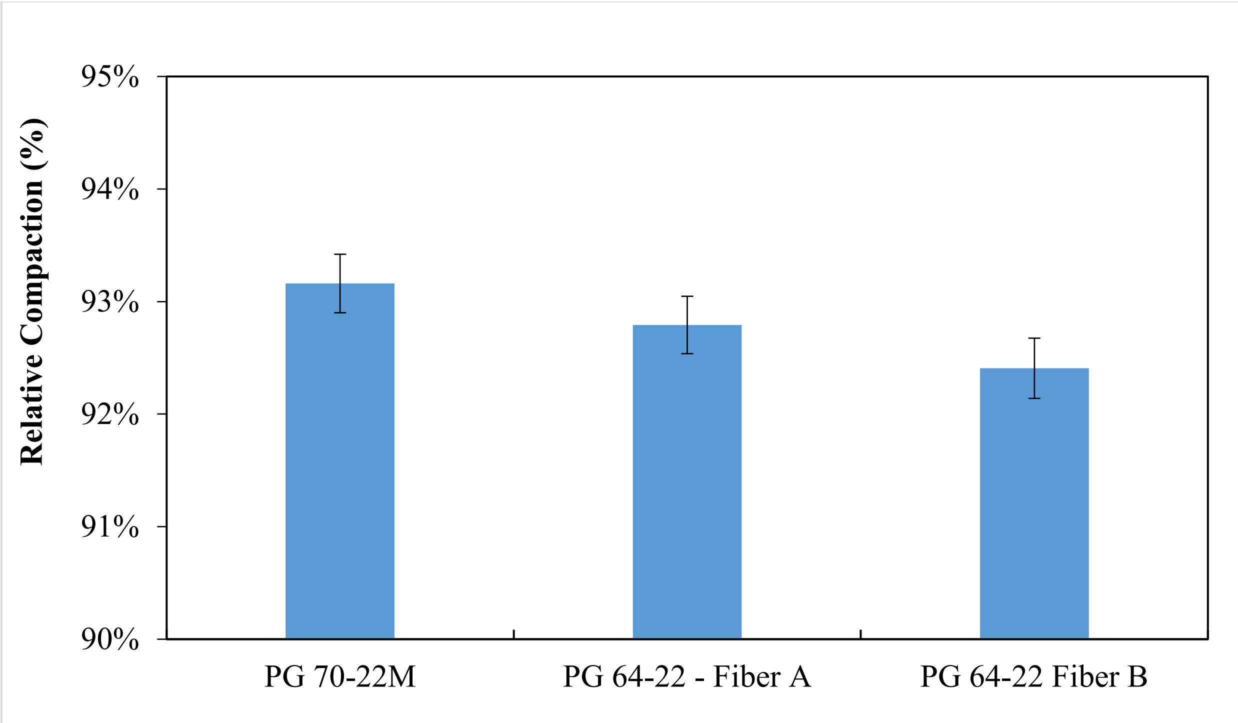


Figure B.3 Average Relative Compaction for City of Kettering Test Sections

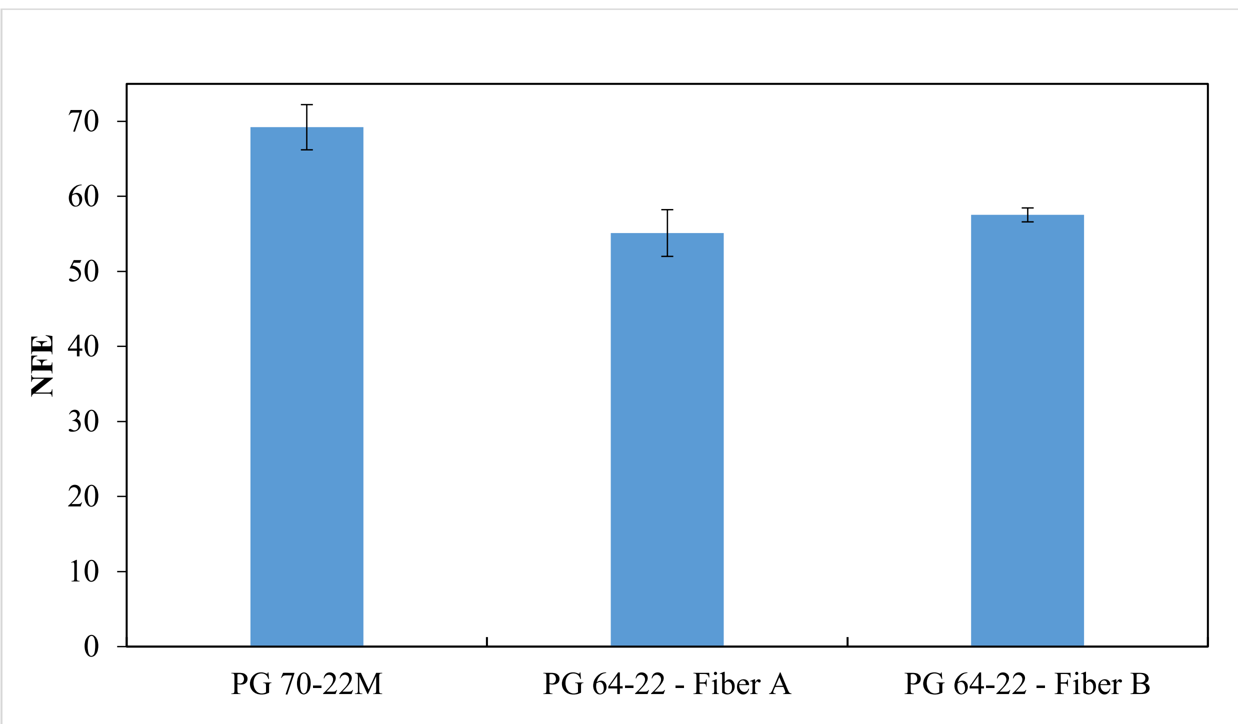


Figure B.4 Normalized Fracture Energy (NFE) for Cores obtained from Columbus Project 1.

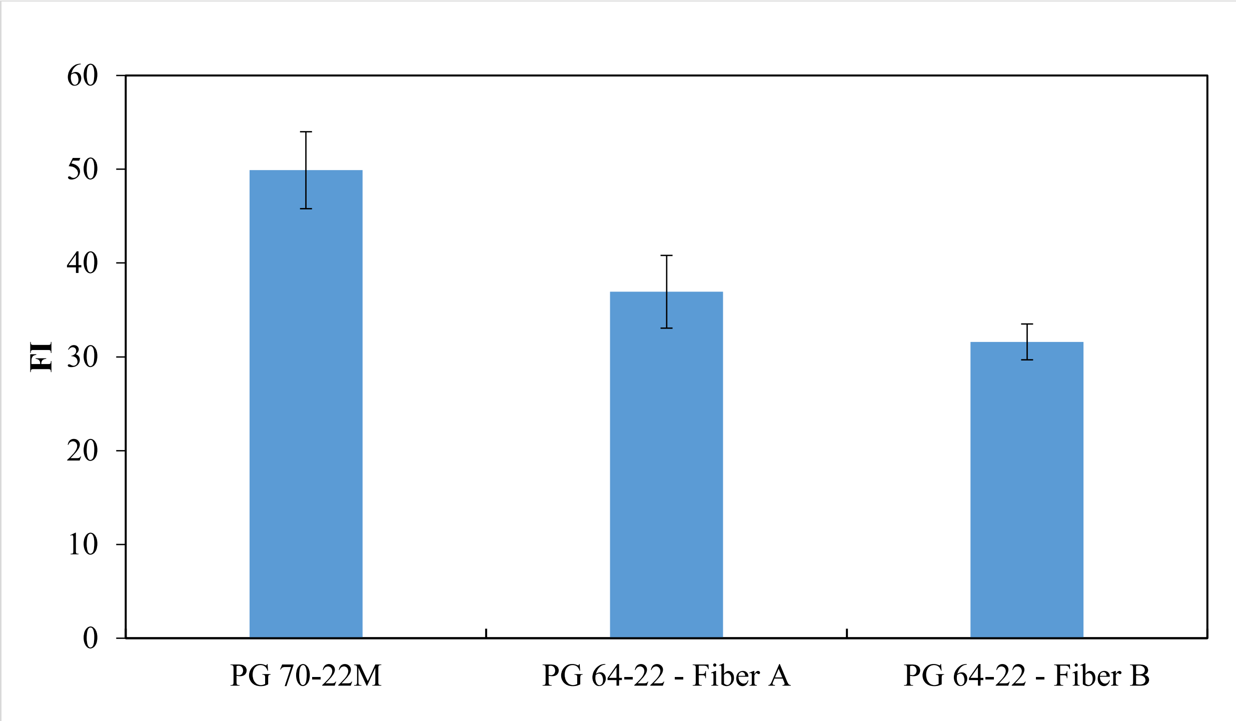


Figure B.5 Flexibility Index (FI) for Field Cores obtained from Columbus Project 1.

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

Figures B.6 and B.7 present the average Indirect Tensile Strength (ITS) and Crack Tolerance Index (CTI) values of the core samples obtained from Columbus Project 1. It is noted that the control mix with stiffer polymer modified binder (PG 70-22M) had a similar ITS and CTI values with the Fiber A mix prepared with a soft PG 64-22 binder. However, when compared with the Fiber B mix with PG 64-22 binder, the control mix with PG 70-22M binder showed higher cracking resistance, especially in terms of CTI values.

Figures B.8 and B.9 present the average ITS and CTI values of the core samples obtained from the sections constructed in the City of Kettering project. It is noted that the control mix with polymer modified asphalt binder (PG 70-22M) seemed to have slightly higher average ITS values as compared to those in the fiber mixes that have softer binder (PG 64-22). In addition, the Fiber B mix seemed to have slightly higher average ITS value than Fiber A mix. On average, Fiber A mix showed the smallest CTI value while Fiber B mix exhibited similar CTI value to PG 70-22M mix.

B.2.3 Overlay Tester Results

Table B.1 presents the results of the overlay tester tests conducted on core samples that were obtained from the City of Columbus project where an asphalt overlay layer was placed with and without SAMI on top of a concrete pavement. It is noted that several samples reached to the maximum number of cycles before failure in the test; therefore, the number of cycles to failure was not obtained for these samples. In general, the core samples with SAMI layer had higher number cycles than other samples. However, no conclusion can be made as the crack prorogated laterally rather than vertically, which typically does not occur in the overlay tester. This might be attributed to the weak plane that developed at the interface between the concrete and overlay layers. Future research is needed to modify the samples preparation and the overlay tester testing procedure to be able to test such composite core samples.

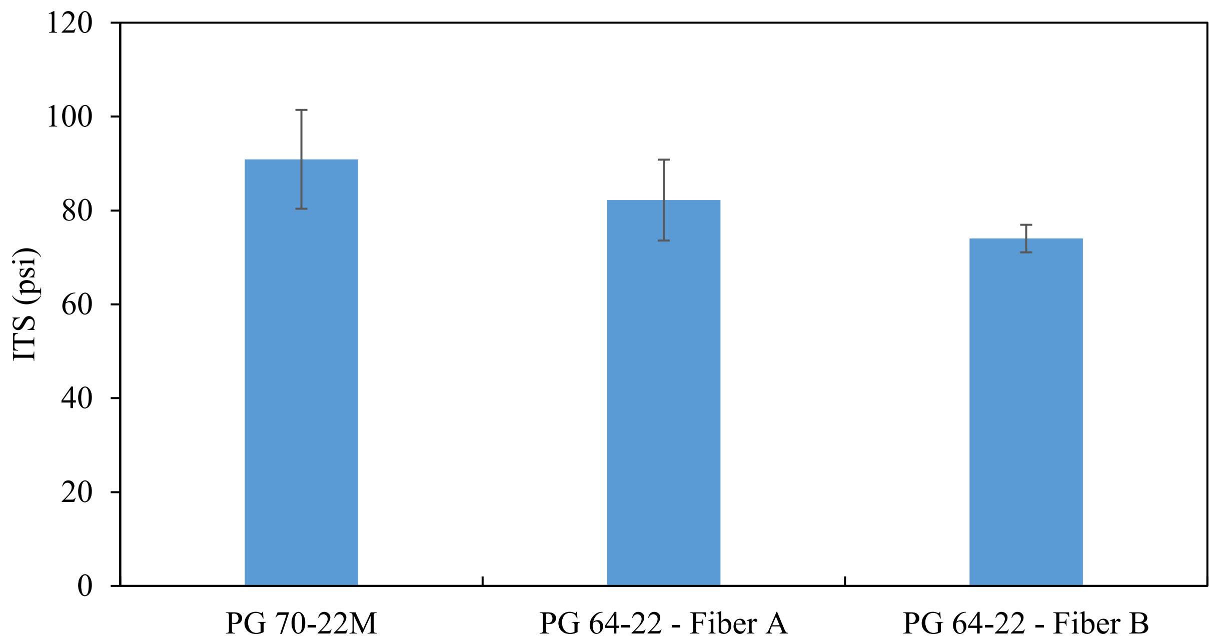


Figure B.6 ITS Values for Field Cores obtained from Columbus Project 1.

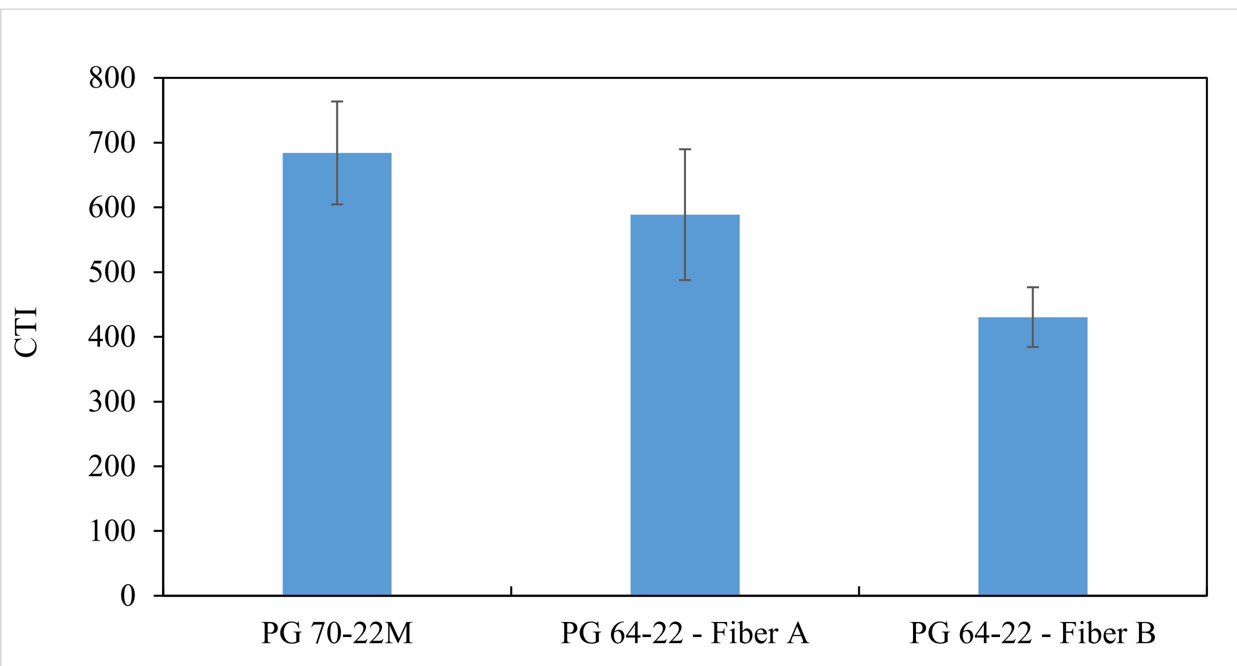


Figure B.7 CTI Values for Field Cores obtained from Columbus Project 1.

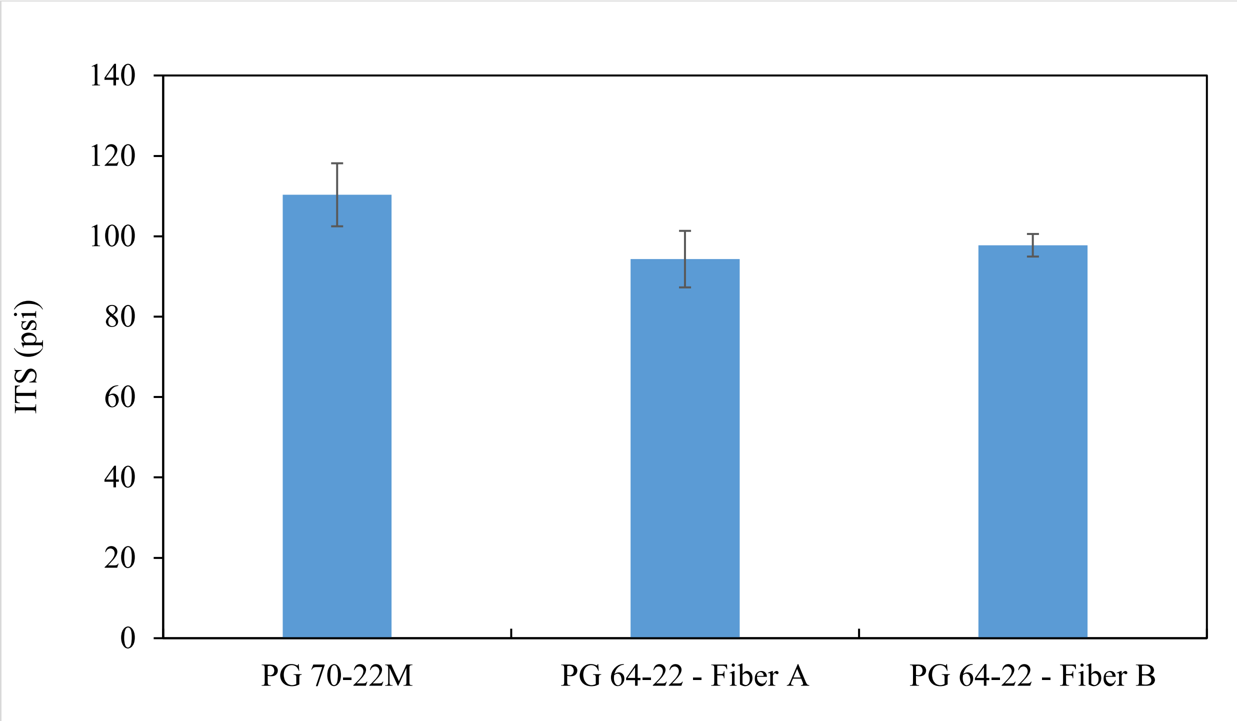


Figure B.8 ITS Values for Field Cores obtained from the City of Kettering. project.

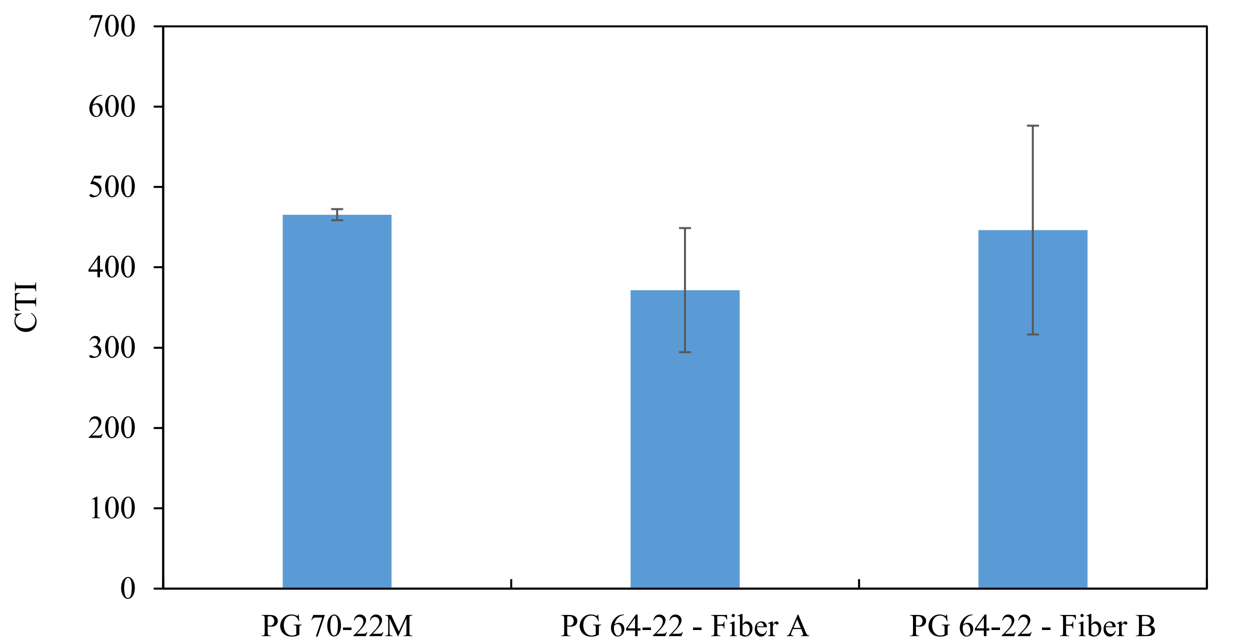


Figure B.9 CTI Values for Field Cores obtained from the City of Kettering project.

Table B.1 Results of Overlay Tester on Core Samples

Section	Specimen	Cycles to Failure	Max Load (lbs)	Average Cycles to Failure
Fiber B	FB1	423	512	680
	FB2	1,000	550	
	FB3	617	328	
Fiber A	FA2	1,000	431	597
	FA3	258	461	
	FA4	533	497	
Control (SAMI)	C2	1,000	383	1000
	C3	1,000	424	
	C4	1,000	404	

B.3 Test Results for Laboratory-Compacted Samples

The fatigue cracking resistance of field produced laboratory compacted samples at intermediate temperature was assessed by the SCB and IDEAL tests. In addition, the low-temperature cracking resistance of the samples was evaluated using the ACCD. A summary of the properties of the asphalt mixes used in the different sections constructed in this study are shown in Table B.2. The results of the conducted tests are discussed in this section.

Table B.2 Tested Mixture Properties

Section	Virgin Binder type	% RAP	Virgin AC%	RAP AC%	Fiber Type
Project 1 – Columbus - W North Broadway street					
Control	PG 70-22M	20	5.3	1.0	No fiber
Fiber A	PG 64-22	20	5.3	1.0	Fiber A
Fiber B	PG 64-22	20	5.3	1.0	Fiber B
Project 2&3 – Columbus - Neil Avenue area & Hingham Lane area					
Control	PG 64-22	20	5.3	1.0	No Fiber
Fiber A	PG 64-22	20	5.3	1.8	Fiber A
Fiber B	PG 64-22	20	5.3	1.8	Fiber B
Project 4– Fayette County - Bloomingburg New Holland Road NW					
Control	PG 58-28	10	6.3	0.5	No Fiber
Fiber A	PG 58-28	10	6.3	0.5	Fiber A
Fiber B	PG 58-28	10	6.3	0.5	Fiber B
Project 5– City of Kettering - Wilmington Pike					
Control	PG 70-22M	20	5.0	0.8	No Fiber
Fiber A	PG 64-22	20	5.0	1.0	Fiber A
Fiber B	PG 64-22	20	5.0	1.0	Fiber B

B.3.1 SCB Test Results

Figure B.10 presents a comparison of the average NFE values for samples compacted in the lab using loose mixtures obtained from the field for Columbus projects. It can be seen from Figure B.10 that the mix with polymer modified binder (PG 70-22M) exhibit a significantly higher value of NFE compared to all mixes prepared with softer binder (PG 64-22). Compared to the control PG 64-22 mix without fiber addition, Fiber B mix showed a similar NFE value, whereas the mix with Fiber A showed a slightly higher value of NFE meaning slightly better cracking resistance.

Figure B.11 presents the average NFE values for Fayette county mixes where Fiber A mix with PG 58-28 binder showed the significantly higher NFE value when compared to all other mixes obtained from Fayette County, including the PG 64-22 mix and Fiber B mix with PG 58-28 binder. While the two control mixes (PG 64-22 and PG 58-28 mixes without aramid fiber) showed similar NFE values, the mix with PG 58-28 and Fiber B showed the lowest NFE value.

Figure B.12 presents the average NFE values for the city of Kettering mixes, it can be seen that Fiber B mix with PG 64-22 binder showed the highest NFE value, while Fiber A with PG 64-22 binder showed a lower value when compared to the 70-22M mix without the aramid fiber.

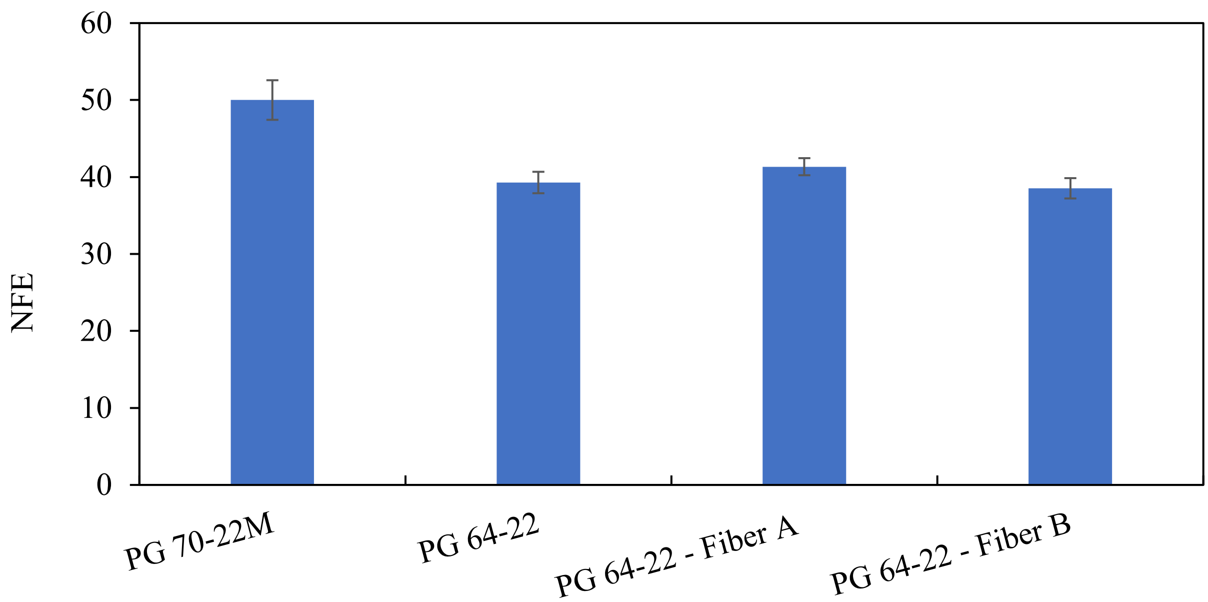


Figure B.10 NFE Values for Lab Compacted Samples of Columbus mixes

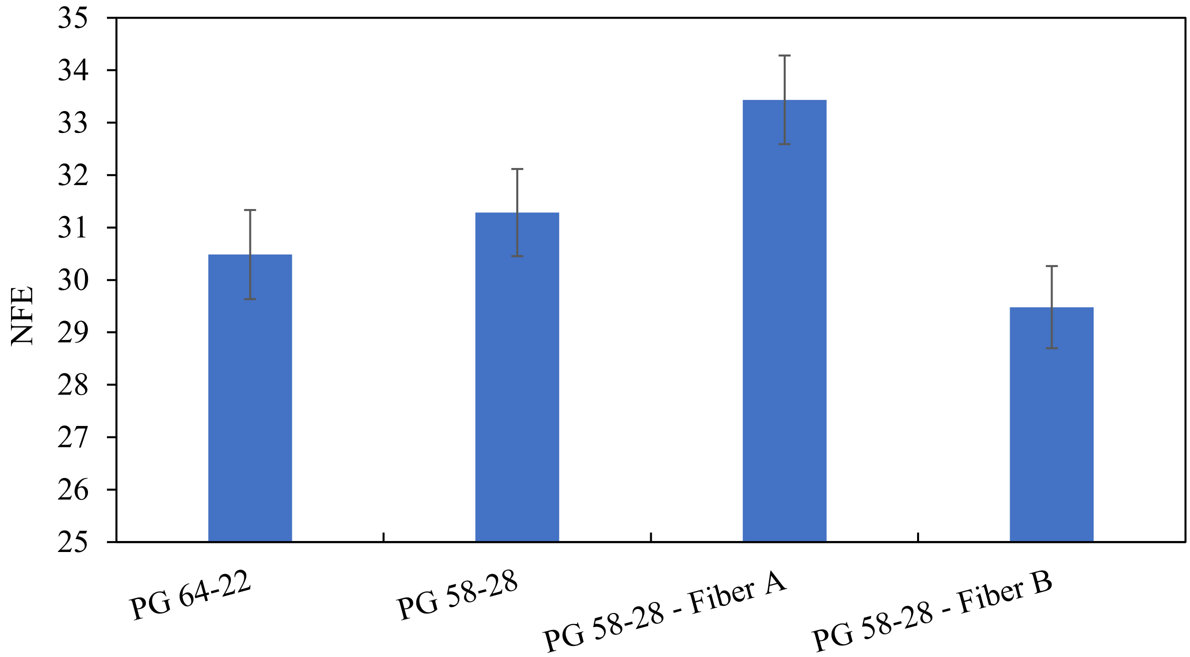


Figure B.11 NFE Values for Lab Compacted Samples of Fayette County mixes

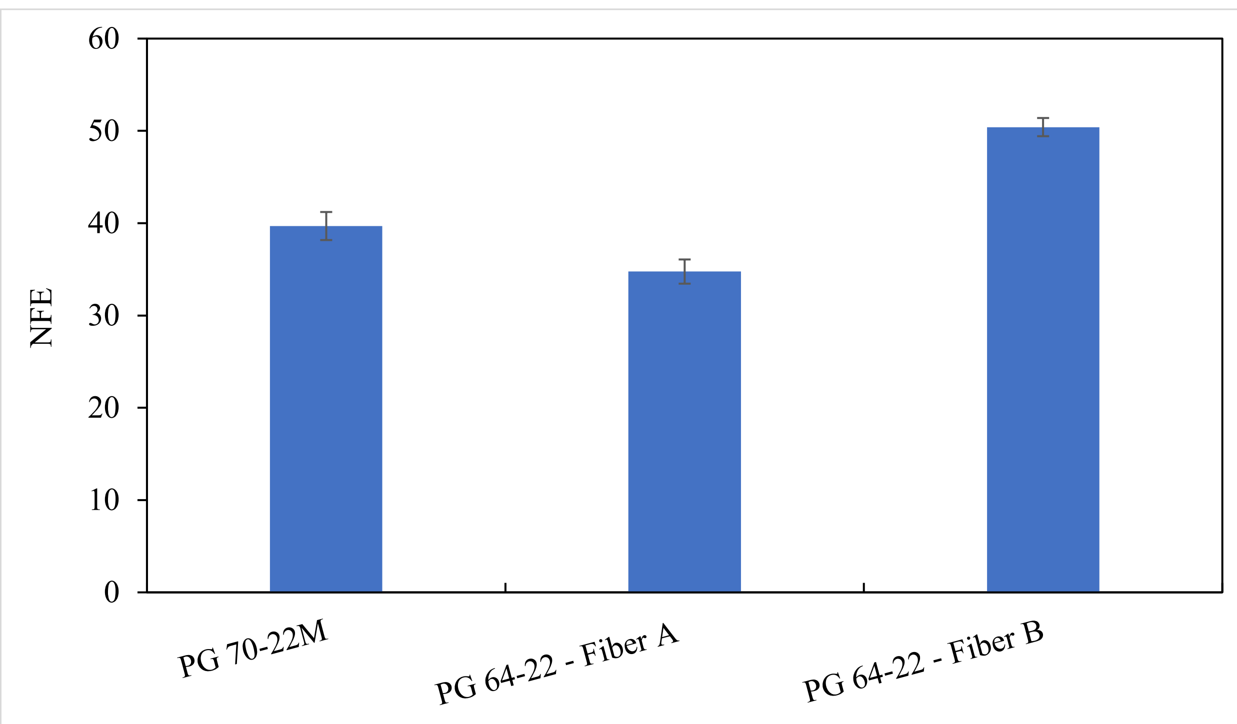


Figure B.12 NFE Values for Lab Compacted Samples of the City of Kettering mixes

Figure B.13 shows the average FI values for the lab compacted samples for Columbus mixes where the binder type exhibited the significant impact. The control mix with polymer modified binder (PG 70-22M) had the highest value of FI compared to all other mixes with softer binder (PG 64-22). Compared to the control PG 64-22 mix without fiber addition, Fiber B mix and Fiber A mix showed higher FI values indicating improved cracking resistance. Fiber A mix showed a slightly higher FI value than Fiber B mix.

Figure 14 presents the average FI values for Fayette County mixes. The mix with Fiber A and softer binder (PG 58-28) showed the highest value of FI compared to all other mixes obtained from Fayette County including the two control mixes with stiff (PG 64-22) and soft (PG 58-28) binders. The results of FI index indicates that the addition of Fiber A resulted in considerable improvement in the cracking resistance of the 404-LVT mixes with PG 58-28. However, the addition of Fiber B did not improve the FI value.

Figure 15 presents the average FI values for the samples prepared using the mixes used in the construction of test sections in the City of Kettering. It is noted that the mix with PG 64-22 binder and Fiber B showed the highest FI value among all mixes used in the test section in the City of Kettering. Furthermore, the average FI value of mix with PG 64-22 binder and Fiber A showed a similar value to that for PG 70-22M mix. This suggests that using PG 64-22 binder mix with aramid fiber will have similar or better resistance to cracking than PG 70-22M mix.

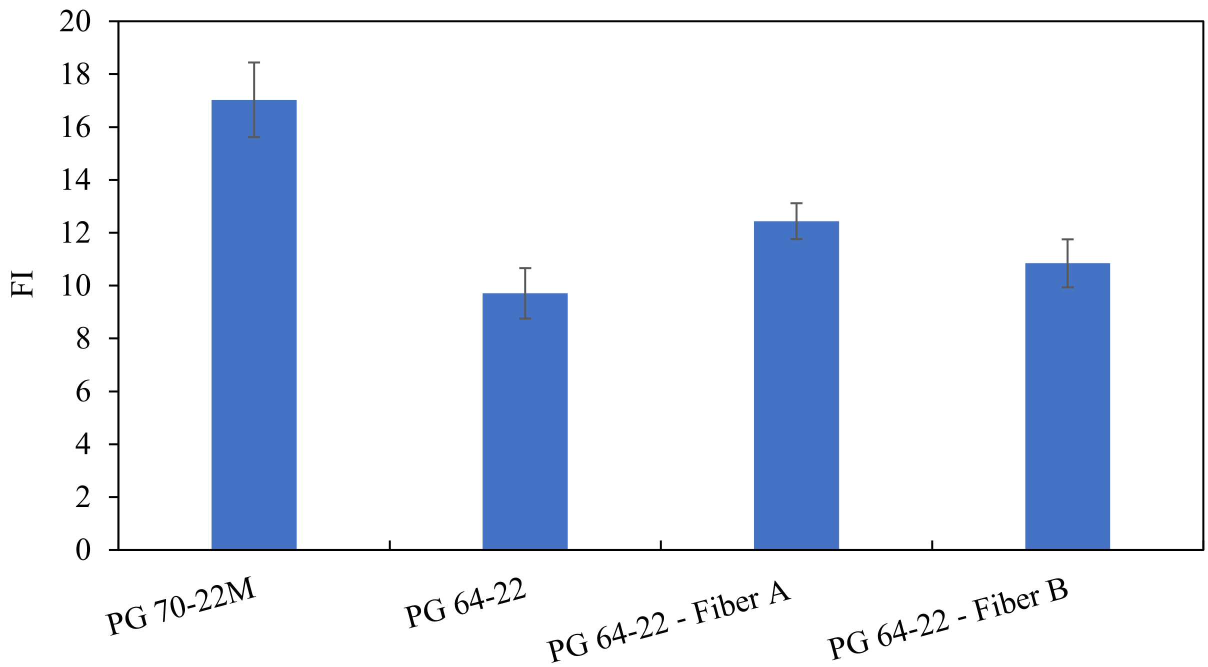


Figure B.13 FI Values for Lab Compacted Samples for Columbus Mixes

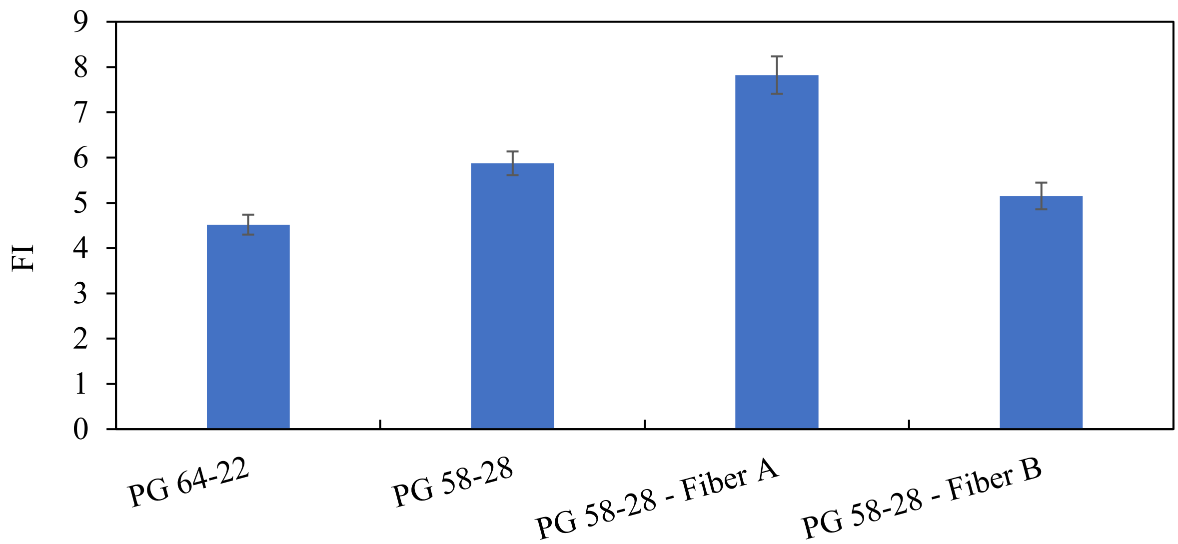


Figure B.14 FI Values for Lab Compacted Samples for Fayette County Mixes

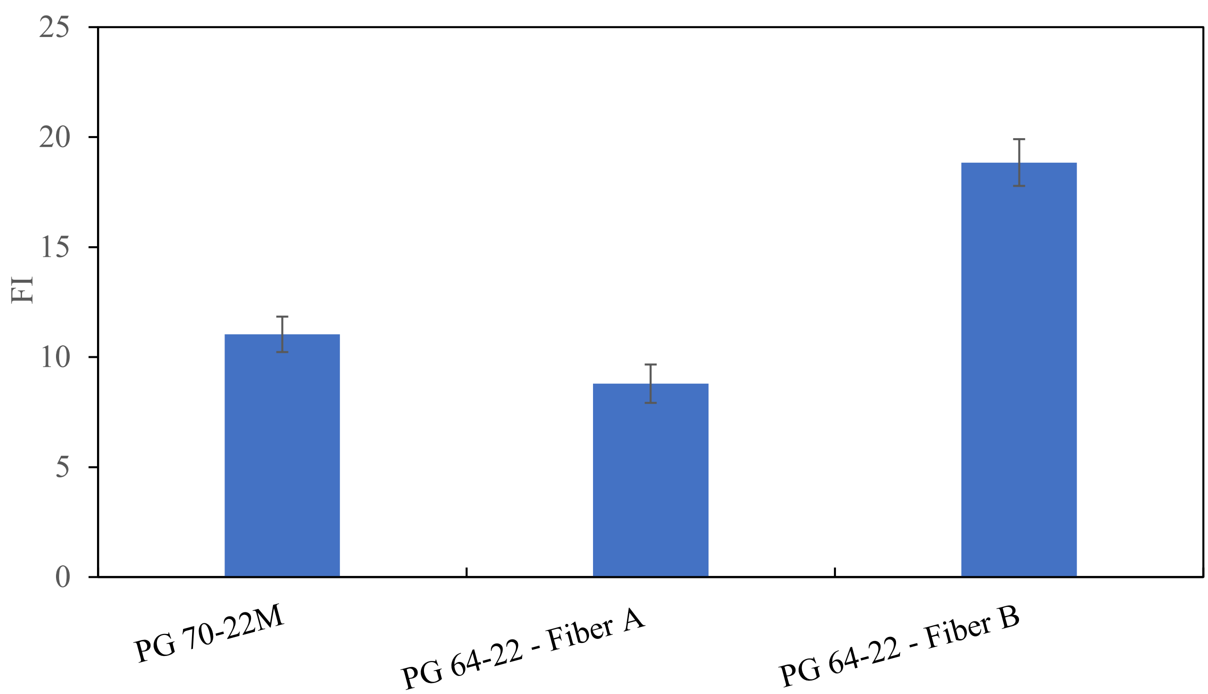


Figure B.15 FI Values for Lab Compacted Samples for the City of Kettering Mixes

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

Figure B.16 presents the average ITS values of the lab compacted samples for the City of Columbus test sections. It is noted that the binder type showed the significant impact on the ITS. The control mix with polymer modified PG 70-22M binder showed the highest value of ITS compared to the other mixes prepared with PG 64-22 binder. The effect of addition of both aramid fiber type showed negligible change in ITS value for PG 64-22 mix.

Figure B.17 presents the average values of ITS for samples prepared using the mixes used in construction of the test sections in Fayette County. It is noted that the binder type (PG 64-22 vs. PG 58-28) had a less significant effect as compared in Columbus projects (PG 70-22M vs. PG 64-22). The mixes with PG 64-22 showed the highest ITS value among all other mixes. In addition, the mixture with PG 58-28 binder with Fiber B showed a higher ITS value than the PG 58-28 mix without fiber addition. However, the inclusion of Fiber A in the mix with PG 58-28 binder did not result in any an improvement on ITS as the ITS value of the mix with PG 58-28 and Fiber A was slightly lower than that for the PG 58-28 mix without fiber addition.

Figure B.18 presents the average ITS values for mixes used in the construction of the test sections in City of Kettering. It is noted that mixture with polymer modified binder PG 70-22M showed a higher value of ITS than mixes with PG 64-22 and Fiber A or Fiber B. In addition, Fiber A mix showed a significantly higher ITS value than that for Fiber B mix.

For both City of Kettering and Columbus projects, PG 70-22M mix showed higher ITS value than mixes with PG 64-22 and aramid fibers. However, the relative magnitude of the differences is significantly different, probably due to different mix types and binder sources used in each project.

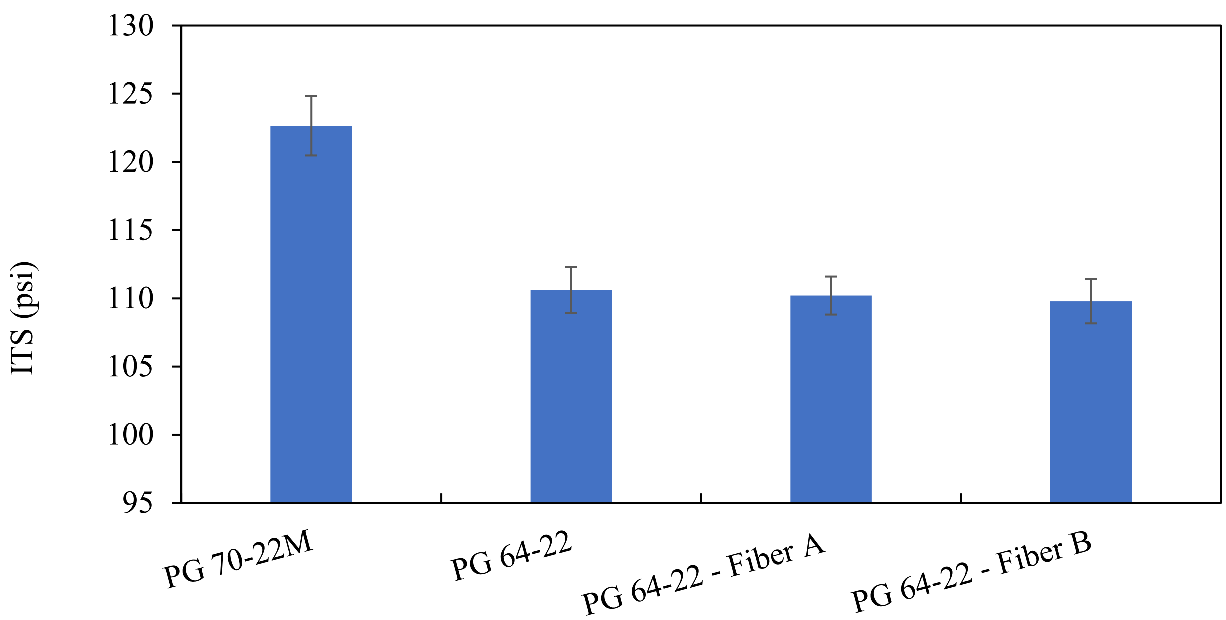


Figure B.16 ITS Values for Lab Compacted Samples for Columbus Mixes

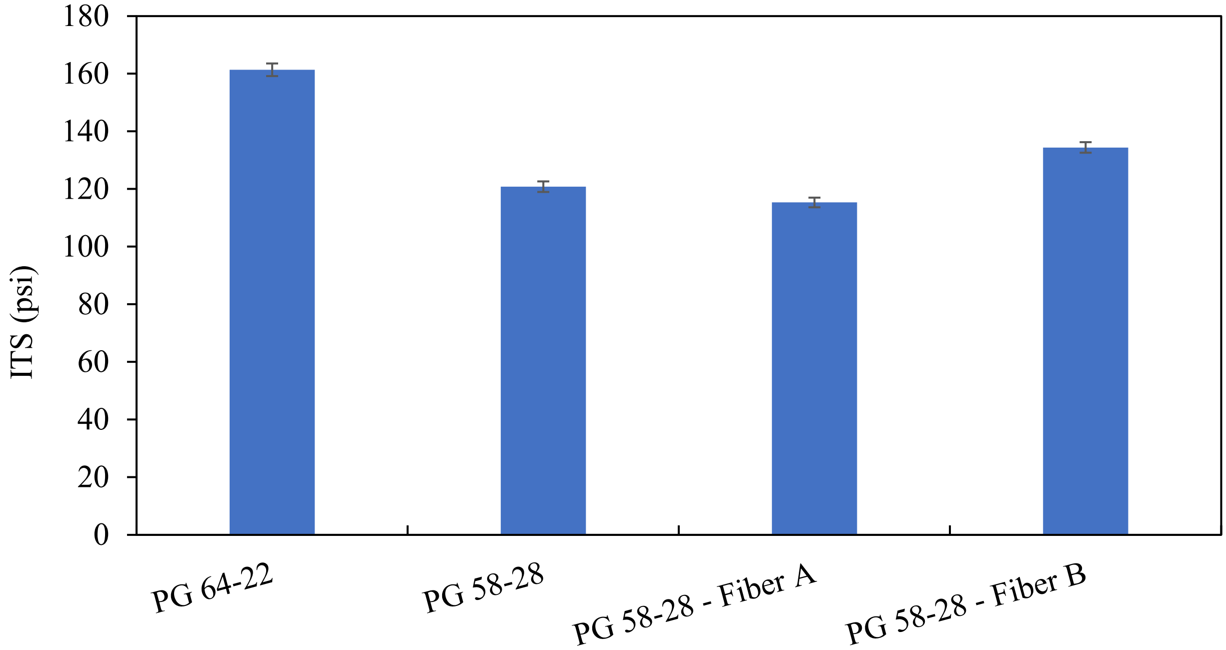


Figure B.17 ITS Values for Lab Compacted Samples for Fayette County Mixes

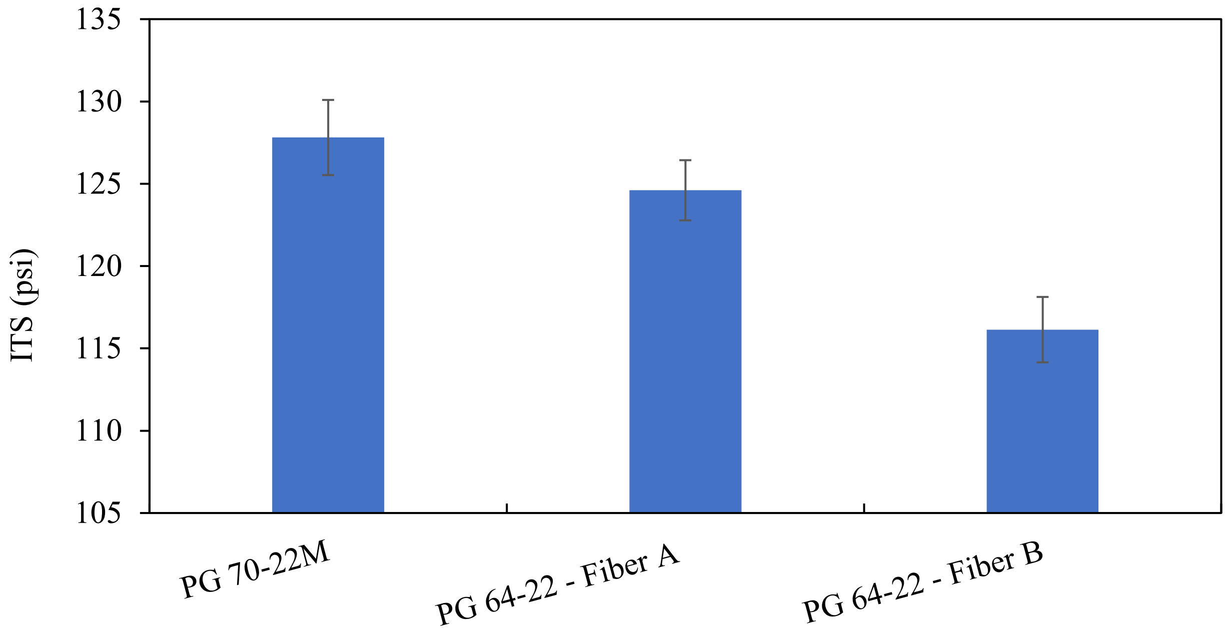


Figure B.18 ITS Values for Lab Compacted Samples for the City of Kettering Mixes

Figure B.19 presents the average CTI values of lab compacted samples for mixtures used in the construction of test sections in the City of Columbus. It is noted that the mixture with PG 70-22M showed the higher CTI compared to the mixture with PG 64-22. In addition, the inclusion of aramid fibers (Fiber A or Fiber B) resulted increasing the CTI value for the PG 64-22 mixes to a level close to that of the polymer modified PG 70-22M control mix. This suggests that the use of aramid fibers might result in an improvement in the cracking resistance similar to that achieved when using polymers.

Figure B.20 presents the average CTI values of lab compacted samples for mixtures used in the construction of test sections in Fayette county. It is noted that the mixture with PG 58-28 binder showed the higher CTI value than that with PG 64-22 binder. This might be attributed to its ductility and flexibility. While the addition of Fiber A to the mix with PG 58-28 increased the CTI value, the addition of Fiber B decreased the CTI value.

Figure B.21 presents the average CTI values for lab compacted samples for mixtures used in the construction of test sections in the City of Kettering mixes. It is noted that mixture with PG 64-22 binder and Fiber B had the higher CTI value compared to the PG 70-22M control mix and the PG 64-22 mix with Fiber A. This suggests that for the mixture with PG 64-22 binder used in this project the Fiber B is more effective in improving the cracking resistance than the Fiber A.

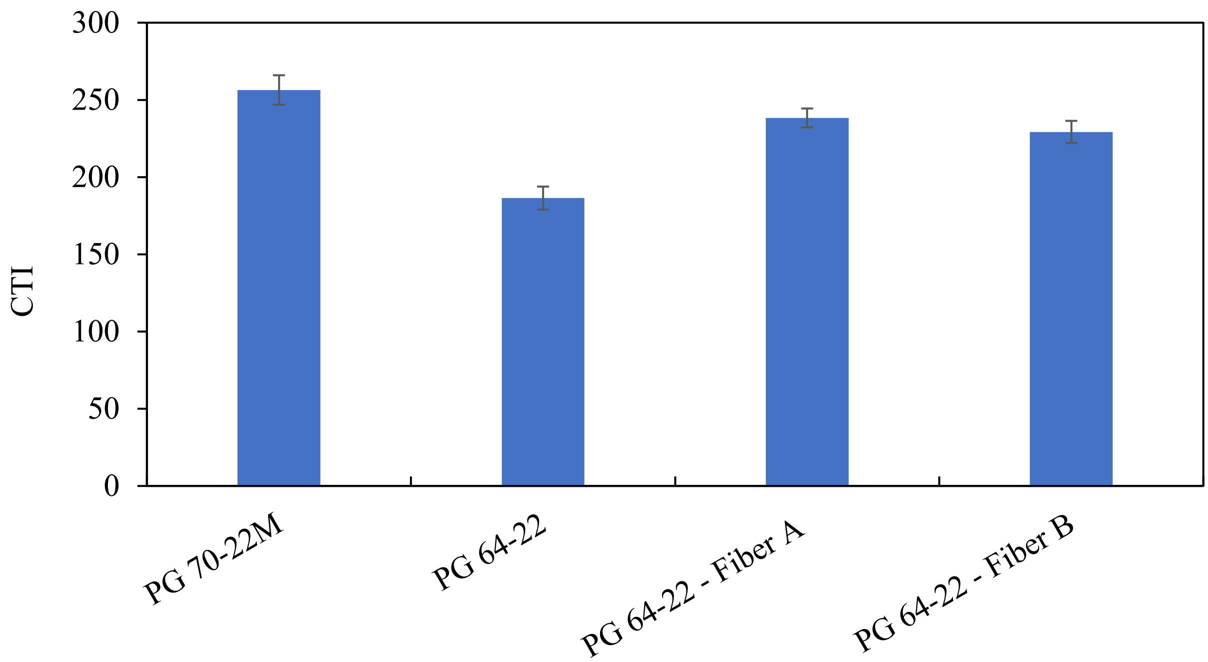


Figure B.19 CTI Values for Lab Compacted Samples for Columbus Mixes

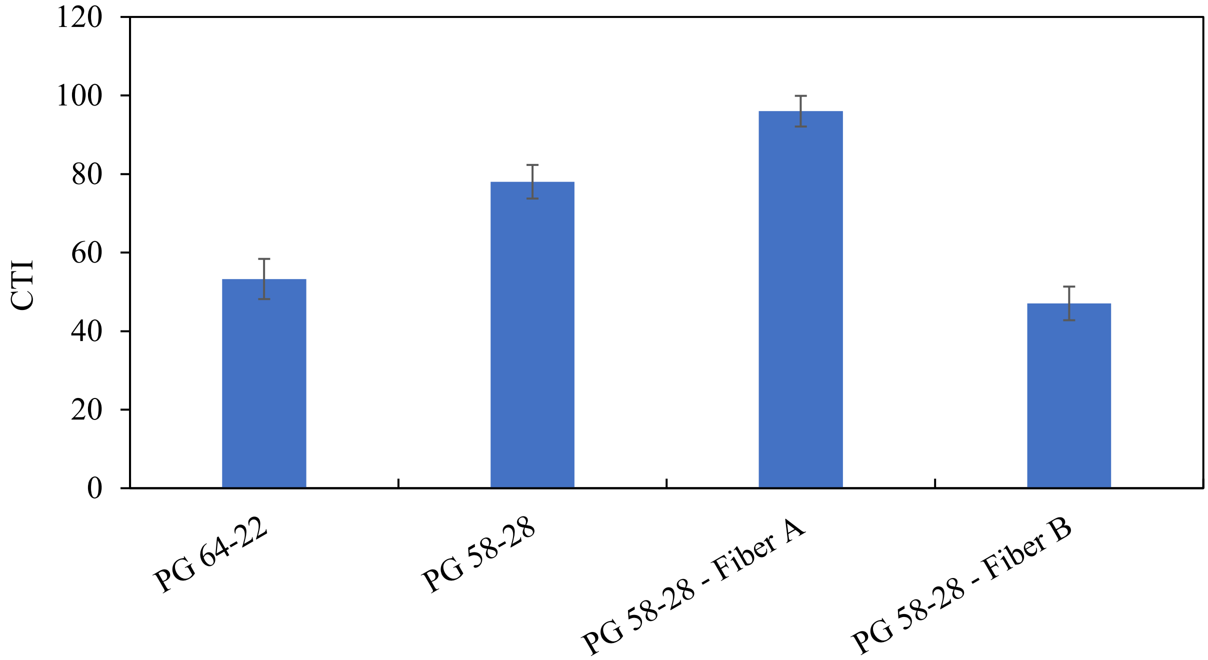


Figure B.20 CTI Values for Lab Compacted Samples for Fayette County Mixes

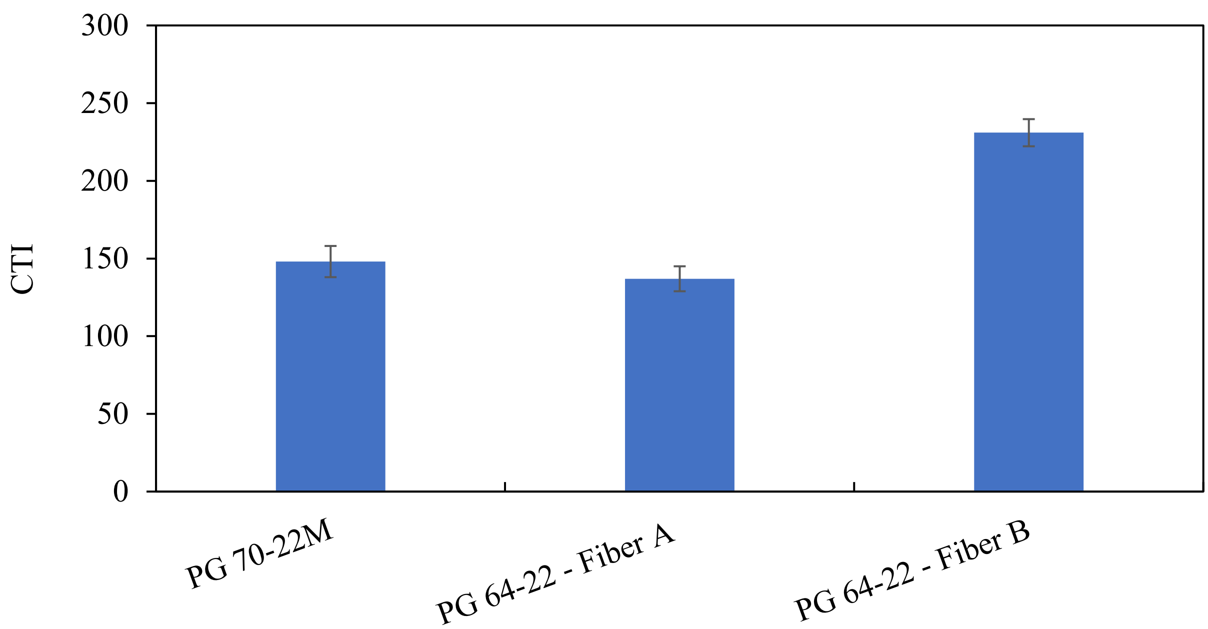


Figure B.21 CTI Values for Lab Compacted Samples for the City of Kettering Mixes

Analysis of Variance (ANOVA) and post ANOVA Least Square Mean (LSM) analyses were conducted using Statistical Analysis Software (SAS) (SAS, 2004) to statistically evaluate the lab testing results. A linear Completely Random Design (CRD) model was used. Tables B.3 and B.4 present the results of ANOVA on the ITS and CTI obtained from the IDEAL tests performed on the mixtures used in the test sections constructed in the City of Columbus projects, respectively.

It is noted that from both tables that the effects of the mixture type on the ITS and CTI values were statistically significant at 95% confidence level, which can be indicated by the P-values in this table.

Table B.3 ANOVA Results for ITS Results for Columbus Projects Mixes.

ANOVA Test Results-ITS		
Effect	F Value	P-value
Mix	9.41	<.0001

Table B.4 ANOVA Results for CTI Results for Columbus Projects Mixes.

ANOVA Test Results-CTI		
Effect	F Value	P-value
Mix	14.18	<.0001

Table B.5 presents the results of the ranking of mixtures based on ITS values, which 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. It is noted that the 70-22M mix had significantly higher ITS value than the 64-22 mixes and PG 64-22 mix without fiber addition as well as the Fiber A mix had almost the same ITS value, followed by the Fiber B mix that had the lowest value of ITS among the mixes in the City of Columbus project. Table B.6 presents the results of the ranking of the different mixtures in Columbus projects in terms of CTI that was obtained from the post ANOVA LSM analysis. The mixture with PG 70-22M binder and mixtures with PG 64-22 and Fiber A or Fiber B had statistically similar CTI values. In addition, the mixtures with PG 64-22 and Fiber A or Fiber B had statistically higher CTI values than the mixture with PG 64-22. This indicates that aramid fibers used (Fiber A and Fiber B) significantly improved the fracture resistance of the mixture with PG 64-22.

Table B.5 Results of Post ANOVA LSM on ITS Results for Columbus Projects Mixes.

Mix	**Estimate**	**Letter Group**
PG 70-22	122.64	A
PG 64-22	110.60	B
PG64-22+ Fiber A	110.20	B
PG 64-22+ Fiber B	109.78	B

Table B.6 Results of Post ANOVA LSM on CTI Results for Columbus Projects Mixes.

Mix	**Estimate**	**Letter Group**
PG 70-22	256.42	A
PG 64-22+ Fiber A	238.34	A
PG 64-22+ Fiber B	229.29	A
PG 64-22	186.43	B

Tables B.7 and B.8 present the results of ANOVA conducted on ITS and CTI of the different mixtures in Fayette County project, respectively. It can be seen from both tables that the results of ITS and CTI for different mixes were statistically significant at 95% confidence level which can be seen form F-values and P-values. Table B.9 presents the results of the ranking of the different mixtures in terms of ITS for Fayette County mixes, which was determined using the post ANOVA LSM analysis. It is noted that the 64-22 mix had significantly higher ITS value than the 58-28 mixes. Fiber B mix with PG 58-28 binder had a higher ITS value than that for PG 58-28 mix without fiber addition, while Fiber A mix with PG 58-28 binder had the lowest value of ITS among Fayette county mixes; slightly lower than that for 58-28 mix without fiber addition. Table B.10 presents the results of the ranking of the different mixtures in Fayette County in terms of CTI that was obtained from the post ANOVA LSM analysis. The Fiber A mix had significantly higher CTI as compared to other mixes. This indicates that Fiber A addition to PG 58-28 mix has increased fracture resistance for the mixtures as measured by CTI criteria. PG 58-28 mix without fiber addition had a higher CTI value than that for PG 64-22 mix, while Fiber B mix had the lowest CTI value.

Table B.7 ANOVA Results for ITS Results for Fayette County Project Mixes.

ANOVA Test Results-ITS		
Effect	F Value	P-value
Mix	104.22	<.0001

Table B.8 ANOVA Results for CTI Results for Fayette County Project Mixes.

ANOVA Test Results-CTI		
Effect	F Value	P-value
Mix	28.96	<.0001

Table B.9 Results of Post ANOVA LSM on ITS Results for Fayette County Mixes.

Mix	**Estimate**	**Letter Group**
PG 64-22	161.38	A
PG 58-28+ Fiber B	134.43	B
PG 58-28	120.81	C
PG 58-28+ Fiber A	115.34	C

Table B.10 Results of Post ANOVA LSM on CTI Results for Fayette County Mixes.

Mix	**Estimate**	**Letter Group**
PG 58-28+ Fiber A	96.0	A
PG 58-28	78.0	B
PG 64-22	53.3	C
PG 58-28+ Fiber B	47.1	C

Tables B.11 and B.12 present the results of ANOVA of the different mixtures in City of Kettering project in terms of ITS and CTI, respectively. It is noted that that the effect of mixtures was statistically significant 95% confidence level on the ITS and CTI. Table B.13 presents the results of the ranking of the different mixtures in terms of ITS for City of Kettering mixes, which was determined using the post ANOVA LSM analysis. It is noted that the mix with polymer modified binder 70-22M and mixture with PG 64-22 and Fiber A had had statically similar ITS values. In addition, the mix with PG 64-22 and Fiber B had the lowest ITS value among all of the mixes used in the City of Kettering. Table B.14 presents the results of the ranking of the different mixtures in City of Kettering in terms of CTI that was obtained from the post ANOVA LSM analysis. The mix with PG 64-22 and Fiber B, had significantly higher CTI as compared to other mixes, including the mix with PG 70-22M binder. However, the difference in CTI values between the 70-22M mix and the PG 64-22 mix with Fiber A is small enough and is not statistically significant. Fiber A mix had slightly lower value of CTI than that for 70-22M mix. This indicates that the addition of the aramid fibers to mixture with PG 64-22 can improve its fracture resistance and result in cracking resistance similar or better to that of a mixture with polymer modified binder PG 70-22M. These results are consistent with those obtained in the City of Columbus projects, where the CTI value for PG 64-22 mixes with aramid fiber is similar to that of PG 70-22M mix.

Table B.11 ANOVA Results for ITS Results for City of Kettering Project Mixes.

ANOVA Test Results-ITS		
Effect	F Value	P-value
Mix	8.44	0.0004

Table B.12 ANOVA Results for CTI Results for City of Kettering Project Mixes.

ANOVA Test Results-CTI		
Effect	F Value	P-value
Mix	35.13	<.0001

Table B.13 Results of Post ANOVA LSM on ITS Results for City of Kettering Mixes.

Mix	**Estimate**	**Letter Group**
PG 70-22	127.81	A
PG 64-22+ Fiber A	124.53	A
PG 64-22+ Fiber B	116.14	B

Table B.14 Results of Post ANOVA LSM on CTI Results for City of Kettering Mixes.

Mix	**Estimate**	**Letter Group**
PG 64-22+ Fiber B	230.96	A
PG 70-22	148.03	B
PG 64-22+ Fiber A	136.96	B

B.3.3.1 Variability Analysis for Indirect Tensile Asphalt Cracking Test (IDEAL-CT) Results

Table B.15 presents the results of statistical variability analysis done on CTI for the fiber mixes obtained at different projects (production days) in the City of Columbus. It is noted from the table that the CTI values for fiber mixes obtained at the different production days had statistically similar CTI values, as all estimate values were close to each other for the same fiber type and all fiber samples had the letter group A. This suggests that the cracking resistance properties of fiber mixes did not significantly change in the different production days for both fiber mixes.

Figures B.22 and B.23 present the coefficient of variation values of ITS and CTI for the fiber mixes obtained at different projects (production days) in Columbus. It can be seen from both figures that the coefficient of variation is not high for both fiber types and it was comparable to the value of coefficient of variability for control mix (PG 64-22 without fiber addition). This may suggest that aramid fibers had the same distribution in the mix during productions.

Table B.15 Variability Analysis Results for Columbus Projects Lab Compacted Samples.

Mix	Location	CTI Estimate	Letter Group
Fiber A	Project 1	251.63	A
Fiber A	Project 3	241.64	A
Fiber B	Project 3	234.05	A
Fiber B	Project 2	232.48	A
Fiber A	Project 2	224.17	A
Fiber B	Project 1	218.84	A

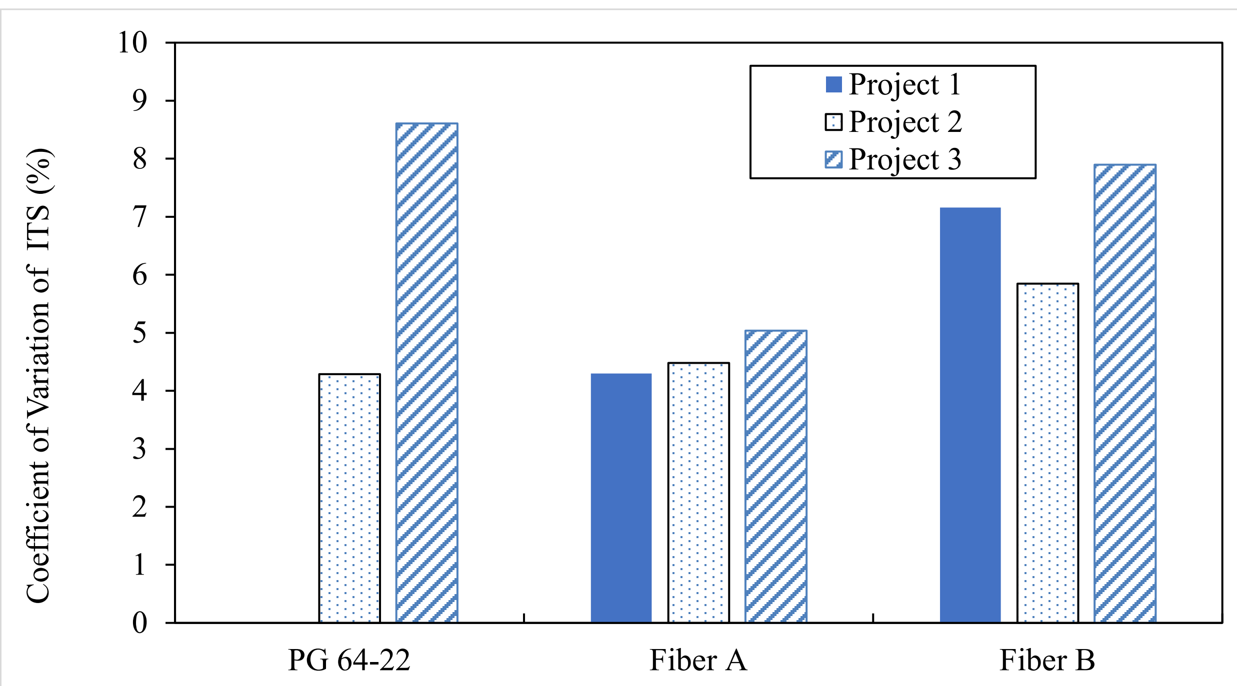


Figure B.22 Coefficient of Variation for ITS Results in Columbus Projects Lab Samples

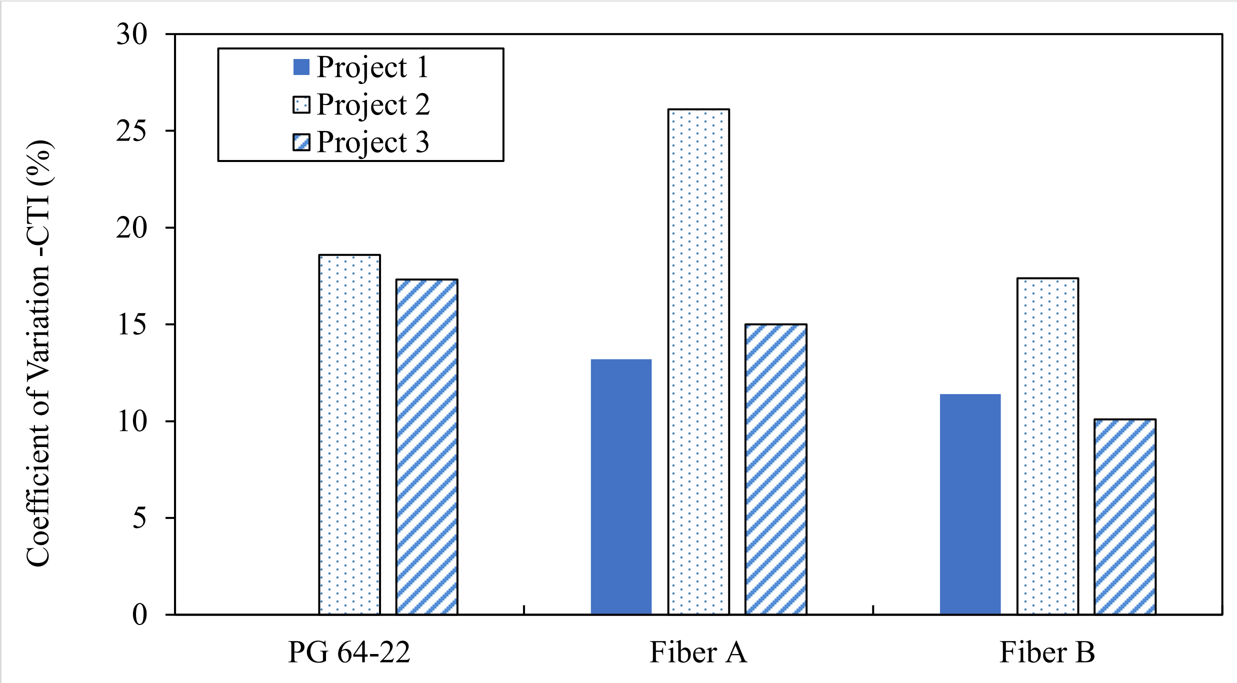


Figure B.23 Coefficient of Variation for CTI Results in Columbus Projects Lab Samples

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

Figure B.24 presents the average cracking temperature obtained using the ACCD test conducted on the samples compacted in the lab from mixtures, which were obtained from test sections in the City of Columbus. The mix with PG 70-22M binder had the lowest cracking temperature compared to other mixes. In addition, the mix with PG 64-22 and Fiber B showed a slightly better improvement on PG 64-22 mix than Fiber A, as the value of cracking temperature was slightly lower for PG 64-22 mix with Fiber B than that for the mix with PG 64-22 only.

Figure B.25 presents the average cracking temperature obtained for Fayette County mixes. It is noted that the control mixture with PG 58-28 binder showed the lowest cracking temperature value. In addition, mix with PG 58-28 and Fiber A showed lower cracking temperature than PG 58-28 mix with Fiber B. Finally, the PG 64-22 mix showed the warmest cracking temperature in all Fayette County mixes, which indicates lower resistance to low-temperature cracking than other mixes in Fayette County.

Figure B.26 presents the average cracking temperature obtained for the mixes used in the City of Kettering project. The mix with PG 70-22M showed colder cracking temperature than those with PG 64-22 and Fiber A or Fiber B. The mixes PG 64-22 and Fiber A showed lower cracking temperature value compared to that for Fiber B mix, which indicates a better low temperature cracking resistance for the PG 64-22 mix with Fiber A.

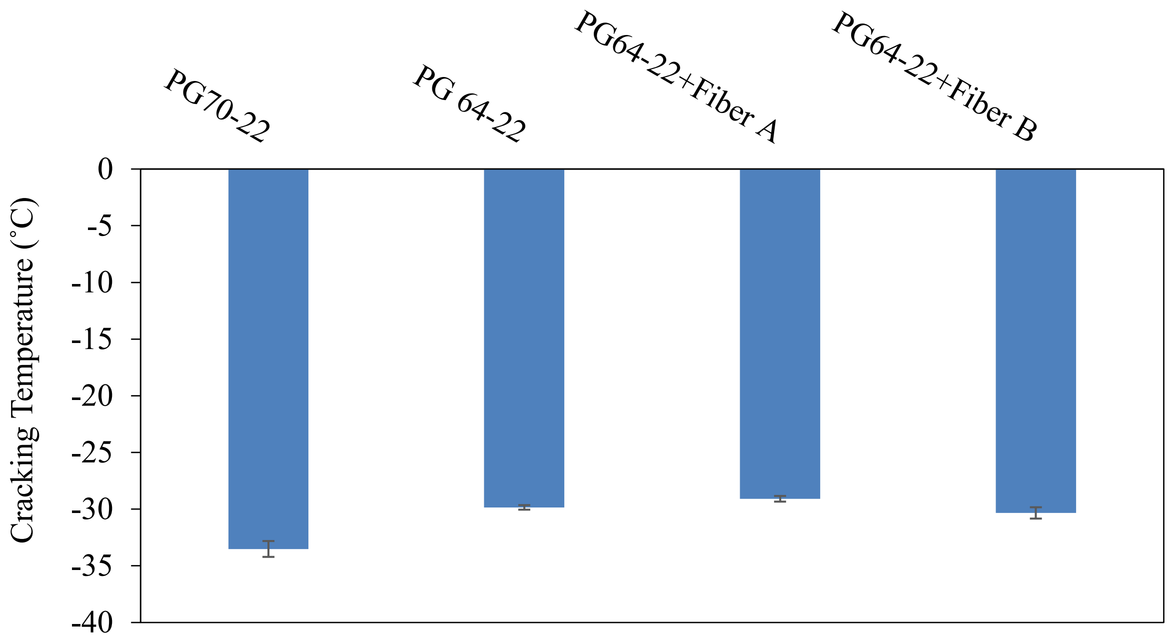


Figure B.24 ACCD Cracking Temperature for Lab Compacted Samples for City of Columbus Mixes

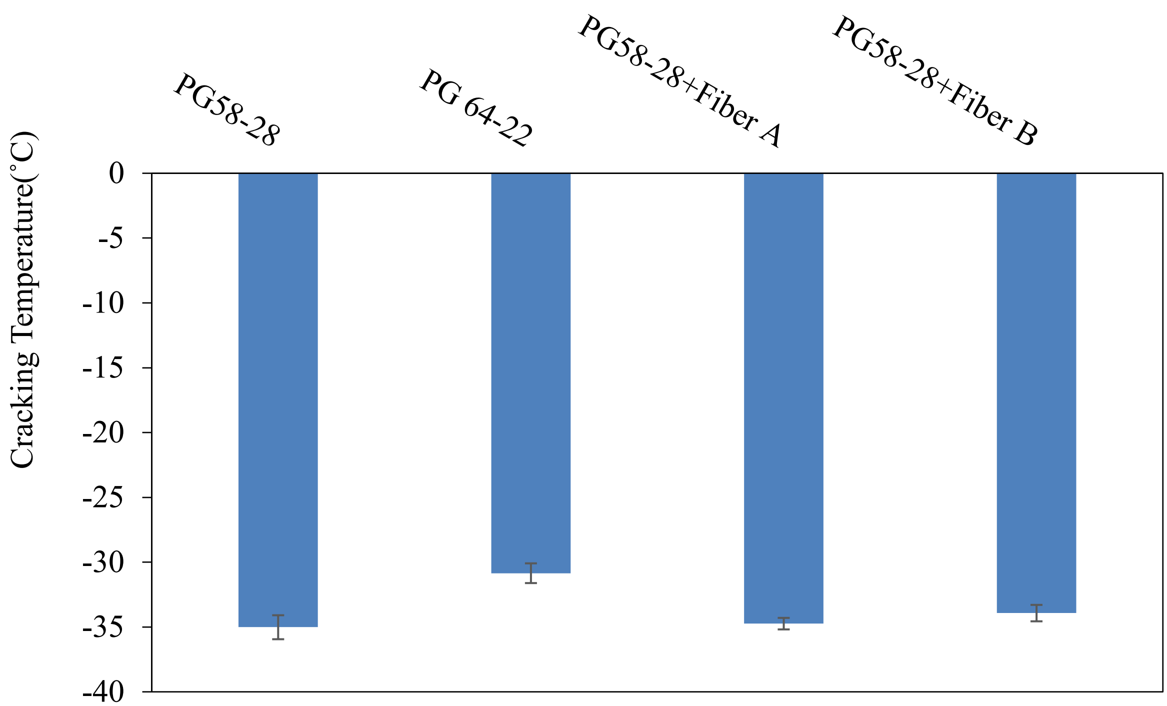


Figure B.25 ACCD Cracking Temperature for Lab Compacted Samples for Fayette County Mixes

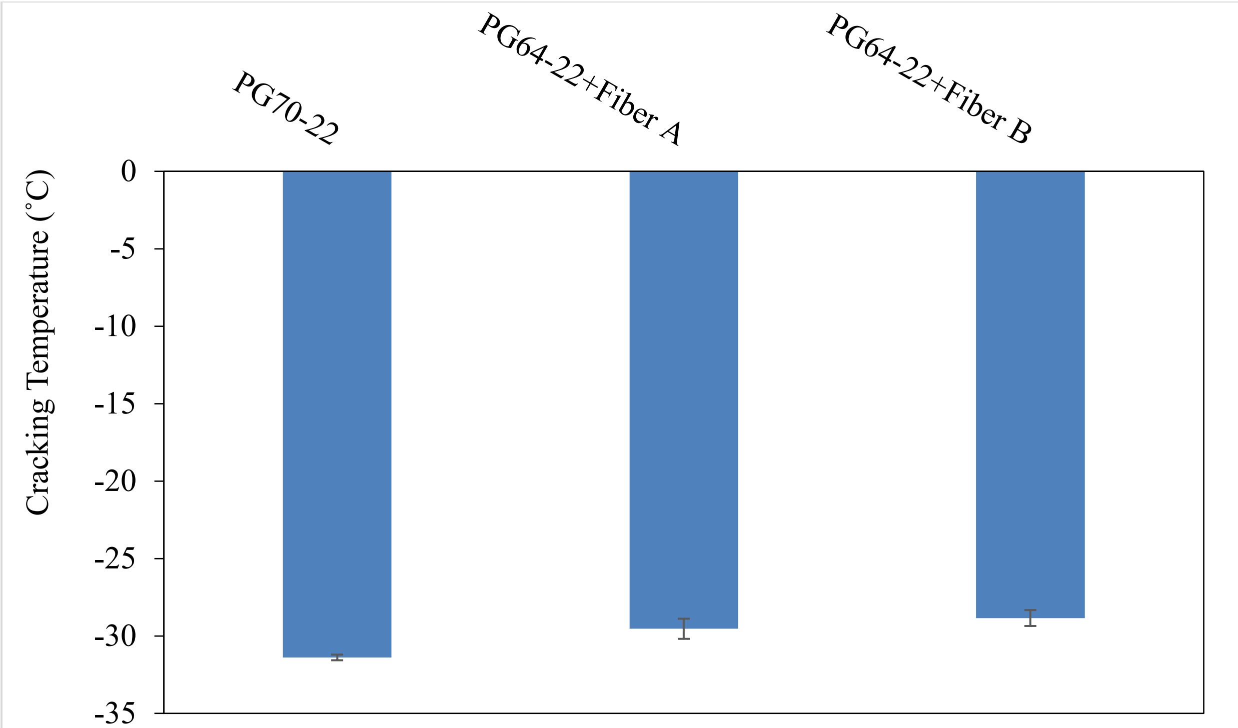


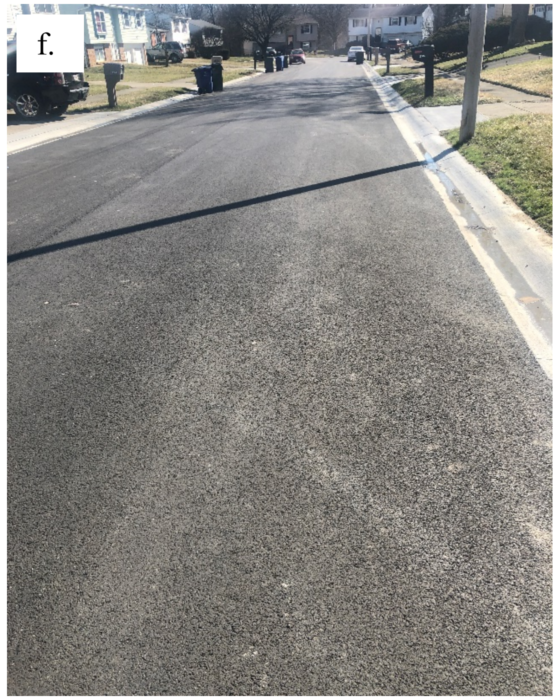
Figure B.26 ACCD Cracking Temperature for Lab Compacted Samples for the City of Kettering Mixes

B.5 Results of Field Evaluation

Performance evaluations were conducted three and six months after the construction of the test sections in this study. Figures B.15 through B.17 presents the pictures taken during the six months evaluation for test sections in City of Columbus, Fayette County, and City of Kettering, respectively. It is noted that there were no observed distresses in the test sections at the City of Columbus or the City of Kettering after six months of construction. For Fayette county sections, it was noted that Fiber A section had no observed distresses after six months of construction, while the control mix section (PG 58-28 mix) and section that included mix PG 58-28 and Fiber B showed hairline transverse cracking at some locations.


a.
b.
c.
d.


e.


f.


g.


h.

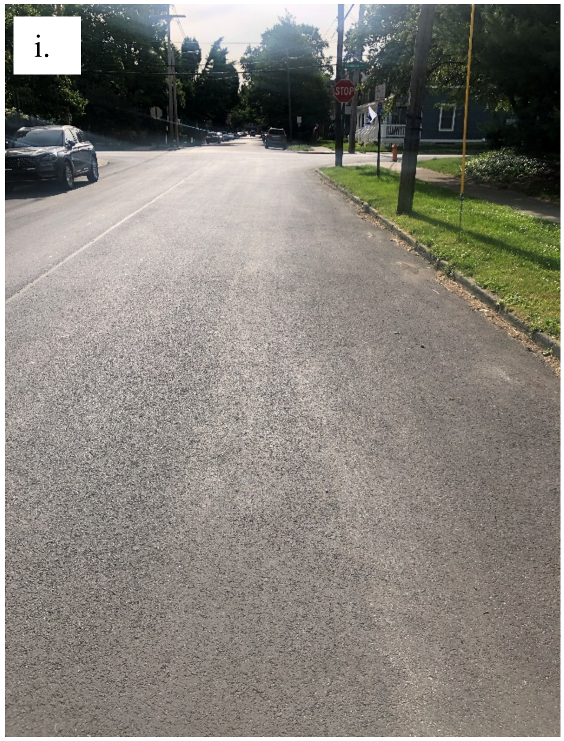


Figure B.15 Pictures Taken of City of Columbus Test Sections after Six Months of Construction: a) Columbus Project 1 – PG 70-22M section, b) Columbus Project 1 – PG 64-22 + Fiber A Section, c) Columbus Project 1 – PG 64-22 + Fiber B section d) Columbus Project 2- PG 64-22, e) Columbus Project 2- PG 64-22 + Fiber A section, f) Columbus Project 2 - PG 64-22 + Fiber B section, g) Columbus Project 3- PG 64-22 section, h) Columbus Project 3- PG 64-22 + Fiber A section, and i) Columbus Project 3- PG 64-22 + Fiber B section.

Figure B.16 Pictures Taken of Fayette County Test Sections after Six Months of Construction: a) Fayette County- PG 58-28 section, b) Fayette County- PG 58-28 + Fiber A section, and c) Fayette County - PG 58-28 + Fiber B section

Figure B.17 Pictures Taken of city of Columbus Test Sections after Six Months of Construction: a) City of Kettering- PG 64-22 + Fiber A section, b) City of Kettering- PG 64-22 + Fiber B section, and c) City of Kettering- PG 70-22M section.

B.6 References

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Appendix D Phase 1 Interim Report

Analysis of Aramid Synthetic Fibers in Asphalt Mixes on Local Roads

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15. Supplementary Notes

16. Abstract

This report summarizes Phase 1 study to evaluate the rutting and cracking resistance of non-polymer-modified aramid fiber-reinforced asphalt mixes used for resurfacing applications on local roads and to compare it to that of polymer-modified asphalt mixes. To determine the factor affecting the performance of aramid fiber reinforced asphalt mixes, a laboratory test plan was developed. The test plan included two types of aramid fibers, two fiber lengths (0.75 in. and 1.5 in.), and two dosage levels. Using single asphalt mix design and PG 64-22 unmodified binder, asphalt mixes were prepared. Additional mixes were also prepared using PG 70-22M polymer modified and PG 58-28 binders with few selected aramid fiber length and dosage. Cracking resistance of asphalt mixes were evaluated using semi-circular bend (SCB) test, IDEAL-CT, and Overlay Tester. Rutting resistance and moisture resistance were evaluated using Hamburg Wheel Tracking (HWT) test. The asphalt concrete cracking device (ACCD) was used to determine the low temperature cracking resistance.

Statistical analyses showed there were very strong interactions among aramid fiber type, fiber length, and dosage. For short length (0.75 in.) fibers, asphalt mixes with Type B (a blend of aramid and polyolefin) fibers showed a significant improvement in cracking resistance. For long length (1.5 in.) fibers, asphalt mixes with Type A aramid fibers showed a significant improvement in cracking resistance. Doubling the supplier recommended dosage resulted in, in many cases, asphalt mixes with significantly reduced cracking resistance. All aramid fiber reinforced unmodified PG 64-22 mixes showed satisfactory resistance to rutting, moisture damage, and low temperature cracking resistance. PG 58-28 mixes with or without aramid fibers showed the highest cracking resistance and low temperature performance among mixes tested. However, their resistance to rutting and moisture damage were significantly lower than other mixes. The optimum aramid fiber formulation for cracking resistant asphalt mixes for Type A aramid fiber was 1.5 in. length and the supplier recommended dosage. The optimum formulation for Type B aramid fiber was 0.75 in. length and the supplier recommended dosage. Life cycle cost analysis indicated that mixes with aramid fibers were less expensive than conventional unmodified and polymer modified asphalt mixes by 25% to 35%.

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Analysis of Aramid Synthetic Fibers in Asphalt Mixes on Local Roads

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Analysis of Aramid Synthetic Fibers in Asphalt Mixes on Local Roads

Executive Summary

This report summarizes Phase 1 study to evaluate the rutting and cracking resistance of non-polymer-modified aramid fiber-reinforced asphalt mixes used for resurfacing applications on local roads and compare it to that of polymer-modified asphalt mixes. To determine the factor affecting the performance of aramid fiber reinforced asphalt mixes, a laboratory test plan was developed. The test plan included two types of aramid fibers (Type A: wax treated aramid fibers and Type B: a blend of aramid and polyolefin fibers), two fiber lengths (0.75 in. and 1.5 in.), and two dosage levels (one time and two times of suppliers' recommended dosage). This 2 x 2 x 2 laboratory factorial design was performed using PG 64-22 unmodified binder and an asphalt mix design commonly used by Local Public Agencies (LPA). Additional tests were performed using PG 70-22M polymer modified and PG 58-28 binders with few selected aramid fiber length and dosage. Cracking resistance of asphalt mixes were evaluated using semi-circular bed (SCB) test, IDEAL-CT, and Overlay Tester. Rutting resistance and moisture resistance were evaluated using Hamburg Wheel Tracking (HWT) test. The asphalt concrete cracking device (ACCD) was used to determine the low temperature cracking resistance. In addition, two 3-year old test sections in the City of Columbus constructed with and without aramid fibers were identified and evaluated to determine the field performance of aramid fiber reinforced unmodified asphalt mixes. The results of Light Weight Deflectometer (LWD) tests performed on-sites indicated that the use of aramid fibers increased the structural capacity of the test sections, showing higher modulus values.

Statistical analyses showed there were very strong interactions among aramid fiber type, fiber length, and dosage. The effects of fiber length or dosage was strongly dependent on aramid fiber type. For short length (0.75 in.) aramid fibers, unmodified PG 6-22 asphalt mixes with Type B (a blend of aramid and polyolefin) fibers showed much higher cracking resistance as measured by SCB, IDEAL-CT, and Overlay Tester than mixes with unmodified PG 64-22 binder, polymer modified 70-22M binder, and unmodified PG 64-22 binder with Type A (wax treated aramid) fibers. For long length (1.5 in.) aramid fibers, unmodified PG 6-22 asphalt mixes with Type A aramid fibers showed much higher cracking resistance as measured by SCB, IDEAL-CT, and Overlay Tester than mixes with unmodified PG 64-22 binder, polymer modified 70-22M binder, and unmodified PG 64-22 binder with Type B aramid fibers. Doubling the recommended dosage by the fiber suppliers resulted in, in many cases, asphalt mixes with significantly reduced cracking resistance. All aramid fiber reinforced unmodified PG 64-22 mixes showed satisfactory resistance to rutting and moisture damage in HWT tests. PG 58-28 binder mixes with or without aramid fibers showed the highest cracking resistance among mixes tested. However, their resistance to rutting and moisture damage were significantly lower than other mixes. The optimum aramid fiber formulation for cracking resistant asphalt mixes for Type A aramid fiber was 1.5 in. length and the supplier recommended dosage. The optimum formulation for Type B aramid fiber was 0.75 in. length and the supplier recommended dosage.

The estimated increase in fatigue lives of unmodified PG 64-22 mixes due to addition of Type A aramid fibers and Type B aramid fibers were 104% and 65%, respectively. Cost analysis showed that unmodified PG 64-22 mix with Type A aramid fiber could be 35% less expensive than unmodified PG 64-22 mix. Unmodified PG 64-22 mix with Type B aramid fiber could be 27% less expensive than unmodified PG 64-22 mix. Unmodified PG 64-22 mix with Type A and Type B aramid fibers could be, respectively, 37% and 29% less expensive than polymer modified PG 70-22M mix.

Based on the results of Phase 1, it is recommended to conduct a field study aimed at comparing the performance of the recommended non-polymer mixtures reinforced with Type A fiber with length of 1.5 in. and non-polymer mixtures reinforced with Type B fiber with length of 0.75 in. An aramid fiber dosage of 2.1 oz per ton of mix should be used for both types, i.e. of 4.2 oz Type A per ton of mix and 16 oz. Type B per ton of mix. The field study should also compare the performance of non-polymer aramid fiber reinforced mixtures to those with polymer modified PG 70-22M binder. In addition, Phase 2 should compare the field performance under different conditions of existing pavement of sections with non-polymer aramid fiber reinforced mixture to those with SAMI and asphalt mixes with non-polymer and polymer modified binders.

2. Project Background

Over the past three decades, polymer-modified asphalt binders have been used in the United States to enhance the performance and service life of asphalt pavements and overlays. Polymer-modified binders have higher stiffness and elasticity as well as better adhesion to the aggregate particles than unmodified binders (*1*). Therefore, polymer-modified binders can enhance the resistance of asphalt mixtures to rutting, cracking, and moisture-induced damage. Previous studies have shown that the use of polymer-modified asphalt mixes instead of unmodified asphalt mixes can improve the performance and subsequently increase the service life of asphalt overlays by up to 6 years (*1*). Although polymer-modified asphalt mixes have several advantages, they are more expensive than those produced with unmodified (neat) asphalt binders. In addition, local public agencies (LPAs) typically requires that the pavement surface and the air temperature are at least 50°F for placing a surface course with a polymer-modified asphalt binder. Most LPAs as well as the Ohio Department of Transportation (ODOT) do not allow paving with polymer-modified asphalt mixes after November 1 (*2*). These requirements limit the time polymer asphalt mixes can be used in the construction season resulting in an increased unpredictability to construction schedules, which can result in additional costs to bid items associated with polymer-modified asphalt placement. Therefore, the use of polymer-modified asphalt mixes by LPAs is typically limited to roads with relatively high truck traffic volumes and/or loads.

Asphalt overlay is a common technique transportation agencies in Ohio use for rehabilitation of structurally or functionally deteriorated roads. One of the main types of distresses that develop in overlays is reflection cracking. This type of cracking develops in an asphalt overlay over an existing crack or joint. Several types of treatments have been proposed and used to control or delay reflection cracking (*3, 4*). One of the most common approaches used by LPAs in Ohio is to install a stress-absorbing membrane interlayer (SAMI) between the existing old pavement and the new overlay. SAMI consists of a highly polymerized asphalt emulsion and a quality crushed aggregate that is installed much like a chip seal. SAMI is used to reduce the tensile stress in the overlay in the vicinity of a crack in the underlying old layer (*4*). The use of SAMI results in an increase in a project cost and duration as it requires more time for its application and curing. Furthermore, the SAMI effectiveness is still not well quantified to date (*4*).

Different technologies have been developed and used to enhance the resistance of asphalt mixes to different types of distresses in new flexible pavements and overlays. One of these technologies is the use of fibers. ODOT has supplemental specification 826 for the use of fibers in asphalt mixes (*2*). This specification allows the use of different types of fibers in asphalt mixes: polyester, polypropylene, and aramid. The aramid fibers are heat-resistant fibers that have a much higher tensile strength than the other two types of fibers. They are mixed with fibrillated polyolefin fibers or wax coated to ensure proper distribution within the mix. Over the last decade, there has been an increased interest in using aramid fibers to enhance the performance of asphalt mixes as they have been shown to enhance the rutting and cracking resistance of the asphalt mixtures (e.g. *5-7*). In addition, aramid fibers can help in absorbing the tensile stresses in an asphalt overlay. Therefore, they can potentially be used to control and/or delay the development of reflection cracking in an overlay; thus, eliminating the need for the SAMI. This can reduce the cost of resurfacing projects and can result in an estimated cost saving of more than $175,000 per year for one city in Ohio where SAMI is extensively used. One of the advantages of non-polymer modified aramid fiber-reinforced asphalt mixes is that they can be placed at temperatures as low as 40ºF (instead of 50ºF for polymer-modified asphalt mixes). In addition, fibers can be easily included in an asphalt mixture during production in both batch and drum plants without the need to modify the binder at the terminal as in the case with some polymer modified asphalt binders.

Despite the potential benefits for the use of aramid fibers in asphalt mixes, limited information is available on the field performance of aramid fiber-reinforced asphalt mixes as overlays on local roads. Furthermore, no research has been conducted to compare their effectiveness in reducing the reflection cracking to that of the SAMI. Therefore, research is needed to evaluate the cost-effectiveness of using non-polymer modified aramid fiber-reinforced asphalt mixes on local roads. The proposed project will assess the performance of non-polymer-modified aramid fiber-reinforced asphalt mixes used on local roads and compare it to that of polymer-modified asphalt mixes. Furthermore, this project will also compare the performance and life cycle costs of overlays constructed using non-polymer-modified fiber-reinforced asphalt mixes without a SAMI to those constructed with non-fiber-reinforced mixes (both polymer-modified and non-polymer-modified) with the use of a SAMI. In addition, the proposed project will develop recommendations for designing a cost-effective non-polymer-modified aramid fiber-reinforced asphalt mixes that can reduce cracking and rutting on local roads.

6. Research Context

The main goal of this study is to evaluate the rutting and cracking resistance of non-polymer-modified aramid fiber-reinforced asphalt mixes used for resurfacing applications on local roads and compare it to that of polymer-modified asphalt mixes. Another objective of this study is to compare the performance of non-polymer-modified fiber-reinforced asphalt mixes without the use of SAMI to non-fiber-reinforced mixes (both polymer-modified and non-polymer-modified) with the use of SAMI to control reflection cracking. The specific objectives of this project include:

- Identify the optimal aramid fiber dosage for use in non-polymer-modified mixes to reduce the rutting and cracking of surface course layers on local roads.
- Provide recommendations for designing cost-effective non-polymer-modified aramid fiber-reinforced asphalt mixes that can reduce cracking and rutting on local roadways.

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

Task 1. Perform Literature Review
Task 2: Develop Laboratory Testing Plan

Task 3: Evaluate Previously Constructed Test Section with Fiber-Reinforced Asphalt Mix Projects in Columbus
Task 4: Conduct Laboratory Testing Plan
Task 5: Conduct Cost-Benefit Analysis
Task 6. Design a Study for Field and Laboratory Testing in Phase 2
Task 7. Prepare and Submit Interim Report
Task 8. Construction of Pavement Test Sections
Task 9. Lab Testing of Field Samples:

7. Research Approach

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

3.1 Literature Review

A comprehensive literature review was conducted in this study on the use of aramid fibers in asphalt mixes particularly non-polymer modified mixtures. A summary of the comprehensive literature review performed in this study is presented in Appendix A.

3.2 Evaluate Previously Constructed Test Section with Fiber-Reinforced Asphalt Mix Projects in Columbus

In this task, the research team obtained all available information for the City of Columbus roadway that had one lane resurfaced with a fiber-reinforced PG 70-22M asphalt mix without SAMI and another resurfaced with a non-fiber-reinforced PG 70-22M asphalt mix with the use of SAMI. In addition, the research team coordinated with the City of Columbus to visit the site to evaluate the pavement condition for the two lanes. The site visit included evaluating the structural capacity of roadway with and without SAMI. This was done using the light weight deflectometer (LWD). The LWD data was used to determine the composite modulus of the current pavement conditions. At least eight 6-inch core samples were also obtained from each lane. The IDEAL-CT, SCB and ACCD tests were conducted on the obtained core samples to determine the fatigue and low-temperature cracking resistance of mixes obtained from both lanes.

3.3 Develop Laboratory Testing Plan

The research team developed a comprehensive laboratory testing plan to evaluate the effects of aramid fibers on the resistance to fatigue cracking, low-temperature cracking, reflection cracking, rutting, and moisture damage of non-polymer modified asphalt mixtures. The following sets of variables were included in the laboratory testing plan:

1. **Asphalt binder type:** The most commonly used non-polymer modified asphalt binders in construction of local roads in Ohio were considered. These will include PG 64-22 and PG 58-28. In addition, a polymer modified asphalt binder meeting Ohio specifications for PG 70-22M will be used for comparison.
2. **Aramid fiber type:** There are two main types of aramid fibers that have been used in previous studies in reinforcing dense graded asphalt mixes: wax treated aramid fibers and a blend of aramid and polyolefin fibers. The research team considered and evaluated both types.
3. **Aramid fiber length:** two different aramid fiber lengths were evaluated: 0.75 inch and 1.5 inch.

4. **Aramid fiber dosage:** The aramid fiber dosage was varied to determine its effect on the mix performance. Three different fiber dosages were considered: recommended dosage, double recommended dosage and 1.5 times the recommended dosage

3.4 Testing Program

3.4.1 Materials

Wax treated aramid fibers and a blend of aramid and polyolefin fibers were used for this study. The recommended dosages by suppliers for the wax treated aramid fibers and the blend of aramid and polyolefin fibers are summarized in Table 1. To facilitate laboratory mixing, the wax treated aramid fibers were provided with fiber and wax separately. Limestone aggregate from Olen at Columbus and RAP from Franklin County were used for preparation of test samples of all mixes.

Table 1. Manufacturer recommended dosage of aramid fibers.

Aramid Fiber Type	Aramid (oz/ton of mix)	Wax/Polyolefin (oz/ton of mix)
Wax Treated	2.1	4.2
Blended with Polyolefin	2.08	15.66

A unique ID was assigned to each asphalt mix to include all four study variables as shown in Table 2. The first 2 letters of each ID are for the binder type, the third letter for the aramid fiber type, the fourth letter for the fiber length, and the remaining letters are for dosage. For example, the mix ID "64AS2" was prepared with PG ***64***-22 binder with wax treated aramid fiber (***A***) having 0.75 inch length (***S***hort) with doubled recommended dosage (x***2***). Total of 15 asphalt mixes were prepared and tested. The first three no-fiber mixes served as a control group to measure the effects

Table 2. Mix variables and coding of asphalt mix ID.

Mix Variable	Code	Description
Asphalt binder type (First 2 letters of ID)	58	PG 58-28
	64	PG 64-22
	70	PG 70-22M
Aramid fiber type (3rd letter of ID)	N	No fiber
	A	Wax treated aramid fiber
	B	Blend of aramid and polyolefin fibers
Aramid fiber length (4th letter of ID)	S	Short = 0.75 inch
	L	Long = 1.5 inch
Aramid fiber dosage (remaining letters of ID)	1	(x1) Recommended dosage
	1.5	(x1.5) 1.5 times recommended dosage
	2	(x2) Doubled recommended dosage

of the presence of aramid fiber in asphalt mixes. The next eight mixes were all prepared with PG 64-22 binder, the most common binder type for Local Public Agencies (LPA), to determine the effects of the aramid fiber type, length and dosage with full factorial design, ensuring sound statistical analysis. Based on the results of eight-mix factorial experiments, four additional asphalt mixes were prepared and tested to validate dosage (x1.5) and another common binder type used by LPAs (PG 58-28 binder).

1.1.1 Asphalt Mixtures

To evaluate the effects of the RAP materials on the mixture performance, a job mix formula (JMF) for an asphalt mixture with RAP that was used in construction of a surface course layer in a resurfacing project in the city of Columbus was obtained from the Kokosing Materials Company. The considered asphalt mixture had a 1/2 inch (12.5 mm) nominal maximum aggregate size (NMAS) and was designed to meet ODOT specifications for Item 441 for medium traffic surface mixtures. The selected mixture included PG 64-22 asphalt binder. The aggregate blend of the selected mixture used included: 47% limestone #8, 32% manufactured sand, 1% baghouse fines and 20% reclaimed asphalt pavement (RAP) that was processed using ODOT 401.04 Method 2.

1.1.2 Mixture Testing

Tests were performed on the mixtures to evaluate their resistance to cracking, moisture damage, low-temperature cracking, and rutting. Reflective and fatigue cracking potential of all asphalt mixes was evaluated using semi-circular bend (SCB) test, IDEAL-CT, and Overlay Tester. Rutting and moisture susceptibility of asphalt mixtures were measured using Hamburg Wheel Tracking test. The asphalt concrete cracking device (ACCD) was used to evaluate the low temperature cracking resistance. All samples for these tests were compacted to a target air void of 7± 0.5% except the low-temperature cracking test using the Asphalt Concrete Cracking Device where compaction was done with 20 number of gyrations to simulate constant compaction effort in Marshall mix design process.

The effects of the fiber length and dosage were studied using PG 64-22 asphalt binder with full factorial design. For PG 58-28 asphalt binder, only one best performing combination of fiber length and dosage was used for each aramid fiber type based on the results of full factorial study with PG 64-22 asphalt binder. It is noted that all mixture in this task will include a RAP content that is typically used by the involved cities. All mixtures will have the same RAP content to eliminate the effect of RAP content on the test results. All asphalt mixes were short-term aged by placing loose mixture for four hours at 135°C prior to compaction.

1.1.2.1 Semi-Circular Bending (SCB) Test

The SCB test was conducted on each mixture to evaluate the fatigue cracking performance at an intermediate temperature of 25ºC. The SCB tests were performed according to the Illinois SCB Test Method (AASHTO TP 124-16: *Determining the Fracture Potential of Asphalt Mixtures Using Semicircular Bend Geometry (SCB) at Intermediate Temperatures)*. In this method, samples with 150-mm diameter were compacted to a height of 150 mm. Each sample was cut in half and the ends trimmed to obtain a thickness of 50 ± 1 mm. Each 50-mm thick sample was then cut in half to create the semi-circular shape. A notch with a depth of 15 mm and a width of 2.5 mm was cut into the center of the sample, as shown in Figure 1. The SCB test was conducted on at least four short-term aged 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.

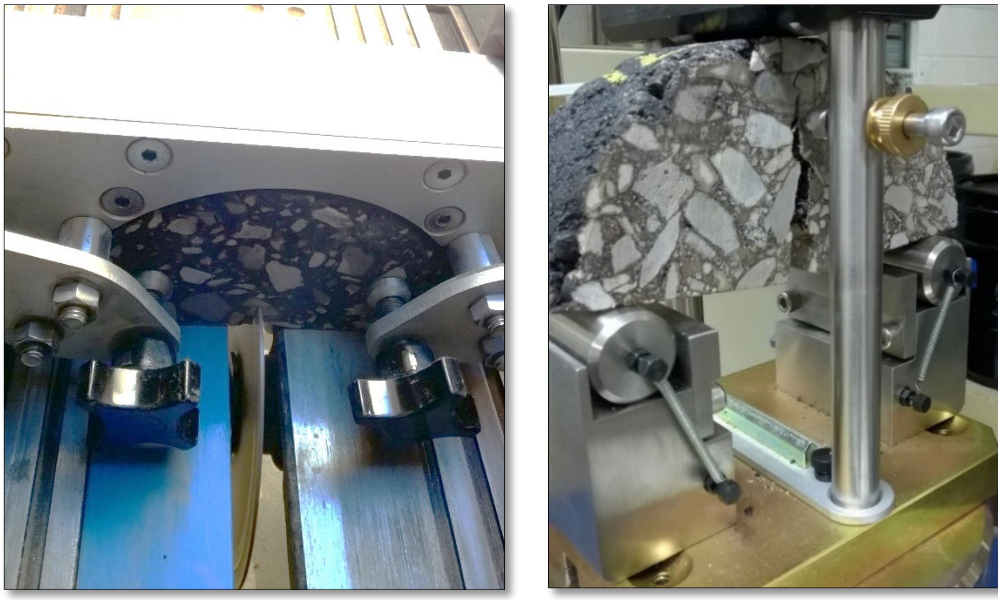

Figure 1. Illinois SCB Sample Preparation and Testing Equipment

The main output of the SCB-IL is a load versus deformation plot. From this plot, the Fracture Energy (FE) and the Flexibility Index (FI) are calculated using Equations 1 and 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 premature cracking (*5*). Since the Fracture Energy is a function of the peak load and displacement, Nazzal et al. (*6*) recommended normalizing the fracture energy values based on the peak strength mixture. Therefore, the normalized fracture energy (NFE) value was used in this study to examine the cracking resistance of the core samples. The higher the FI and NFE, the better the cracking resistance of asphalt mixes.

$$FE = \frac{W_f}{Area_{lig}} \text{ x } 10^6 \tag{1}$$

Where:

FE = fracture energy (Joules/m^2)

W_f = work of fracture, or area beneath load vs. displacement curve up to peak load (Joules)

$Area_{lig}$ = ligament area, ligament thickness × length (mm^2)

$$\text{FI} = \frac{G_F}{|m|} \text{ x A} \tag{2}$$

Where:

$|m|$ = absolute value of slope at inflection point

A = unit conversion (0.01)

1.1.2.2 IDEAL-CT

Zhou et al. (*7*) recently developed a test called IDEAL-CT where 150-mm diameter specimen is compacted to 62±2-mm thickness and tested without cutting or trimming. This test is similar to the traditional indirect tensile test (IDT). However, Zhou et al. (*7*) proposed a new procedure to analyze the IDT load – displacement curve, which was inspired by the laws of crack propagation (*8, 9*). Based on this procedure, a parameter called cracking tolerance index (CTI) is determined using Equation (3) and as shown in Figure 3. It is noted that Zhou et al. (*7*) found that CTI correlates well with the field cracking performance of asphalt mixtures.

$$CTI = \frac{G_f}{|m_{75}|} \times \left(\frac{l_{75}}{D}\right) \tag{3}$$

G_f: is the fracture energy which is the total area under load – displacement curve (work of fracture) divided by the area of cracking face (thickness, t x D)
D: is sample diameter (mm)
l_{75}: is displacement corresponding to the 75 percent of the peak load at the post-peak stage
m_{75}: is slope calculated as shown in Figure 2 using the following equation

$$|m_{75}| = \left|\frac{P_{85}-P_{65}}{l_{85}-l_{65}}\right| \tag{4}$$

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

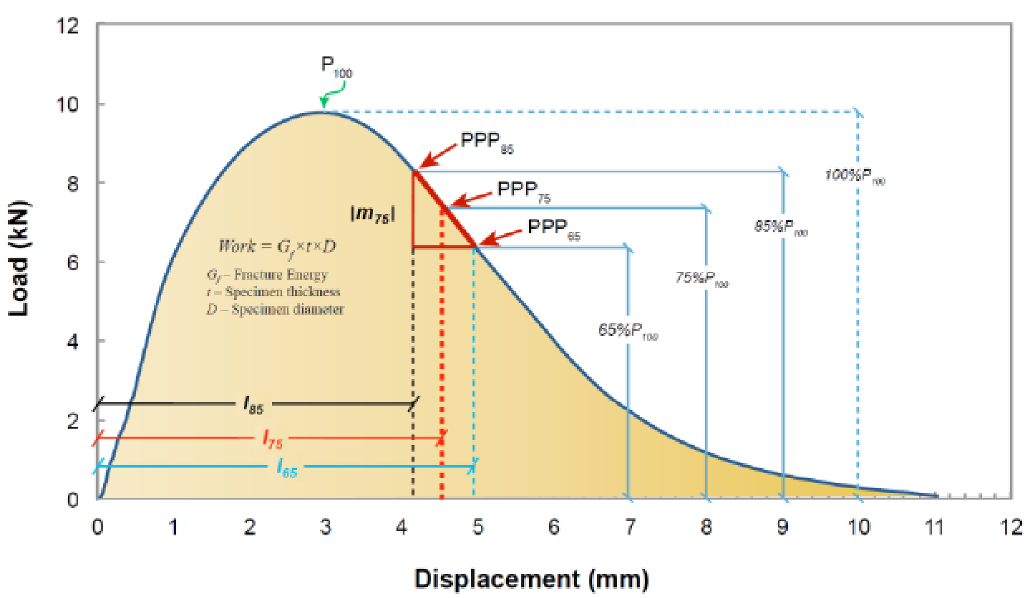

Figure 2. Illustration of the slope $|m75|$ in CTI calculation (*7*)

1.1.2.3 Overlay Tester (OT)

Overlay tester was initially developed to evaluate the reflection crack resistance of hot mix asphalt (HMA) overlay and also proposed for characterization of fatigue crack resistance (*9*). For OT test, a 150 mm diameter compacted specimen is trimmed to dimensions of 150mm length 75mm width and 38mm thickness. As shown in Figure 3, the trimmed specimen is bonded to a movable and a fixed aluminum plates with 2mm gap that opens and closes. As the test begins at a constant temperature (25°C), the movable plate slide horizontally in a cyclic triangular wave form to a constant displacement of 0.6 mm (0.025 in.). One cycle of OT loading is defined as the sliding block reaches the maximum displacement and returns to its initial position in 10 seconds. The test continues up to 1,200 cycles or the load to the maximum displacement reduced by 93% in comparison to the maximum load recorded for the first opening cycle.

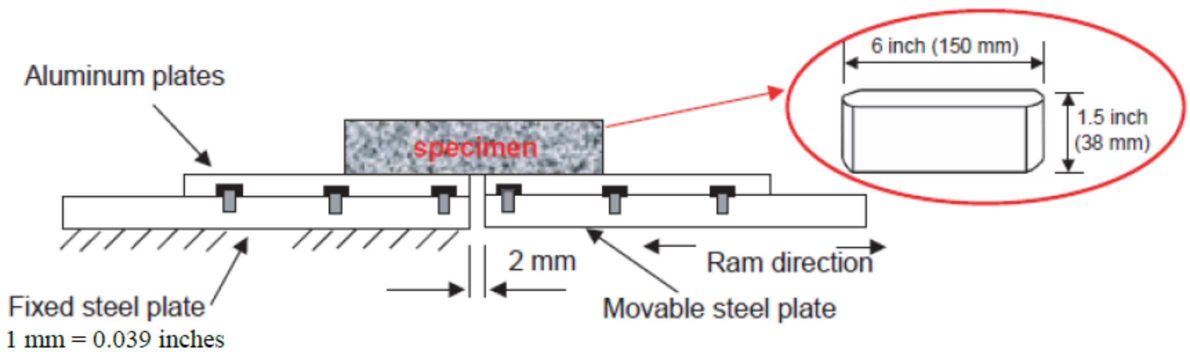

Figure 3. Schematics of Overlay Tester (OT)

1.1.2.4 Asphalt Concrete Cracking Device (ACCD)

ACCD test is a concentric thermal stress restrained specimen test or concentric TSRST to evaluate the low-temperature cracking resistance of asphalt mixtures (*10*). In this test, short-term aged 150-mm diameter specimen is compacted to 50 to 55-mm thickness. Then, the middle 60-mm diameter was cored out to fit with ACCD ring for testing. A 22.4-mm (0.88-inch) long-notch was cut at the outer surface of the 150-mm diameter 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 4). After holding for one hour at 10°C, the chamber was cooled to -60°C at 10°C per hour. As the temperature decreased, the contraction of the asphalt mix specimen was restrained by the ACCD ring, developing tensile stress within the test specimen and compressive stress within the ACCD ring. Four samples can be typically tested at the same time. The temperature and strain of each ACCD ring were continuously recorded throughout the test. The temperature corresponding to the maximum slope of the ACCD strain-temperature curve was considered as the onset on thermal cracking. The point at which the slope of the strain-temperature curve equals to eighty percent of the maximum slope after the onset of cracking is defined as the ACCD cracking temperature. A computer program determines the maximum slope and the ACCD cracking temperature as shown in Figure 4. The ACCD strain at the failure is related to the strength of the mixes.

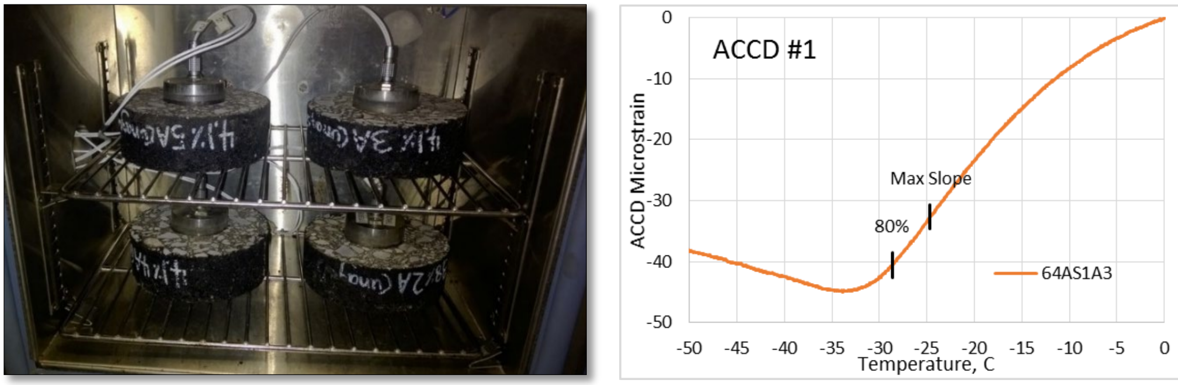

Figure 4. ACCD test setup and typical test results

1.1.2.5 Hamburg Wheel Tracking

Hamburg Wheel Tracking (HWT) is used to measure rutting and moisture resistance of asphalt mixtures (*11*). HWT test was performed following AASHTO T324 procedure where a steel wheel with the load of 705N (158 lb) travels back-and-forth at a rate of 52 passes per minute on the test specimen submerged in 50°C water. The steel wheel has a diameter of 203mm (8 in.) and a width of 47mm (1.85 in.). Figure 5 shows the HWT tester capable of testing two sample simultaneously.

A typical HWT rut depth – number of pass relationship is also shown in Figure 5. For the first few passes, specimen goes through a consolidation phase followed by a steady-state creep slope until asphalt binder starts to strip from aggregate and to exhibit a steep slope known as a strip slope. The intersection of the creep slope and the strip slope is defined as a stripping inflection point (SIP). The magnitude of the maximum impression is used as a measure of rutting resistance and SIP as a measure of the resistance to moisture damage.

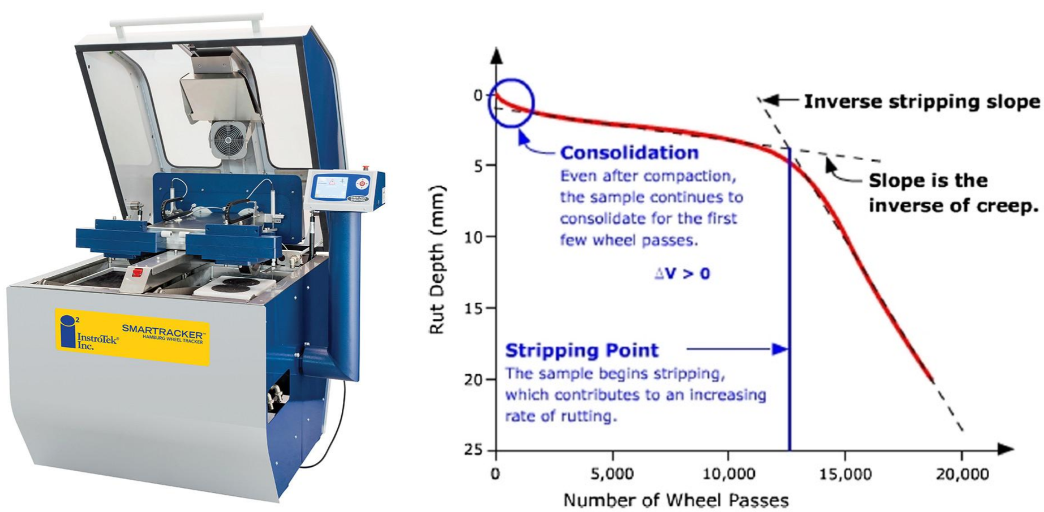

Figure 5. Hamburg Wheel Tracking Tester and typical results

3.5 Cost Analysis

In this study, Equivalent Uniform Annual Costs (EUAC) of asphalt mixes were used to determine the cost effectiveness of aramid fibers in asphalt mixes. In EUAC calculation shown in Equation 5, initial and all future costs including maintenance and repairs throughout the analysis period are expressed as a single cost in terms of the present year monetary value, known as Net Present Value (NPV).

$$EUAC = NPV\left[\frac{i(1+i)^n}{(1+i)^n - 1}\right] \tag{5}$$

Where
NPV: net present value
i: discount rate (4%)
n=analysis period (= service life)

For service life estimation, it was assumed that fatigue/reflective cracks were only distress to be considered. The service life of aramid fiber reinforced asphalt mixes, conventional unmodified, and polymer modified asphalt mixes were estimated based on cracking resistance measured by SCB, IDEAL-CT, and Overlay Tester and their relationship with pavement performance. The estimated service life was used as the analysis period for EUCA calculation.

8. Research Findings and Conclusions

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

4.1 Literture Review Findings

- Several research studies reported that aramid fiber-reinforced asphalt mixtures have much better rutting resistance than unreinforced asphalt mixtures.
- In general, aramid fiber-reinforced asphalt mixtures were reported to have better rutting resistance than polymer-modified asphalt mixtures. However, one study suggested that the improvement was significant at a higher fiber content rather than that the dose recommended by the manufacturer.
- Aramid fibers were reported to provide additional tensile strength in the resulting composite and potentially can increase the amount of strain absorbed during the fatigue and fracture process of the mixture.
- In general, the lab test results showed that the fiber-reinforced mixes had better performance under high fatigue strains, while polymer-modified mixes performed better under small to medium fatigue strains.
- Results of field studies indicated that the aramid fibers improved the fatigue cracking resistance of asphalt mixture and had better fatigue performance than both the polymer-modified and non-polymer-modified asphalt mixes.

- The incorporation of aramid fibers into an asphalt mixture was reported to delay the development and propagation of cracks, resulting in less cracking in aramid reinforced pavement sections.
- Previous studies reported slight to no improvement in low-temperature properties of asphalt mixtures due to the use of aramid fibers.
- Adding fibers to the original mix did not impact its compactability in the laboratory and did not seem to change its volumetrics. Therefore, fibers were not found to affect the mix design parameters.
- Limited work has been done to compare the two types of aramid fibers.
- One study found that the longer fibers (1.5” in length) appeared to perform better than regular-size fibers (0.75” in length) in improving the fracture characteristics of asphalt concrete materials. However, another studies found that using shorter fibers can result in better performance for the reinforced asphalt mixture.
- Increasing the fiber dosage was reported to improve the performance of the reinforced asphalt mixture up to a certain limit. That limit was about 4 times the dosage recommended by the manufacturer.

4.2 Analysis Findings

- Evaluation of two 3-year old local roadways in City of Columbus indicated all sections of unmodified PG 64-22 and polymer modified PG 70-22M mixes with and without aramid fiber reinforcement were in good condition with pavement condition rating (PCR) ranging 92-99.
- Light Weight Deflectometer (LWD) tests performed on-sites indicated that the use of aramid fibers increased the structural capacity of the local roads, showing higher modulus values.
- The results of SCB and IDEAL-CT tests on the cores taken from the local roadways showed that the effectiveness of aramid fibers on PG 70-22M polymer modified mix was not clear.
- For short length (0.75 in.) aramid fibers, unmodified PG 6-22 asphalt mixes with Type B (a blend of aramid and polyolefin) fibers showed much higher cracking resistance as measured by SCB, IDEAL-CT, and Overlay Tester than mixes with unmodified PG 64-22 binder, polymer modified 70-22M binder, and unmodified PG 64-22 binder with Type A (wax treated aramid) fibers.
- For long length (1.5 in.) aramid fibers, unmodified PG 6-22 asphalt mixes with Type A aramid fibers showed much higher cracking resistance as measured by SCB, IDEAL-CT, and Overlay Tester than mixes with unmodified PG 64-22 binder, polymer modified 70-22M binder, and unmodified PG 64-22 binder with Type B aramid fibers.
- Doubling the recommended dosage by aramid fiber suppliers resulted in, in many cases, asphalt mixes with significantly reduced cracking resistance.
- All aramid fiber reinforced unmodified PG 64-22 mixes showed satisfactory resistance to rutting and moisture damage.
- PG 58-28 binder mixes with or without aramid fibers showed the highest cracking resistance among mixes tested. However, their resistance to rutting and moisture damage were lower than other mixes.
- The optimum aramid fiber formulation for cracking resistant asphalt mixes for Type A aramid fiber was 1.5 in. length and the supplier recommended dosage. The optimum formulation for Type B aramid fiber was 0.75 in. length and the supplier recommended dosage.

- The estimated increase in fatigue lives of unmodified PG 64-22 mixes due to addition of the optimum Type A aramid fiber and Type B aramid fiber were 104% and 65%, respectively.
- Cost analysis showed that unmodified PG 64-22 mix with Type A aramid fibers could be 35% less expensive than unmodified PG 64-22 mix.
- Cost analysis showed that unmodified PG 64-22 mix with Type B aramid fibers could be 27% less expensive than unmodified PG 64-22 mix.
- Cost analysis showed that unmodified PG 64-22 mix with Type A aramid fibers could be 37% less expensive than polymer modified PG 70-22M mix.
- Cost analysis showed that unmodified PG 64-22 mix with Type B aramid fibers could be 29%, less expensive than polymer modified PG 70-22M mix.

7. Recommendations for Implementation

Based on the results of Phase 1, it is recommended to conduct a field study aimed at comparing the performance of the recommended non-polymer mixtures reinforced with Type A fiber with length of 1.5 in and non-polymer mixtures reinforced with Type B fiber with length of 0.75 in. An aramid fiber dosage of 2.1 oz per ton of mix should be used for both types (i.e. 4.2 oz. of Type A per ton of mix and 16 oz Type B per ton of mix. The field study should also compare the performance of non-polymer aramid fiber reinforced mixtures to those with polymer modified PG 70-22M binder. In addition, Phase 2 should compare the field performance under different conditions of existing pavement of sections with non-polymer aramid fiber reinforced mixture to those with SAMI and asphalt mixes with non-polymer and polymer modified binders. To achieve that, the field study should include constructing the following test sections in the different participating LPAs:

City of Columbus Test Sections:

a) Three test sections constructed part of a project with an asphalt overlay on top of a brick road. The sections should use the following:
   1. Surface course mix with PG 64-22 and Aramid Fiber A.
   2. Surface course mix with PG 64-22 and Aramid Fiber B.
   3. Surface course mix with PG 64-22 but without any fiber (control mix). This section will have a SAMI layer.

b) Three test sections constructed as part of a project with an asphalt overlay on top of a concrete road. The sections should use the following:
   1. Surface course mix with PG 64-22 and Aramid Fiber A.
   2. Surface course mix with PG 64-22 and Aramid Fiber B.
   3. Surface course mix with PG 64-22 but without any fiber (control mix). This section will have a SAMI layer.

c) Three test sections constructed as part of a project with an asphalt overlay for an arterial road project. The sections should use the following:
   1. Surface course mix with PG 64-22 and Aramid Fiber A.
   2. Surface course mix PG 64-22 and Aramid Fiber B.
   3. Surface course mix PG 70-22M but without any fiber (control mix).

Fayette County Test Sections
Three test sections should be constructed with the following surface course mixes:

1. Mix with PG 64-22 and Aramid Fiber A.
2. Mix with PG 64-22 and Aramid Fiber B.
3. Mix with PG 64-22 but without any fiber (control mix).

City of Kettering Test Sections
Three test sections should be constructed with the following surface course mixes:

1. Mix with PG 64-22 and Aramid Fiber A.
2. Mix with PG 64-22 and Aramid Fiber B.
3. Mix with PG 70-22M but without any fiber (control mix).

The field study should also include evaluating the cracking resistance of the core samples obtained from the different test sections. In addition, the loose asphalt mixes should be obtained to prepare samples that will be compacted to a target air void of 7±0.5%. The SCB, IDEAL-CT, and HLWT tests should be used to evaluate the cracking and rutting performance as well as the durability of the field-produced lab-compacted samples.

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Appendix A Literature Review

A.1 Introduction

Asphalt overlays are commonly used for the rehabilitation of deteriorated flexible and rigid pavements. Several technologies have been developed and used to enhance the resistance of asphalt mixes to different types of distresses in new flexible pavements and overlays. One of these technologies is the use of fibers. Over the past decades, some research studies were conducted to evaluate the use of different types of fibers in dense-graded mixtures, which included: glass, carbon, carpet, cellulose, and synthetic polymeric (i.e. polypropylene, nylon, polyester, and aramid) fibers (*1*). In recent years, there has been an increased interest in using a heat resistant synthetic fiber that has a very high strength, called aramid fibers, in asphalt mixtures (*2*). These fibers have a minimum melting temperature of 800°F and a tensile strength of 400,000 psi. Two main types of aramid fibers have been used in asphalt mixes (Figure A.1): 1) a blend containing aramid fibers mixed with polyolefin fibers and 2) wax-treated aramid fibers. Table A.1 presents the main properties of these two types of aramid fibers that have been used in asphalt mixtures.

During the past decade, several studies have been conducted to evaluate the ability of aramid fibers to improve the rutting and cracking resistance of asphalt mixes and enhance the performance of asphalt overlays. This document presents a comprehensive summary of all active and completed studies on the use of aramid fibers in asphalt mixes. The focus of this review is on the effect of these fibers in reducing the fatigue cracking, reflection cracking, low-temperature cracking, and rutting of asphalt mixtures. In addition, the literature review is used to identify the factors that affect the performance of aramid fiber reinforced mixes including the properties of aramid fiber (such as the fiber length and dosage) as well as the delivery process for the aramid fibers.

A.2 Performance of Fiber Reinforced Mixes

Several studies have evaluated the effect of aramid fibers on the resistance of asphalt mixes to fatigue, reflection, and low-temperature cracking as well as rutting. The following subsections summarizes the results of these studies.

Figure A.1. Main Types of Aramid Fibers: a) Blend of Aramid and Polyolefin Fibers, b) Wax-Treated Aramid Fibers.

Table A.1. Properties of Aramid Fibers

Property	Wax-Treated Aramid Fiber	Blend of Polyolefin and Aramid Fibers
Form	Wax-treated aramid fiber and cut fiber clips	Blend of aramid And polyolefin fibers
Composition	50% aramid+50% Sasobit	13% aramid+87% polyolefin fibers
Recommended length	1.5 inch	0.75 inch
Recommended dosage	4.2 oz. per ton of mix	1 lb per ton of mix
Cost	$30.5 to $38.1 per pound depending on the amount.	$6.25 to $6.75 per pound depending on the amount.

A.2.1 Cracking Resistance Performance

Jaskuła et al. (*2*) reported that using the aramid and polyolefin fiber blend at a dosage of 1 lb. per ton resulted in improving the resistance of asphalt mixtures to fatigue cracking and low-temperature cracking. In addition, Kaloush et al. (*3*) reported that the tensile strength and fracture energy of mixes reinforced with the blend of aramid and polyolefin fibers were higher than those of the control unreinforced mix. The crack propagation resistance of the fiber-reinforced mixes was also 40 times higher than the control mix. They also reported that after two years from construction, the control section with the unreinforced mix had three times more cracking than the section constructed with fiber-reinforced mixes. Behnia (*4*) evaluated the effect of wax treated aramid fibers on asphalt mixtures. When using the recommended dosage of 4.2 oz. per ton, the wax treated aramid fibers enhanced the low-temperature and fatigue cracking of asphalt mixes.

A study by Gibson et al. (*5*) investigated the fatigue cracking performance for a fiber reinforced asphalt mixture versus polymer modified and non-polymer modified asphalt mixes in the Federal Highway Administration (FHWA) Accelerated Loading Facility (ALF). It was reported that fatigue-cracking resistance for the fiber-reinforced asphalt mixture was significantly better than that of both the polymer modified and non-polymer modified asphalt mixes. However, laboratory-testing results did not confirm the full-scale performance evaluation. Gibson and Li (*6*) investigated the cracking resistance of two sets of mixes from the same FHWA project mentioned earlier. It was indicated based on the results of the dynamic modulus test that the polymer modified mixes had more improvement to cracking resistance than the fiber reinforced mixes. However, based on the results of cyclic fatigue testing, it was reported that fiber reinforced mixes had better performance under high fatigue strains, while polymer modified mixes performed better under small fatigue strains.

Kaloush and Zeiada (*7*) investigated the effect of the inclusion of aramid fibers on the cracking resistance of an asphalt overlay in a local rehabilitation project in Tempe, Arizona. A blend of polypropylene and aramid fibers was utilized to reinforce conventional densely graded asphalt mixes (Figure A.2). It was reported that the blend of fibers was designed to reinforce the hot mix asphalt (HMA) in three directions. Batching and mixing were done at a local asphalt plant using a PG 70-10 asphalt binder with 5.0% asphalt content and ¾ inch as the nominal maximum aggregate size. A fiber dose of one pound of fibers per one ton of mix was used in the asphalt mix. Test sections constructed with control mix and fiber reinforced mixes were monitored for field performance. Loose samples of each mixture were obtained and tested using the triaxial shear strength, dynamic modulus, flow number, fatigue cracking, C* line integral for crack propagation, and indirect tensile tests. For fatigue resistance, it was reported that the fiber reinforced mix performed better at low strain levels, while the control mix performed better at high strain levels. The Mechanistic-Empirical Pavement Design Guide (MEPDG) software was used to confirm that the fiber reinforced mix is better to be used on roads with high traffic speeds. It was also reported that the tensile strength and fracture energy for the fiber-reinforced mix were higher at all testing temperatures and that the crack propagation resistance was 40 times higher than the control mix. Using the MEPDG software, the potential cost savings were calculated based on the reduced asphalt layer thickness of 30% to 40% when using the fiber-reinforced asphalt compared to a conventional mix asphalt. Furthermore, after 2 years from construction of test sections, it was reported that the control mix had about three times the amount of cracks found in the fiber-reinforced overlay.

Figure A.2. Loose Sample of a Plant-Produced Fiber-Reinforced Asphalt Mixture (*7*)

In a study by Muftah et al. (*8*), three types of fibers were studied to evaluate for performance of asphalt mixes and to optimize the addition of fibers in asphalt mixes. Three types of fibers were evaluated in this study, which included: (1) a blend of aramid and polyolefin fibers, (2) wax treated aramid fibers, and (3) glass fiber. The study consisted of both laboratory investigation and field evaluation after the construction of four 0.4 ft thick overlay test sections that included three fiber reinforced mixes and one control mix. Mixes were prepared in a local asphalt plant at fiber doses of 1.04, 0.28, and 3.11 lb/ton of fibers 1, 2, and 3, respectively. However, different doses of fibers were investigated in the laboratory prepared mixes. During construction, loose mixes and core samples were obtained. Laboratory testing included Dynamic Modulus, Flow Number, Hamburg Wheel-Track (HWT), Semi-Circular Bending, Creep compliance, and Indirect Tensile tests. The dynamic modulus and creep compliance data were used as inputs for the MEPDG software in order to develop a prediction model for fiber reinforced mixture performance. It was reported that at intermediate and high temperatures, the cracking resistance had no significant improvement until cracking happens that is when fibers start to reduce crack propagation. Muftah et al. (*8*) also reported no significant difference in the creep compliance between the control mix and the mixes reinforced with the blend of aramid and polyolefin fibers and with the wax treated aramid fibers. Weakness in the bonding between the fibers and the other constituents of the mix was reported, and the researchers recommended using adhesion promoters to overcome this problem.

Mateos and Harvey (*9*) conducted a study to evaluate the impact of the addition of synthetic fibers on the mechanical properties of an asphalt mixture used in California, and to identify the possible applications of reinforced asphalt mixtures based on their performance. The use of aramid fiber in one dense graded asphalt mix having a ¾ inch nominal maximum aggregate size, 15% reclaimed asphalt pavement (RAP) content, PG 64-10 and siliceous aggregate was implemented. Figure A.3 shows the type of aramid fiber that was used and the resulting asphalt mixture. In this study, the fiber dose was set to 0.013 percent of the total mix weight as recommended by the aramid fiber manufacturer. This dose corresponded to 4.2 ounces of aramid fibers with wax coating (2.1 ounces of aramid fiber) per ton of mix. The original and the fiber reinforced asphalt mixture differed only in the addition of fibers, with no change in mixture volumetrics, aggregate gradation, and asphalt binder content. Flexural fatigue resistance, flexural stiffness, and stiffness and rutting resistance were evaluated in this study. Results of dynamic modulus and phase angle showed an insignificant impact for the fiber on the stiffness of asphalt mixture at intermediate temperatures. The addition of the fibers resulted in a 90 percent increase in fatigue life at the 600 $\mu\varepsilon$ strain level. This indicated that the resistance to cracking of asphalt mixes can be improved by the addition of the aramid fibers when subjected to high strains in the field such as in the case of overlays placed jointed concrete pavements or flexible pavements with considerable cracking. Finally, the results of the tests conducted in this study showed an insignificant impact for wax-treated aramid fibers on the stiffness of asphalt mixture at low temperatures.

A study by Ho et al. (*10*) compared the performance of fiber-reinforced polymer-modified asphalt concrete (FPMAC) to that of polymer-modified asphalt concrete (PMAC) through laboratory testing and a two-year field evaluation. Fibers used in this study were a blend of polyolefin and aramid fibers. A fiber dose of one pound per ton of asphalt mix was used. The results of this study indicated that after two years following construction, the FPMAC section had significantly better cracking resistance as the accumulative length of cracks were found to be 11.6 ft. and 123.2 ft. for FPMAC and PMAC sections, respectively. The results the laboratory tests indicated that the thermal cracking resistance was improved by the addition of fibers, as the fiber-reinforced asphalt mixes had higher relaxation moduli.

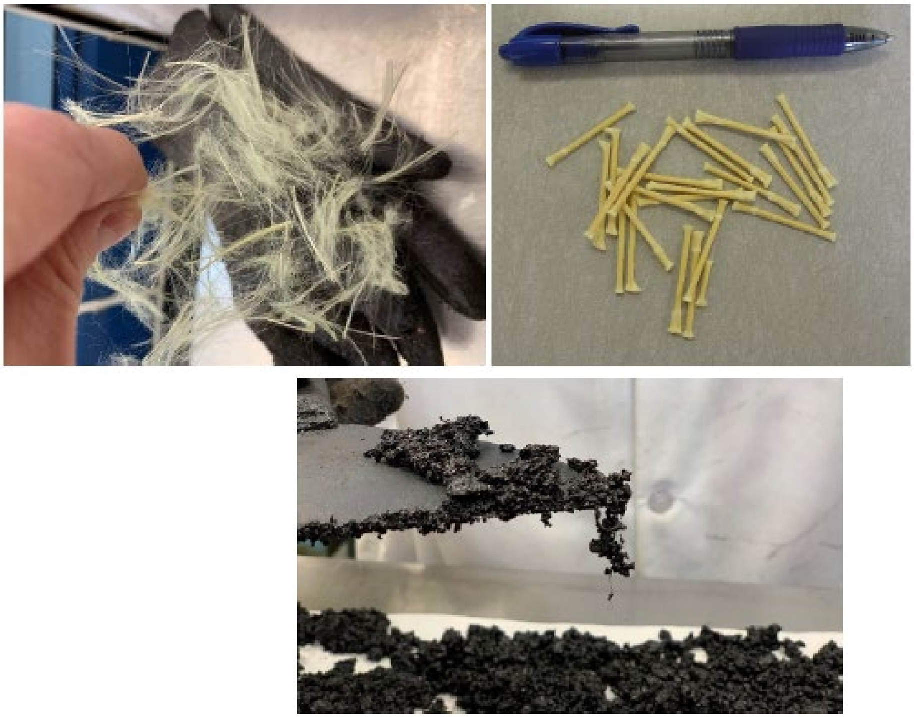


Figure A.3. Type of Aramid Fibers and Resulting Asphalt Mixture used by Mateos and Harvey (*9*)

A study by Takaikaew et al. (*11*) evaluated the effect of aramid and polyolefin fibers on the mechanical properties and performance of the asphalt mixtures. A higher tensile strength for fiber-reinforced asphalt concrete mixture was recorded as compared to the control mix. In addition, the resilient modulus of fiber reinforced studied mixtures was improved significantly, which suggested that aramid fibers can improve the fatigue life of reinforced mixtures.

Maurer and Malasheskie (*12*) studied different options for preventing reflective cracking. The options included the use of fabric interlayer, a stress-absorbing membrane interlayer (SAMI), and a fiber-reinforced mix. The fiber-reinforced mix presented the best reflective cracking performance in the field, with more than 50 percent reduction in reflective cracking as compared to the control mix.

A.2.2 Rutting Resistance Performance

Kaloush et al. (*6*) reported that the shear strength of asphalt mixes reinforced with blend of aramid and polyolefin fibers was significantly improved as compared to that of the control mix. In addition, it was reported that permanent deformation resistance, based on the flow number test results, was 15 times higher than that of the control mix. The dynamic modulus was also higher at all test temperatures.

The results of a study by Muftah et al. (*8*) showed that rutting resistance of mixes reinforced with a blend of aramid and polyolefin fibers and wax-treated aramid was improved by using a higher fiber content than the dosage recommended by the manufacturer. Results of a study by Mateos and Harvey (*9*) reported an improvement on the high-temperature stiffness due to the addition of wax-treated aramid fiber, which indicated that those fibers can increase the rutting resistance of the mix.

Kassem et al. (*13*) evaluated the inclusion of a blend of polyolefin and aramid fibers to investigate their effects on asphalt mixture performance using advanced material characterization and performance prediction models. Visco-Elasto-Plastic Continuum Damage (VEPCD) modeling and Mechanistic-Empirical pavement analysis based on the dynamic modulus test results were performed to predict the performance of the mixtures using different pavement structures and under different climatic and traffic conditions. Fibers were added to the heated aggregate before mixing at a rate of one pound per ton, as recommended by the supplier. Ten different asphalt mixtures were prepared. Based on the results of this study, fibers were found to provide better resistance to permanent deformation as the recovery from strains was faster.

Ho et al. (*10*) evaluated the performance of polymer-modified asphalt mixes reinforced using a blend of polyolefin and aramid fibers. The results of this study indicated that fiber-reinforced mixes had better permanent deformation resistance as their dynamic modulus values were higher as compared to the control mix. It was also reported that no rutting problems were observed in the test sections constructed using the fiber-reinforced mixtures two years after construction.

A.2.3 Moisture Susceptibility Performance

Kassem et al. (*13*) evaluated the moisture susceptibility for fiber-reinforced asphalt mixtures by conducting a freezing-thawing process on the mixture samples and obtaining the percentage retained stiffness or the dynamic modulus $|E^*|$ stiffness ratio (ESR). The test results indicated that the ESR ranged from 84.1% to 92.8%, which indicates a slight decrease in the stiffness of the mixtures after the addition of the fibers. However, this was considered a minor difference, and it was concluded that the addition of the fibers had no significant effect on the moisture susceptibility of the asphalt mixtures.

A.3 Factors Affecting Performance

Different factors were reported to affect the performance of asphalt mixes reinforced with aramid fibers. These included the fiber type, fiber dosage, fiber length, asphalt binder type, and fiber distribution. The following subsections summarize the results of studies that evaluated the effects of these factors on the performance of fiber-reinforced asphalt mixes.

A.3.1 Fiber Type

Muftah et al. (*8*) compared the effects of wax treated aramid fibers and a blend of aramid and polyolefin fibers on the performance of asphalt mixes. While the manufacturer-recommended dose of 1.0 lb. per ton was used for the mixes reinforced with a blend of aramid and polyolefin fibers, a dose of 0.26 lb. per ton was used for the wax treated aramid fibers reinforced mixes. In general, the mix using the wax-treated aramid fiber showed a slightly better resistance to fatigue cracking, low-temperature cracking and rutting. However, negligible improvement in mix performance was reported in this study when using the dose recommended by the manufacturer.

A.3.2 Fiber Dosage

Previous studies also evaluated the effect of the fiber dosage on the performance of an asphalt mixture. Behnia (*4*) studied the effect of increasing the fiber dosage of wax-treated aramid from 0 to 10 oz. per ton. He found that the improvement in the low-temperature and fatigue cracking due to using wax treated aramid fiber increased with the increase of the fiber dosage. Muftah et al. (*8*) evaluated the effect of using three different dosages of a blend of aramid and polyolefin fibers (1 lb. per ton, 2 lbs. per ton, and 3 lbs. per ton) on the performance of asphalt mixes. The researchers found that rutting resistance of the fiber-reinforced mixes was improved at fiber contents higher than the dose recommended by the manufacturer (of 1 lb. per ton). It was recommended that different doses of fibers should be evaluated during the design process to determine the optimum dose.

A.3.3 Fiber Length

Limited studies evaluated the effect of fiber length on the performance of reinforced asphalt mixes. Behnia (*4*) examined the effect of using wax-treated aramid fibers that were 0.75 inch (19 mm) and 1.5 inch (38 mm) long. The results of this study found that the longer fibers (1.5" long) appeared to perform better than regular-sized fibers (0.75") the fracture characteristics of the asphalt mixtures.

Kassem et al. (*14*) studied the effect of the fiber length of the aramid and polyolefin fiber blend on the performance of dense-graded asphalt mixtures. Three different fiber lengths were evaluated: 0.2 inch, 0.4 inch, and 0.75 inch. The results of this study showed that the resistance to rutting and fatigue cracking of the asphalt mixes was improved as the fibers becomes shorter. The authors attributed this finding to the higher level of dispersion of fibers within the mix as the fiber length decreased.

A.3.4 Asphalt Binder Type

Some studies also evaluated the effect of the type of asphalt binder on the performance of asphalt mixtures containing aramid fibers. Jaskuła et al. (*2*) found that the improvement in fracture characteristics due to the blend of aramid and polyolefin fibers was more pronounced in asphalt mixes prepared using neat unmodified asphalt binders than those prepared using polymer-modified asphalt binders. Kassem (*14*) evaluated the effect of the binder type on the improvement achieved by including a blend of aramid and polyolefin fibers in asphalt mixtures. Two different binder types were used; an unmodified PG 64-22 binder and a polymer-modified PG 76-22. The results of this study indicated that the effect of the fibers was more significant when added to mixes containing an unmodified binder.

A.3.5 Fiber Distribution

Uniform distribution of fibers in an asphalt mixture is essential for the improved performance of these mixtures. Limited studies have been conducted to evaluate the distribution of aramid in asphalt mixtures. Noorvand et al. (*15*) assessed the aramid fiber dispersion in fiber-reinforced asphalt mixtures as part of a resurfacing project in Arizona using a procedure developed by Arizona State University. The fiber distribution was classified into four main states: bundle, agitated bundle, cluster, and individual (Table A.2). Based on that, the fiber dispersion was quantified using the following equation:

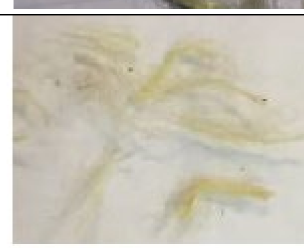
$$ADSR = F_I = \frac{M_I}{M_a} \times 100$$

where:
ADSR: Aramid fiber dispersion state ratio
F_I: Aramid fibers in the individual state
M_I: Mass of aramid fibers in the individual state, and
M_a: Total extracted aramid mass prior to separation

The results of this study showed that the mixture reinforced with a blend of polyolefin and aramid fibers had a good dispersion with 87-90% of the fibers in the individual state (ADSR = 87% and 90%), while the majority of the wax-coated aramid fiber was in the agitated bundle state with 13-19% of aramid fibers in the individual state (Figure A.4).

However, in another study conducted by (*16*), Advanced Asphalt Technologies (AAT) and the Asphalt Institute (AI), evaluated the dispersion of wax treated aramid fibers in asphalt mixtures. The results of AAT and AI testing showed that the wax-treated aramid fiber mixes had an ADSR ratio ranging between 80% and 89%, which suggested good dispersion of the this type of aramid fibers (*16*).

Table A.2: Aramid Fiber Dispersion (*15*)

Term	Definition	Example
Bundle	A group of many aramid fibers that shows no clear indication of disturbance. This is the original condition of aramid fibers.	
Agitated Bundle	A grouping of aramid fibers similar to the bundled condition, but that that has been visually agitated and has lost some of the individual aramids.	
Cluster	A grouping of individual aramid fibers that are more dispersed than the agitated bundle.	
Individual	Single fibers completely separated from other aramids with no resemblance of previous fiber states*.	

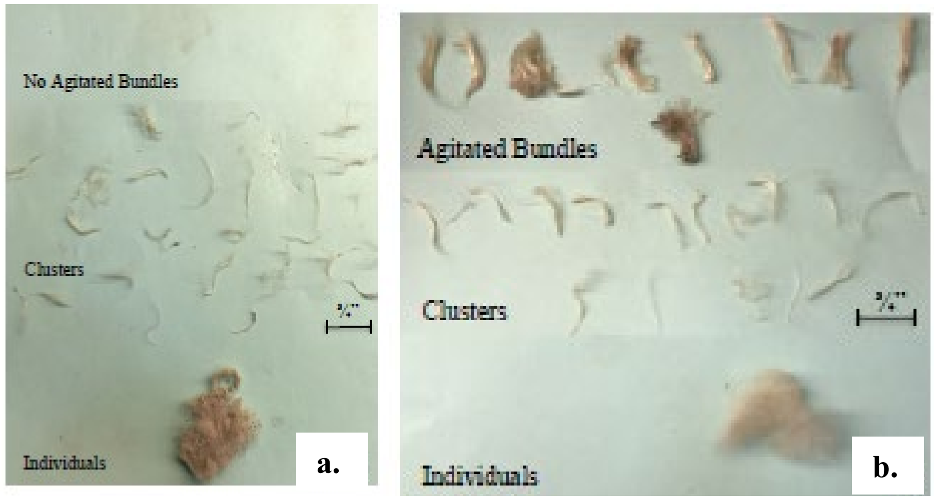


Figure A.4. Aramid Fibers Extraction State from a Single Sample; a- Blend of Polyolefin and Aramid Fibers, b- Wax-Coated aramid (*15*)

Bayomy et al. (*17*) measured the fiber content in asphalt mixtures using two different methods for separating the fiber from the asphalt mixes. The first method consisted of two steps. The first step was to extract the asphalt binder from mixes according to AASHTO T 164. The second step involved the ignition of the remaining fiber-aggregate mixture in an ignition oven at 1,200ºF (650°C). A higher fiber content was measured by this method than the target values, which indicated burning of a considerable amount of fine aggregate in the ignition oven at 1,200ºF (650°C). Accordingly, a similar method was evaluated that used a calcium chloride solvent for separating the fiber and aggregate instead of using an ignition oven. The fiber collected in this method was dried in the oven at 212 ± 40°F to a constant mass in the oven. This proposed lab method showed measured fiber contents that were approximately close to the target values for the wax treated fiber mix, but it was unsuccessful for the mix with the blend of pol and aramid fibers. It was reported that in the blend of polyolefin and aramid fibers, the fiber structure was completely trapped by the fine aggregate, which made it difficult to separate the fibers from the aggregate.

Muftah et al. (*8*) reported based on observations during the construction of the aramid fiber-reinforced test sections that there was a concern about the uniformity of the fiber injection into the asphalt mix at the plant. To this end, it was observed that, in many instances, the fibers clumped and were blown as balls into the feeder. The clumping of the fibers would have produced non-homogenous fiber-modified mixes that could lead to loosing the benefits of using them. Therefore, it was recommended to monitor the distribution of the fibers during the production of the asphalt mixture. Also, it was indicated that there is a great need for a field quality control test to measure the uniformity of fiber distribution and injection at the mix plant.

A.4 Fiber Delivery Systems

The two types of aramid fibers have different delivery systems for dispensing the fibers into the asphalt mix at the asphalt plant. The following subsections provide more details about these delivery systems.

A.4.1 Delivery Systems for Wax-Treated Aramid Fiber

Two delivery systems are used for adding wax-treated aramid fibers to an asphalt mixture: a line vac. compressed air delivery system and the "MD3+" system. The line-vac. compressed air delivery system (Figure A.5) is a manual system that costs about $4,000 or it can be rented along the technicians to run it. The system consists of a metering station and a continuous dosing station. The metering station determines the required weight of the fiber based on plant production speed, while the dosing station continuously delivers the weighed dosage every 30 seconds using an outflow hose placed inside the RAP collar funnel.

The "MD3+" feeder (https://youtu.be/qugu6u52VB8), shown in Figure A.6, is an automated dosing system that costs approximately $25,000 or can be rented along with a technician to run it. This system has a weigh hopper that meters the required fiber dose based on the plant production speed. The hopper can hold 40 lb of fiber, which is enough to produce about 150 tons of a fiber-reinforced asphalt mix. Once the weigh hopper drops its metered amount, the final feeder pan delivers the fiber to a power funnel. A 2-inch diameter vacuum hose is attached to the power funnel and delivers a continuous flow of fiber to the RAP control weigh hopper.

A.4.2 Delivery Systems for the Blend of Aramid and Polyolefin Fibers

Three delivery systems are available for incorporating the blend of aramid and polyolefin fibers into an asphalt mixture: the big shot, Voyager feed, Hi Tech feeders. The big shot is a manual system similar to the line-vac. delivery system. It is either free or can cost up to $1,700 depending on the project size. The big shot (Figure A.7) quickly and safely moves the fiber from ground-level storage to the asphalt drum. The big shot requires only a PVC pipe, a few hangers, and a supply of compressed air. The Voyager feeder (Figure A.8) is used in-plant as a continuous feed application. It is a fully automated delivery system. The Voyager feeder costs $40,000 to purchase or 0.50 cents per pound if rented. It automatically and continuously dispenses the proper amount of fibers. The Voyager feeder (https://www.youtube.com/watch?v=Ce8eyenVfLg) can be remotely controlled by the plant operator. The Voyager comes in two models: one for stationary in-plant applications and one for mobile use. The stationary model is available in a standard capacity of 33 cubic feet or a larger size of 53 cubic feet, while the mobile Voyager is only available in 33 cubic feet capacity. The Hi Tech feeders 10K shown in Figure A.9 (https://www.youtube.com/watch?v=9Yz0zmohkiI) is an automated dispenser system for introducing fibers that similar to the Voyager. The Hi Tech feeder costs about approximately $30,000.

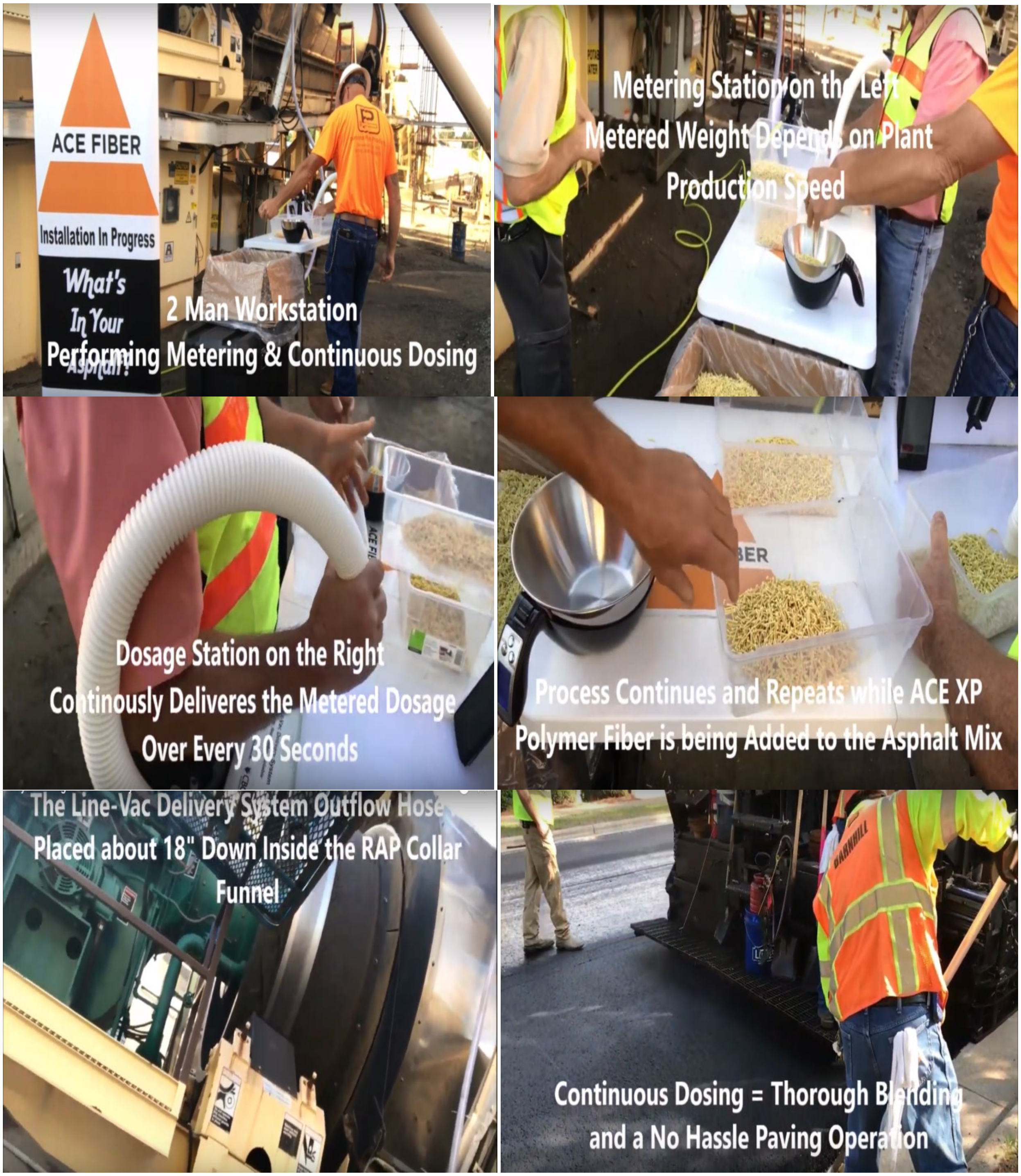


Figure A.5. The Line Vac. Compressed Air Delivery System

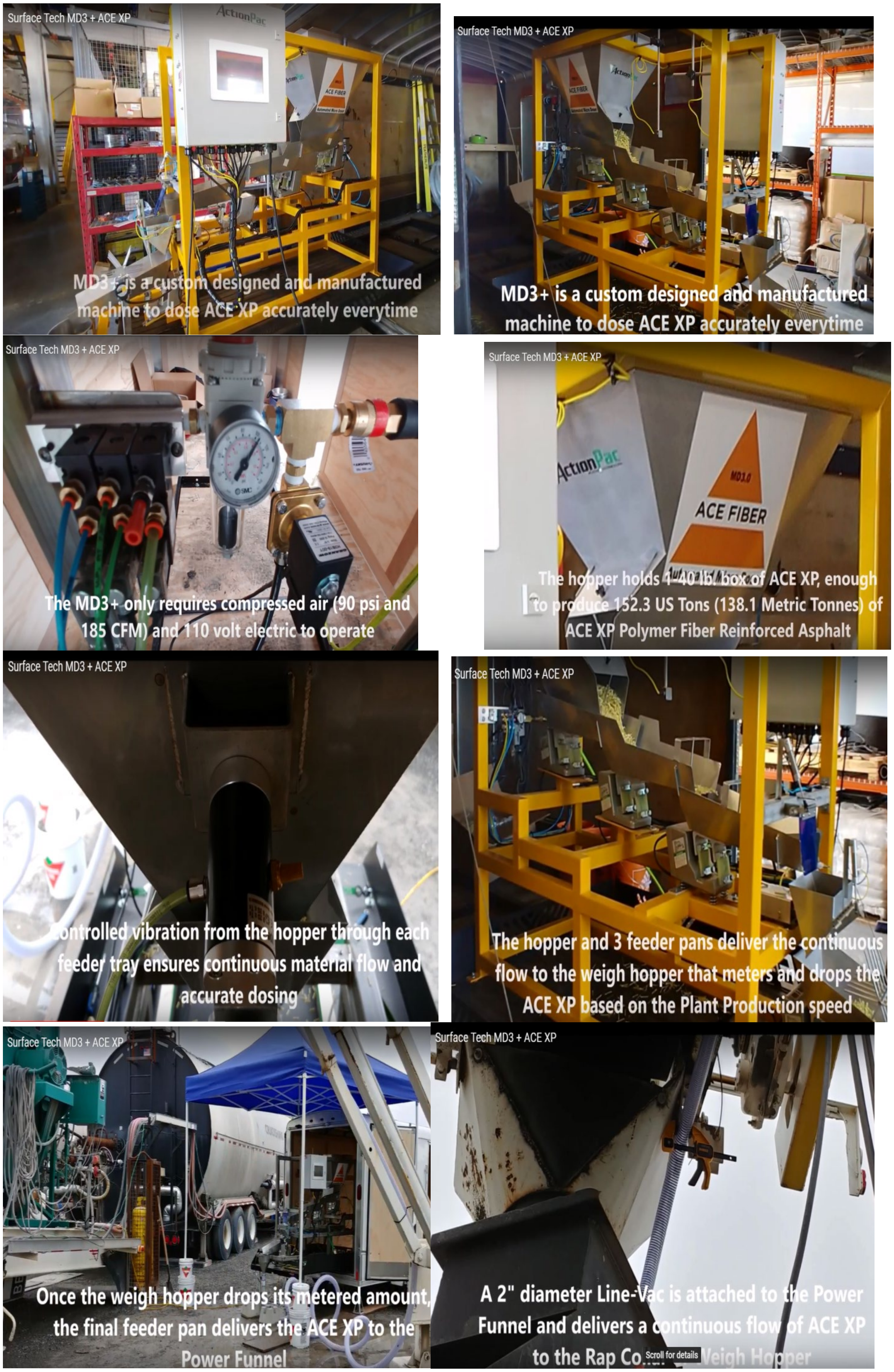


Figure A.6. The MD3+ Feeder System

Figure A.7. The Big Shot Delivery System

Figure A.8. The Voyager Delivery System

Figure A.9. The Hi Tech Feeder

A.5 Effect of Fibers on Volumetrics and Mix Design

Mateos and Harvey (*9*) reported that the use of aramid fibers to reinforce a dense graded asphalt mixture having 15% RAP content did not have any impact on the compactability and volumetric properties of these mixes. Based on the results of density measurements of field cores and lab specimens from loose plant mixes, Bayomy et al. (*17*) reported that the volumetric properties of asphalt mixes were not affected by the addition of fibers. They attributed this finding to the very small weight of fiber added to the mixture.

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Appendix B Evaluation of Previously Constructed Fiber-Reinforced Asphalt Mix Projects

In this task, the research team obtained all available information for the City of Columbus roadway that had one lane resurfaced with a fiber-reinforced PG 70-22M asphalt mix without stress absorbing membrane interlayer (SAMI) and another resurfaced with a non-fiber-reinforced PG 70-22M asphalt mix with the use of SAMI. Table B.1 shows the detail of these projects and Figure B.1 shows the locations of the roadways used in this task.

Table B.1. Roadways with fiber-reinforced non-fiber-reinforced asphalt mix in City of Columbus

Street	Lane	Construction Date	Notes	Description
Atlin Ave.	EB	9/7/2016	SAMI accidentally applied to both directions	PG 64-22 with aramid fiber
Atlin Ct.	WB	9/7/2016		PG64-22 only
Atlin Ct.	Both	9/8/2016	Fiber asphalt with trackless tack (no SAMI)	PG64-22 with aramid fiber
Walcutt Rd.	SB	10/29/2016	No SAMI	PG 70-22M with aramid fiber
Walcutt Rd.	NB	10/29/2016	SAMI was applied	PG 70-22M with aramid fiber

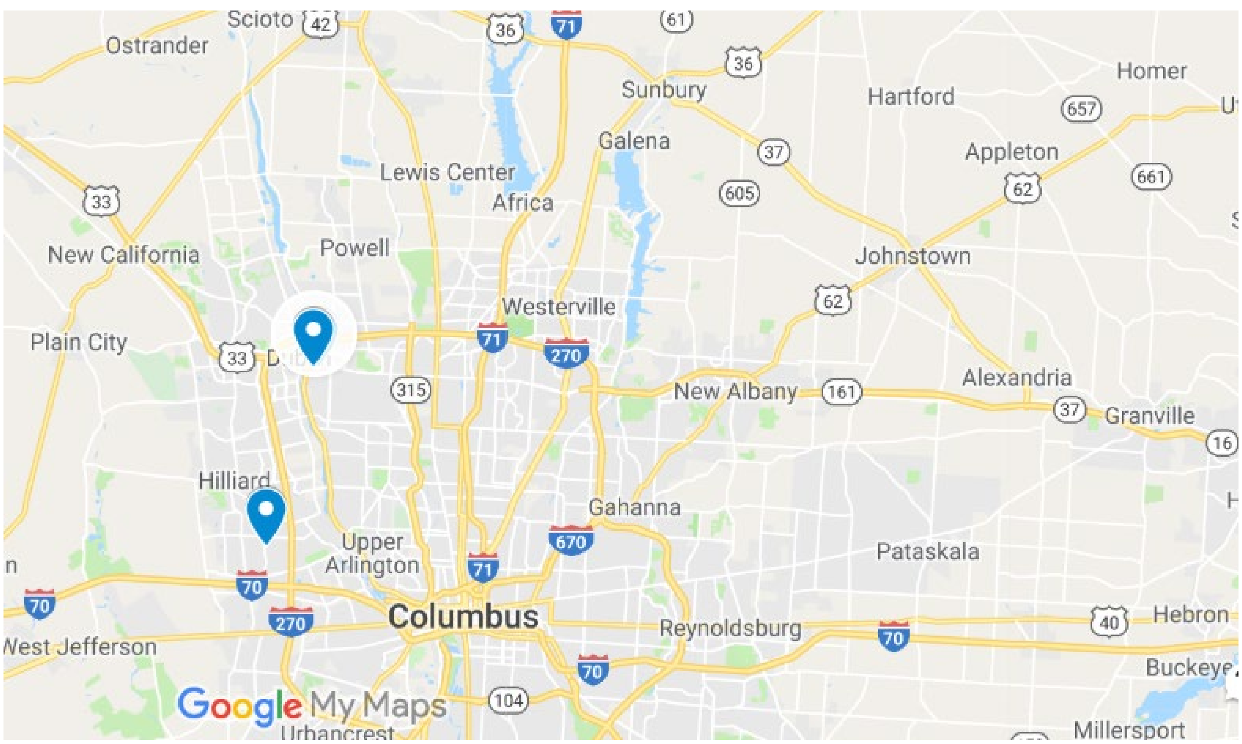

Figure B.1. Location of roadways with fiber-reinforced asphalt mixes in City of Columbus.

In addition, the research team coordinated with the City of Columbus to visit the site to evaluate the pavement condition for the two lanes. The site visit included evaluating the structural capacity of roadway with and without SAMI. This was done using the light weight deflectometer (LWD). The LWD data was used to determine the composite modulus of the current pavement conditions. At least eight 6-inch core samples were also obtained from each lane. The IDEAL-CT, SCB and ACCD tests were conducted on the obtained core samples to determine the fatigue and low-temperature cracking resistance of mixes obtained from both lanes. Figure B.2 shows LWD measurement and coring operation at the field. The roadways were about three years old at the time LWD measurement and coring and they were relatively distress-free as seen in the background of Figure B.2.

Descriptions of the test methods used in this task are presented in Appendix C and the results of the pavement condition evaluation, LWD, and laboratory tests on the field cores are presented and discussed in Appendix D.

Figure B.2. Light weight deflectometer (LWD) measurement (left) and coring (right) at the field.

Appendix C Testing Program

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

C.1 Materials

The research team developed a comprehensive laboratory testing plan to evaluate the effects of aramid fibers on the resistance to fatigue cracking, low-temperature cracking, reflection cracking, rutting, and moisture damage of non-polymer modified asphalt mixtures. The following sets of variables were included in the laboratory testing plan:

1. **Asphalt binder type:** The most commonly used non-polymer modified asphalt binders in construction of local roads in Ohio were considered. These include PG 64-22 and PG 58-28. In addition, a polymer modified asphalt binder meeting Ohio specifications for PG 70-22M was used for comparison.

2. **Aramid fiber type:** There are two main types of aramid fibers that have been used in previous studies in reinforcing dense graded asphalt mixes: wax treated aramid fibers and a blend of aramid and polyolefin fibers. The research team considered and evaluated both types.

3. **Aramid fiber length:** two different aramid fiber lengths were evaluated: 0.75 inch and 1.5 inch.

4. **Aramid fiber dosage:** The aramid fiber dosage was varied to determine its effect on the mix performance. Three different fiber dosages were considered: recommended dosage, doubled recommended dosage and 1.5 times the recommended dosage

The recommended dosages by suppliers for the wax treated aramid fibers and the blend of aramid and polyolefin fibers are summarized in Table C.1. To facilitate laboratory mixing, the wax treated aramid fibers were provided with fiber and wax separately.

Limestone aggregate from Olen at Columbus and RAP from Franklin County were used for preparation of test samples of all mixes.

Table C.1. Recommended dosage of aramid fibers.

Aramid Fiber Type	Aramid (oz/ton of mix)	Wax/Polyolefin (oz/ton of mix)
Wax Treated	2.1	2.1
Blended with Polyolefin	2.08	15.66

A unique ID was assigned to each asphalt mix to include all four study variables as shown in Table C.2. The first 2 letters of each ID are for the binder type, the third letter for the aramid fiber type, the fourth letter for the fiber length, and the remaining letters are for dosage. For example, the mix ID "64AS2" was prepared with PG ***64***-22 binder with wax treated aramid fiber (***A***) having 0.75 inch length (***S***hort) with doubled recommended dosage (x***2***). Total of 15 asphalt mixes were prepared and tested as shown in Table C.3. The first three no-fiber mixes served as a control group to measure the effects of the presence of aramid fiber in asphalt mixes. The next eight mixes were all prepared with PG 64-22 binder, the most common binder type for Local Public Agencies (LPA), to determine the effects of the aramid fiber type, length and dosage with full factorial design, ensuring sound statistical analysis. Based on the results of eight-mix factorial experiments, four additional asphalt mixes were prepared and tested to validate dosage (x1.5) and another common binder type used by LPAs (PG 58-28 binder).

Table C.2. Mix variables and coding of asphalt mix ID

Mix Variable	Code	Description
Asphalt binder type (First 2 letters of ID)	58	PG 58-28
	64	PG 64-22
	70	PG 70-22M
Aramid fiber type (3rd letter of ID)	N	No fiber
	A	Wax treated aramid fiber
	B	Blend of aramid and polyolefin fibers
Aramid fiber length (4th letter of ID)	S	Short = 0.75 inch
	L	Long = 1.5 inch
Aramid fiber dosage (remaining letters of ID)	1	(x1) Recommended dosage
	1.5	(x1.5) 1.5 times recommended dosage
	2	(x2) Doubled recommended dosage

Table C.3. Asphalt control mixes and aramid fiber-reinforced asphalt mixes tested in this study

	Mix ID	Binder	Fiber Type	Fiber Length	Fiber Dosage
No Fiber Mixes	58N	PG 58-28	None	NA	NA
	64N	PG 64-22	None	NA	NA
	70N	PG 70-22M	None	NA	NA
Mixes for Main Statistical Test	64AS1	PG 64-22	A	0.75	x 1
	64BS1	PG 64-22	B	0.75	x 1
	64AS2	PG 64-22	A	0.75	x 2
	64BS2	PG 64-22	B	0.75	x 2
	64AL1	PG 64-22	A	1.5	x 1
	64BL1	PG 64-22	B	1.5	x 1
	64AL2	PG 64-22	A	1.5	x 2
	64BL2	PG 64-22	B	1.5	x 2
Additional Mixes	64AL1.5	PG 64-22	A	1.5	x 1.5
	64BS1.5	PG 64-22	B	1	x 1.5
	58AL1.5	PG 58-28	A	1.5	x 1.5
	58BS1	PG 58-28	B	0.75	x 1

C.2 Asphalt Mixtures

To evaluate the effects of the aramid on the pavement performance, a job mix formula (JMF) for an asphalt mixture that was used in construction of surface course layer in a resurfacing project in the City of Columbus was obtained from the Kokosing Materials Inc. The asphalt mixture had a 1/2 inch (12.5 mm) nominal maximum aggregate size (NMAS) and was designed to meet ODOT specification for Item 441 for medium traffic surface mixtures. The selected mixture included PG 64-22 asphalt binder. The aggregate blend of the selected mixture consisted of: 47% #8 limestone, 32% manufactured sand, 1% baghouse fines and 20% reclaimed asphalt pavement (RAP) processed according to ODOT Item 401.04 Method 2. Total and virgin binder contents were 6.4% and 5.2% by weight of total mix, respectively. The gradation of the aggregate blend is shown in Figure C.1. It is noted that the RAP was manually sieved on a ½'' sieve and split to ensure the consistency of the RAP portion in the blend. Once split, the RAP was left to air-dry for 24 hours, then oven-dried at 110 °C for 3 hours.

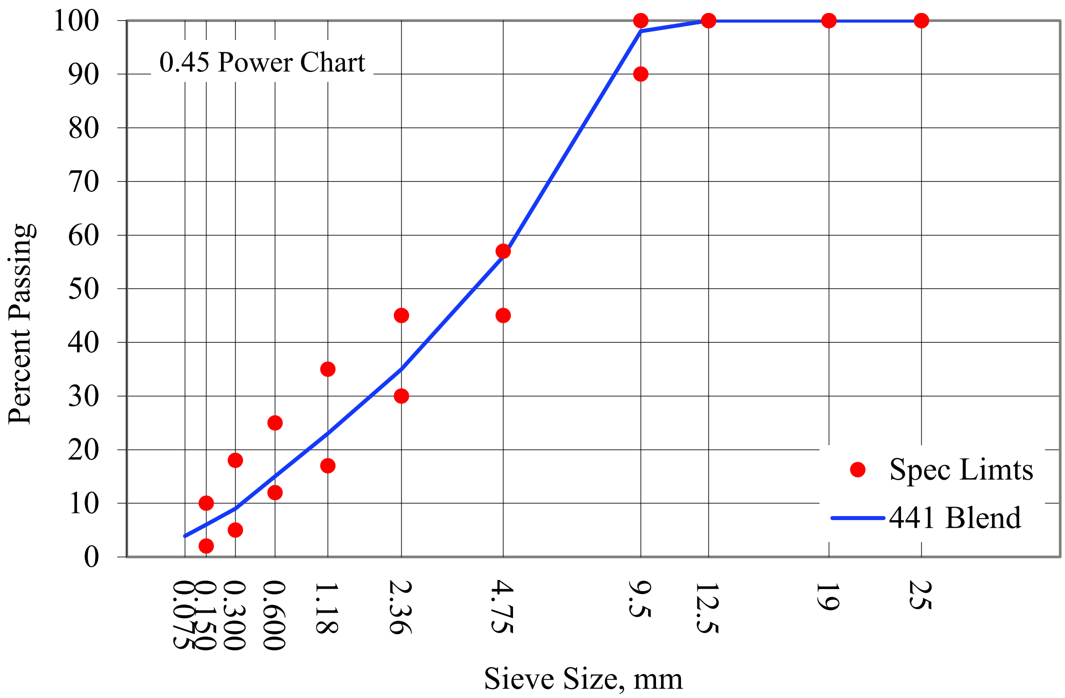

Figure C.1 Gradation used in this study

For better dispersion of both aramid fibers, fiber strands were separated prior to mixing by applying compresses air on the fibers in a mason jar covered with meshed fabric. Aramid fiber mixing procedures recommended by suppliers were followed. For the wax treated aramid fiber, wax was added to the heated aggregates in the mixing bucket first. Then, the dispersed aramid fibers were slowly added during the recommended mixing time of 3-5 minutes. For the blend of aramid and polyolefin fibers, first, the aramid fibers were placed in the middle of the heated aggregates in the mixing bucket. After pouring the desired amount of asphalt binder, the polyolefin fibers were added to the asphalt binder prior to mixing.

C.3 Mixture Testing

Tests were performed on the mixtures to evaluate their resistance to cracking, moisture damage, low-temperature cracking, and rutting. All samples for these tests were compacted to a target air void of 7± 0.5% except the low-temperature cracking test using the Asphalt Concrete Cracking Device where compaction was done with 20 number of gyrations to simulate constant compaction effort in Marshall mix design process.

Figure C.2 shows the asphalt mixture testing plan as well as the testing variables. The effects of the fiber length and dosage were studied using PG 64-22 asphalt binder with full factorial design. For PG 58-28 asphalt binder, only one best performing combination of fiber length and dosage was used for each aramid fiber type based on the results of full factorial study with PG 64-22 asphalt binder. It is noted that all mixture in this task will include a RAP content that is typically used by the involved cities. All mixtures (polymer and non-polymer modified mixtures) will have the same RAP content to eliminate the effect of RAP content on the test results.

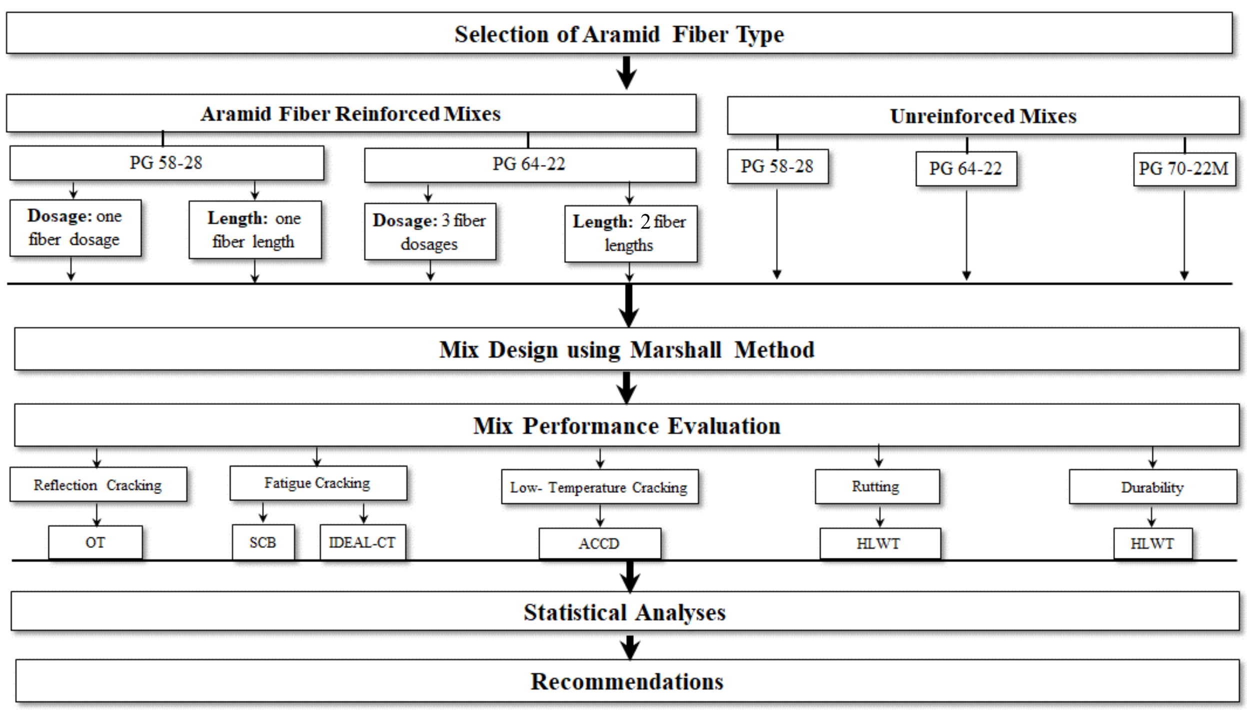

Figure C.2 Laboratory testing plan

C.3.1 Semi-Circular Bending (SCB) Test

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

Figure C.3. Illinois SCB Sample Preparation and Testing Equipment

Figure C.4. Instrotek© Auto SCB Testing Equipment

The main output of the SCB-IL is a load versus deformation plot, as shown in Figure C.5. From this plot, the Fracture Energy (FE) and the Flexibility Index (FI) are calculated using Equations C.1 and C.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 premature cracking (*1,2*). Since the Fracture Energy is a function of the peak load and displacement, Nazzal et al. (*3*) recommended normalizing the fracture energy values based on the peak strength mixture. Therefore, the normalized fracture energy (NFE) value was used in this study to examine the cracking resistance of the core samples. The higher the FI and NFE, the better the cracking resistance of asphalt mixes.

$$FE = \frac{W_f}{Area_{lig}} \text{ x } 10^6 \tag{C.1}$$

Where:

FE = fracture energy (Joules/m^2)

W_f = work of fracture, or area beneath load vs. displacement curve up to peak load (Joules)

$Area_{lig}$ = ligament area, ligament thickness × length (mm^2)

$$\mathrm{FI} = \frac{G_F}{|m|} \text{ x A} \tag{C.2}$$

Where:

$|m|$ = absolute value of slope at inflection point

A = unit conversion (0.01)

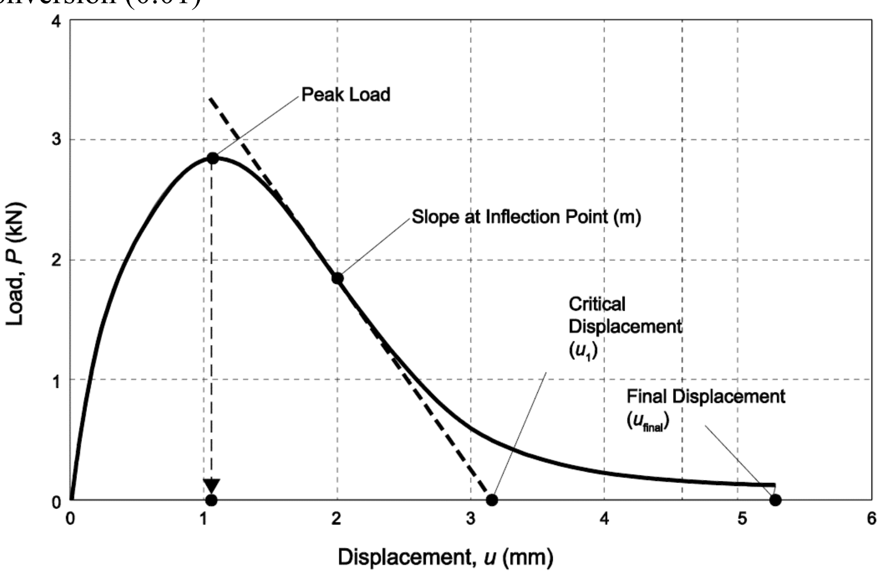

Figure C.5 Plot of Load vs. Displacement Obtained from Illinois SCB Test (*2*)

C.3.2 IDEAL-CT

Zhou et al. (*4*) recently developed a test called IDEAL-CT where 150-mm diameter specimen is compacted to 62±2-mm thickness and tested without cutting or trimming. This test is similar to the traditional indirect tensile test (IDT). However, Zhou et al. (*4*) proposed a new procedure to analyze the IDT load – displacement curve, which was inspired by the laws of crack propagation (*5, 6*). Based on this procedure, a parameter called cracking tolerance index (CTI) is determined using Equation (C.5) and as shown in Figure C.5. It is noted that Zhou et al. (*4*) found that CTI correlates well with the field cracking performance of asphalt mixtures.

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

G_f: is the fracture energy which is the total area under load – displacement curve (work of fracture) divided by the area of cracking face (thickness, t x D)
D: is sample diameter (mm)
l_{75}: is displacement corresponding to the 75 percent of the peak load at the post-peak stage
m_{75}: is slope calculated as shown in Figure C.6 using the following equation

$$|m_{75}| = \left|\frac{P_{85}-P_{65}}{l_{85}-l_{65}}\right| \quad \text{(C.6)}$$

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

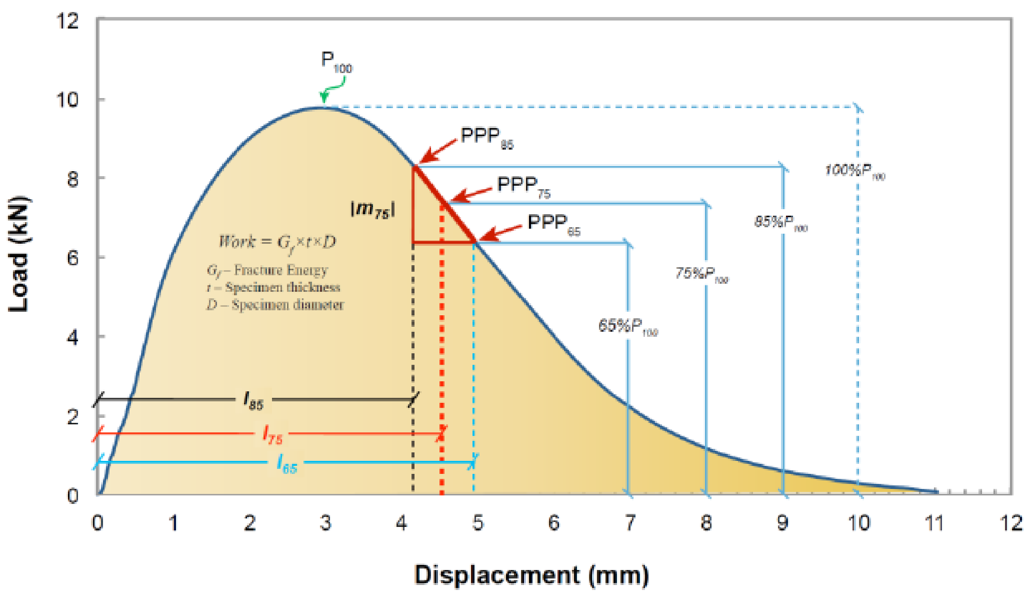

Figure C.6 Illustration of the slope |*m*75| in CTI calculation (*4*)

C.3.3 Overlay Tester (OT)

Overlay tester was initially developed to evaluate the reflection crack resistance of hot mix asphalt (HMA) overlay and also proposed for characterization of fatigue crack resistance (*6*). For OT test, a 150 mm diameter compacted specimen is trimmed to dimensions of 150mm length 75mm width and 38mm thickness. As shown in Figure C.7, the trimmed specimen is bonded to a movable and a fixed aluminum plates with 2mm gap that opens and closes. As the test begins at a constant temperature (25°C), the movable plate slide horizontally in a cyclic triangular wave form to a constant displacement of 0.6 mm (0.025 in.). One cycle of OT loading is defined as the sliding block reaches the maximum displacement and returns to its initial position in 10 seconds. The test continues up to 1,200 cycles or the load to the maximum displacement reduced by 93% in comparison to the maximum load recorded for the first opening cycle.

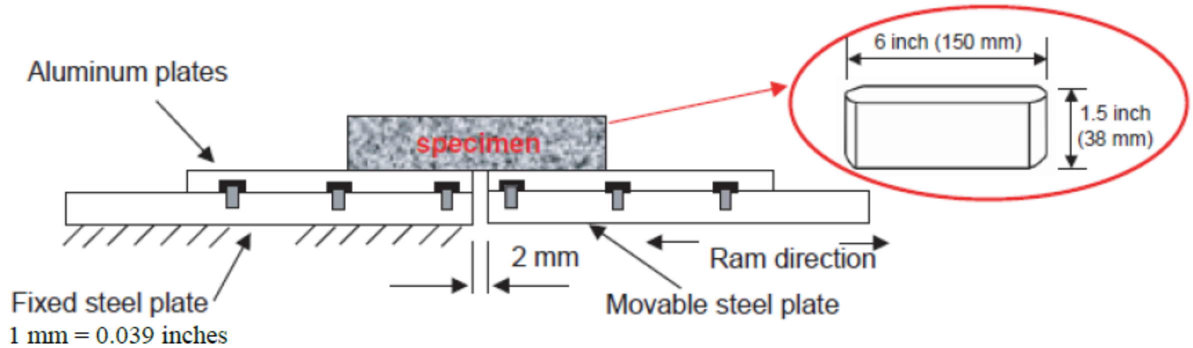

Figure C.7 Schematics of Overlay Tester (OT)

C.3.4 Asphalt Concrete Cracking Device (ACCD)

ACCD test is a concentric thermal stress restrained specimen test or concentric TSRST to evaluate the low-temperature cracking resistance of asphalt mixtures (*7*). In this test, short-term aged 150-mm diameter specimen is compacted to 50 to 55-mm thickness. Then, the middle 60-mm diameter was cored out to fit with ACCD ring for testing. A 22.4-mm (0.88-inch) long-notch was cut at the outer surface of the 150-mm diameter sample to control the location of the crack. The test specimen and the ACCD ring were heated for 60 minutes at 65°C, and the tapered end of the heated ACCD ring was placed in the center hole of the heated test sample. The sample with the ACCD ring was placed in an environmental chamber (Figure C.8). After holding for one hour at 10°C, the chamber was cooled to -60°C at 10°C per hour. As the temperature decreased, the contraction of the asphalt mix specimen was restrained by the ACCD ring, developing tensile stress within the test specimen and compressive stress within the ACCD ring. Four samples can be typically tested at the same time. The temperature and strain of each ACCD ring were continuously recorded throughout the test. The temperature corresponding to the maximum slope of the ACCD strain-temperature curve was considered as the onset on thermal cracking. The point at which the slope of the strain-temperature curve equals to eighty percent of the maximum slope after the onset of cracking is defined as the ACCD cracking temperature. A computer program determines the maximum slope and the ACCD cracking temperature as shown in Figure C.9. The ACCD strain at the failure is related to the strength of the mixes.

Figure C.8 ACCD test setup

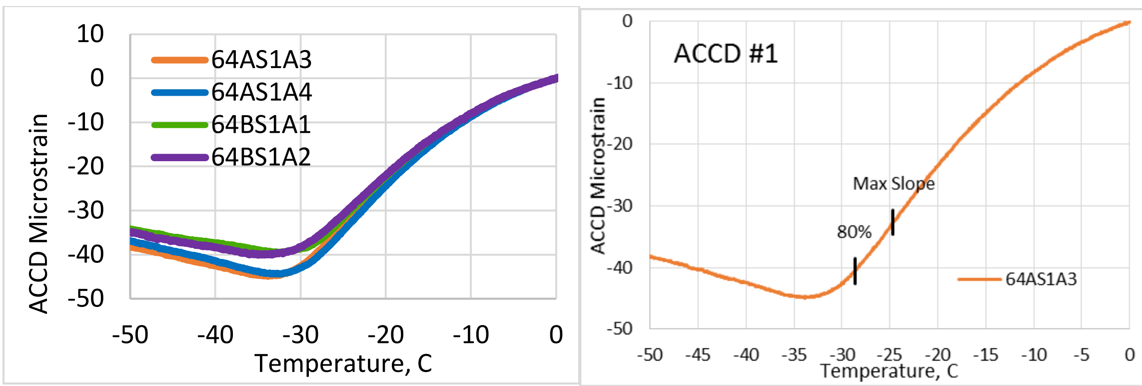

Figure C.9 Typical ACCD test results (left) and analyzed data (right)

C.3.5 Hamburg Wheel Tracking

Hamburg Wheel Tracking (HWT) is used to measure rutting and moisture resistance of asphalt mixtures (*8*). HWT test was performed following AASHTO T324 procedure where a steel wheel with the load of 705N (158 lb) travels back-and-forth at a rate of 52 passes per minute on the test specimen submerged in 50°C water. The steel wheel has a diameter of 203mm (8 in.) and a width of 47mm (1.85 in.). Figure C.10 shows the HWT tester capable of testing two sample simultaneously. Asphalt mixtures with HWT rut depth less than 12.5mm (0.5 in.) after 20,000 cycles are considered acceptable. Figure C.11 shows HWT test specimens of a rut/moisture susceptible mix and rut/moisture resistant mix.

A typical HWT rut depth – number of pass relationship is shown in Figure C.12. For the first few passes, specimen goes through a consolidation phase followed by a steady-state creep slope until asphalt binder starts to strip from aggregate and to exhibit a steep slope known as a strip slope. The intersection of the creep slope and the strip slope is defined as a stripping inflection point (SIP). The magnitude of the maximum impression is used as a measure of rutting resistance and SIP is used as a measure of the resistance to moisture damage.

Figure C.10 Hamburg Wheel Tracking Tester

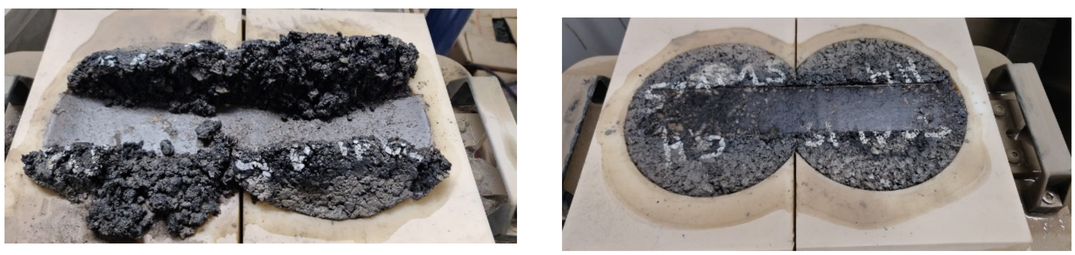

Figure C.11 Results of rut and moisture susceptible (left) and resistant (right) mixes in HWT

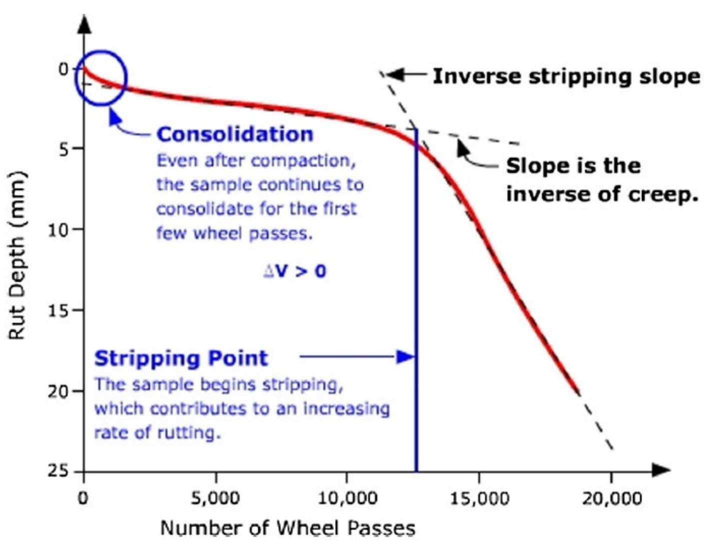

Figure C.12 Typical Hamburg Wheel Tacking results

C.4 References

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Appendix D Test Results and Data Analysis

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

D.1 Evaluation of Previously Constructed Test Section with Fiber-Reinforced Asphalt Mix Projects in Columbus

Two previous test sections in the City of Columbus constructed with and without aramid fibers were identified and evaluated. This section presents the results of on-site testing using Light Weight Deflectometer (LWD), pavement condition rating, and IDEAL-CT, SCB, and ACCD tests performed on the core samples.

The LWD data was used to determine the composite modulus of the current pavement conditions. Figure D.1 presents the average results of the LWD tests performed multiple times on two selected test sites. For Atlin Ct. test site, the pavement constructed with PG 64-22 binder with aramid fiber showed slightly higher modulus than the pavement constructed with PG 64-22 binder without aramid fiber. A similar results were observed for Walcutt Rd. test site where the modulus of the section constructed with PG 70-22M with aramid fiber was higher than that of section constructed with PG 70-22M only, indicating that the aramid fiber added structural capacity to the sections.

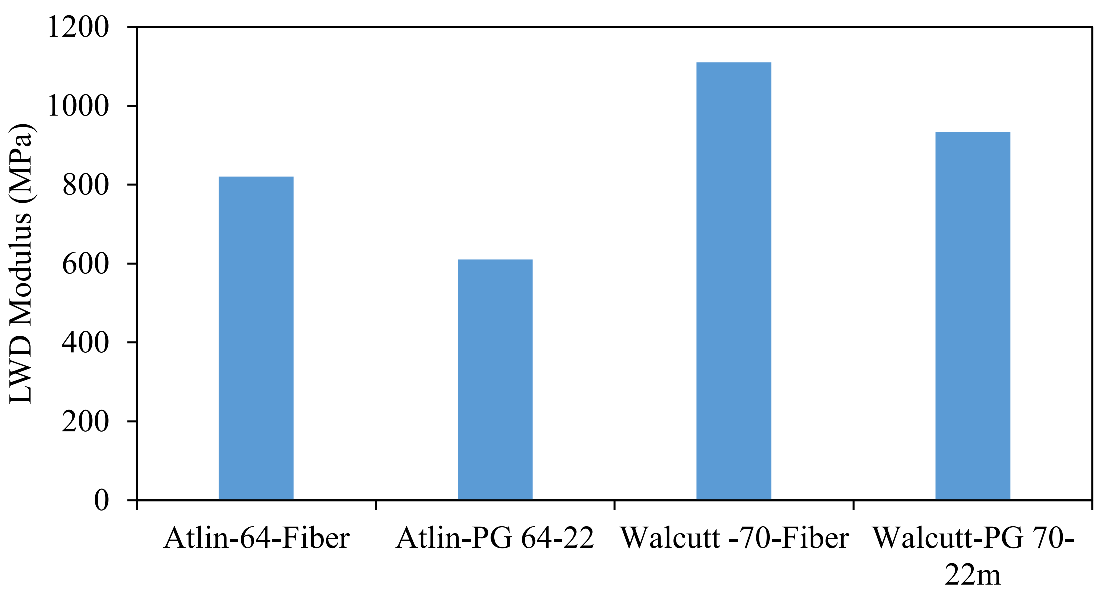

Figure D.1 LWD modulus determined test sites at Atlin Ct. and Walcutt Rd.

Prior to perform laboratory tests on the cores from the test sites, air void was first determined. The average air voids, presented in Figure D.2, showed significant variation. The difference in air void between two sections at Atlin Ct. was 1.7% and at Walcutt Rd. was 1%.

Figures D.3 and D.4 showed the average Flexibility Index (FI) and the average Normalized Fracture Energy (NFE) from SCB tests. For Atlin test site, the cores containing aramid fibers showed lower cracking resistance in terms of FI and NFE values than the cores containing no aramid fibers. This observation is most likely due to significantly higher air void in the cores containing aramid fibers. For Walcutt test site, in terms of FI, the cores with 70-22M polymer modified binder and aramid fibers showed relatively lower cracking resistance and, in terms of NFE, similar or slightly better cracking resistance than the cores with PG 70-22M polymer modified binder only. This observation seems in agreement with the previous studies which showed that the improvement in fracture resistance by addition of aramid fibers were more effective in unmodified asphalt binders than in polymer modified binders (*1,2*).

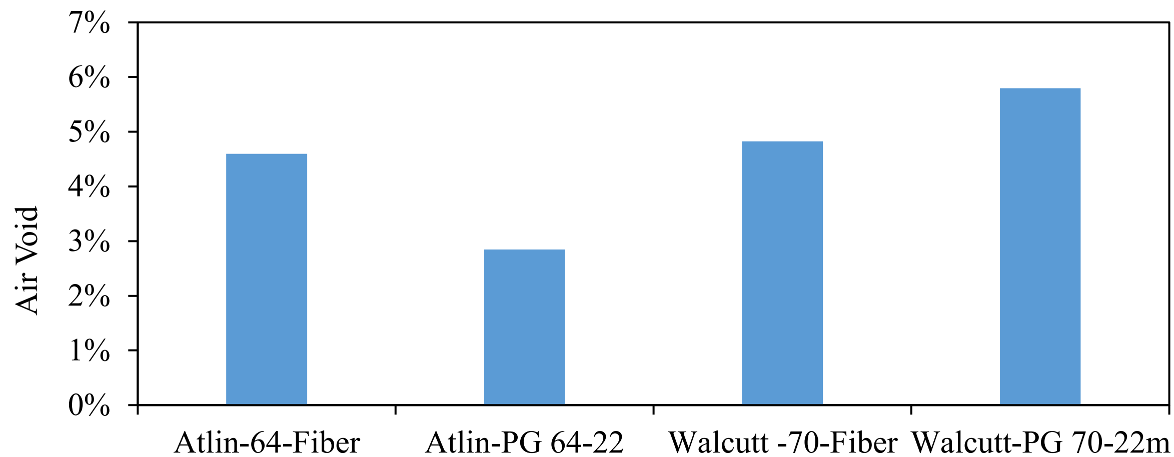

Figure D.2 Air voids of field cores

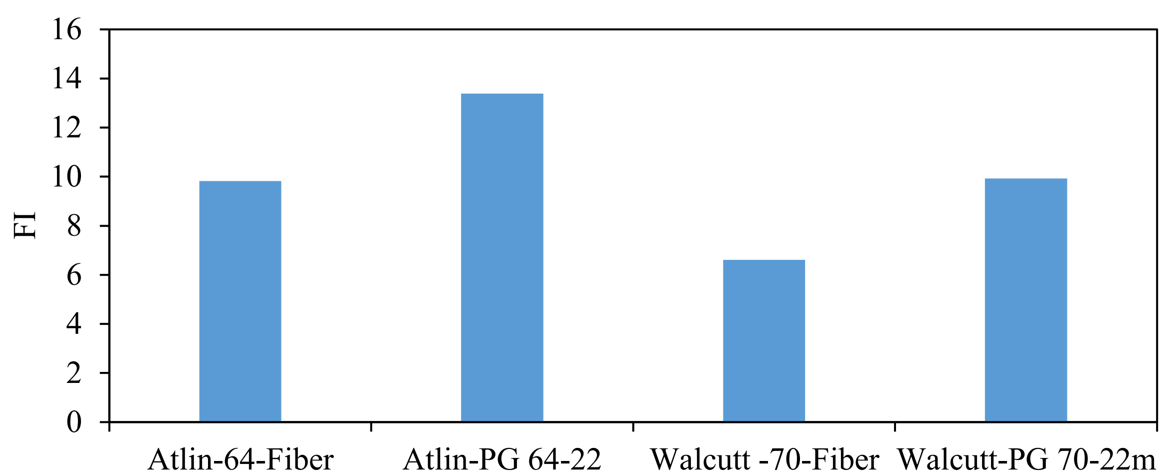

Figure D.3 Flexibility Index (FI) of field cores

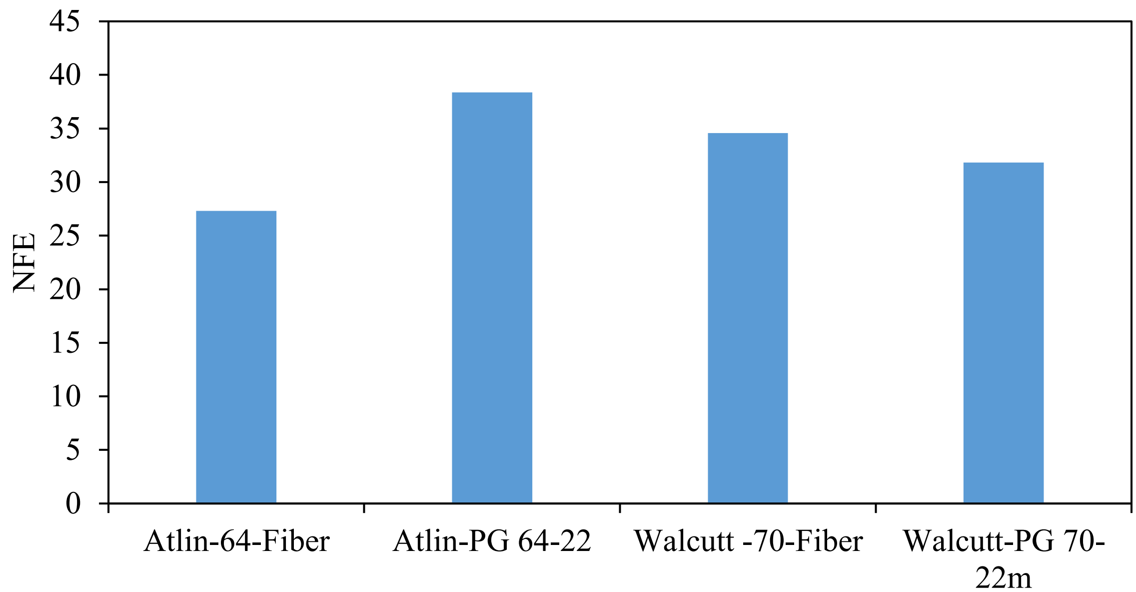

Figure D.4 Normalized Fracture Energy (NFE) of field cores

Figures D.5 and D.6 show the results of average Indirect Tensile Strength (IDT) and Cracking Tolerance Index (CTI) measured by IDEAL-CT, respectively. For Atlin test site, the cores with unmodified PG 64-22 with and without aramid fibers showed similar average ITS values. However, the average CTI value of cores containing aramid fibers is significantly lower than that of cores containing no aramid fibers, indicating relatively poor cracking resistance. For Walcutt Rd. site, the average ITS value of cores containing PG 70-22M and aramid fibers is significantly higher than that of cores containing PG 70-22M only. However, the average CTI value of cores containing PG 70-22M and aramid fibers is lower than that of cores containing PG 70-22M only.

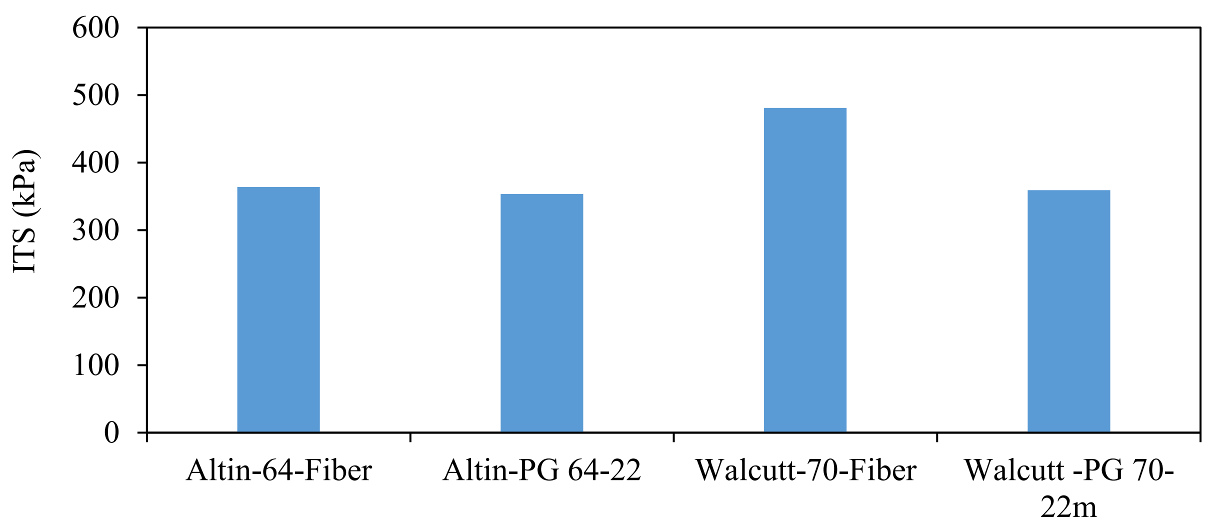

Figure D.5 Indirect Tensile Strength (ITS) of field cores

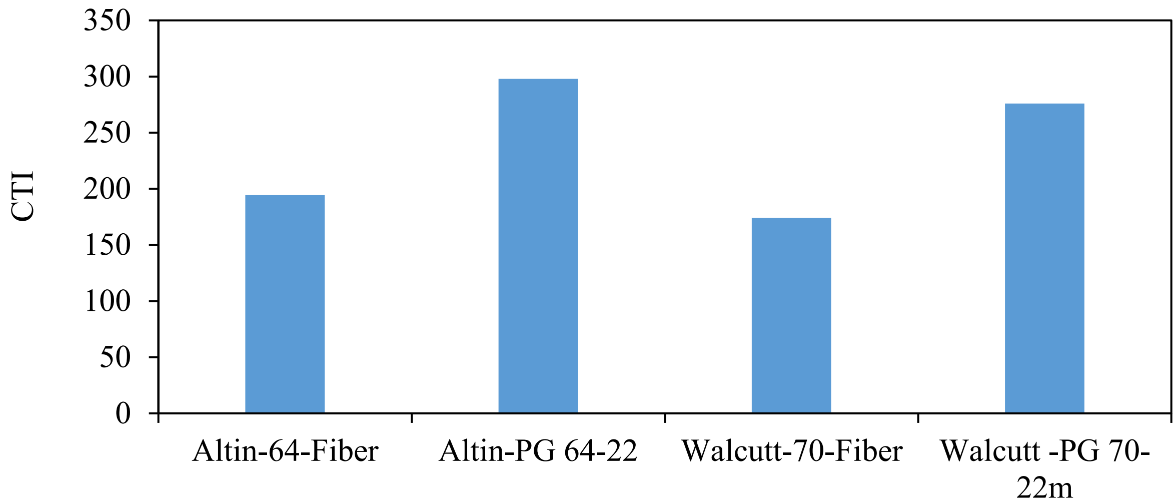

Figure D.6 Cracking Tolerance Index (CTI) of field cores

Figures D.7 and D.8 show the average cold cracking temperatures and the strain at the failure determined by Asphalt Concrete Cracking Device (ACCD). There is no clear trend for the effects of aramid fiber addition to both asphalt binder types. However, it is important to note that the cracking temperatures of all cores with and without aramid fibers were significantly lower than the intended low temperature PG grade, -22°C, ensuring satisfactory low temperature performance. The ACCD strain at failure is a parameter related to the strength of asphalt mixes. The average ACCD strains at failure for both PG 64-22 with aramid fibers and PG 70-22M with aramid fibers are slightly higher than their counterparts. The rank of the average ACCD stains at failure appears to be similar to the rank of IDT shown in Figure D.5.

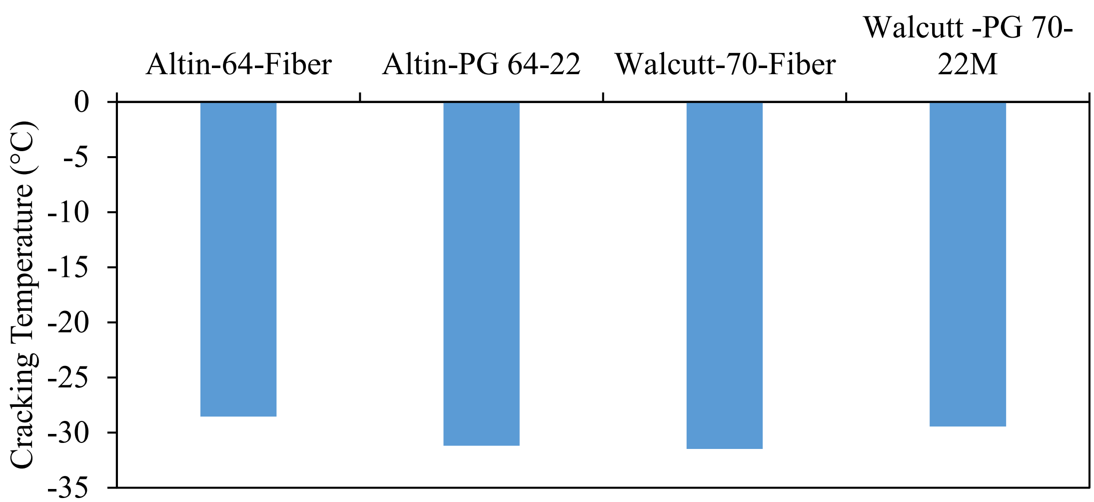

Figure D.7 ACCD Cracking Temperature (Tcr) of field cores

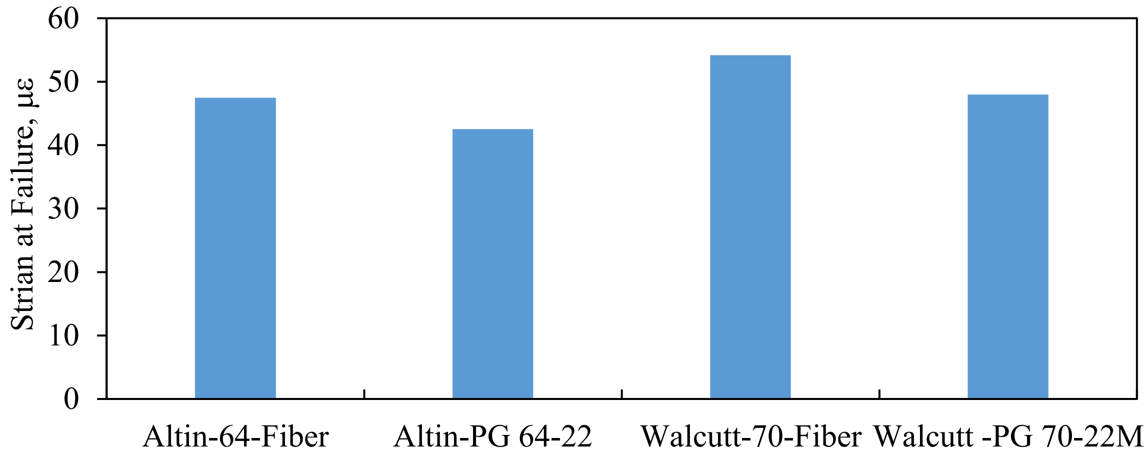

Figure D.8 ACCD strain at failure for field cores

Pavement condition rating (PCR) is a mathematical expression of pavement distresses determined by visual inspection. PCR depends on the distress type, severity, and extent and can be calculated using Equation (D.1).

$$\mathrm{PCR} = 100 - \sum_{i=1}^{n} \mathrm{Deduct}_i \qquad (D.1)$$

Where:

n = number of observable distresses, and

$Deduct_i$ = (Weight for $distress_i$) x (Weight for severity) x (Weight for extent)

Figure D.9 shows PCR for the test sites. The test sites were approximately three years old at the time of inspection and relatively distress-free. PCR values range from 92 for Walcutt PG 70-22M only section and 99 for Atlin Ct. PG 64-22 with aramid fibers section.

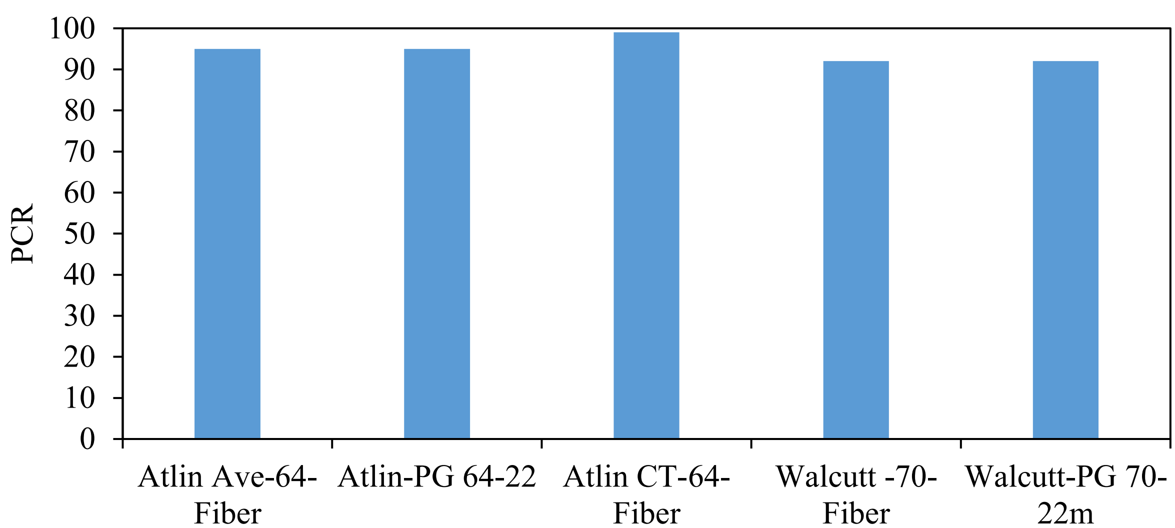

Figure D.9 Pavement Condition Rating (PCR) of field cores

In summary, two local roadways constructed 2016 in City of Columbus were evaluated to determine the effectiveness of aramid fiber reinforcement on unmodified PG 64-22 and polymer modified PG 70-22M mixes. All sections were in good condition with PCR values ranging from 92 to 99. Light Weight Deflectometer (LWD) tests performed on-sites indicated that the use of aramid fibers increased the structural capacity of the local roads, showing higher modulus values. SCB and IDEAL-CT tests were used to measures crack resistance in the laboratory. Unfortunately, the cores taken from the unmodified PG 64-22 sections in Altin Ct. had very different air void contents between the aramid fiber section (4.6%) and the no fiber section (2.9%). This made the interpretation of SCB and IDEAL-CT test results very difficult. The cores taken from the modified PG 70-22M section in Walcutt Rd. had comparable air voids between the aramid fiber section (4.8%) and the no fiber section (5.8%). The results of SCB and IDEAL-CT test showed that the effectiveness of aramid fibers on PG 70-22M mix was not clear. This finding appears to be in agreement with two previous study results that the addition of aramid fibers to a polymer modified asphalt binders was not as effective as the addition of aramid fibers in unmodified asphalt binders. ACCD test results indicated that the low temperature cracking potential of the aramid fiber reinforced asphalt mixes were at the acceptable level and comparable to that of mixes with no aramid fibers.

D.2 Results of Tests Performed on Laboratory Prepared Samples

Laboratory tests were performed on samples prepared in the laboratory following the test plan presented in Figure C.2 to determine the fatigue cracking, rutting, low temperature cracking, and moisture resistance using Semi-Circular Bend (SCB) test, IDEAL-CT, Overlay Tester, Hamburg Wheel Tracking (HWT) tester, and Asphalt Concrete Cracking Device (ACCD). Originally, three fiber length was plan to be used in this investigation. However, due to unavailability of 0.5 inch length aramid fibers for one of the suppliers, tests were proceeded with only two commonly used fiber lengths (0.75 and 1.5 inch) were used. The first set of tested samples included asphalt mixes prepared with PG 58-28, PG 64-22, and PG 70-22M without aramid fibers to serve as a control group where the results of aramid fiber asphalt mixes to be compared against. The second set of tested samples consisted of full factorial design for three test variables (2 fiber types x 2 fiber lengths x 2 dosages = 8 asphalt mixes) prepared with PG 64-22 unmodified asphalt binder. To be more specific, the fiber type variable included wax treated aramid fibers and blended aramid and polyolefin fibers; the fiber length variable included 0.75 and 1.5 inch length; and the dosage variable included the supplier's recommended dosage and 1.5 time of the recommended dosage.

Analysis of Variance (ANOVA) identifies statistically significant factors affecting independent variables. For each teat results, ANOVA was performed using mix ID as the only factor to determine the statistical differences of 15 asphalt mixes. Post hoc analysis was also performed to determine the detailed differences among 15 asphalt mixes using Tukey Honest Significant Difference (HSD) procedure with 95% confidence level. In the post hoc Tukey analysis, samples with the same group lettering have no statistical difference among them. Only the results of post hoc multiple comparisons of means are presented in this section.

To determine the effects of fiber type, length, dosage, and their interaction, another ANOVA was performed on the eight mixes of full factorial PG 64-22 asphalt mixes. The results this ANOVA are presented following the post hoc analysis results.

D.2.1 Semi-Circular Bend (SCB) Test

In SCB test, the cracking resistance of asphalt mix is expressed by Flexibility Index (FI) and Normalized Fracture Energy (NFE). The higher the FI or NFE value, the better the cracking resistance of asphalt mix. Figure D.10 shows FI of all asphalt mixes tested. A horizontal line was drawn at FI value for the control asphalt mix, asphalt mix with PG 64-22 with no aramid fiber (64N), for easy comparison. Tables D.1 and D.2, show post hoc multiple comparisons of FI and ANOVA analysis for aramid fiber variables. The differences of average FI values of 15 asphalt mixes are statistically significant. The effects of aramid fiber on the cracking resistance were dependent on the binder type, aramid fiber type, fiber length and dosage. The detailed difference can be found from the results of the post hoc Tukey multiple comparisons of means in Table D.1. All PG 58-28 mixtures, regardless containing aramid fibers or not, showed the highest cracking resistance and belonged to Groups A and B. On the other hand, asphalt mixes with PG 64-22 and PG 70-22M without aramid fiber belonged to Group G with lowest FI values, indicating the worst cracking resistance. Other mixes that belonged to the lowest FI value group (G) were PG 64-22 asphalt mixes with the short-length wax treated aramid fibers (64AS1 and 64AS2) and the long-length blended aramid/polyolefin fibers (64BL1 and 64BL2), regardless of dosages used. Following the largest FI values of the asphalt mixes with PG 58-28 asphalt mixes, ones with the next largest FI values or cracking resistance were PG 64-22 asphalt mixes with long-length wax treated aramid fibers and PG 64-22 asphalt mixes with short-length blended aramid polyolefin fibers. This observations is also confirmed in ANOVA of asphalt mixes used in the factorial design as shown in Table D.2. There were significant interactions between the aramid fiber type and length and also between the aramid fiber type and dosage. The interactions between the aramid fiber type and length can be clearly seen in Figure D.1. When the length of the wax treated aramid fibers (A type) were doubled, FI values of the corresponding asphalt mixes were significantly increased. However, the length of the blended aramid polyolefin fibers (B type) were doubled, FI values of the asphalt mixes significantly decreased for both dosages used. When doubling the dosage, asphalt mixes with both 0.75 and 1.5-inch length blended aramid polyolefin fibers showed significant reduction in FI values. However, for wax treated aramid fiber, only 0.75-inch length asphalt mix showed reduction in FI values by doubling the dosage.

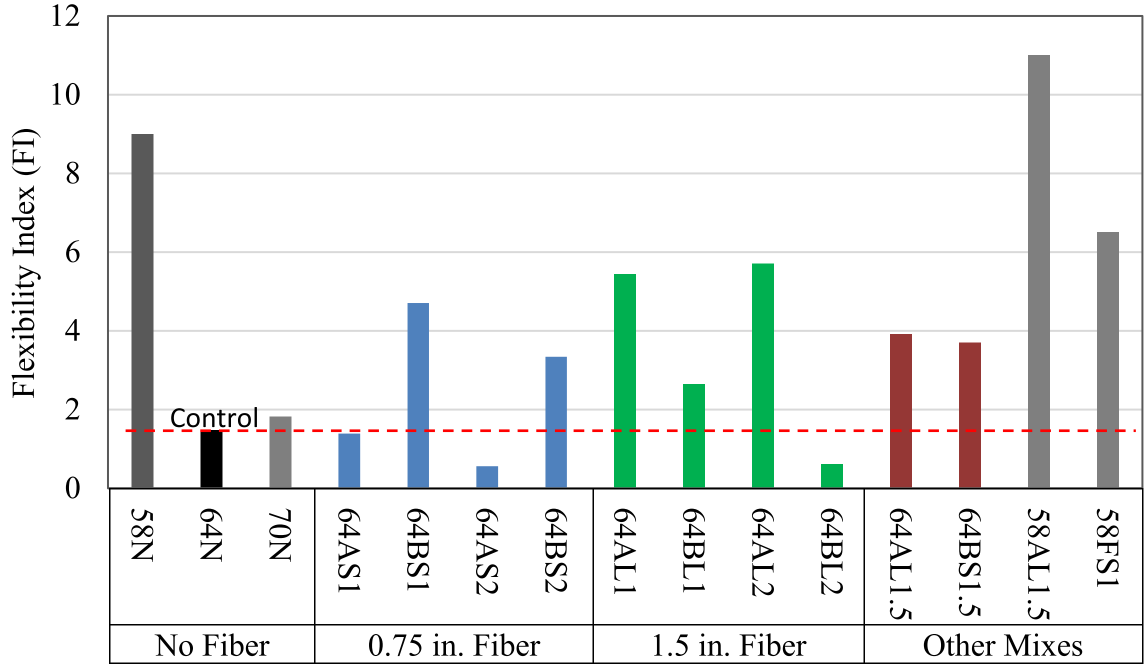

Figure D.10 Flexibility Index (FI) determined by SCB test

Table D.1 Post hoc analysis multiple comparisons for FI

Mix ID	Average FI	Group						
58AL1.5	11.0	A						
58N	9.0	A	B					
58BS1	6.5		B	C				
64AL2	5.7			C	D			
64AL1	5.4			C	D			
64BS1	4.7			C	D	E		
64AL1.5	3.9			C	D	E	F	
64BS1.5	3.7				D	E	F	
64BS2	3.3				D	E	F	
64BL1	2.6					E	F	G
70N	1.8						F	G
64N	1.5						F	G
64AS1	1.4						F	G
64BL2	0.6							G
64AS2	0.6							G

Table D.2 ANOVA of FI to determine significant factors

Source	Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	224.507	6	37.418	40.061	.000
Intercept	511.761	1	511.761	547.911	.000
Fiber	2.380	1	2.380	2.548	.117
Length	18.560	1	18.560	19.871	.000
Dose	12.394	1	12.394	13.270	.001
Fiber * Length	**173.229**	**1**	**173.229**	**185.466**	**.000**
Fiber * Dose	**8.363**	**1**	**8.363**	**8.954**	**.004**
Length * Dose	.055	1	.055	.059	.809
Error	47.635	51	.934		
Total	868.047	58			
Corrected Total	272.142	57			

R Squared = 0.825; **Bold** = Statistically significant variable with p-value < 0.05

Figure D.11 shows Normalized Fracture Energy (NFE) of 15 asphalt mixes determined from SBC test results. Tables D.3 and D.4 show post hoc multiple comparisons of NFE means and ANOVA to determine the factors affecting NFE. Similar performance trends as seen for FI were observed for NFE. Three asphalt mixes with PG 58-28 binder showed the largest NFE probably due to the low stiffness of the mixes at the test temperature (25°C). The worst NFE Groups H and I in Table D.3 included asphalt mixes prepared with PG 64-22 binder with short length (0.75 in.) wax treated aramid fibers (64AS1, 64AS2), asphalt mixes with long length (1.5 in.) blended aramid polyolefin fibers (64BL1, 64BL2) and asphalt mixes prepared with PG 64-22 and PG 70-22M binder only (64N, 70N). There also were statistically significant interactions among fiber type, length, and dosage as shown in Table D.4. The changes in crack resistance measured by NFE due to doubling the fiber length from 0.75 to 1.5 in. opposite for the two types of aramid fibers; NFE values for asphalt mixes with the wax treated aramid fibers were increased and NFE values for asphalt mixes with the blended aramid polyolefin fibers were decreased. The NFE responses to doubling the dosage were also different for two types of aramid fibers. Doubling the dosage of the blended aramid polyolefin fibers caused significant reduction in NFE of asphalt mixes for both 0.75 and 1.5 in. fiber lengths as shown in Figure D.11. However, doubling the dosage of the wax treated 1.5 in. length aramid fibers showed increased NFE value.

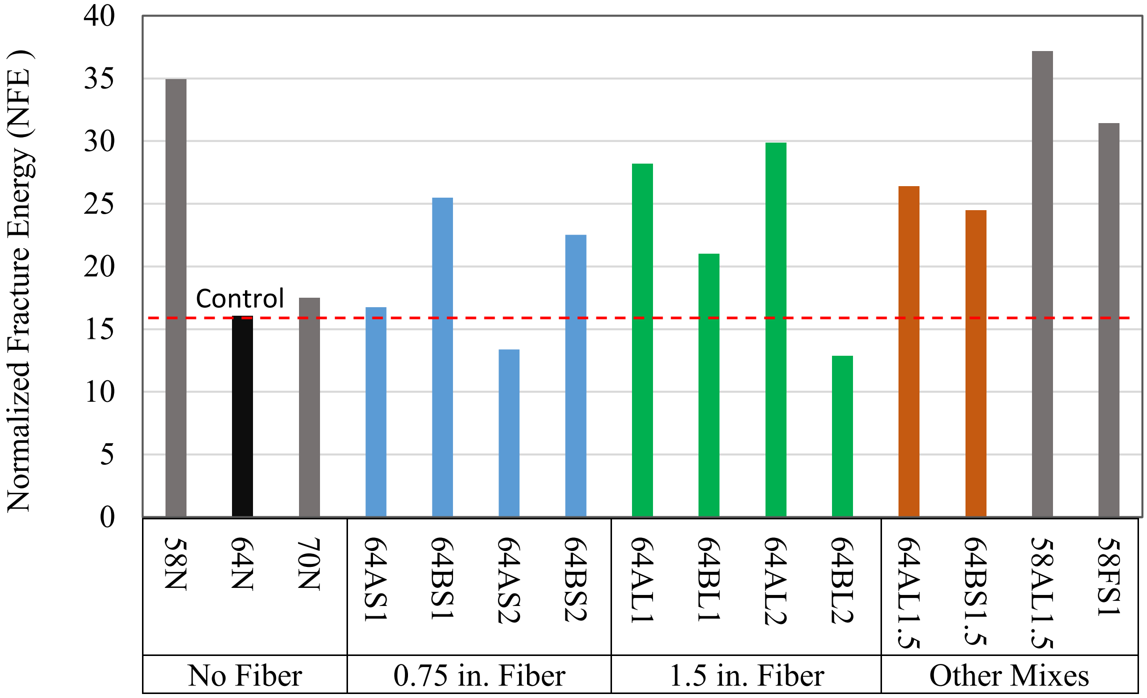

Figure D.11 Normalized Fracture Energy (NFE) determined by SCB test

Table D.3 Post hoc analysis for multiple comparisons of NFE means

Mix ID	Average NFE	Group								
58AL1.5	37.2	A								
58N	34.9	A	B							
58BS1	31.4	A	B	C						
64AL2	29.9		B	C	D					
64AL1	28.2			C	D	E				
64AL1.5	26.4			C	D	E	F			
64BS1	25.5				D	E	F			
64BS1.5	24.5				D	E	F			
64BS2	22.5					E	F	G		
64BL1	21.0						F	G	H	
70N	17.5							G	H	I
64AS1	16.8							G	H	I
64N	16.1								H	I
64AS2	13.4									I
64BL2	12.9									I

Table D.4 ANOVA of NFE to determine significant factors

Source	Sum of Squares	df	Mean Square	F	Sig.
Corr Model	2108.234	6	351.372	42.8	.000
Intercept	24893.753	1	24893.753	3038.1	.000
Fiber	26.250	1	26.250	3.2	.079
Length	**194.285**	**1**	**194.285**	**23.7**	**.000**
Dose	**118.512**	**1**	**118.512**	**14.4**	**.000**
Fiber * Length	**1589.564**	**1**	**1589.564**	**193.9**	**.000**
Fiber * Dose	**102.887**	**1**	**102.887**	**12.5**	**.001**
Length * Dose	1.329	1	1.329	0.1	.689
Error	417.882	51	8.194		
Total	29806.497	58			
Corrected Total	2526.116	57			

R Squared = 0.835; **Bold** = Statistically significant variable with p-value < 0.05

D.2.2 IDEAL-CT Test

Figure D.12 shows the cracking tolerance index (CTI), a measure of the resistance to cracking determined from the IDEAL-CT results, for 15 asphalt mixes tested. Tables D.5 and D.6 show post hoc multiple comparisons of CTI means and ANOVA to determine the factors affecting CTI. As seen in Table D.5, the best performing Group A in terms of CTI value includes the asphalt mixes with PG 58-22 asphalt binder containing each type of aramid fiber (58AL1.5 and 58BS1 mixes) and the asphalt mix with PG 64-22 binder and long length wax treated aramid fiber at 1.5 times of recommended dosage (64AL1.5). It is worth to note that asphalt mix with soft PG 58-28 binder alone without aramid fiber (58N) showed significantly low CTI value.

The effects of the aramid fiber on the CTI cracking resistance value in IDEAL-CT test results were not as clear as in SCB test results. For IDEAL-CT ANOVA statistical model in Table D.6, R^2 value was 0.459, whereas for SCB R^2 values were 0.825 and 0.835 for FI and NFE, respectively. The only significant term explaining CTI in the AVONA was the interaction term between the fiber type and the dosage. For the short and long length wax treated aramid fiber (64AS and 64AL) mixes, doubling the dosage resulted in reduction of CTI values. However, for the short length blended aramid polyolefin fiber mix (64BS), doubling the dosage significantly increased CTI value while for the long length blended aramid polyolefin fiber mix (64BL) decreased CTI value.

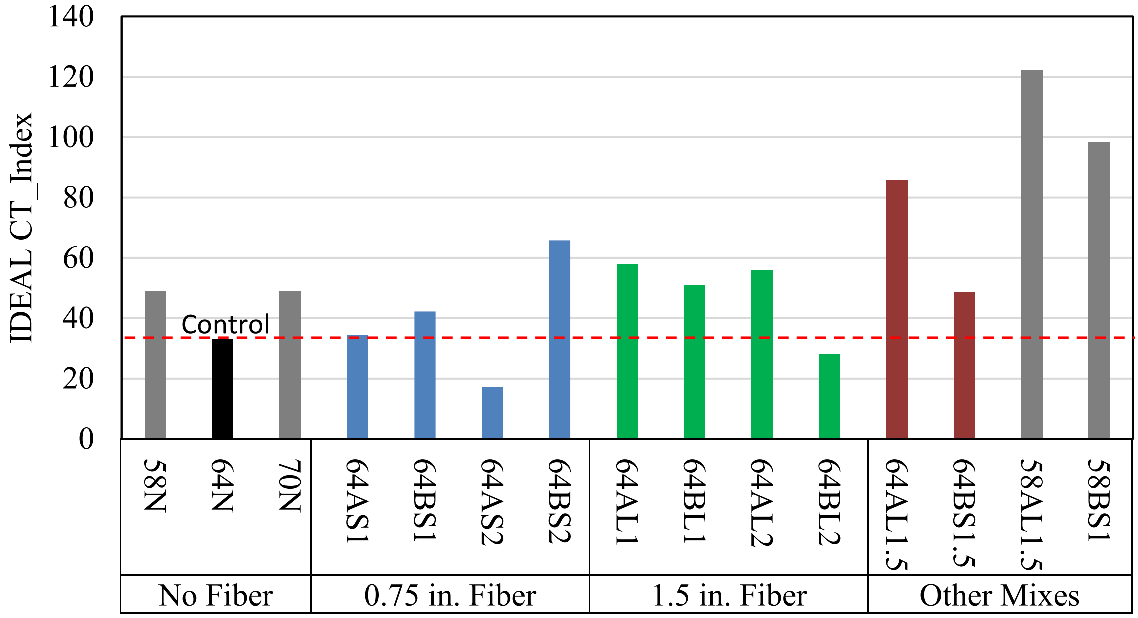

Figure D.12 Cracking tolerance index (CTI) determined by IDEAL-CT

Table D.5 Post hoc analysis for multiple comparisons of CTI means

Mix ID	Average CTI	Group			
58AL1.5	136.1	A			
58BS1	98.1	A	B		
64AL1.5	85.8	A	B	C	
64BS2	65.8		B	C	D
64AL1	58.1		B	C	D
64AL2	55.9		B	C	D
64BL1	50.9		B	C	D
70N	49.0		B	C	D
58N	48.9		B	C	D
64BS1.5	48.6		B	C	D
64AS1	34.5		B	C	D
64BS1	34.4		B	C	D
64N	33.3		B	C	D
64BL2	28.1			C	D
64AS2	17.2				D

Table D.6 ANOVA of CTI to determine significant factors

Source	Sum of Squares	df	Mean Square	F	Sig.
Corr Model	4371.911	6	728.652	2.683	.047
Intercept	43028.803	1	43028.803	158.444	.000
Fiber	67.838	1	67.838	.250	.623
Length	1.671	1	1.671	.006	.938
Dose	945.742	1	945.742	3.482	.078
Fiber * Length	295.191	1	295.191	1.087	.310
Fiber * Dose	**2617.308**	**1**	**2617.308**	**9.638**	**.006**
Length * Dose	866.005	1	866.005	3.189	.090
Error	5159.863	19	271.572		
Total	56314.247	26			
Corrected Total	9531.774	25			

R Squared = 0.459; **Bold** = Statistically significant variable with p-value < 0.05

D.2.3 Overlay Tester

Figure D.13 shows the number of cycles to failure (N_f) for 15 asphalt mixes tested with Overlay Tester. Tables D.7 and D.8 show post hoc multiple comparisons of N_f means and ANOVA to determine the factors affecting it. As seen in the previous two test results, the highest N_f was observed in three asphalt mixes with soft PG 58-28 binder with or without either aramid fiber and they were all grouped together in Table D.7. The effects of the aramid fibers on N_f were dependent on the fiber type, length, and dosage. The results of ANOVA for N_f in Table D.8 show statistically significant interactions between the aramid fiber type and length and also between fiber length and dosage. Among asphalt mixes with short length (0.75 in.) aramid fibers, asphalt mixes with the blended fiber performed better than the mixes with wax treated fiber for each respective dosage level. However, among asphalt mixes with long length (1.5 in.) aramid fibers, asphalt mixes with the wax treated fiber performed better than the mixes with blended fiber for each respective dosage.

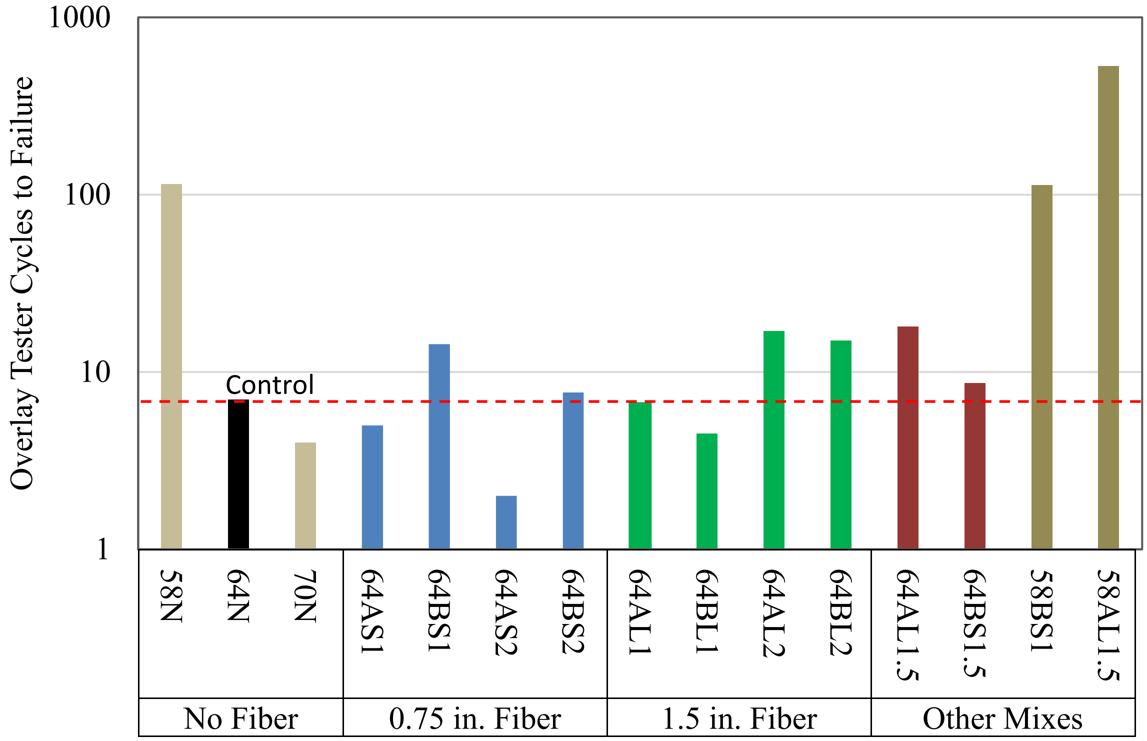

Figure D.13 Overlay Tester results

Table D.7 Post hoc analysis for multiple comparisons of Overly Tester N_f means

Mix ID	Average Nf	Group			
58AL15	485.0	A			
58N	102.1	A	B		
58FS1	100.3	A	B		
64AL1.5	32.2		B	C	
64FS1	11.7		B	C	D
64AL2	10.6		B	C	D
64FL2	9.0			C	D
64BS1.5	8.3			C	D
64FS2	7.4			C	D
64AL1	6.6			C	D
64N	6.1			C	D
64AS1	4.9			C	D
70N	3.9			C	D
64FL1	3.7			C	D
64AS2	2.0				D

Table D.8 ANOVA of Overly Tester N_f to determine significant factors

Source	Sum of Squares	df	Mean Square	F	Sig.
Corr Model	1.344	6	.224	1.983	.128
Intercept	14.100	1	14.100	124.792	.000
Fiber	.138	1	.138	1.221	.286
Length	.070	1	.070	.616	.444
Dose	.000	1	.000	.000	.991
Fiber * Length	**.567**	**1**	**.567**	**5.023**	**.040**
Fiber * Dose	.049	1	.049	.432	.520
Length * Dose	**.492**	**1**	**.492**	**4.357**	**.053**
Error	1.808	16	.113		
Total	17.804	23			
Corrected Total	3.152	22			

R Squared = 0.426; **Bold** = Statistically significant variable with p-value < 0.05

D.2.4 Hamburg Wheel Tracking Test

Hamburg Wheel Tracking (HWT) is typically used as pass-fail test in mix design process for rutting and moisture damage control. Texas DOT (TEX-242-F) uses 12.5 mm maximum HWT rut depth criteria where the number of wheel pass varies with the high temperature PG grade of asphalt binder used. For binders with PG 64, PG 70, and PG 76 grades, the required number of passes are 10,000, 15,000, and 20,000, respectively. Iowa DOT (Section 2303) uses stripping inflection point (SIP) to control moisture damage of asphalt mixes. For standard traffic, SIP is required to be greater than 10,000 passes and for heavy and very heavy traffic, it is 14,000 passes.

Table D.9 and Figure D.14 summarize rut depths and stripping inflection points (SIP) determined from Hamburg Wheel Tracking (HWT) tests for 15 asphalt mixes. Except one test sample, all asphalt mixes with PG 58-28 asphalt binder with or without aramid fibers (58N, 58AL1.5, 58BS1) failed before it reached 20,000 passes and showed SIP between 8,000 and 14,000 passes. It appears that the addition of aramid fibers slightly improved the moisture resistance of asphalt mixes as evidenced by slightly larger SIP of asphalt mixes with aramid fibers than SIP of no fiber asphalt mix (58N). For asphalt mixes with PG 64-22 and PG 70-22 binders with and without aramid fibers, rutting resistance and moisture resistance of the asphalt mixes were at acceptable levels, having rut depth less than 12.5mm with 20,000 wheel passes and SIP greater than 14,000 passes. Tables D.10 and D.11 show post hoc multiple comparisons of rut depth means and ANOVA to determine the factors affecting it. The only statistically significant at 95% confidence level was aramid fiber type. Some of asphalt mixes with wax treated aramid fibers (64AS1 and 64AL2) showed significantly larger rut depth than that of PG 64-22 binder control mix (64N). These two asphalt mixes were grouped together with asphalt mixes with PG 58-28 binder as poorly performing mixture (Group B) in Table D.10.

Table D.9 Hamburg Wheel Tracking test results

Mix ID	Rut Depth at 20,000 passes, mm		Stripping Inflection Point (SIP), passes	
	rep 1	rep 2	rep 1	rep 2
58N	25.0*	25.0*	10,739	7,984
64N	3.8	6.0	-	-
70N	3.1	3.2	-	-
64AS1	6.9	8.9	-	15,336
64BS1	3.1	3.4	-	-
64AS2	3.8	0.7	-	-
64BS2	3.4	4.2	-	-
64AL1	5.2	3.9	14,998	-
64BL1	3.6	3.0	-	-
64AL2	4.0	10.5	-	14,204
64BL2	4.7	4.1	-	-
64AL1.5	7.2	3.5	-	-
64BS1.5	3.8	4.2	-	-
58AL1.5	25.1*	2.2	14,523	-
58BS1	25.1*	25.0*	10,192	11,156

* Failed

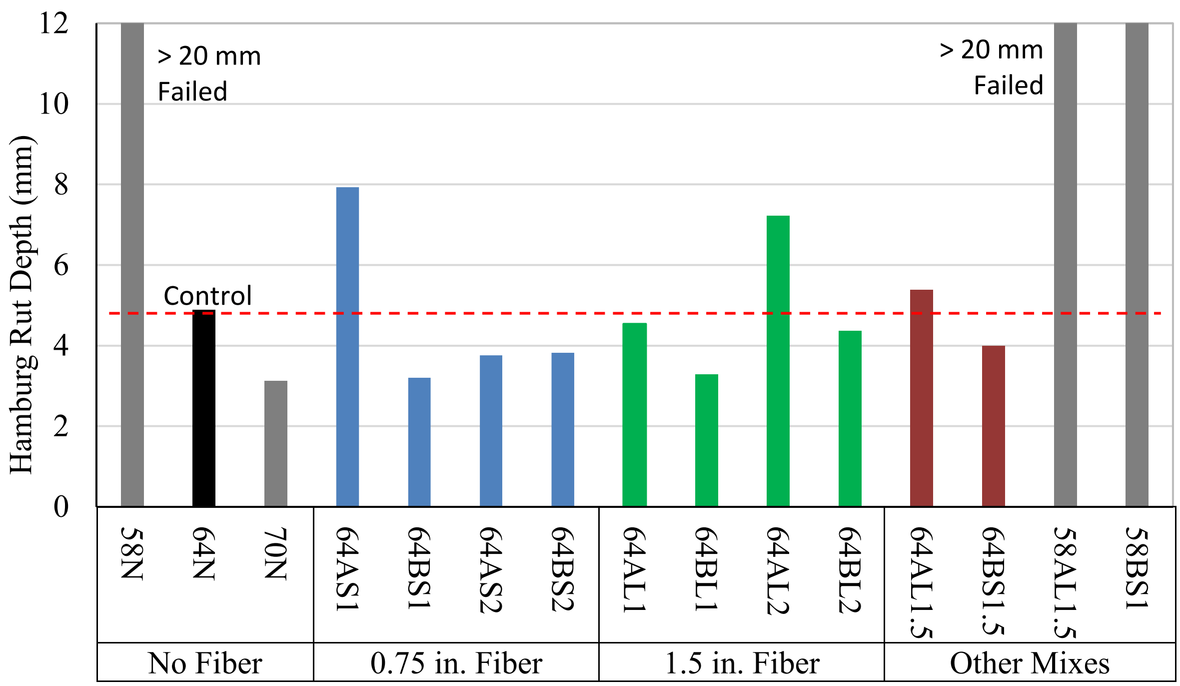

Figure D.14 Hamburg Wheel Tracking rut depth at 20,000 passes

Table D.10 Post hoc analysis for multiple comparisons of Overly Tester N_f means

Mix ID	Average Rut Depth, mm	Group	
70N	3.1	A	
64FS1	3.2	A	
64FL1	3.3	A	
64AS2	3.8	A	
64FS2	3.8	A	
64FS1.5	4.0	A	
64FL2	4.4	A	
64AL1	4.5	A	
64N	4.9	A	
64AL1.5	5.4	A	
64AL2	7.2	A	B
64AS1	7.9	A	B
58AL15	13.7	A	B
58N	25.0	A	B
58FS1	25.1		B

Table D.11 ANOVA of HWT rut depth to determine significant factors

Source	Sum of Squares	df	Mean Square	F	Sig.
Corr Model	35.405	6	5.901	1.520	.275
Intercept	363.474	1	363.474	93.627	.000
Fiber	**19.228**	**1**	**19.228**	**4.953**	**.053**
Len	.116	1	.116	.030	.867
Dose	.011	1	.011	.003	.959
Fiber * Len	.078	1	.078	.020	.890
Fiber * Dose	2.576	1	2.576	.664	.436
Len * Dose	13.396	1	13.396	3.451	.096
Error	34.939	9	3.882		
Total	433.818	16			
Corrected Total	70.344	15			

R Squared = 0.503; **Bold** = Statistically significant variable with p-value < 0.05

D.2.5 Asphalt Concrete Cracking Device test

Figure 15 shows the thermally induced cracking temperature (T_{cr}) determined using the Asphalt Concrete Cracking Device (ACCD) for 15 asphalt mixes. Tables D.12 and D.13 show post hoc multiple comparisons of the average cracking temperature and ANOVA to determine the factors affecting it. Overall, with exception of 64BL2 mix, addition of the wax treated or the blended aramid fibers did not adversely affect the low temperature performance of asphalt mixes. For the asphalt mixes with PG 58-28 binder, the addition of the wax treated and the blended aramid fiber significantly lowered the cracking temperature by 4°C. ANOVA shown in Table D.13 indicates that there was a statistically significant interaction between the fiber type and the length. For short length (0.75 in.), the effects of both aramid fiber type on ACCD T_{cr} was negligible. However, for long length (1.5 in.), asphalt mixes with the wax treated aramid fibers showed colder T_{cr} for both single and double dosages (64AL1 and 64AL2) than the control mix (64N). However, mixes with the blended polyolefin and aramid fibers showed colder T_{cr} for single dosage and warmer T_{cr} for double dosage.

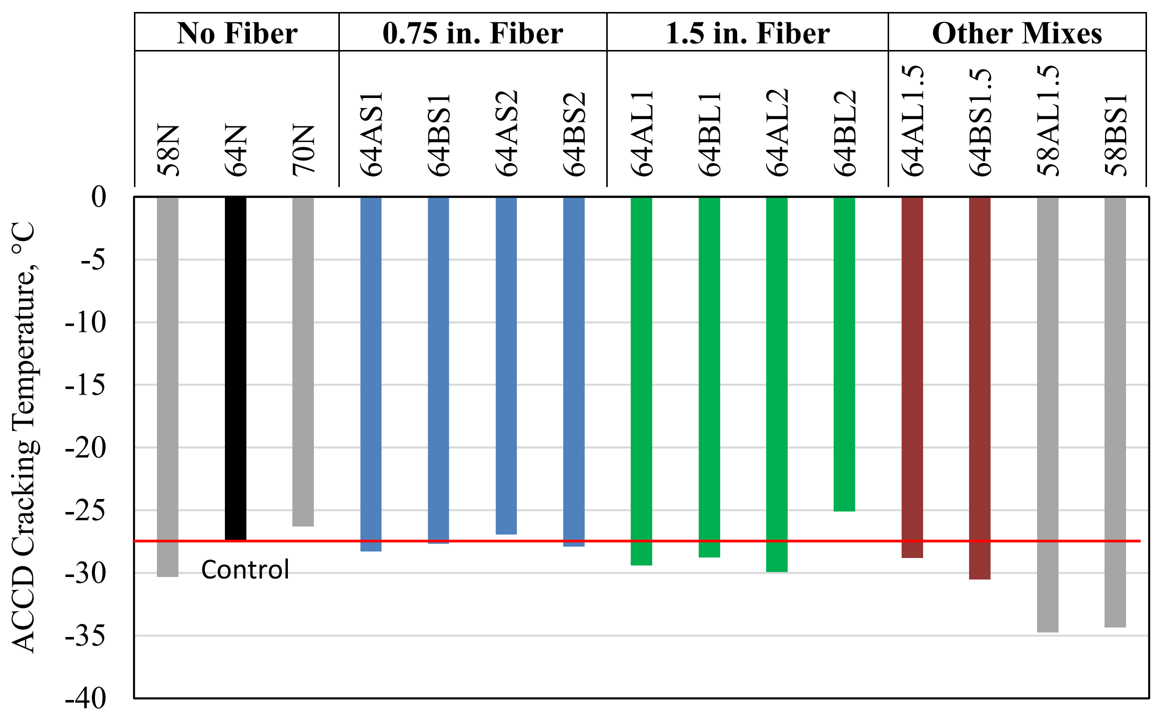

Figure D.15 ACCD cracking temperature (T_{cr})

Table D.12 Post hoc analysis for multiple comparisons of ACCD T_{cr}

Mix ID	Average ACCD T_{cr}, °C	Group						
58AL1.5	-34.7	A						
58BS1	-34.3	A						
58N	-30.3		B					
64AL2	-29.9		B	C				
64BS1.5	-29.8		B	C	D			
64AL1	-29.4		B	C	D	E		
64BL1	-28.8		B	C	D	E		
64AL1.5	-28.4		B	C	D	E	F	
64AS1	-28.3		B	C	D	E	F	
64BS2	-27.9		B	C	D	E	F	
64BS1	-27.7			C	D	E	F	
64N	-27.4				D	E	F	G
64AS2	-26.9					E	F	G
70N	-26.3						F	G
64BL2	-25.1							G

Table D.13 ANOVA of ACCD T_{cr} to determine significant factors

Source	Sum of Squares	df	Mean Square	F	Sig.
Corr Model	23.782	6	3.964	3.318	.052
Intercept	12540.080	1	12540.080	10498.6	.000
Fiber	**6.566**	**1**	**6.566**	**5.497**	**.044**
Len	1.410	1	1.410	1.181	.305
Dose	4.676	1	4.676	3.915	.079
Fiber * Length	**8.338**	**1**	**8.338**	**6.980**	**.027**
Fiber * Dose	1.736	1	1.736	1.453	.259
Length * Dose	1.056	1	1.056	.884	.372
Error	10.750	9	1.194		
Total	12574.613	16			
Corrected Total	34.532	15			

R Squared = 0.689; ; **Bold** = Statistically significant variable with p-value < 0.05

Appendix E Cost Analyses

Among asphalt mixes with PG 64-22 asphalt binder and aramid fibers, ones prepared with 1.5 inch aramid fiber at the supplier's recommended dosage and 1.5 times of the recommended dosage showed best cracking resistance for Type A wax treated aramid fiber (64AL1 and 64AL1.5 mixes). For type B aramid and polyolefin blended fibers, the asphalt mix with 0.75 inch fiber length at the supplier's recommended dosage (64BS1 mix) showed the best cracking resistance. The cost effectiveness of these three aramid fiber mixes was determined in comparison with PG 64-22 unmodified and PG 70-22M polymer modified asphalt mixes without aramid fiber (64N and 70N mixes). To perform life cycle cost analysis (LCCA), the expected performance or service life of each candidate mix needs to be determined. In this section, the first part describes the performance prediction of the each asphalt mix and the latter part describes the results of cost analysis of asphalt mixes containing aramid fibers.

E.1 Performance Prediction of Asphalt Mixtures

All candidate asphalt mixes with PG 64-22 asphalt binder with aramid fibers showed adequate performance against the low temperature cracking and rutting. Based on this fact, it was assumed that the service life of each asphalt mix would be determined by fatigue cracking failure. The fatigue life or the number of cycles to failure for each asphalt mix was estimated from relationships developed from a well-controlled FHWA fatigue study.

FHWA constructed test sections at the FHWA Pavement Test Facility (Figure E.1) with various asphalt mixtures with identical pavement structure to study fatigue behavior of asphalt mixes. While continuously applying traffic loading using two units of Accelerated Loading Facility (ALF), the fatigue performance characteristics of these test sections were recorded and have been compared with various laboratory test results including SCB Flexibility Index (FI) (*1*), IDEAL-CT Cracking Tolerance Index (*2*) and the number of cycles to failure in Overlay Tester (*3*). These relationships between FHWA ALF data and the laboratory test data are presented in Figures E.2, E.3, and E.4 for SCB, IDEAL-CT, and Overlay Tester, respectively. All three relationships showed high goodness of fit with R-square values ranging from 89% to 96%.

Figure E.1 FWHA Pavement Test Facility (PTF) shown with two Accelerated Loading Facility (ALF) machines

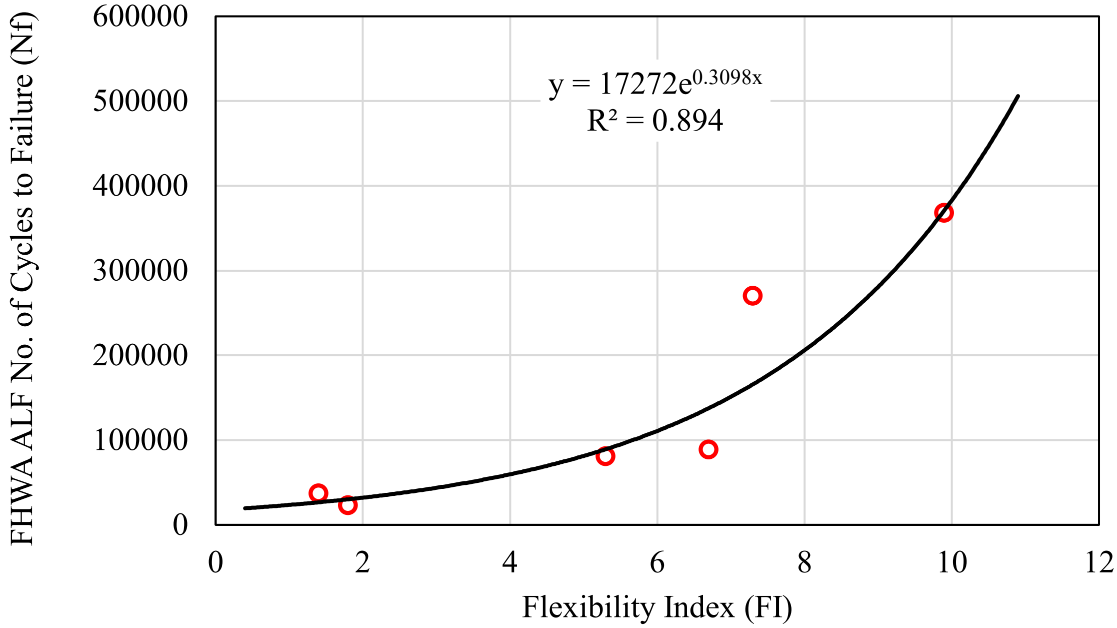

Figure E.2 FHWA ALF number of cycle to fatigue failure versus SCB Flexibility Index (FI)

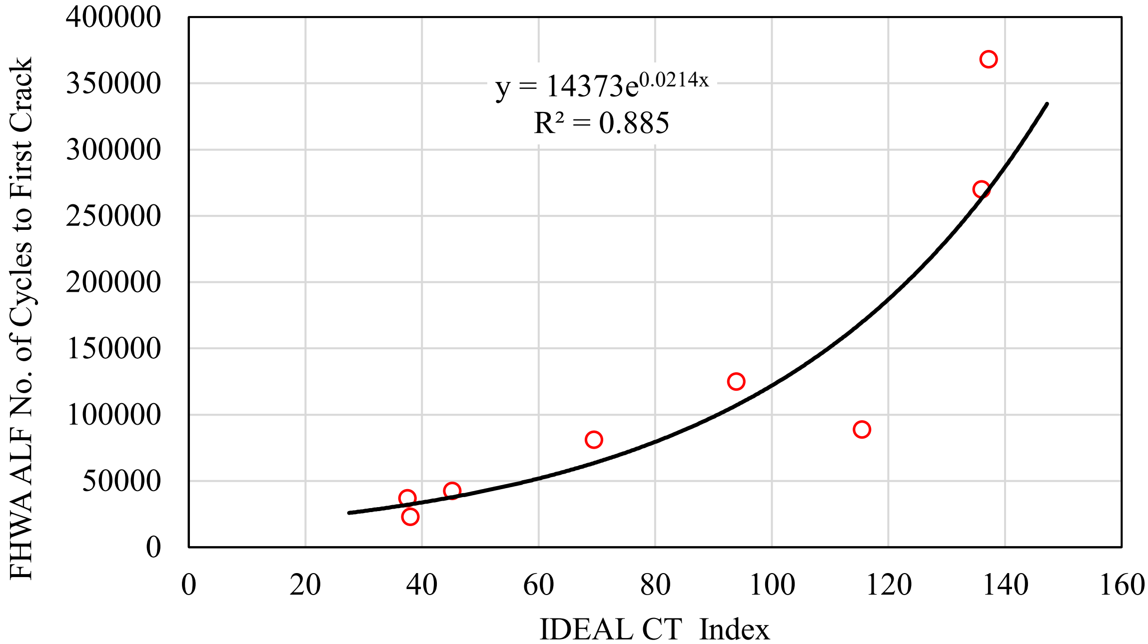

Figure E.3 FHWA ALF number of cycle to fatigue failure versus IDEAL-CT CT Index

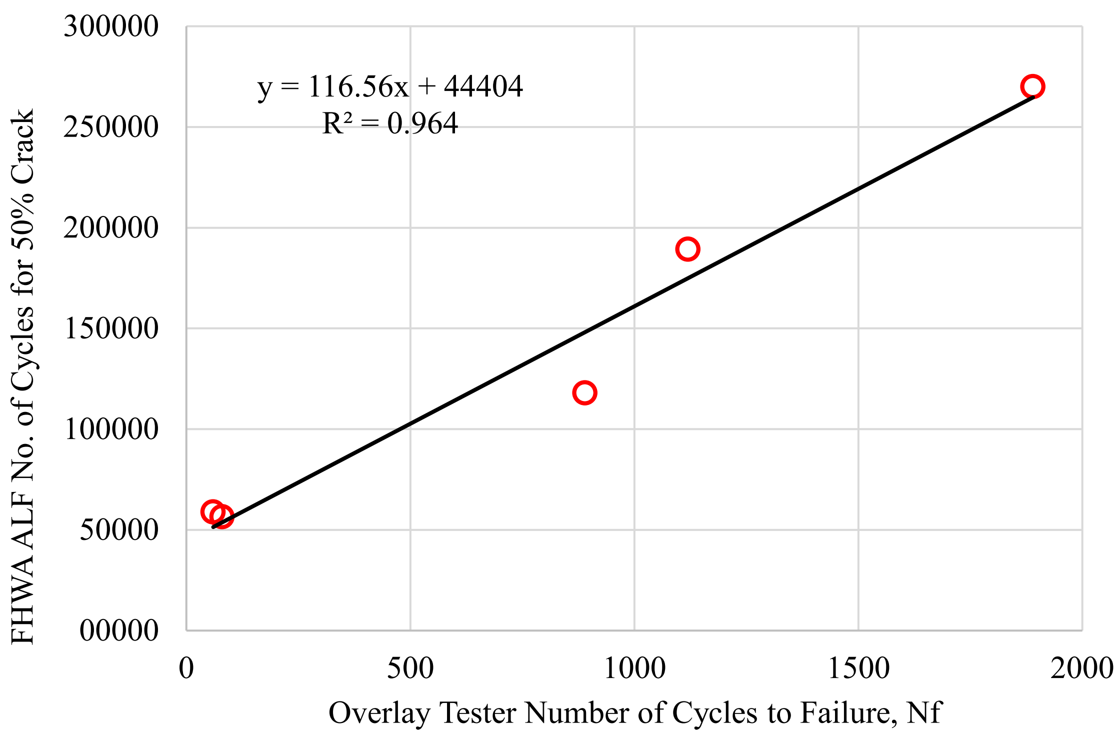

Figure E.4 FHWA ALF number of cycle to fatigue failure versus Overlay Tester

Table E.1 shows the predicted numbers of cycles to failure for all five asphalt mixes calculated using the best fit equations in Figures E.2, E.3, and E.4. Percent increase of number of cycles to failure with respect to PG 64-22 asphalt mix (64N) and the expected service life were also presented in Table E.1. It should be noted that the expected service life for an unmodified PG 64-22 mix overlay with a typical 1.5 in. thickness was assumed to be 9 years. The service lives of other mixes were calculated by proportionally increasing the 9 year service life as much as the average percent increase of predicted number of cycles to failure with respect to PG 64-22 mix.

Table E.1 Predicted service life of asphalt mixes

	Predicted Nf (x 1000)			% Increase of Nf with Respect to PG 64-22 Mix				Service Life, year
Mix ID	OT	IDEAL	SCB	OT	IDEAL	SCB	Average	
PG 64-22	45	29	27	-	-	-	-	9.0
PG 70-22M	45	41	30	-1%	40%	11%	17%	10.5
64AL1.5	47	60	57	3%	105%	109%	72%	15.5
64AL1	45	50	93	0%	70%	241%	104%	18.4
64BS1	46	35	74	2%	21%	172%	65%	14.9

E.2 Cost Analysis of Aramid Fiber in Asphalt Mixture

Equivalent Uniform Annual Costs (EUAC) of asphalt mixes were used to determine the cost effectiveness of aramid fibers in asphalt mixes. In EUAC calculation shown in Equation E.1, initial and all future costs including maintenance and repairs throughout the analysis period are expressed as a single cost in terms of the present year monetary value, known as Net Present Value (NPV).

$$EUAC = NPV\left[\frac{i(1+i)^n}{(1+i)^n-1}\right] \qquad (E.1)$$

Where

NPV: net present value
i: discount rate (4%)
n=analysis period (= service life)

In this study, by assuming all future costs are equal for roadways built with five considered asphalt mixture types, the initial cost was used as NPV. Using the unit costs given in Table E.2, the initial costs for unit lane-mile overlay with 1.5 inch thickness and 12 feet width were calculated. Table E.3 and Figure E.5 show EUACs calculated using Equation E.1 and the initial cost as NPV. Discount rate of 4% was used for EUAC calculation. Figure E.6 shows cost ratio calculated by dividing EUAC of polymer and aramid fiber modified asphalt mix by EUAC of PG 64-22 asphalt mix.

Table E.2 Unit cost of materials used for initial cost calculation

Material	Unit Cost
PG 64-22 Asphalt Mix	$149.50 per Cubic Yard
PG 70-22M Asphalt Mix	$174.96 per Cubic Yard
Type A Aramid Fiber	$8.50 per ton of mix
Type B Aramid Fiber	$6.75 per ton of mix

Table E.3 Equivalent Uniform Annual Cost (EUAC) of roadways built with aramid fibers and control asphalt mixes

	Average Nf Increase	Service Life in Year	Initial Cost of Overlay per Lane-Mile	EUAC (Yearly Cost) per Lane-Mile
PG 64-22	-	9.0	$43,853	$5,898
PG 70-22M	17%	10.5	$51,322	$6,068
64AL1.5	72%	15.5	$51,333	$4,512
64AL1	104%	18.4	$48,840	$3,806
64BS1	65%	14.9	$47,813	$4,332

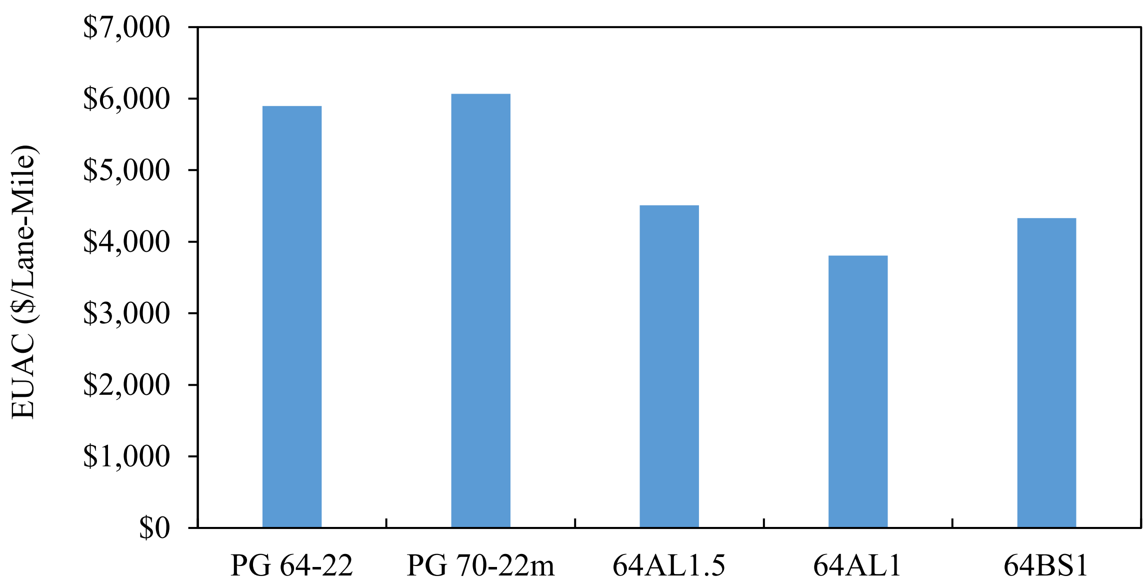

Figure E.5 Equivalent Uniform Annual Cost (EUAC) of roadways built with aramid fibers and control asphalt mixes

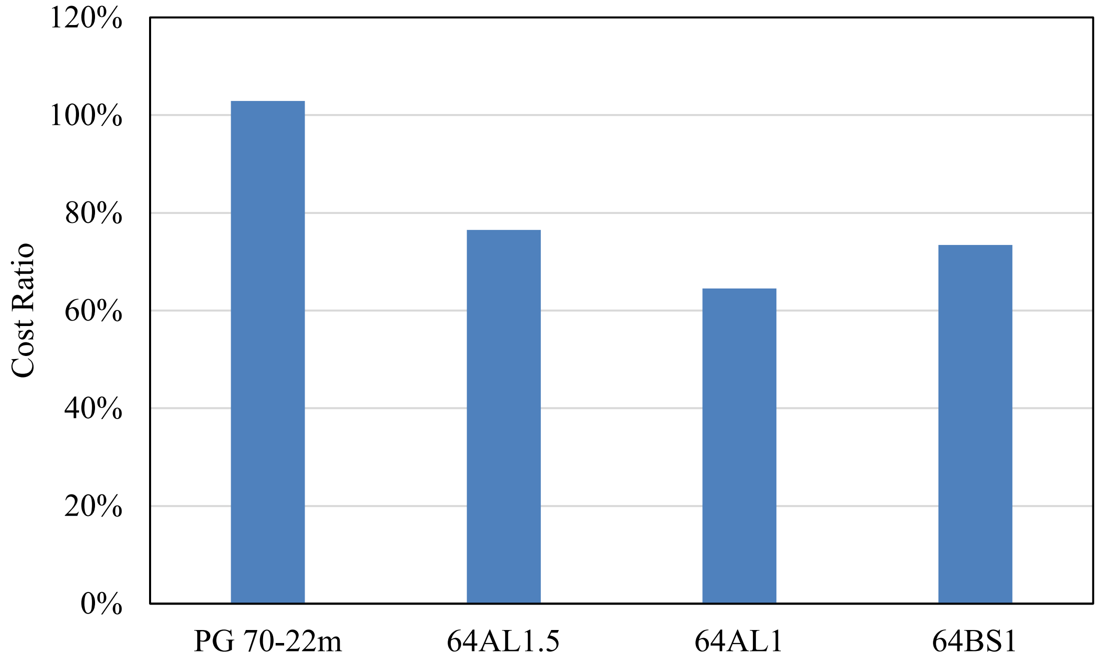

Figure E.6 Cost ratio of roadways built with aramid fibers and polymer modified asphalt mixes with respect to PG 64-22 asphalt mix

In comparison to the commonly used unmodified PG 64-22 asphalt mix, both Type A (wax treated) and Type B (blended with PO fiber) aramid fiber modified asphalt mixes showed a significant economic benefit with large reductions in the Equivalent Uniform Annual Cost (EUAC) while the PG 70-22M polymer modified asphalt mix did not show any economic benefit showing 3% increase in EUAC. For Type A wax treated aramid fibers, asphalt mixes with 1.5 inch fiber length at 1.5 times the supplier's recommended dosage (64AL1.5) showed 24% reduction in EUAC while asphalt mixes with 1.5 inch fiber length at the supplier's recommended dosage (64AL1) showed 35% reduction in EUAC. For Type B blended aramid fibers with 0.75 inch fiber length at the supplier's recommended dosage (64BS1) showed 27% reduction in annual cost as expressed by EUAC. Based on this observation, for Phase 2 field trial, it is recommended to use the wax treated aramid fiber (Type A) with 1.5 inch length at the supplier's recommended dosage (0.26 lb per ton of mix) and the polyolefin blended aramid fiber (Type B) with 0.75 inch at the supplier's recommended dosage (1.1 lb per ton of mix).

E.3 References

1- Al-Qadi, I., Ozer, H., Lambros, J., El Khatib, A., Singhvi,P., Khan, T., Rivera, J., Doll B. (2015) Testing Protocols to Ensure Performance of High Asphalt Binder Replacement Mixes Using RAP and RAS. Final Report FHWA-ICT-15-017, Illinois Department of Transportation, Springfield, IL

2- Zhou, F. (2019) Development of an IDEAL Cracking Test for Asphalt Mix Design, Quality Control and Quality Assurance. NCHRP IDEA Project 195, Transportation Research Board, Washington D.C.

3- Gibson, N., Qi, X., Shenoy, A., Al-Khateeb, G., Kutay, E., Andriescu, A., Stuart, K., Youtcheff, J.,and Harman, T. (2012) Performance Testing for Superpave and Structural Validation. Final Report FHWA-HRT-11-045, FHWA