IDAHO TRANSPORTATION DEPARTMENT
RESEARCH REPORT

RP 237

Evaluation of Fiber-Reinforced Asphalt Pavements: Laboratory Study

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Prepared for
Idaho Transportation Department
Research Program
Division of Highways, Resource Center
http://itd.idaho.gov/highways/research/

June 2016

1. Report No.
FHWA-ID-16-237

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Evaluation of Fiber-Reinforced Asphalt Pavements: Laboratory Study

5. Report Date
June 2016

6. Performing Organization Code
KLK568

7. Author(s)
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8. Performing Organization Report No.

9. Performing Organization Name and Address
University of Idaho
Department of Civil Engineering
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10. Work Unit No. (TRAIS)

11. Contract or Grant No.
UI-14-02

12. Sponsoring Agency Name and Address
Idaho Transportation Department
Division of Highways, Resource Center, Research Program
PO Box 7129
Boise, ID 83707-7129

13. Type of Report and Period Covered
Final Report
04/01/2014 - 06/30/2016

14. Sponsoring Agency Code
RP 237

15. Supplementary Notes
Project performed in cooperation with the Idaho Transportation Department and the Federal Highway Administration.

16. Abstract
The Idaho Transportation Department (ITD) initiated a field project to evaluate the effectiveness of using fibers to mitigate rutting and fatigue distresses at US-30 east of Montpelier in south Idaho. The project was constructed in August 2014 to address the observed excessive rutting and fatigue cracking. The constructed project is a 3.22-mile road stretch where 0.4 ft of the existing asphalt surface was milled and replaced by a new HMA overlay. The project length was divided into four sections that are approximately equal in length. Three sections were built with fiber-modified dense graded asphalt mixes. The fibers used were polyethylene blended with aramid fibers provided by Forta Fi Corporation; aramid fibers treated with wax (ACE fibers) provided by Surface-Tech, Inc., and glass fibers provided by Nycon Corporation. Fiber contents and methods of fiber addition were established and controlled by the vendors during field production. The fourth section was built with a conventional unmodified mix as a control section. The mix design included high RAP content (47%). All mixes had the same mix design with no alteration due to fiber addition. ITD intended to evaluate the long-term performance of the four pavement sections by monitoring the field performance over number of years. This report is about Phase 1 of the project and is limited the evaluation of the laid asphalt mixes using standard lab testing procedures. To perform the lab testing program, plant mix samples from the field were collected and used to prepare specimens in the lab for various lab characterization tests. In addition, cores were also collected to verify the mix design volumetrics and to conduct some other lab tests. Performance evaluation by laboratory tests included dynamic modulus, flow number, Asphalt Pavement Analyzer (APA), Hamburg Wheel Track, Indirect Tension (IDT), and Creep Compliance tests. Analysis of laboratory test results indicated that there is no significant difference in performance of rutting, fatigue and low temperature cracking among the four mixes. Performance evaluation using the AASHTOWare Pavement ME Design software revealed similar conclusions where predicted performance over a 20-year design life did not vary significantly among the four mixes. It is the authors' belief that the non-uniformity of the fiber dispersion in the mixes as observed during construction and the relatively small fiber contents recommended by the vendors could have contributed significantly to these results.

17. Key Words
Fiber-Reinforced Asphalt Pavements (FRAP), mix design, performance evaluation.

18. Distribution Statement
Copies available online at
http://itd.idaho.gov/highways/research/archived/closed.htm

19. Security Classification (of this report)
Unclassified

20. Security Classification (of this page)
Unclassified

21. No. of Pages
95

22. Price
None

FHWA Form F 1700.7

METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS					APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH					LENGTH		
in	Inches	25.4		mm	mm	millimeters	0.039	inches	in
ft	Feet	0.3048		m	m	meters	3.28	feet	ft
yd	Yards	0.914		m	m	meters	1.09	yards	yd
mi	Miles (statute)	1.61		km	km	kilometers	0.621	Miles (statute)	mi
		AREA					AREA		
in^2	square inches	645.2	millimeters squared	cm^2	mm^2	millimeters squared	0.0016	square inches	in^2
ft^2	square feet	0.0929	meters squared	m^2	m^2	meters squared	10.764	square feet	ft^2
yd^2	square yards	0.836	meters squared	m^2	km^2	kilometers squared	0.39	square miles	mi^2
mi^2	square miles	2.59	kilometers squared	km^2	ha	hectares (10,000 m^2)	2.471	acres	ac
ac	Acres	0.4046	hectares	ha					
		MASS (weight)					MASS (weight)		
oz	Ounces (avdp)	28.35	grams	g	g	grams	0.0353	Ounces (avdp)	oz
lb	Pounds (avdp)	0.454	kilograms	kg	kg	kilograms	2.205	Pounds (avdp)	lb
T	Short tons (2000 lb)	0.907	megagrams	mg	mg	megagrams (1000 kg)	1.103	short tons	T
		VOLUME					VOLUME		
fl oz	fluid ounces (US)	29.57	milliliters	mL	mL	milliliters	0.034	fluid ounces (US)	fl oz
gal	Gallons (liq)	3.785	liters	liters	liters	liters	0.264	Gallons (liq)	gal
ft^3	cubic feet	0.0283	meters cubed	m^3	m^3	meters cubed	35.315	cubic feet	ft^3
yd^3	cubic yards	0.765	meters cubed	m^3	m^3	meters cubed	1.308	cubic yards	yd^3
Note: Volumes greater than 1000 L shall be shown in m^3									
		TEMPERATURE (exact)					TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (°F-32)	Celsius temperature	°C	°C	Celsius temperature	9/5 °C+32	Fahrenheit temperature	°F
		ILLUMINATION					ILLUMINATION		
fc	Foot-candles	10.76	lux	lx	lx	lux	0.0929	foot-candles	fc
fl	foot-lamberts	3.426	candela/m^2	cd/cm^2	cd/cm^2	candela/m^2	0.2919	foot-lamberts	fl
		FORCE and PRESSURE or STRESS					FORCE and PRESSURE or STRESS		
lbf	pound-force	4.45	newtons	N	N	newtons	0.225	pound-force	lbf
psi	pound-force per square inch	6.89	kilopascals	kPa	kPa	kilopascals	0.145	pound-force per square inch	psi

Acknowledgements

This study was sponsored by Idaho Transportation Department (ITD) and FHWA. Authors would like to acknowledge the financial and technical support of these organizations. Many individuals from ITD served as project technical advisory committee and contributed a great deal to the development and performance of this research. This includes but not limited to Dan Harelson (PE), Jesse Barrus (PE), Mike Santi (PE), Ned Parrish and John Arambarri (PE). The APA testing was conducted at the ITD Headquarter labs in Boise, Idaho. Authors acknowledge and would like to thank all those for their professional and insightful advises and feedback throughout the project.

Dr. Karen Thompson of the English Department at the University of Idaho served as the technical editor of the report. Peer review of the report was conducted by Dr. Dave Newcomb of Texas Transportation Institute (TTI). Their efforts and support are greatly appreciated.

Technical Advisory Committee

Each research project is overseen by a technical advisory committee (TAC), which is led by an ITD project sponsor and project manager. The Technical Advisory Committee (TAC) is responsible for monitoring project progress, reviewing deliverables, ensuring that study objective are met, and facilitating implementation of research recommendations, as appropriate. ITD's Research Program Manager appreciates the work of the following TAC members in guiding this research study.

Project Sponsor – Ed Bala, P.E.

Project Manager – Dan Harelson, P.E.

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Mike Santi, P.E.
Ned Parrish

FHWA-Idaho Advisor – Kyle Holman, P.E.

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List of Acronyms

AASHTO	American Association of State Highway and Transportation Officials
AC	Asphalt Concrete
ALF	Accelerated Pavement Testing
AMPT	Asphalt Mixture Performance Tester
APA	Asphalt Pavement Analyzer
CMOD	Crack Mouth Opening Displacement
FRAC	Fiber Reinforced Asphalt Concrete
FWD	Fracture Work Density
HMA	Hot Mix Asphalt
HWTD	Hamburg Wheel Tracking Device
IDT	Indirect tensile Test
ITD	Idaho Transportation Department
Jc	Fracture parameter (J-sub-c)
MEPDG	Mechanistic-Empirical Pavement Design Guide
NMAS	Nominal Maximum Aggregate Size
OGFC	Open Graded Friction Course
PG	Performance Grade
PP	Polypropylene
RAP	Recycled Asphalt Pavement/Reclaimed Asphalt Pavement
RTFO	Rolling Thin Film Oven
SGC	Superpave Gyratory Compactor
SMA	Stone Matrix Asphalt
VFA	Voids Filled with Asphalt
VMA	Voids in Mineral Aggregate

Executive Summary

Introduction

One of the most popular and common methods to increase the concrete strength and reduce its cracks is fiber reinforcement. This technique has been widely investigated for Portland Cement Concrete (PCC) since 1950's. Even though hot mix asphalt (HMA) accounts for approximately 94% of the paved roadways in United States, previous research conducted using fibers in dense-graded asphalt mixes was limited and did not bring a clear conclusion about benefits of fibers in HMA.

Most of the previous studies, including laboratory and field performance of fiber-reinforced dense graded HMA, have led to mixed results. Some studies showed that fibers improved mix performance in rutting and fatigue. This is due to the extra tensile strength of the fibers in the material. The additional interconnection between aggregates allows the material to gain extra strain energy before cracking or fracture happens. Different types of fiber reinforcement, including glass, polyester, polypropylene, asbestos, carbon, cellulose, Kevlar and recycled waste fibers have been used. Additionally, fiber-reinforcement of HMA has evolved to include a blend of different fibers to achieve different performance aspects. In other cases, the fibers have not caused any significant improvement.

Project Description

The Idaho Transportation Department (ITD) had a project to improve and rehabilitate a 3.22-mile section of US-30 at Montpelier in south Idaho. This road section is a truck route to Wyoming. Due the heavy truck loads, the road experienced severe cracking and rutting. The rehabilitation project included milling 0.4 ft of the existed cracked surface layer and replace by a new asphalt mix. To minimize rutting and potential cracking, the project developing team suggested using fibers to improve the HMA surface layer. Addition of fibers was based on suggestion and recommendation from various sources including fiber vendors. ITD decided to try to use three vendors and planned to divide the construction project into 4 sections. One section to be built with conventional unmodified Hot-Mix Asphalt (HMA) and the other three sections were to be built with fiber modified asphalt mixes. The four sections were approximately with equal lengths. The three types of fibers used in the project included polypropylene and aramid fiber blend that was provided by Forta Fi Corporation; aramid fibers that have been wax treated by a proprietary process which is referred to as ACE fibers and was provided by Surface-Tech, Inc.; and glass fibers that was provided by Nycon Corporation. The mix design of the HMA for the project included 47% Rap of the exiting roadway. The mix design of the high RAP HMA was developed and conducted at the National Center for Asphalt Technology (NCAT) at Auburn University, Alabama. The mix design was developed for the control mix with no fibers added following the specifications of Superpave SP5 category of ITD. Fiber addition was added as per recommendation of each vendor at the mix plant during mix production. Forta-Fi recommended 1 lb/ton (Fiber/HMA weight), Surface-Tech recommended 1/3 lb/ton and Nycon recommended 3 lb/ton. Due to the very small weight ratios of fibers to mix, the Job Mix Formula of the fiber-modified mixes were not altered and the addition of the fibers did not affect the mix volumetrics.

The original plan was that ITD would monitor the built sections to determine whether the fibers improve the pavement performance and mitigate the cracking and rutting distresses over the planned performance period. However, and at a later stage in the project planning process, the project development team suggested a parallel study to evaluate and characterize the materials to be placed in the four sections. Hence, this project (labeled as Phase 1 – Lab study) was developed. The project was constructed in August 2104. ITD will continue field performance evaluation of the pavement sections over number of years. The field performance data to be collected will be studied and analyzed under another task as a Phase 2 of the project.

Therefore, it is important to keep in mind that the main objective of this lab study was to evaluate the field mixes as they were placed. The UI research team was neither involved in the development of the mix design nor the selection and the process of the fiber addition. The mix design was developed at NCAT at Auburn University and the fibers were added according to the recommendation of the vendors at the project site. Fibers were added to the mix by blowers under the control and supervision of each vendor.

Research Methodology

The main goal of the lab study was to evaluate the performance of fiber-modified mixes using standard lab tests. And, to develop the material properties of the mixes to be used with the AASHTOWare Pavement ME Design software to predict and compare the expected field performance of these mixes.

Plant mix samples were brought to the lab from each section. Samples were collected mid-way during the production process for each section to insure that there is no overlap of fiber mixes that may occur at the transition from one section to another. In addition to the loose plant mix samples, field cores were extracted and delivered to the lab. The cores were used to evaluate and verify the mix volumetrics. They were also used to conduct some lab tests that are specified to be performed on field cores rather than lab compacted samples, such as IDT and creep compliance tests.

Mix design evaluation and verification of the mix volumetrics was performed on Gyratory samples that were compacted from loose field mixes. Results of the volumetric properties of the HMA were verified and fibers did not alter the mix design. Mix production quantities revealed that the final fiber contents that were actually added were 1.04 lb/ton for the Forta Fi section, 0.28 lb/ton for the ACE fibers section and 3.11 lb/ton for the Nycon glass fiber section.

The research team conducted lab tests to determine rutting resistance, fatigue cracking resistance, and low temperature thermal cracking resistance. The research team used the Flow Number, Asphalt Pavement Analyzer (APA) and Hamburg Wheel Tracking tests to evaluate the mixes potential to resist rutting. For fatigue bottom-up cracking, the team adopted the concept of the Fracture Work Density, which was measured from the Indirect Tension test (IDT) at normal temperature (68 °F). The values of the vertical deformation measured in the IDT test was used to evaluate the mixes potential to resist fatigue top-down cracking. Furthermore, the team conducted a fracture test using the semi-circular bending test on notched samples to measure the fracture parameter Jc, which indicates mix potential to resist fatigue cracking. The evaluation of the mix resistance to low temperature cracking was performed using the concept of the Fracture Work Density (FWD) of the IDT test but performed at low temperature of 14°F.

A separate task was developed to evaluate the degree of dispersion and uniformity of the fiber distribution in the mixes using X-ray Tomography.

All results of lab tests along with the project information of structure design, traffic and climatic data were used to run the AASHTOWare Pavement ME Design software for the four pavement sections. This task allowed for comparing the performance of various mixes in the field. Since the current version of the software at ITD is based on the global calibration factors, the resulting performance indicators would reveal reasonable comparison but not absolute evaluation of the field performance.

Key Findings

Based on the test results from this research project, the key findings are summarized below:

- Loose mixes from the field were used to verify the Job Mix Formula that was developed for the neat unmodified mix. Results revealed that the JMF was verified for all mixes and that the fibers did not alter the mix design. Furthermore, volumetric analysis of field cores verified the field compaction.

- Rutting resistance as measured by Flow Number, APA and Hamburg Wheel-Track tests of the fiber mixes were comparable to the control mix. Fiber modified mixes did not show significant improvement over the control mix. ANOVA statistical analysis procedure was adopted on HWT and Flow Number tests, and it confirmed that there is no significant difference in the rutting performance as measured by these tests.

- For the fatigue cracking (bottom-up and top-down cracking), the fibers did not add significant tensile strength to resist cracking. This result also coincided with other reported studies. The reason could be related to the dispersion and the orientation of the fibers in the mix. In other words, the fibers did not experience any tensile stress until the pavement experience excessive stresses that lead to cracking of the mix.

- Similar to the fatigue evaluation, the fracture work density of the fiber mixes measured at low temperature did not show significant improvement of the fiber mixes to resist low temperature cracking.

- Performance prediction using the AASHTOWare Pavement ME Design software confirmed the above conclusions. This is intuitively expected since the only variables that are changed for the software runs were the material properties. All other design inputs including pavement structure, traffic and climate were kept the same for all runs.

- Observations during the construction of the test sections at the project site of the fiber feeding process revealed that there is a concern of the uniformity of the fiber injection to the mix plant. It was observed that, in many instances, the fibers clumped and were blown as balls into the feeder. The clumping of fibers would have produced non-homogenous fiber-modified mixes that could lead to loss the benefits of using them. Therefore, it is critical to monitor the distribution of the fibers during the production.

- The researchers believe that the used fiber contents are considerably low, which was the main reason for not being able to capture any significant effect of the fiber presence in the mix. In addition, the degree of fiber dispersion and the uniformity of its distribution in the mixes are questionable. The attempt to evaluate that by X-ray Tomography did not reveal any meaningful results. The fiber threads were so fine and could not be detected in the x-ray images. However, physical lab test using an adapted extraction method confirmed the fiber content for one type but did not work for the others.

Recommendations for Further Study

During the lab study, the research team identified few gaps that would need further consideration to better evaluate the effectiveness of adding fibers to HMA. Some of these factors include:

1. More than one mix needs to be investigated. For example, the nominal max size of the mix and aggregate gradation may have an effect on the outcome performance of the fiber-modified mixes.
2. The fiber contents adopted in this study were suggested by the vendors. A study is needed to optimize on the fiber content of each type and its relation to the mix gradation and size.
3. The mix adopted in this study has a relatively high RAP content (47%). It was not clear whether this high RAP has altered the effect of fibers. Therefore, more analysis is needed for mixes with only virgin aggregates or at lower RAP contents to isolate the RAP factor.
4. There is a great need for a field quality control test to measure the uniformity of fiber distribution and injection to the mix plant.

Chapter 1
Introduction

Background

Fiber reinforcement has been used for decades in both Portland Cement Concrete (PCC) as well as Asphalt Concrete mixes. Technologies of using fibers in PCC mixes have been widely investigated since the 1950's, and shown to play a significant role in mitigating concrete cracks and increasing strength. On the other hand, research on using fibers to improve the performance of Hot Mix Asphalt (HMA) for pavement applications is rather limited. A recent NCHRP Synthesis No. 475 summarized the state of practice of using fibers in asphalt pavements.(2) The report indicated that most of the states in the US have used fibers in open graded mixtures. A limited number of states have used fibers in dense graded asphalt mixes. Types of fibers used included mineral, glass, cellulose, and synthetic polymer fiber. The design procedure of the fiber mixes is the same as of the conventional mixes; however, the purpose of using fibers is different. In the stone matrix asphalt (SMA) and open graded friction courses (OGFCs) or porous friction courses (PFCs), the primary use of fibers is to control the draindown of the binder in the mix. In the case of dense graded mixes, fibers are used to enhance the mix performance. Some studies suggested the enhancement in mix performance could be linked to the extra tensile strength due to the addition of fibers. Fibers also would enhance the interconnection between aggregates, which allows the material to gain additional strain energy before cracking or fracture happens.(3) Different types of fiber reinforcement, including glass, polyester, polypropylene, asbestos, carbon, cellulose, Kevlar and recycled waste fibers have been used .(2,5,6,7,8) Additionally, fiber-reinforcement of HMA has evolved to include a blend of different fibers to achieve different performance aspects.(9,10,11)

Problem Statement

The Idaho Transportation Department had planned to rehabilitate US-30 at Montpelier, South Idaho. The road is a heavy truck route leading to the neighbor state of Wyoming. Due to heavy truckloads, the road has manifested rutting and cracking. The initial plan was to mill the upper 0.4 ft of the asphalt layer, which suffered most of the cracking and rutting and replace it by a new hot-mix asphalt (HMA) overlay. In order to address the observed distresses of rutting and cracking, it was suggested to ITD by fiber vendors to modify the HMA overlay layer by fibers with the claim that adding fibers would improve cracking and rutting resistance of the overlaid roadway. Hence, ITD project team decided to use different vendors in order to try to test various types of fibers in this project. Furthermore, it was then considered that this project could be considered as a pilot study to determine the effectiveness of using fibers in HMA to address cracking and rutting in the state highways.

The initial plan and the main goal was to do the performance evaluation by monitoring the roadway over number of years. However, ITD decided to involve the University of Idaho to evaluate the materials that will be laid in the field. Hence, this lab phase of the project was proposed.

Objectives

The main goal of the ITD rehabilitation project on US-30 at Montpelier was to address rutting and fatigue problems encountered at that heavily truck traffic road. ITD decided to use fiber modified mixes to address these problems and use the project as a pilot study to determine the effectiveness of using fibers in HMA to improve cracking and rutting resistance.

The objective of this research project (RP 237) was to conduct a laboratory evaluation of the mixes that are placed at the US-30 project. The scope of this lab-based phase is limited to material characterization of the laid mixes (as they are) and determine whether there are significant changes in mixes' properties upon adding the fibers. Furthermore, the lab study aimed at developing material properties of the mixes that enable the prediction of performance using the AASHTOWare Pavement ME Design software.

It is planned that pavement evaluation of the constructed sections will be conducted to monitor the field performance of these mixes, at least once a year. At a later stage, the field data collected during the performance evaluation period will be analyzed and reported under a separate task to be conducted in the future.

Project Description

As stated in the project problem statement that ITD has observed severe rutting and fatigue cracking at US-30 in South Idaho. This route is a truck route that connects to the neighbor state of Wyoming. A project to recycle and inlay a 3.22-mile stretch on that road from MP 435.281 east of Montpelier to MP 438.500 at Dingle was developed to rehabilitate that road. Road alignment and location is shown in Figure 1. The project involved milling and overlaying 0.4 ft of the existing roadway. The construction project was conducted in August 2014 under contract Reference Number A013 (104), Key No. 13104.

In order to evaluate the effectiveness of adding different types of fibers, the project was divided into four sections, which are almost equal in length. One section is left with no fiber modification and considered as a control section, and the other three sections were modified, each with one type of fibers. Three types of fibers were proposed to ITD by three vendors:

- Forta Fi Corporation (aramid and polypropylene fibers)
- Surface Tech Corporation (ACE fiber: Wax Treated Aramid Fiber)
- Nycon Corporation (glass fibers)

The study included four sections, approximately equal in length:

- Section 1 – Unmodified Control section starting at MP 435.281
- Section 2 – Forta Fi fiber modified with the rate of 1 lb/ton. Section 2 starts at MP 436.010
- Section 3 – Surface Tech ACE fibers, rate 1/3 lb/ton. Section starts at MP 436.800, and
- Section 4 – Nycon glass fibers, rate 3 lb/ton. The section starts at MP 437.600 to end of the project alignment at MP 438.376

Fiber contents and methods of adding fibers to the mixtures were established and performed by the fibers' vendors. Description and properties of these fibers will be presented later in the report.

The non-modified Control mix was designed with 47% RAP from the existing road. The mix design was conducted at the National Center for Asphalt Technology (NCAT) at Auburn University. It followed the Superpave SP5 specification of the state of Idaho. NCAT Job Mix formula showed that the version binder grade was PG 70-28, and the RAP binder was PG 64-28. The final PG is 70-28 as determined by NCAT. The fiber-modified sections adopted the same mix design. No change in the mix volumetric. Fibers were to be added at the asphalt plant during construction in accordance with the manufacturers' specifications.

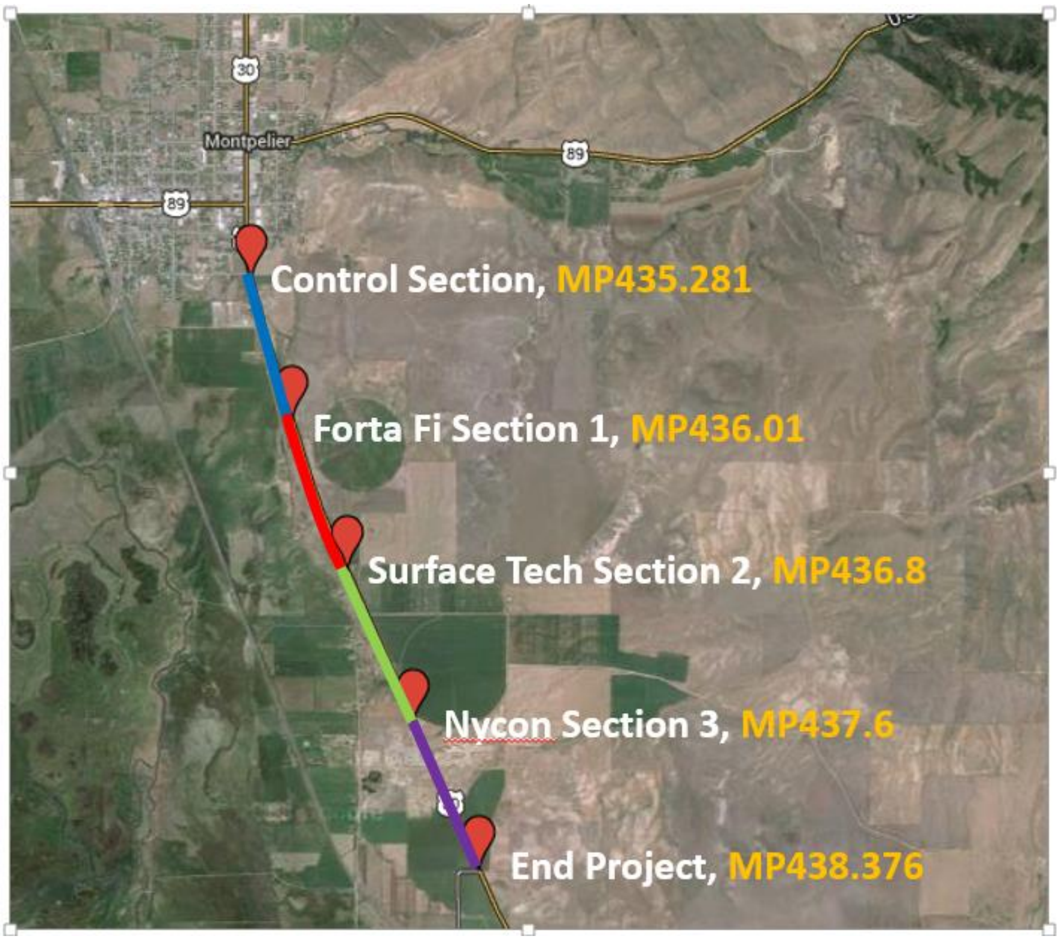


Figure 1. Project Location and Sections Identification on US-30 at Montpelier, South East Idaho

Scope of Research and Project Tasks

As mentioned earlier, this laboratory study is limited to the lab evaluation of the laid mixes in the field. The research team was neither involved in the planning of the field project nor the mix design of the control mixes. Hence, this lab study was divided into limited tasks as described below:

Task 1: Literature Review on different technologies used in using fibers in HMA and their effect on asphalt pavement performance.

Task 2: More in-depth study focused on the three types of fibers proposed for this project

Task 3: Documentation and description of the Mix Design and construction record of the test sections.

Task 4: Lab Testing and Data Analysis.

Task 5: Performance Prediction using AASHTOWare Pavement ME Design Software to evaluate the expected performance of the proposed mixes and test sections.

Task 6: Evaluation of Fiber Dispersion in the Mix Using X-Ray Tomography.

Task 7: Modeling Fiber-Reinforced HMA.

Task 8: Development of the Final Report.

Report Organization

This report presents the research work completed for the performance evaluation during Phase-1 of the project, which dealt only with the lab study. It is organized in six chapters as described below:

Chapter 1 provides the introduction of this research project, presents the problem statement, research objectives and project description.

Chapter 2 presents a literature review of fiber reinforcement asphalt pavements, mix design, laboratory and field performance of fiber-modified mixes.

Chapter 3 presents the fiber characterizations and mix design of the project.

Chapter 4 presents the laboratory testing methods and results for performance evaluation of the modified fiber asphalt mixes, including resistance to rutting, fatigue cracking and thermal cracking.

Chapter 5 presents the result and analysis of field performance prediction from AASHTOWare for all of fiber mixes.

Finally, **Chapter 6** summarizes the key findings from this research and presents recommendations for ITD consideration.

Chapter 2
Review of Literature and Current Practice

This chapter presents a literature review of relevant studies on modified fiber asphalt mixtures. A recent NCHRP Synthesis No. 475 summarized the state of practice of the use of fibers in asphalt pavements.(2) The report indicated that most of the states have used fibers in open graded mixtures. A limited number of states have used fibers in dense graded asphalt mixes. The materials used in those projects are mineral, glass, cellulose, and synthetic polymer fiber. The design procedure of the fiber mixes is the same as of the conventional mixes; however, the purpose of using fibers is different. In the stone matrix asphalt (SMA) and open graded friction courses (OGFCs) or porous friction courses (PFCs); the primary use of fibers is to control the draindown of the binder in the mix. In the case of dense graded mixes, the use of fibers is to enhance the mix performance. Nevertheless, the results have shown the benefits of fibers are inconsistent. In some studies, the fibers improved the mix resistance to rutting and cracking, but in others, no significant difference was observed in the fiber-reinforced mixes. The following literature presents different results of the performance of fiber reinforced asphalt mixes.

General Performance

There have been several recent studies on the effects of fiber finishes or treatment during the manufacturing process on HMA. Putman investigated the effects of finishes applied to polyester fibers on the asphalt binders and mastics properties.(3) In this research, asphalt binders were blended with finishes that were extracted from the fibers. The mastics were similarly made with binder and fibers, with and without finish, to separate the effects of the finish. The findings of this research indicated that the source of the asphalt crude plays a significant role on how the fiber finish affects the binders and mastics. Also, different finishes had different effects on binder properties. The main outcome of this research is that different polyester fibers, even from the same producer, may not always have the same performance in the asphalt mix. It is essential to use fibers that are compatible with the specific asphalt binder because of the effect of the binder source on the interaction between the binder and the finish.

Alrajhi at Arizona State University studied the effect of adding different fiber quantities on the asphalt mixture and binder performance.(4) The laboratory evaluation was conducted by using sixteen different amounts and blends of the fibers with several combinations of aramid and polypropylene fibers. The asphalt mixture tests included the indirect tensile strength and the dynamic modulus. The binder tests included: softening point, penetration, and Brookfield viscosity tests. The binder test results showed that the best viscosity temperature susceptibility performance would be from the fiber blend of 75% polypropylene and 25% aramid, the dynamic modulus test results confirmed this finding as well. Generally, adding fibers to the HMA resulted in an increase in the stiffness of the mix. From the indirect tensile strength results, the aramid fibers showed more effect on post peak failure than the polypropylene fibers as manifested by higher fracture energy.

Rutting

Jahromi and Khodai conducted a study evaluating the properties of modified carbon fibers asphalt mixtures.(5) The laboratory tests included: creep compliance, indirect tension, repeated load indirect tensile test and Marshall Stability. The findings indicated that adding carbon fibers resulted in decrease in flow and increased air voids. Nevertheless, the addition of carbon fibers to the mix improved Marshall Stability, increased rut resistance and fatigue life.

Mahrez and Karim stated that addition of glass fibers into stone mastic asphalt (SMA) produced variable Marshall Stability data, and a decrease in stiffness and stability of the mixture.(6) In a following study, the authors evaluated the rutting resistance and creep of glass fiber-reinforced SMA mixtures by using wheel tracking test. They reported that mixtures containing glass fibers had higher resilient modulus and more resistance to rutting.

Bueno et al conducted a study on evaluating the effect of randomly distributed synthetic fiber on the mechanical response of a cold-mixed densely graded asphalt mixtures.(7) The laboratory investigation included Marshall, static and cyclic tri-axial tests. The evaluated properties included density, air voids, Marshall Stability and flow, elastic, and resilient moduli. The asphalt mixtures were treated with different staple polypropylene fibers lengths (10, 20, and 40 mm long), and fiber content of 0.1 and 0.25%. The findings indicated that presence of fibers in a mix is the main reason for a small variation in mixture shear strength tri-axial parameters, as well as for significant drops in the mixture resilient moduli when compared to control mixtures. It did not, however, affect the permanent strains of the mixtures. Also, addition of fibers to cold densely graded emulsified asphalt mixes reduced Marshall Stability and the dry density of the mix.

Chen et al investigated the effect of different types of fibers on the volumetric and mechanical properties asphalt mixtures.(8) Four different fibers were used: polyester, polyacrylonitrile, lignin, and asbestos fibers. They used Marshall Stability tests to measure the mechanical and volumetric properties of asphalt mixtures. Moisture susceptibility and dynamic stability tests were used to examine the performance of the mixes. The results showed that generally, presence of fibers in the mixtures decreased the bulk specific gravity, while increased the optimum asphalt content, air void, voids in mineral aggregate and Marshall Stability. Optimum asphalt content, Marshall Stability, and dynamic stability increased initially and then decreased with increasing fiber content. It also showed that the polyacrylonitrile and polyester fibers had higher stability due to their higher networking effect. On the other hand, the asbestos and lignin fibers increased the optimum asphalt content due to their higher absorption. The test results using a fiber content of 0.35% by mass of mixture for the polyester fiber were used for final proportions.

Tapkin investigated the effect of polypropylene fibers on the behavior of the mix.(9) The fibers were added up to 0.3%, 0.5% and 1% by weight of the mix. For fiber-reinforced specimens it was observed that the Marshall Stability values increased and flow values decreased in an obvious manner. The fatigue life of these specimens was improved as well. The properties of asphalt concrete were enhanced due to adding polypropylene fibers. The fiber-reinforced asphalt mixture reflected good resistance to rutting, prolonged fatigue life and better reflection cracking resistance.

Abtahi et al stated that among various modifiers used to improve the performance of asphalt-concrete (AC) mixtures, fibers have a leading position due their unique potential.(10) His work focused on polypropylene (PP) and glass fibers as a novel concept of hybrid reinforcement of AC mixtures. Since both glass fiber reinforced AC and PP fiber modified AC mixtures exhibited improved performance compared to other fibers, these two types of fibers were used together to investigate possible additive improvement in the performance of the AC mixtures. PP fibers with the length of 12 mm were blended with bitumen at different percentages, and glass fibers with the length of 12 mm were also added to aggregates. A combination of 0.1% of glass fiber plus 6% of PP presented the best hybrid reinforcement. Hybrid reinforced asphalt concrete (HRAC) samples were prepared using a Superpave gyratory compactor and tested for Marshall Stability. Volumetric analysis was done following the standard procedures. In the case of the normal bituminous specimens, penetration, softening point and ductility tests were carried out. Because of the tacky property of PP fiber around its melting point and the high modulus of glass fiber, the hybrid mixture increased stability and decreased flow. These results supported the idea that PP can significantly affect the properties and improve the consistency of the mixture. Therefore, this novel HRAC approach was suitable for use in hot regions due to growth in the void total mix (VTM) and stability.

Taher declared that due to the environmental conditions, construction, design errors, and more importantly due to the increase in the number of vehicles, especially those with high axle loads, two major distresses occur in road pavement: fatigue cracking and rutting.(11) Using additives such as different types of polymer and fiber in asphalt concrete (AC) could be a solution to prolong the service life of asphalt pavement. His work also included summarized previous research that had been done on the effects of using different types of additives and aggregate gradation. The finding of his research as well as his review indicated that fatigue and rutting resistance can be enhanced by addition of fibers increasing the amount of strain energy absorbed during fatigue and fracture process of the mix in the resulting composite. Moreover, polymers and fibers provided 3D networking effect in asphalt concrete and significantly stabilized the binder on surface of aggregate, thus, successfully prevented from any movement at higher temperature.

Su and Hachiya investigated the use of fiber reinforcement with recycled asphalt pavement (RAP) in airfield surface course pavements.(12) The authors declared that adding of cellulose fibers increased the optimum binder content, and this led to improved Marshall Stability and provided less mass loss by the Cantabro test. The improvement of fibers was more noticeable when modified binder was used rather than virgin binder. The conclusion of their study was that the fiber addition to RAP containing modified binder increased the dynamic stability (wheel tracking test) making it suitable for airports with heavy loading.

Fatigue

A research project by Federal Highway Administration (FHWA) studied the performance of fiber reinforced asphalt mixture in the laboratory and using full-scale accelerated pavement testing.(13) In one of 12 test lanes in the FHWA's accelerated loading facility (ALF), polyester fibers were added to the mix. The concentration of the fibers were 0.3 % by aggregate mass. The results indicated that the fatigue cracking of the fiber reinforced section was considerably less than those of the polymer modified and unmodified sections. Fatigue results in the lab did not match the full scale performance using an earlier variation of an axial fatigue (push-pull) methodology that was not conducted in an AMPT where the analysis used slightly different analytical mathematics along with a conventional 50% modulus reduction failure criteria.

In a following study, Gibson et al. examined the cracking resistance of two independent sets of mixtures from the FHWA full-scale accelerated loading facility and a Pennsylvania DOT trial section.(14) Both sets had the same materials; a control mixture and a mixture with SBS modified binder. The same mix with synthetic (polyester) fiber reinforcement. Two methods of cracking characterization were evaluated; direct tension monotonic strength and simplified viscoelastic continuum damage. The results of dynamic modulus test indicated that the polymer modification has more effect than fiber modification. Cyclic fatigue test results showed both fiber modified mixes and SBS have better performance than the control mix in both sets of materials. In the cyclic fatigue tests, the fiber mixes performed better at higher fatigue stains, however, the SBS modified mix performed better under small fatigue strains.

Guo et al. conducted a research study that focused on the use of polyester fiber reinforced asphalt mixtures.(15) The goal of this study was to examine the influence of fibers on the durability of asphalt pavement. Two types of asphalt mixtures were used. One was a densely graded asphalt mixture with 0.2% fibers, and the other was stone matrix asphalt (SMA) with 0.1% fibers. The results showed that adding fibers reduces the pavement crack propagation. It was concluded that, polyester fiber reinforced mixtures behaved much better in the fatigue resistance than that of non-fiber mixtures.

Lee et al. studied the influence of fibers on the fatigue cracking resistance of asphalt concrete.(16) The fatigue resistance was based on the fracture energy. The recycled carpet fibers (Nylon) were used in this study. The experimental program was designed with two phases: the single fiber pull-out test which to determine the critical length of the fiber, and that was 9.2 mm. Then the indirect tension strength tests were conducted on samples with two different fiber lengths 6 and 12 mm. The concentration of the fibers were 0.25, 0.5, and 1%. The results indicated that mixes with 1% and 12 mm results in 85% higher fracture energy than control specimens. The increased fracture energy shows a potential for better asphalt fatigue life.

Jun Yoo et al studied the characteristics of plastic fiber reinforced Hot-Mix Asphalt Mixtures. He concluded that in order to enhance the fatigue life of any mixture, the structural integrity of that mixture must be improved.(17) Since a conventional asphalt mixture may have performance limitations, many geosynthetic fabric approaches have evolved such as: geogrid, geotextile, or geomembrane layers at the bottom the mixture or on the top of a subgrade. Although these interlayer techniques allow for improvement in the HMA pavements' performance by mitigating ruts or delaying reflective cracks, other parameters such as toughness, tensile strength, and shear strength of HMA mixtures need to be enhanced. The issue with these fabrics is its inability to mix with the asphalt mixtures. On the other hand, utilizing a new plastic fibers within asphalt mixtures, as shown in the study enhances the structural integrity of the entire mixture which leads to significant improvements in phenomenological toughness and fatigue life. The improved performance of fiber reinforced mixtures over conventional hot-mix asphalt mixtures was measured by indirect cyclic fatigue tests in loading-control modes and four-point bending beam tests in displacement-control modes as the author indicated.

Thermal Cracking

Ahmed et al declared that the type and quantity of asphalt mixtures directly affect highway quality.(18) Different types of additives and modifiers have been used in asphalt mixtures to mitigate the distresses that lead to the pavement failure. One of the most extensively studied additives is fiber which provides 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. Although the increase in track axle loads, tire pressure, and the difference in pavement temperature led to the severity of permanent deformation and thermal cracking, mixtures with polypropylene fibers seem to be a promising solution to provide additional tensile strength in the resulting composite. In this study, using Marshall Methodology, indirect tensile strength, indirect creep test, and ultrasonic testing, several parameters of asphalt mixtures were evaluated: polypropylene fiber content, asphalt cement content, aggregate gradation and testing temperature. The obtained results confirmed that the addition of (0.3%) polypropylene fiber by weight of total mix with type (A) aggregate grading produced more flexible mixtures. Thus they were significantly more resistant to permanent deformation and thermal cracking.

Xu et al. studied the reinforcing effects and mechanisms of fibers on asphalt concrete (AC) mixtures with respect to temperature and water effects.(19) The four different types of fibers included: polyester, polyacrylonitrile, lignin and asbestos were evaluated. Laboratory tests were conducted on the fiber reinforced AC (FRAC) to determine its strength, strain and fatigue behavior. Results show that fibers have substantially improved the asphalt mixture resistance to permanent deformation as well as fatigue life and toughness. The flexural strength and ultimate flexural strain, and the split indirect tensile strength at low temperature were similarly enhanced. The polyester and polyacrylonitrile fibers improved rutting resistance and fatigue life more significantly than lignin and asbestos fibers. That might be as a result of their greater networking function. Unlike lignin and asbestos fibers that result in greater flexural strength and ultimate flexural strain, this networking function might result in greater asphalt stabilization effect. Furthermore, the researchers concluded that a 0.35% fiber content by mass of mixture achieved the optimum performance outputs of permanent deformation resistance and split indirect tensile test for polyester fiber.

Huang et al. investigated the influence of the conductive additives on the mechanical performance of asphalt.(20) The test results of this study showed the variation of electrical and mechanical properties versus conductive additives such as steel and carbon fibers. In Huang et al.'s tests, steel fibers significantly improved rutting resistance, but not the fracture energy and strength of the mix.

Different Conclusions

Jiang and McDaniel investigated the field performance of asphalt overlays with various thicknesses. The overlays were on pavements with and without cracking and seating of the existing concrete surface.(21) Polypropylene fibers with a concentration of 0.3% by weight of the mix were used in the intermediate and base layers of the overlays. The evaluation of 8 years field performance showed that adding fibers to the base and intermediate layers of a normal overlay section did not reduce cracking because reflective cracking is caused by horizontal and vertical movements. However, the researchers declared that fibers delayed and reduced cracking on both cracked and seated sections. Also, there was no noticeable difference between the cracked and seated sections with fibers only in the base versus the in base and intermediate layers.

A study in Indiana conducted by McDaniel and Shah was to evaluate the use of seven different asphalt additives or modifiers.(22) These additives included: polymers, gelled asphalt, and crumb rubber, as well as polyester fibers. The polyester fibers were added to an asphalt overlay over jointed concrete pavement. The fibers content was 0.3% by weight of the mix. The mixing of fibers was done in both dry and wet mixing processes with 30 s and 35 s mixing time in a batch plant, respectively. The results showed that polymerized asphalt cement (PAC), styrene butadiene rubber (SBR), and asphalt rubber mixtures were the most effective to resist cracking. Polyester fiber had slightly more cracking than the other additives. All the mixes including the control mix did not show significant rutting under heavy interstate traffic. The outcome of this research suggested that additives were not necessary to accomplish good performance.

One of the studies initiated in 1985 and conducted by Oregon DOT was on six test sections with fibers and polymer modified binders.(23) There were two control sections and two fiber sections. One section included polypropylene fibers and another included polyester fibers. The structure of the test sections was 1.5 to 2 in of HMA layer with an unmodified base course (4 to 4.5 in.) over an existing pavement with severe alligator and thermal cracks. The performance for 10 years and application of more than 1.5 to 1.7 million equivalent single-axle loads showed that both fiber sections were comparable to the controls, with average rut depths of 13 to 16 mm. Similarly for the fatigue cracking, the fiber sections performed comparably to the control one. However, the polypropylene fibers had better performance than the polyester fibers in terms of block cracking, and both of them performed better than the control.

In a study for the New Jersey DOT, Bennert compared the performance of plant produced mixes with and without a combination of polyolefin and aramid fibers.(24) The mix design was for traffic of 3 to 10 million equivalent single axle load. The lab performance tests included dynamic modulus, Flow number, beam fatigue test, and cycles to failure in the overlay tester. The results showed that fiber mixes had lower modulus values at high temperatures compared to the control mix. At low temperatures the control mixes were slightly stiffer than the fiber mixes. Phase angle results showed that control mixes were more elastic than the fiber mixes. The flow number test also indicated that control mixes had better resistance to rutting than fiber mixes by achieving higher number of cycles to 5% strain. The results of the beam fatigue test showed comparable results, however, the overlay test results revealed that the fiber mix had much greater resistance to crack propagation than the control one.

Huang and White tested cores and slabs taken from test sections that were constructed on two high traffic ways in 1990 in Indiana.(25) The test sections contained polypropylene fiber modified asphalt overlays. The lab testing included complex modulus testing on cores, and fatigue testing of beams cut from the pavement slabs. Dynamic modulus test results indicated that the fibers decreased the modulus, but did not affect the phase angle. However, beam fatigue testing showed that the use of fiber mixes had better fatigue life than the control one. On the other hand, the extraction of the fibers from the mixes showed that the actual fiber contents in the plant-produced mixes varied from the target content in most samples (4% to 43% from the target). Although the other properties of the mix were within the specifications, the field densities were low. The air void contents of the fiber mixes were higher than those of the controls indicating that fibers could make the compaction harder.

In this project, three different synthetic fibers have been use as mentioned earlier. Even though no intensive research has been done on the proposed fibers, the following is some collected works on the performance of these fibers.

Fibers Performance Summary

There are different types of fibers that can be used as additive to the HMA such as: polypropylene, steel, polyester, cellulose, fabric and carpet, carbon, and aramid fibers. Based on different laboratory tests and analysis data, there are general findings about the benefits of adding fibers to the HMA, but they are inconsistent. For the studies that showed improved performance of asphalt mixtures, all kind of synthetic fibers showed the same trend. At high temperature, modified fiber asphalt mixtures are stiffer and that result in better rut resistance. In terms of fatigue cracking, most of the studies also showed that fiber reinforced mixes perform better than non-reinforced mixes. The reason may be that fibers 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. However, at low temperatures, some studies indicated no difference between the reinforced and non-reinforced mixes, and the performance of both mixes is comparable. The type of fiber should be compatible with the binder to get the best performance. The widely used and recommended fiber types are polypropylene and aramid fibers.

Review on Modeling Fibers in Portland Cement Concrete

Most of the literature available on modeling of fiber-reinforced mixes are on Portland cement Concrete Mixes. Therefore, the research team has conducted this review in an effort to simulate the effect of fibers on Asphalt mixes.

Portland Cement Concrete is strong in compression but weak in tension. Its tensile strength is about 10% of the compressive strength. To overcome the tensile strength weakness, concrete must be reinforced by materials that can withstand tension such as steel and fibers. During its service life, a reinforced concrete structure is expected to have minor cracks in the tension zone which may affect the structural performance. This performance deteriorates due to repeated loads and exposure to extreme environments. The need for more sustainable transportation infrastructure such as pavements and bridges is the driving force toward tougher concrete structures. Fiber Reinforced Concrete (FRC) is sometimes employed to strengthen the aging structures. FRC offers higher strength and fatigue resistance than normal concrete which is attractive for highways.

Analytical models and numerical simulations have been used to examine the micromechanics of fiber reinforce concrete and describe the mechanical behavior of this composite material. Mainly, modeling fibers and fabrics in concrete can be classified into three levels based on the scale of the modeling. Microstructure modeling is commonly the focus of the fiber cement matrix interface to explain the pullout mechanism between the fabrics and cement matrix and to simulate the bonding between fabrics and cement paste. Meso-scale modeling is used to link the responses at the micromechanics level to structural responses in the macroscopic leveling studying the crack evolution and tension responses of the Fiber Reinforced Cement Composites. Macro-scale modeling of fiber reinforcement is used to simulate the flexural response of structural elements. (26)

The initial stiffness of the concrete is much higher than the post crack stiffness, and this reduction in the stiffness causes excessive deformation due to the application of loads. For this reason, the ability of reinforced concrete composites to carry loads after cracking is a very important issue. At the crack locations, even though the concrete has lost most of its tensile strength, it is still able to carry some tension forces between two parallel cracks, causing the material response to appear stiffer than the expected response of an assumed zero concrete tensile strength. This improvement in the stiffness depends upon the cracking mechanisms in reinforced members such as crack width, crack spacing, and the bonding between reinforcing materials such as fibers and matrix. The tension stiffening is observed in all reinforcing materials including fibers, and it is typically evaluated by three main approaches: experimental, analytical, and numerical. (27)

It is an important phase in material research to conduct experimental programs and establish empirical equations for specific set of factors that need to be studied. The obtained experimental data can provide important information of material behaviors that can be explained by empirical equations to show the relationship between the input variables and measured responses.

A Numerical Approach is commonly used when the behavior of the material is complex. Many factors are required to develop the mathematical models. Using several parameters may lead to long derivative equations that are not easy to solve. Finite element method is the most extensively used numerical tool to solve these complex equations. It has been used to simulate cracking and tensile behavior and bond mechanism of different materials. Mobasher et al. studied the toughening mechanisms in the brittle matrix composites. (28) In this study, both finite element method and non-linear fracture mechanics were used. In the finite element analysis approach, the fibers were modeled by means of spring elements which resist the opening of existing cracks in the matrix. These nonlinear spring elements can be imposed with load deformation responses obtained from fiber pullout tests. Barros et al. developed a constitutive model based on non-linear analysis of the steel fiber reinforced concrete slabs supported on soil. (29) The fiber reinforcement influences the energy absorption capacity which needs to be taken into account in the material constitutive relationship. To deal with the elasto-plastic behavior of concrete, the theory of plasticity was applied. Additionally, to simulate the concrete cracking behavior as well as soil non-linear behavior, the researchers utilized a smeared-crack model and springs on orthogonal direction to the slope, respectively. Also, the loss of contact between the slab and the soil was taken into account to create a reliable performance model based on the results of the experimental research.

An analytical approach can be employed to explain physical behaviors of crack evolution in tension specimens. The analytical models can be formulated on the basis of the relationship between the bond stress and crack patterns, and several of these models have been developed. A model to predict the stresses and forces of reinforced concrete beam with glass fiber reinforced plastic (GFRP) was proposed by An et al. (30) In order to accurately assess the behavior of the beam, the research focused on five performance assumptions 1) linear strain distribution throughout the beam; 2) small deformations; 3) tensile strength of concrete was ignored; 4) shear deformation was ignored; 5) perfect bond between concrete and GFRP. The researchers used classical flexural theory and strain compatibility to evaluate effects of variables such as material strength, modulus of elasticity, and reinforcement ratios of the steel and GFRP. Then those data were compared with experimental results**.** Another model was developed by Sakai and Suzuki in which the stress distributions are functions of both the crack opening and crack ligament length by using exponentially decaying parameters. **(31)** R-Curves were then used to account for increased energy dissipation and simulate the crack growth in the matrix response subjected to the closing pressure. Mobasher et al. indicated that this approach can be used to model the effect of fiber content on the flexural response of concrete reinforced with AR glass fibers. This can be achieved by developing a nonlinear curve fit model to the experimental data for the flexural load-CMOD response. One can back calculate the stress-strain response of the composite required to satisfy the experimentally obtained load-CMOD response. (32)

The analytical models for fiber pullout tests are classified into three approaches: 1) perfect interface model; 2) fracture mechanical model; and 3) cohesive interface model.

Perfect Interface Model (Stress Approach)

This model was originally developed by Cox in 1952. This model assumes bonding between the fiber and matrix was perfect, which means the displacements and tractions were continuous at the interface. (33)

The interface can be seen as an axis-symmetry problem which simplifies the problem to 2D problem rather than 3D problem. Many other researchers later used the elastic equations for an axis symmetric stress state to formulate the pullout model. However, their solutions were very difficult and in many cases they were too complex. A further simplification from 2D to 1D problem was done to obtain better results. Nayfeh (1977) derived the second order differential equation for the fiber force distribution in the fiber for the pull-push test. The interface between the fiber and matrix was defined by the shear lag parameter which was dependent on the Young's modulus and shear modulus of the fiber and matrix.

Fracture Mechanical Model (Energy Approach)

According to the stress approach, the debonding of mixes starts when shear stress is greater than the shear strength limit. However, a fracture at the interface of the fiber and matrix occurs differently. Once the energy in the system exceeds the energy limit, the crack surfaces along the fiber direction are created as a consequence of the release of the energy. The relation of the energy required for crack propagation and the increase of surface energy was first described by Griffith in 1920. (34) The law of energy conservation used in the fracture mechanic can be written as

$W=U+KE+Us$

Where W is the external energy, U is the internal energy which consist of elastic and inelastic deformation, KE is the Kinetic energy, and Us is the surface energy due to crack propagation.

According to static or quasi-static pullout test, KE is insignificant and can be omitted; thus, the energy equilibrium can be presented as proposed by Li (1992). (34)

$W= Ue +Uf+Us$

Where Ue is the elastic strain energy in the bonded region and Uf is the inelastic energy due to friction in the debond region.

It has been proposed that the entire interface is divided into two regions: the bonded area containing two intact materials and the debonded region where damages occur at different degrees. The constant fraction bond strength in damaged region is treated as a shear stress. Based on this assumption, researchers derive expressions for the energy release rate G. However, the other realistic models for bond behaviors at the interface and the analytical forms are challenging and hard to achieve.

Cohesive Interface Model (Stress Approach)

Theoretically, two composite materials are assumed to be perfectly bonded at the interface to ensure the highest material performance, nevertheless, it is almost impossible to achieve in many composite materials. For example, concrete reinforced by steel fiber contains a thin interphase layer between concrete matrix and fibers and creates a transition zone containing calcium hydroxide, a porous layer of calcium silicate hydrates, and ettringite. Due to different material properties other than the matrix materials, this transition zone has a strength that 30% lower than the matrix materials. Because this zone extends from the surface of the fiber up to only 50 micrometers, it was renamed to an interface (with zero thickness). This approximation leads to the displacement discontinuity between the reinforcing elements and matrix itself. As a consequence, the shear stress at the interface represents only a function of local slip and shall be called bond stress versus slip relation (BSR). In this principle, the cement based matrix is connected to the fiber by an independent BSR model. The pullout boundary value problem can be expressed by second order differential equations. The most accurate BSR model that starts with elastic response and followed by nonlinear portion up to the peak, then continued by the softening post peak response is very complex and not easy to derive for the analytical equation. (26, 27)

This literature review presented summaries of models that have been established to simulate the behavior of fibers in Portland cement concrete to determine the role of fibers on the tensile stress strain response and the fracture toughness of the composite.

Chapter 3

Fibers Characterization and Mix Design

This chapter presents test methods and the results of fiber characterization and mix design. The fibers are characterized based on their types and content. The mix design and the volumetric properties of these mixes are described below.

Materials and Experiments

Mix Design

The mix design of the control and the three fiber sections were developed by an independent contractor approved by Idaho Transportation Department (ITD). The assumption is the dosages of fibers added to this mix did not affect the mechanical properties of the mix. The evaluation of samples that were taken during the construction by ITD quality control showed no significant change in VMA, VFA, and other mix properties, and they remain within the specified production limits. The SP5 mix had ¾ in nominal maximum aggregate size (NMAS), and the gradations of the mix is shown in Table 1. The mix also contained 47% RAP which was milled from the existing pavement of the same project. This situation was unique for the project since only one source of RAP is introduced in the mix design, which minimizes the variability of RAP materials. The performance grade of the RAP binder was PG 64-28 which is lower than the virgin binder that has a performance grade of PG70-28. The optimum asphalt content of the project mix was 4.8%. The virgin binder added to the mix was only 1.97%, and the rest was contributed by the RAP binder. Table 2 shows a summary of the mix volumetric properties. More details about the mix design and job mix formula is shown in Appendix A.

Table 1. Final Blended and RAP Aggregates Gradation

Sieve Size (mm)	25.0	19.0	12.5	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Blended Agg. (% Passing)	100	99	83	66	39	26	20	16	12	8	4.9
RAP Agg. (% Passing)	100	98	87	73	44	29	21	17	14	10	5.7
Virgin Agg. (%Passing)	100	100	79	60	35	24	19	15	10	5.6	4.2

Table 2. Volumetric Properties and Requirements

	Control mix	ITD Specs.
Optimum AC (%) (In Total)	4.8	---
Virgin Asphalt added (%)	1.97	---
Air Voids (%)	4	4
%Gmm @ Ndes	95.9	96
VMA (%)	13.6	13 min
VFA (%)	70.40%	65-75
Dust-to-Asphalt Ratio	1.1	0.8-1.6
%Gmm @ Nmax	97.6	⩽ 98.0
Laboratory Mixing Temperature (deg in F)	300 deg.	-
Laboratory compacting Temperature (deg in F)	275 deg.	-
Avg. Plant Mixing Temperature (deg in F)	320 deg.	

Fiber Characterizations

Three different fibers from different vendors were used in this study. The first type was a blend of polypropylene and aramid fibers from Forta Fi, the second was aramid fibers that is treated from Surface Tech and referred to as ACE fibers, and the third was a glass fiber from Nycon. All fibers have comparable lengths which are ¾” to ½” (19mm to 13 mm). The amounts of fibers added to the mix were based on the vendors’ recommendations. The percentages were 1lb/ton, 0.28 lb/ton, and 3 lb/ton of HMA, respectively.

Forta Fi Fibers

Forta Fi fibers is a blend of aramid fibers and polypropylene fibers.(35) Both fibers have the same length of ¾” (19mm). The specific gravities are 1.44 and 0.91 respectively.

The tensile strength of the aramid fibers is up to 400 ksi with a decomposition or break down temperature of 800 ^{o}F. However, the polypropylene fibers has a much lower tensile strength, 70 ksi, and a break down temperature of

Figure 2. Forta Fi Fibers

315 °F. Figure 2 shows the shape and the color of the fiber blend.

Kaloush and Biligiri conducted a laboratory performance evaluation of fiber-reinforced asphalt mixtures in a comparison with control mixture from a field test section in Tempe, Arizona.(36) This mixture includes the Forta fi blend (polypropylene and aramid). The researchers reported less shear deformation and higher residual strength in the triaxial strength test. Rutting performance tests indicated that fiber reinforced asphalt mixtures accumulated less permanent strain and showed higher flow numbers than the control mixture. A significant increase in the dynamic modulus values of FRAC was detected at high temperatures. However, at lower temperatures the FRAC mixture were comparable to the control mix. Also, FRAC mixtures exhibited higher tensile strength, total fracture energy and slower crack propagation according to the Indirect Tensile Strength test (IDT) and C* line integral test, respectively. Finally, the FRAC showed better fatigue resistance at 40° F; however, the control outperformed the FRAC mixture at high strain levels at 70° F.

On the other hand, Mondschein et al. examined the effect of Forta Fi fibers on the lab produced asphalt mixture performance in terms of permanent deformation and fatigue.(37) Four different asphalt mixes were used. The fibers were dosed in the mixture in quantities of 1 lb per 1 ton of asphalt mixture. The laboratory findings of this study declared that “the compaction of the mixture is not negatively affected by the application of fibers. The better understanding of the behavior of 3D reinforcement will need a wider scope of testing, ideally in trial sections to be long term monitored along with the traffic loads and weather conditions.”

ACE Fibers

ACE fibers from Surface Tech consist only of aramid fibers with ¾” (19 mm) in length, and have a specific gravity of 1.44 with a tensile strength of 400 ksi.(38) The break down temperature is 800 °F. These fibers were treated with melted wax to provide more control of fiber mixing and weighing down the fibers due to its light weight. Figure 3 presents the aramid fibers with the Wax treatment.

No published scientific research has been performed yet on the ACE fibers. However, brochures from Surface Tech Company, the producer of the fibers, shows a Texas Overlay Test on fiber reinforced sample. The results indicate that there is an increase in the number of the cycles from 500 cycles to 1,200 cycles for the overlay tester. Also, the Hamburg Wheel tracking test shows the number of cycles to rut failure is 8000 in the control mix and 14,000 cycles for the fiber mix. There is not much information about the amount of the fibers in these mixes. So far, the ACE fibers have been used in some projects in Oregon and Washington State.

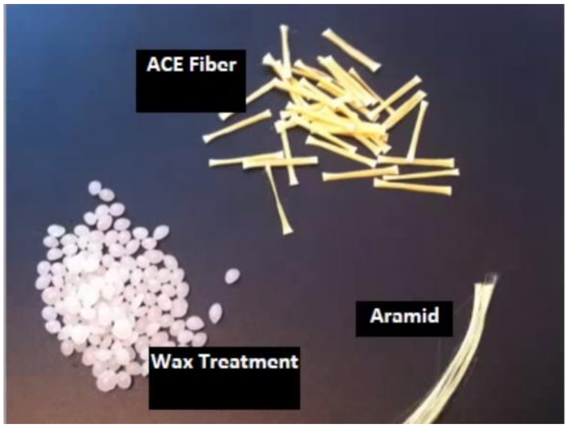


Figure 3. ACE Fibers

Nycon Glass Fibers Type E

Nycon type E fibers are made of Glass fiber as shown in **F**igure 4, and provided by Nycon Company.(39) The fibers' length is ½" (13mm) and has a specific gravity of 2.7. The tensile strength is 300 ksi. It is known that the melting of the fiber glass is 2075°F for these fibers. The water absorption is less than 1%.

There is some research about a successful use of the glass fibers in the Portland Cement Concrete (PCC). However, there is no research published on the effect of Nycon type E glass fibers on HMA performance.

Figure 4. Nycon Type E Fibers

Field Production

The fiber-modified sections adopted the same mix design without any alteration, and the fibers were added at the asphalt plant as per each vendor's specifications. The four construction sections at US-30 project are: Section 1 (from MP 435.281 to 436.01) was the unmodified control; Section 2 (from MP 436.01 to 436.8) was the Forta-Fi fiber-modified with a rate of one lb/ton; Section 3 (from MP 436.8 to 437.6) was the Surface-Tech ACE fiber-modified with a rate of one third lb/ton; and Section 4 (from MP 437.6 to 438.376) was the Nycon glass fiber-modified with a rate of three lb/ton. The rate of fibers addition was specified by the vendors. The method of fiber addition of all three types was the same. The asphalt plant was a continuous production plant and the fibers were blown into the drum dryer at the inlet of the RAP (Figure 5). Analysis of the production quantities in the project construction reports indicated the average actual rate of fiber addition for each mix was very close to the designated rate specified. The actual quantities for the sections are 1.04, 0.28 and 3.11 lb/ton for Forta-Fi, Surface Tech, and Nycon respectively. These contents are close to the specified amount by the vendors, and are roughly equivalent to 0.05%, 0.01% and 0.16% by the HMA mix weight.

Field samples of the plant mix of each section were collected by ITD personnel in accordance to ITD standard procedures. Plant mix samples were collected mid-way from each section to insure that it is an average representative of the laid mix. This was also to avoid any possible overlap between types of fibers at the boarder of sections. In addition to the loose plant mix samples, field cores were extracted for density and volumetric analysis as per ITD standard procedures. Additional cores were extracted from the shoulders to have sufficient number of core samples for lab testing.

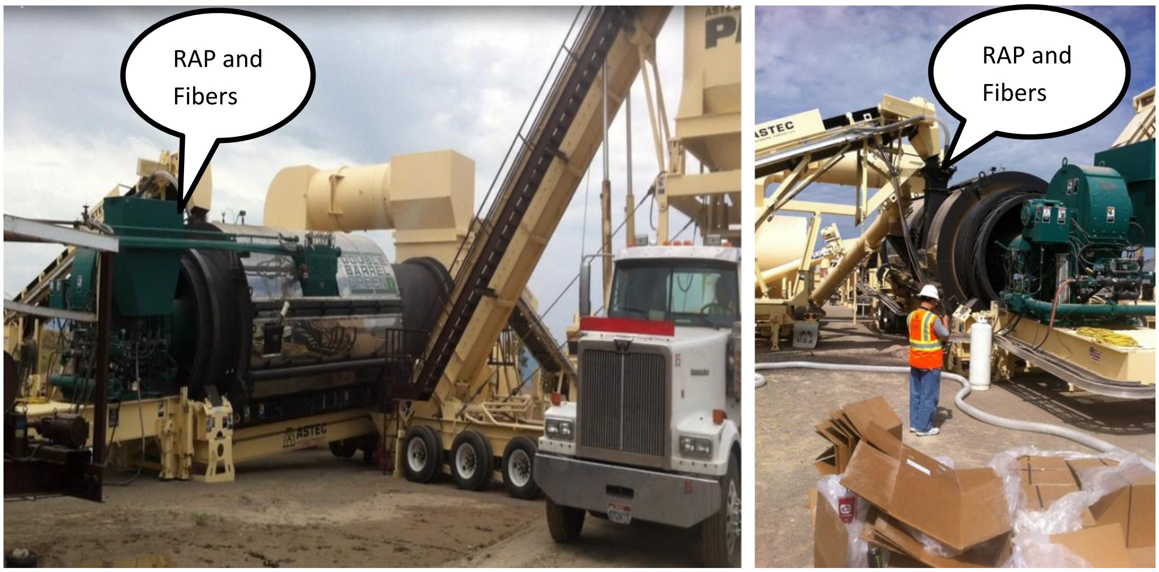


Figure 5. Process of Blowing Fibers into the HMA plant

Lab Trials for Extraction of Fibers

Three test sections were designed with specific fiber content, and the experimental procedure was planned based on the assumption that each asphalt mix has the desired fiber content with uniform distribution. However, the high variation in test results revealed the distribution of added fiber was not uniform. Therefore, it was necessary to measure the fiber content in asphalt mixes. For this purpose, two different methods were followed to separate the fiber from asphalt mixes.

The first method included two steps. In the first step, asphalt binder was extracted from asphalt mixes according to AASHTO T-164. In the second step, fiber-aggregate mixture from the extraction was ignited in NCAT ignition oven at the temperature of 1200^{o}F (650°C). Laboratory tests showed this temperature can burn 99 percent of fiber, whereas ignition in lower temperatures led to a considerable amount of fiber leftover after ignition. Figure 6 presents the schematic steps of this method.

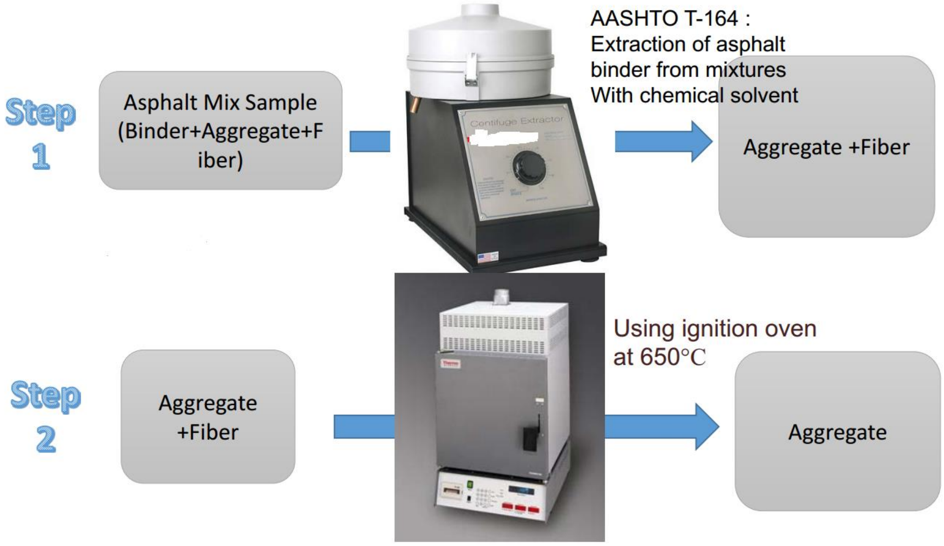


Figure 6. Schematic Steps of Proposed Method to Identify Fiber Content

Measured fiber content from this method was much higher than target values which indicated that considerable amount of fine aggregate was burned during second step in the ignition oven at 1200^{o}F (650°C). Therefore, a new method was evaluated to measure the fiber content in asphalt mix. This method was similar to the first but instead of using an ignition oven, calcium chloride solvent was used to separate fiber and aggregate. Light fibers that suspended in the solvent could be collected from the surface of solvent. Finally, collected fibers were washed to remove remaining fine aggregate in their structure. The fiber collected in this way was dried to constant mass in the oven at the temperature of 212±40°F. Figure 7 presents the final result of this procedure for Surface Tech fiber mixes.

Figure 7. (a) Aggregate-Fiber Mix after Extraction (AASHTO T-164) (b) Collected SURFACETECH Fiber

Table 3 illustrates the fiber content for Surface Tech (ACE) fiber mix. The proposed lab method showed that the measured fiber content is approximately close to the target values.

Table 3. Results of Fiber Content for ACE Fiber

Measured Asphalt Content from Extraction Method(AASHTO T-164)	4.9%
Target Asphalt Content (JMF)	4.8%
Measured Fiber Content	.0172%
Target Fiber Content for Surface Tech	.015%

The proposed lab method was not successful for the other two types of fibers. In the case of Nycon, the fibers were heavier than the solution, so they settled with the aggregate. For the case of Forta Fi fiber mixes, the fiber structure completely trapped the fine aggregate, making the separation of fiber and aggregate difficult by means of this method. Further study is needed in this area.

Chapter 4

Laboratory Performance Evaluation of Fiber-Reinforced Asphalt Mixes

This chapter presents methods and results of laboratory performance tests including: rutting resistance, fatigue cracking resistance, and low temperature thermal cracking resistance.

Rutting Resistance

Rutting resistance of mixes was tested by dynamic modulus, flow number, APA test and Hamburg Wheel test. Those tests are used to characterize different aspects of mixes for rutting resistance. Dynamic modulus of mixes is the indicator of stiffness of mixes, while flow number is to describe lateral shear resistance of mixes. APA test is conducted to indicate the resistance to consolidation type of rutting as well as the Hamburg Wheel test.

Dynamic Modulus and Flow Number

The research team conducted the dynamic modulus test in accordance with AASHTO T 342-11.(42) The test was conducted on standard 6 inches Gyratory compacted samples. Specimens were fabricated by Pine-AFG1 Superpave gyratory compactor to achieve a height of 6.7 inches (170 mm). Trial and error were used to determine the number Gyrations that lead to the target height. After compaction, the specimens were cored and saw cut to the size of 5.9 inches (150mm) in height and 4 inches (100mm) in diameter with air voids level of 7±0.5 %. *AASHTO T209, Standard Method of Test for Determining the Theoretical Maximum Specific Gravity* (*G_{mm}*)(40)*, and AASHTO T166, Standard Method of Test for Determining the Bulk Specific Gravity* (*G_{mb}*)(41) were the test methods that used to conduct the volumetric analysis of the samples. The prepared samples were tested in the Asphalt Mixture Performance Tester (AMPT), which meets the AASHTO T 342-11(33) requirements. The temperatures used for dynamic modulus test were: 40℉, 70℉, 100℉, and 130℉. At each temperature, six different loading frequencies: 25, 10, 5, 1, 0.5, 0.1 Hz, were applied. For each mixture, a total of three specimens were fabricated and tested in order to confirm the results. After the raw data was obtained, the dynamic modulus values of all samples was averaged at each combination of temperature and frequency sets, standard deviation (STD) and coefficient of variance (COV) were calculated for each temperature and frequency. The averaged data of all tested samples were used to calculate the dynamic modulus master curve for each mixture. The computed E* master curve is used in the AASHTOWare Pavement ME Design to predict the mechanistic responses of pavement under various combinations of pavement temperature and vehicle speed in order to find the influence of fiber content on the pavement behavior.

The flow number test was conducted by the research team using a loading cycle of 1.0 second in duration, which consists of a 0.1 second haversine load followed by a 0.9 second rest at a testing temperature of 130°F. As shown in Figure 8, the flow number is the number of load repetitions when the permanent deformation rate reaches a minimum This test is typically conducted at the end of the E* test, which is performed at the same temperature, 130°F. However, in this project the Flow Number test was conducted on new samples to avoid the consolidation effect from the dynamic modulus test. The Flow point and cycles were automatically calculated and recorded by using the Simple Performance Tester software UTS005 version 1.33. This protocol is in accordance with *AASHTO TP79-13, Standard Method of Test for Determining the Dynamic Modulus and Flow Number for Hot Mix Asphalt (HMA) Using the Asphalt Mixture Performance Tester (AMPT).* (43) The researchers then compared measured flow numbers to the minimum flow number values that were developed in NCHRP Project 9-33 for hot mix asphalt (HMA) as shown below in table 4.

Table 4. NCHRP Project 9-33 Recommended Minimum Flow Number Requirements (44)

Traffic Level, Million ESALs	Minimum Flow Number, Cycles (HMA)	Minimum Flow Number, Cycles (WMA)
<3	-	-
3 to <10	50	30
10 to <30	190	105
Equal or >30	740	415

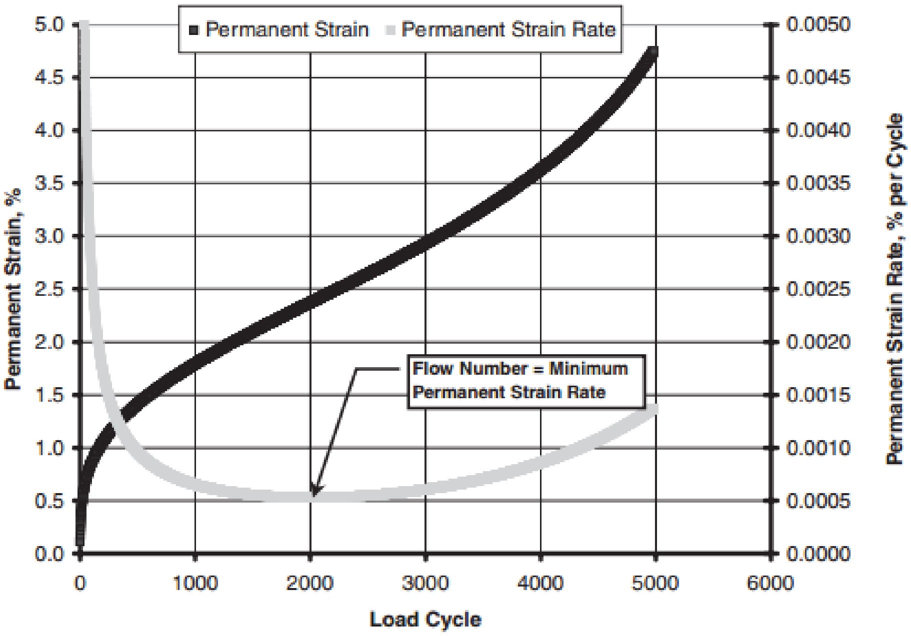


Figure 8. Schematic of Typical Flow Number Test Data (44)

Asphalt Pavement Analyzer

The Asphalt Pavement Analyzer (APA) test was used to evaluate the mixture resistance to permanent deformation. The test was conducted at the ITD headquarters laboratory in accordance with AASHTO TP 63 (45) Samples were compacted for each mix with air void of 7±0.5% and height of 4.53 in. (115mm), and three replicates were tested for each mix. Test temperature depends on the upper temperature range of the virgin grade. The APA test was at 158 ^{o}F (70^{o}C) for all mixes. The rolling wheel pass was 60 cycles per minutes for a total of 8000 cycles. According to ITD specification,(1) the maximum rut depth of mixture class SP5 (the mix that used in this study) under APA testing does not exceed 0.2 in (5.08mm).

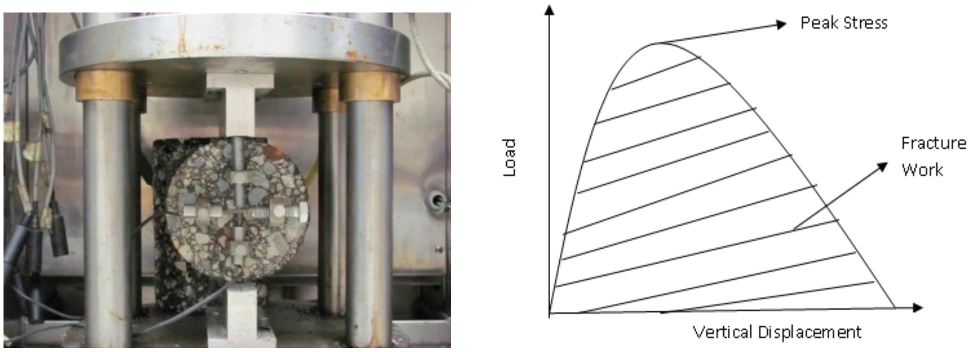
Hamburg Wheel Tracking

The Hamburg Wheel Tracking Device (HWTD), can be used to evaluate rutting and stripping potential. The team conducted the test in accordance with Tex-242-F.(46) The HWTD tracks a loaded steel wheel back and forth directly on a HMA sample. The test was typically conducted on Superpave Gyratory Compactors (SGC) compacted samples using three replicates for each mix type. Each sample has an air void level of 7±0.5% and size of 2.3±0.1 in. (58±2mm) in height and 5.9 in. (150mm) in diameter. Most commonly, the 1.85 inch (47 mm) wide wheel is tracked across a submerged (underwater) sample for 20,000 cycles (or until 20 mm of deformation occurs) using a 158 lb (705 N) load. Rut depth is measured continuously with a series of LVDTs on the sample. Three replicates have been used for each mix.

Fatigue Cracking Resistance

Indirect Tension Test

The research team used the fracture work density and vertical failure deformation from indirect tensile test (IDT) to evaluate mixture resistance for bottom-up cracking and top-down cracking, respectively.(47) The definition of fracture work density was as fracture work divided by sample volume, and fracture work was determined as the entire area under the load versus the vertical displacement curve.(48) And vertical failure deformation was defined as vertical displacement under the peak load, which could indicate ductility of mixes, as illustrated in Figure 9.



(a) (b)

Figure 9. Indirect Tensile Test (a) Indirect Tensile Test Set-up and (b) Load-Displacement Curve of Indirect Tensile Test

A servo-hydraulic Geotechnical Consulting Testing System (GCTS) with an environmental chamber was used to test the samples. Four linear variable differential transformers (LVDTs) were mounted on the front and back of sample to measure the deformations during the tests. Once the LVDTs are attached, the specimen is placed in a loading apparatus, which consists of top and bottom plates with loading strips of the proper curvature to load the specimens, shown in Figure 9. Fatigue tests were performed at 68 °F with a deformation rate of 2 inches per minutes by the GCTS ram. The deformation was continued until the load on the sample achieved a value close to zero. Three samples for each type of mix were tested, and the average value and coefficient of variation (COV) were calculated and presented.

Fracture Parameter, Jc

Another indicator of fracture resistance is referred to as Jc.(49) and read as (J-sub-c). The Jc parameter is defined as a path independent integration of strain energy density, traction, and displacement along an arbitrary contour path around the crack. The test is conducted at room temperature of approximately 68±2°F (20 ±1°C) as a bending test on a notched semi-circle samples as shown in Figure 10. The Value of Jc was determined from the applied load versus the vertical deformation relationship.(49, 50) The strain energy U, which is equal to the area underneath the load-deformation curve, was determined. After determining the strain energy, the ratio of the strain energy to the specimen thickness, U/b, for each specimen was plotted against the notch depth, a. The value of Jc was obtained from the slope of the U/b versus a best straight line fit. Four data points used to develop such a line fit, and therefore, three specimens with different notch depth (0, 0.25, 0.5, and 0.75 in.) were tested for the Jc calculation. For each notch depth, three replicate specimens were used to evaluate test repeatability. All the samples were compacted in the lab from field loose mixes. More details about Jc sample preparation is well described in previous research project. (49, 50)

Figure 10. Fracture Test using Semicircular Notched Samples in Bending (Jc)

Low Temperature Thermal Cracking Resistance

The low temperature property of the mixture was characterized by the test of creep compliance and indirect tensile (IDT) strength. (51) The nondestructive creep compliance test for each sample was conducted first at temperature of -4°F, 14°F and 32°F with dead load duration of 100s. And then IDT strength test was carried out under temperature of 14°F at a displacement rate of 0.1 inch/min. The deformation was continued until the load on the sample achieved a value of zero and the specimens completely split. The value of creep compliance and IDT strength were used for MEPDG thermal cracking model to predict mixture performance which will be presented in chapter 5. And fracture work density of mixture from IDT strength test at 14°F was calculated to compare the resistance of thermal cracking performance of mixtures with different types and percentages of fibers.

Since the resistance of low temperature thermal cracking was also considered as long-term performance of the mixtures, samples used for thermal cracking test were prepared following the same procedure as IDT fatigue test.

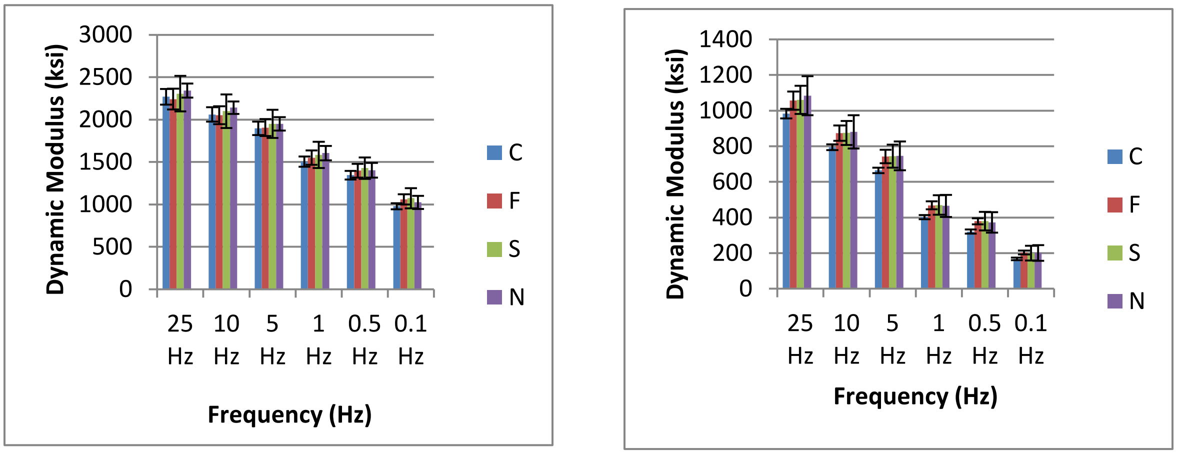
Results and Discussion

Stiffness

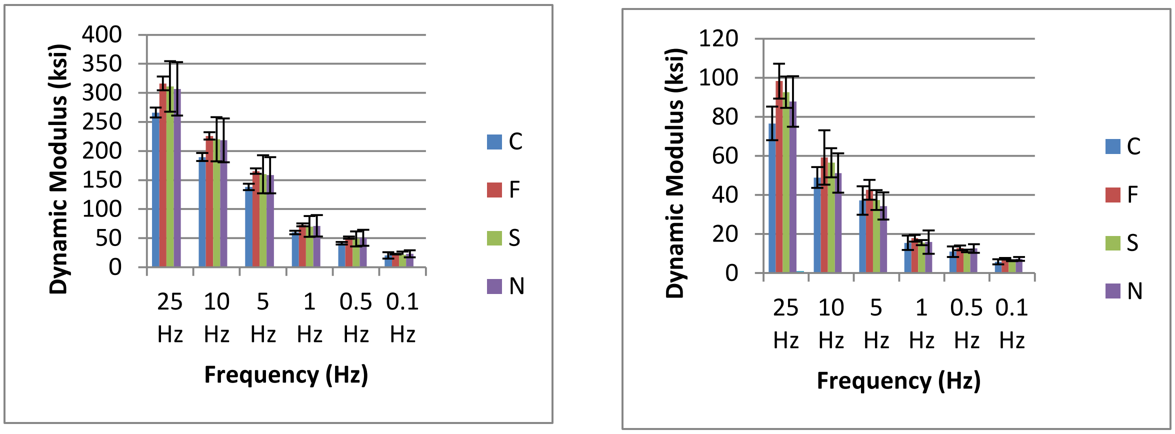
Dynamic modulus testing

Our research team determined dynamic modulus values as inputs to MEPDG program for performance predictions Figures 11 and 12 present the dynamic modulus results and master curves of the mixes respectively. In these figures the notations C, F, S and N refer to Control, Forta Fi, Surface Tech and

Nycon mixes respectively. Even though the mixes have different fiber types and contents, the master curves of the dynamic modulus indicated that at the high frequency (or low temperature) level at which the dynamic modulus is not sensitive to variation of asphalt binder, the dynamic modulus values of all the fiber mixes were comparable to each other. At low frequency (or high temperature) level at which the dynamic modulus is sensitive to the asphalt binder, the results also indicated that there is no significant difference among the mixes as shown in table 8 in Appendix B. At intermediate temperatures, the lowest dynamic modulus values were observed in the control mix. Among the fiber mixes, the results indicated that Forta Fi fibers increased the dynamic modulus values at 70 °F and 100 °F. Surface Tech fibers showed the same trend at 70 °F only. But, there was no significant difference between the control and Nycon mix. This finding showed that fibers may not add significant improvement to the mix performance at low and at high temperatures.



(a) E* Results at 40 °F **(b) E* Results at 70 °F**



(c) E* Results at 100 °F **(d) E* Results at 130 °F**

Figure 11. (a), (b), (c), and (d) Dynamic Modulus Values at 40 °F, 70 °F, 100 °F, and 130 °F Respectively

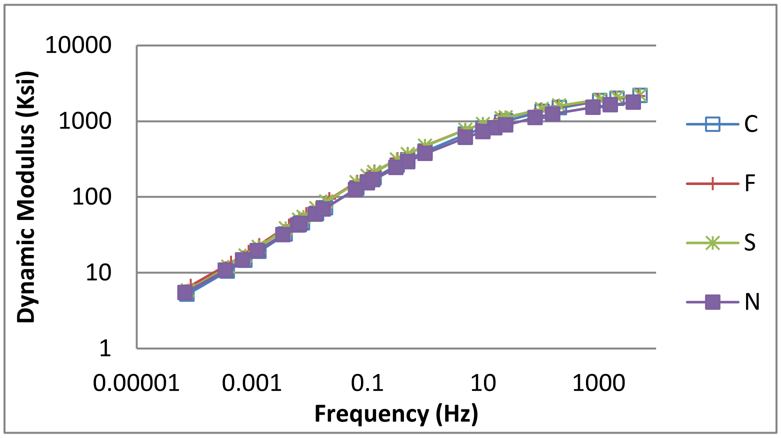


Figure 12. Master Curves of the Mixes at 70 °F Reference Temperature

Note: C: Control mix, F: Forta Fi mix, N: Nycon mix and S: Surface Tech mix

Rutting Resistance

Flow number test

According to the NCHRP Report 702,(44) the recommended minimum flow numbers, based on the traffic levels for the project mixes (10-30 million ESALs) is 190. The results as presented in Figure 13 showed that all of the average of three replicates for each mix satisfy these criteria. A comparison of the flow numbers of the fiber mixes indicates that they had higher numbers than the control mix, which mean higher resistance to lateral shear failure. However, the statistical analysis of ANCOVA as shown in table 10 in Appendix B indicated that this difference is not significant. The results again showed that fibers did not offset the stiffening effects on the mix at high temperature. The accumulated micro strain with the number of cycles for each mix is presented in Figure 14.

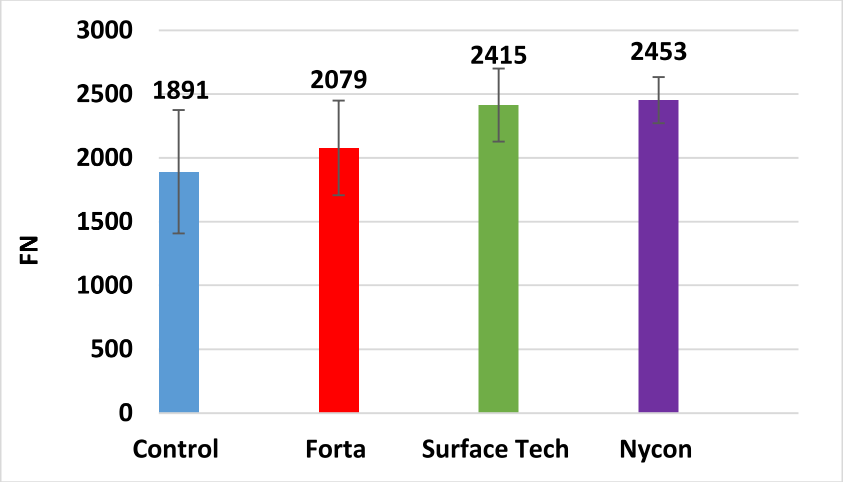


Figure 13. Average Flow Number Test Rresults of Mixes

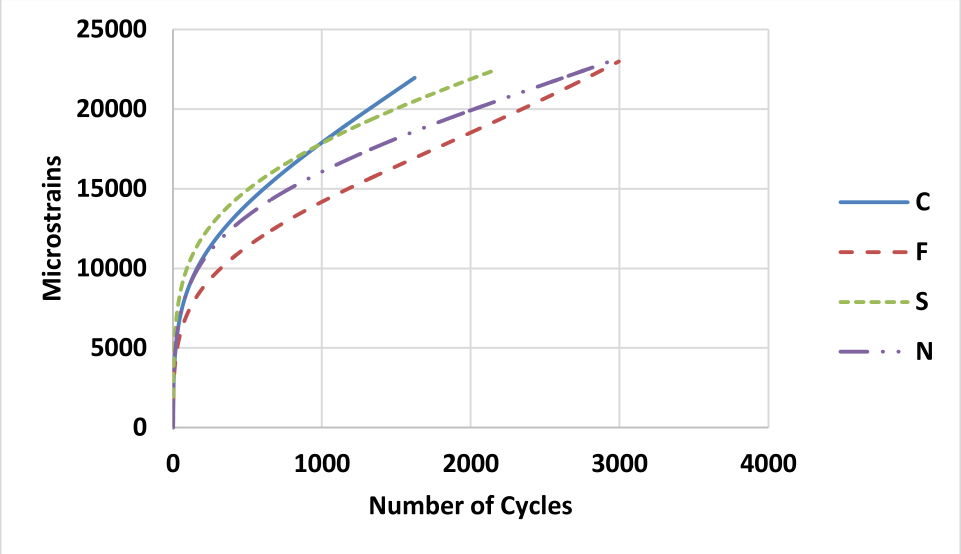
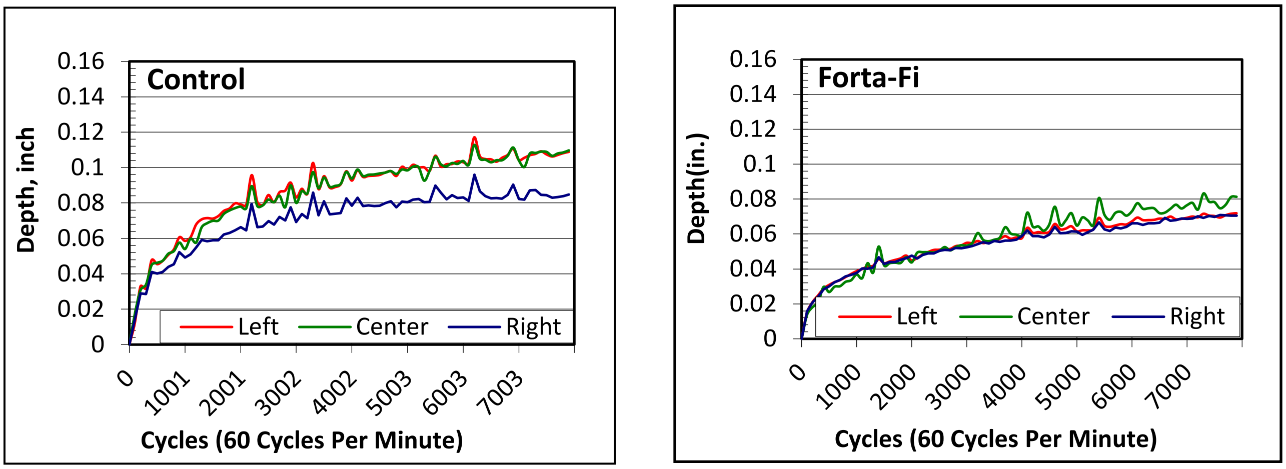


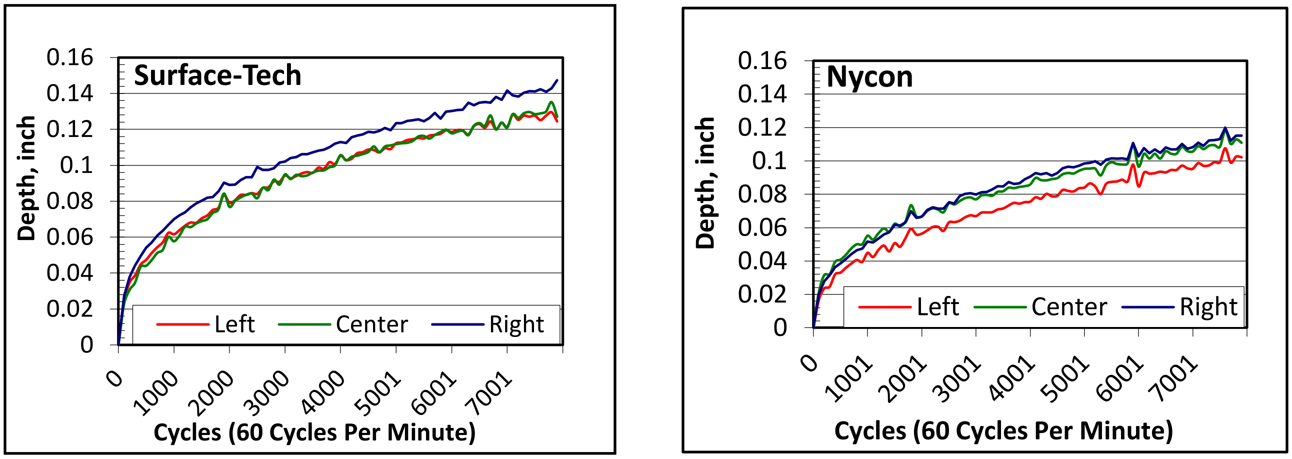
Figure 14. Average Micro-strain Vs. Number of Cycles of the Flow Number Test

Automated Asphalt Pavement Analyzer (APA)

In addition to stiffness evaluations from the dynamic modulus and flow number tests, the Asphalt Pavement Analyzer (APA) test can provide a direct evaluation of rutting resistance. Figure 15 presents the rut depth of the four mixes as was provided by the ITD headquarters lab. The test was done on three Gyratory samples that were compacted at 7% +/- 0.5% air voids. Results as shown by the plots reveal that at 7000 cycles, the average rut depth of the three samples are 0.07, 0.09, 0.12 and 0.10 inches for the Control, Forta Fi, Surface Tech and Nycon mixes respectively. When analyzing these results along with those found in the Hamburg wheel track test (HWT), the variability of rutting could not be confirmed and that it is concluded there is no significance difference in the rutting results among the four mixes.



(a) Control **(b) Forta-Fi**



(C) Surface Tech. **(d) Nycon**

Figure 15. (a), (b), (c), and (d) Automated Asphalt Pavement Analyzer (APA) Test Results

Hamburg Wheel Track test

Figure 16 presents the results of Hamburg Wheel track (HWT) tests for the four types of mixes. Each line indicates the average of four samples. The results of ANOVA analysis as shown in table 11 for the final rut depth at 20,000th cycle revealed no significant difference among mixes in terms of rutting based on HWT test results. It is to be noted that in this analysis ANOVA was used rather than ANCOVA since HWT testing was done on lab samples where air voids were under control. ANCOVA was used on analysis of core samples to suppress the effect of air voids variability. Although Figure 16 indicates that the utilization of fiber showed slight improvement in the rutting performance of asphalt mixes this improvement is not significant statistically. Possible reason could be due to the non-uniform distribution of fiber during mixing procedure.

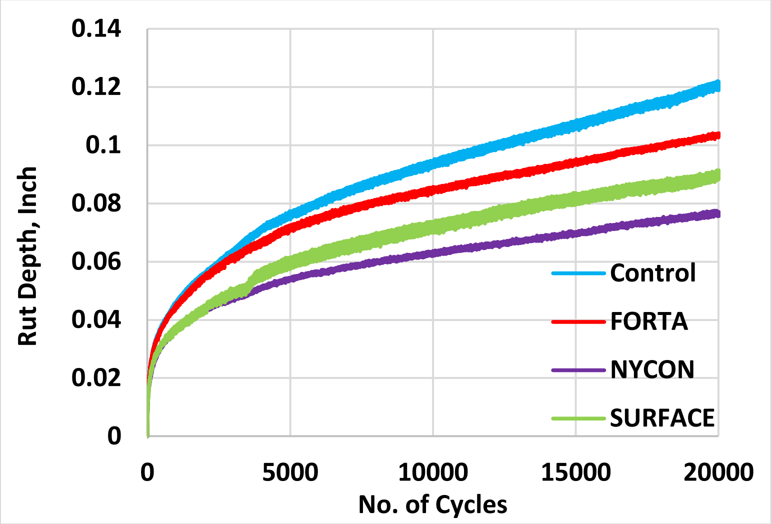
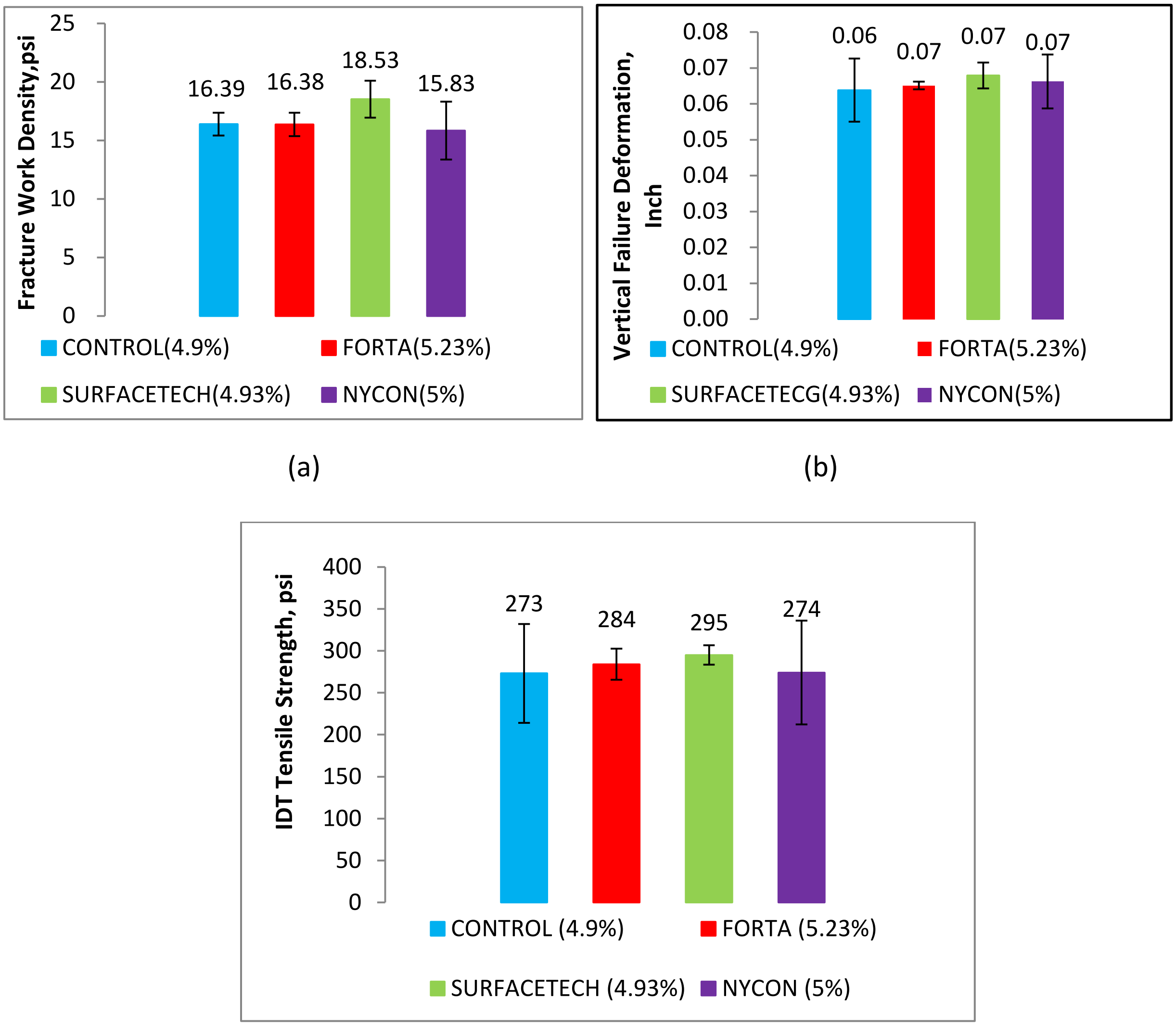


Figure 16. Hamburg Wheel Track (HWT) Test Results

Fatigue Cracking Resistance

Figure 17 presents the results of fracture work density, vertical failure deformation and tensile strength at 68 °F for four types of mixes. For each type of mix, the average value of three replicates is presented (Numbers in parentheses indicate the average ir void of three core samples). The mixes statistically have comparable fracture work density and vertical failure deformation. The ANCOVA analysis in table 15 and 16 revealed that no significant difference is evident among different types of mixes in terms of fracture work density and vertical failure deformation.



(a)

(b)

(c)

Figure 17. (a) Fracture Work Density, (b) Vertical Failure Deformation (at 68℉) and (c) IDT Tensile Strength

Figure 18 presents the results of Jc test of the all mixes at 68°F. The Jc is an indicator of fatigue cracking resistance. The higher the Jc value is, the better the cracking resistance. The results showed that Nycon had the highest result, which means better resistance to fracture, followed by Surface Tech then Forta Fi. The statistical analysis of the ANCOVA as presented in Table 19 in Appendix B points out this difference is not significant. That means all mixes behaved the same in terms of fatigue cracking resistance, and no superior performance was observed in the fiber-reinforced mixes.

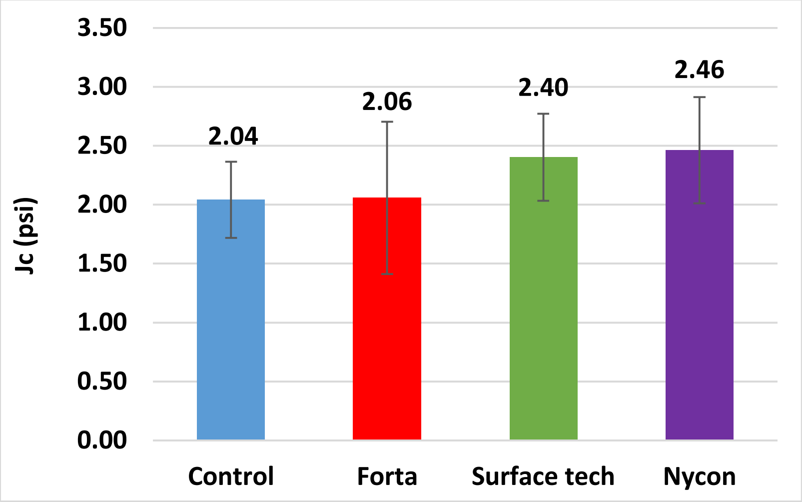


Figure 18. Jc Test Results of the Fiber Mixes at 68 °F

Low Temperature Thermal Cracking Resistance

Figure 19 presents the results of fracture work density for IDT test at low temperature. Fracture work density values among different types of mixes are statistically comparable. This indicates samples with fiber do not have advantageous performance in comparison to control mixes against thermal cracking. This may be explained by non-uniform distribution of fiber in the plant mix procedure which caused some field cores to have a low amount of fiber.

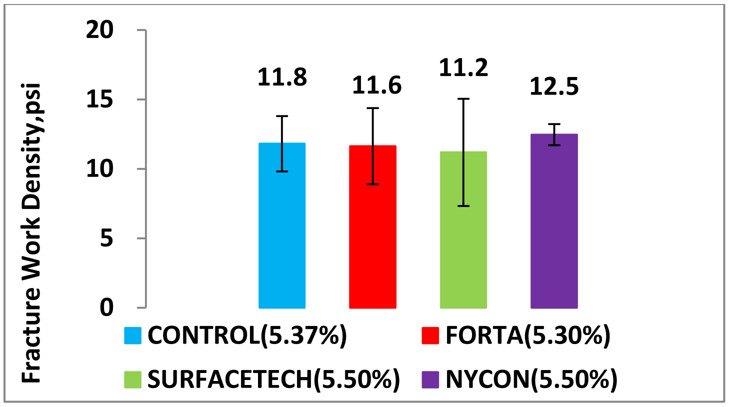


Figure 19. Fracture Work Density at 14℉

Creep Compliance Test

The time-temperature superposition principal was used to develop master curves for a wide range of time. Figure 20 presents the creep compliance master curves for asphalt mixes. Each master curve indicates the average of three replicates. As can be seen, average creep compliance master curves for four types of mixes are close. Furthermore, the slopes of creep compliance master curves which are an appropriate indicator to thermal cracking resistance are comparable for four types of mixes.

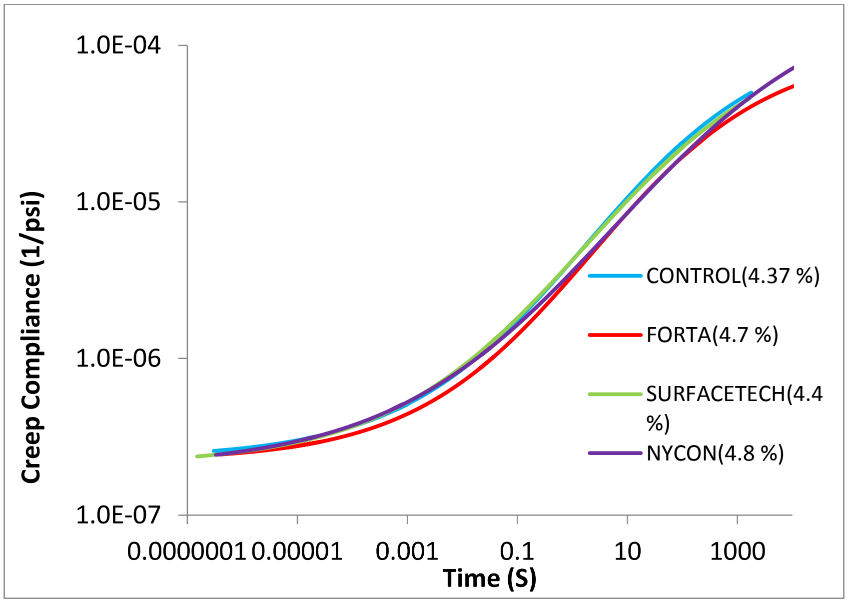


Figure 20. Creep Compliance Master Curves at 68° F Reference Temperature

The creep compliance values at low, intermediate, and high time-temperature combination levels are shown in Figures 21 through 23. The ANCOVA analysis results as shown in Table 22 indicate that no significant difference is evident among different types of mixes in terms of creep compliance in these levels.

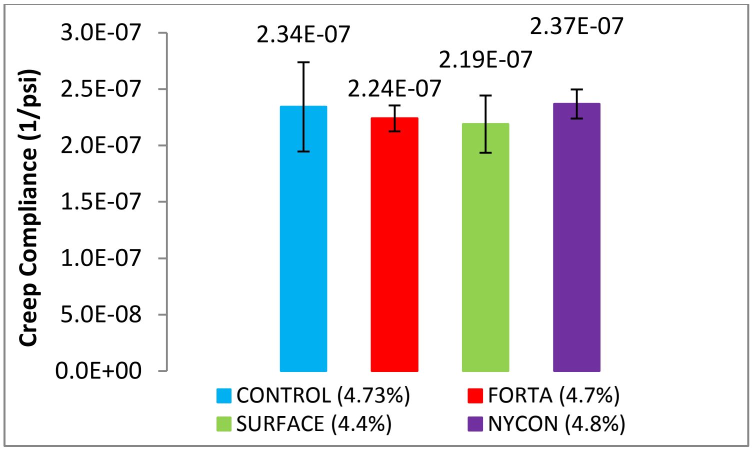


Figure 21. Creep Compliance at Low Time-Temperature Level (-4°F and 1s)

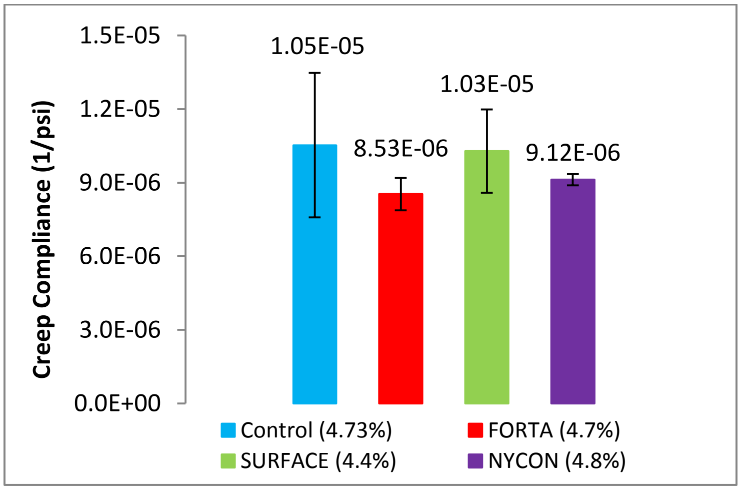


Figure 22. Creep Compliance at Intermediate Time-Temperature Level (68°F and 10s)

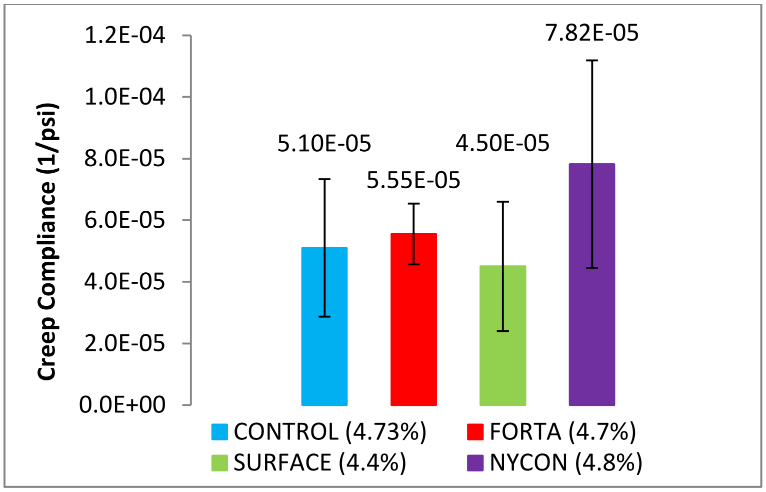


Figure 23. Creep Compliance at High Time-Temperature Level (86°F and 100s)

Fatigue life

Expected fatigue life for bottom-up cracking was calculated based on phenomenological fatigue model outlined by Wen.(39) Equation 2 presents the fracture work density model.

$$N_f = 3.75 \times 10^{-5} (\frac{1}{\varepsilon_t})^{0.147} (FWD)^{1.92} h^{0.135} \qquad (2)$$

Where N_f is the number of repetitions to fatigue; ε_t is the tensile strain at critical location, microstrain; FWD is the fracture work density, psi; h is the thickness of asphalt layer, in. Tensile strain at the bottom of asphalt concrete overlay was calculated for the standard 18 kip single axle load by Everstress software. Everstress is a linear elastic layer program developed by the Washington State Department of Transportation. Table 5 presents the details of pavement structure for the test section. Moduli values for the surface layers are assigned based on the results in this research, where the layer moduli of the base and subgrade were assigned based on the R-values of these layers.

Table 5. Generalized Pavement Structure for Test Section

Layer Number	Type of Layer	Thickness(Inch)	Modulus(ksi)
1	AC Overlay	4.8	564^{C}-655^{F}-575^{S}-595^{N}
2	Existing AC	4.8	350
3	Base:3/4” aggregate	7.2	45.40
4	Subbase: granular	19.2	34.30
5	Subgrade	-	15.43

Note: C: Control mix, F: Forta Fi mix, S: Surface Tech mix, and N: Nycon mix.

Table 6 presents the fatigue life for different fiber reinforced mixes and control mix. As shown, mixes with Surface Tech fiber indicate higher fatigue life in comparison to other mixes that relates to high fracture work density of these mixes. It should be noted that this model was calibrated based on the Accelerated Load Facility (ALF) data at the FHWA Turner-Fairbank Highway Research Center. Hence, its prediction values may not be valid for the field performance of asphalt concrete pavements.

Table 6. Fatigue Life for Bottom-Up Cracking

Mix	Strain(Micro)	FWD(psi)	h(inch)	N_f
Control	38.11	38.11	4.8	211493
Forta Fi	39.87	39.87	4.8	209702
Surface Tech	38.68	38.68	4.8	267156
Nycon	39.02	39.02	4.8	197193

X-ray Tomography

This task was initially added to the project to investigate the dispersion of fibers in the mix. This approach stemmed from previous research using X-Ray Tomography technology to analyze asphalt mix internal structure. The technology was also used to investigate the crack propagation in HMA mixes.

Brief review of some of these studies are presented here. Bahia et al. stated that the two dimensional (2-D) imaging techniques is efficient approach to characterize the microstructure of the HMA, and it can capture the structure of the aggregates inside the mix.(53) This technique could be used to introduce an elaborated method to characterize the internal structure and correlated it to the rutting resistance performance. The researchers used a processed digital images for different samples with different gradations and binder contents under different compaction efforts. The results show that there is a correlation between the internal structure indices and rutting resistance. Also, the indices were successfully used to capture the effect of compaction effort, gradation quality, and binder modification on the mixture internal structure.

Masad et al. used the 2D imaging techniques to investigate the difference in the internal structure of asphalt mixes compacted by linear kneading compactor (LKC) and Superpave gyratory compactor (SGC).(54) In order to study the internal structure of these mixes., the distribution and orientation of aggregates and the aggregate to aggregate contacts were used as quantifying measures. The results revealed that the LKC specimens are relatively randomly distributed. However, the SGC specimens tend to be more orientated toward the horizontal direction.

In a following study, Masad et al. measured the orientation of aggregates in asphalt mixes that have different compaction efforts (different number of gyrations) and in field cores.(55) The researchers found that the anisotropy in gyratory samples became more noticeable with the increase in the number of gyrations (compaction effort) up to a certain point. After that the anisotropy level decreased and the orientation of the aggregates became more randomly distributed.

Tashman et al. examined the relationship between the compaction effort and the aggregate orientation.(56) In this study, the authors used samples compacted by Superpave gyratory compactor and compared them to field core samples. The results indicated that the aggregate anisotropic distribution was less in the SGC specimens than the field cores, and the imaging analysis showed a tendency for coarse aggregates to move toward the edge in SGC specimens. The researchers also compared samples before and after triaxial compression tests at high temperatures, and they analyzed the CT images to characterize the change in the air voids. The results showed a uniform air-voids distribution in the horizontal direction and a non-uniform distribution in the vertical direction from field cores studied using CT.

X-ray CT has also been used to detect the cracks in asphalt mixes by using computerized tomography techniques to detect the development of the crack.(57,58,59) However, there is not enough research on the use of X-ray tomography techniques to investigate the distribution of some additives inside asphalt mixes such as: rubbers and fibers.

Field core samples were prepared for X-ray Tomography test, hoping that it would reveal better image about the dispersion of the fibers in the mix. The scanning was performed with high-resolution at the X-ray CT scan facility at the University of Texas at Austin (UTCT). In this machine, X-ray beams are radiated from all directions to the specimen. Passing X-ray through the specimen can decrease the X-ray intensity and this variation is measured by detectors in the plane of specimen. By processing the data of detectors gray scales cross sections of the specimen are constructed. Data from detectors determine the attenuation coefficient of sample that is function of density, atomic number and X-ray energy. By combining these images (slices) the 3D image of sample can be obtained. The thickness of each image is related to X-ray beam and detector plane.

Figure 24 shows the final image of Forta Fi fiber field cores. These images were analyzed based on above explanation. As can be seen, no fiber is detectable in these images. The size and density of fiber are less than the capacity of X-ray machine. Furthermore, by using X-ray machine with low energy range the X-ray beam cannot penetrate specimen. Since the results did not reveal any significant conclusion and fibers were not actually detected, it was decided to abandon the test and do not continue for other mixes. Further studies are needed in this area.

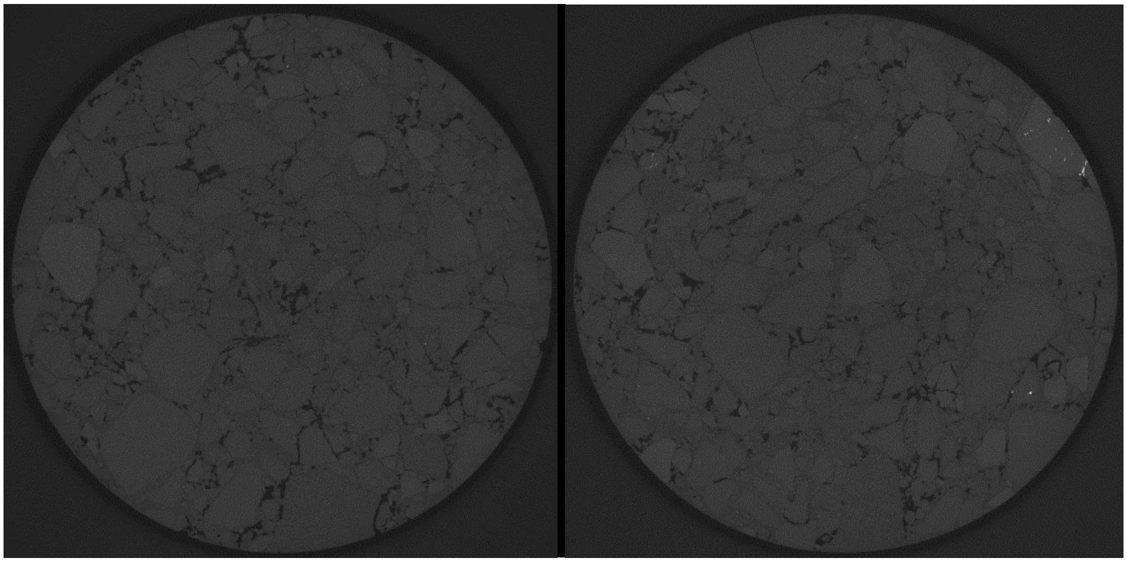


Figure 24. Forta Fiber Specimen Used for High Resolution X-ray CT Scanning

Summary

This chapter summarizes the laboratory performance evaluation of modified fiber mixes in terms of rutting resistance, fatigue cracking resistance and low temperature thermal cracking resistance.

Based on the test results, it is concluded that the mixtures' rutting resistance to lateral shear failure, indicated by the flow number, did not increase significantly by adding fibers to the mix. The Asphalt Pavement Analyzer and Hamburg Wheel Tracking tests also indicated the presence of fibers did not add significant value to the mix resistance to rutting.

Fatigue cracking resistance was evaluated by the Fracture Work Density measured in the indirect tension test and the Jc parameter from the semicircular bending test of notched samples. Both test results indicated that the mixes performed comparably and that no significant difference is expected in the resistance to fatigue.

Fracture work Density test performed at Low Temperature also indicated that the fiber mixes had similar fracture work density values to resist thermal cracking and no significant improvement was observed.

Fiber dispersion in the mix was not detectible using X-ray Tomography, and hence this technology needed further investigation.

Chapter 5
Performance Prediction

AASHTOWare Pavement ME Design Input Parameters and Their Significance

Chapter 4 presents the laboratory analysis of the material properties of the study mixes. However, it is not plausible to evaluate the predicted pavement performance in the field of these mixes without considering realistic traffic and climate conditions. The research team employed AASHTOWare Pavement ME Design software to evaluate the performance of flexible pavements. The purpose of this chapter is to evaluate the effects of fibers on pavement performance based on the identified properties of the mixes and AASHTOWare Pavement ME Design analysis.

Structure of the Pavements

The pavement structure of the sections were modeled as of 4.8 inches of new asphalt layer over 4.8 inches of old existing asphalt. The sublayers were assigned 7.2 inches of crushed base material over 19.2 inches of crushed sub-base. The class of asphalt material was SP5; the 0.75 inch maximum size crushed base material had an estimated R-value of 80; and the subgrade soil consists mainly of gravel with silt and sand with an assigned R-value of 60. Figure 32 in Appendix C presents the details of the layers' structure. The FWD values obtained from ITD were used to back calculate the resilient modulus of the existing HMA layer. All data related to the layers properties is in Appendix C.

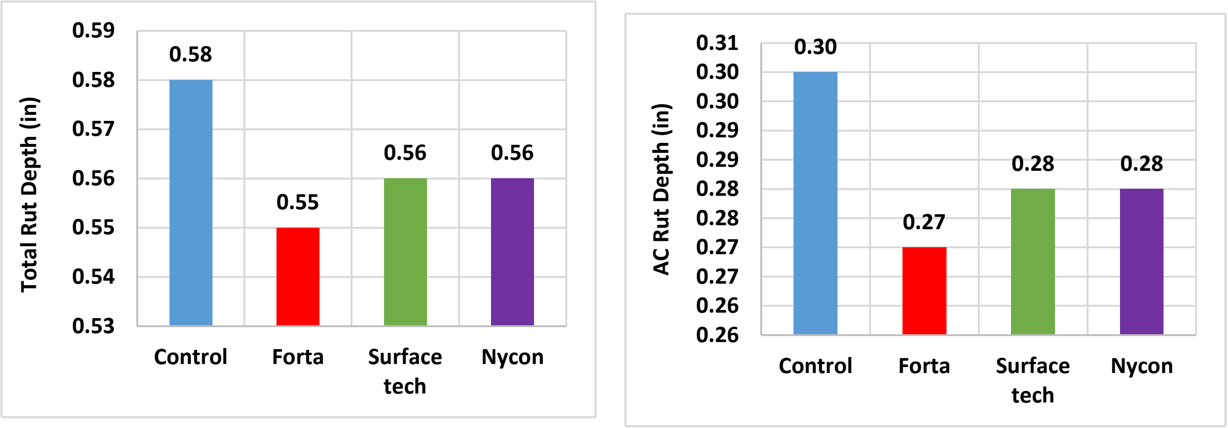
Analysis

The input data needed for the AASHTOWare Pavement ME Design analysis were either provided by the ITD or measured directly in the laboratory by the research team. For the predicted pavement performance, the reliability was 90 percent for a design life of 20 years. The performance prediction characteristics for the pavements include fatigue, rutting, thermal cracking, and roughness. The climatic data are based on weather station in Pocatello, ID. The ITD measured the AADTT which is presented in Figure 30 in the Appendix. Vehicle class distribution and the adjustment factors were obtained from the ITD and shown in Tables 24 and 25. As of this writing, the State of Idaho's local calibration factors for the AASHTOWare Pavement ME Design are not available. Currently, ITD in cooperation with University of Idaho is working on a new project to establish the local calibration factors for the state. Accordingly, the research team used the nationally calibrated distress models in the AASHTOWare Pavement ME Design software. The AASHTOWare Pavement ME Design requires complex shear modulus and phase angle data for RTFO-aged binder residue at several temperatures for Level 1 and Level 2 asphalt inputs. Table 27 in Appendix C provides details of the Level 1 inputs of the binder.

Results and Discussion

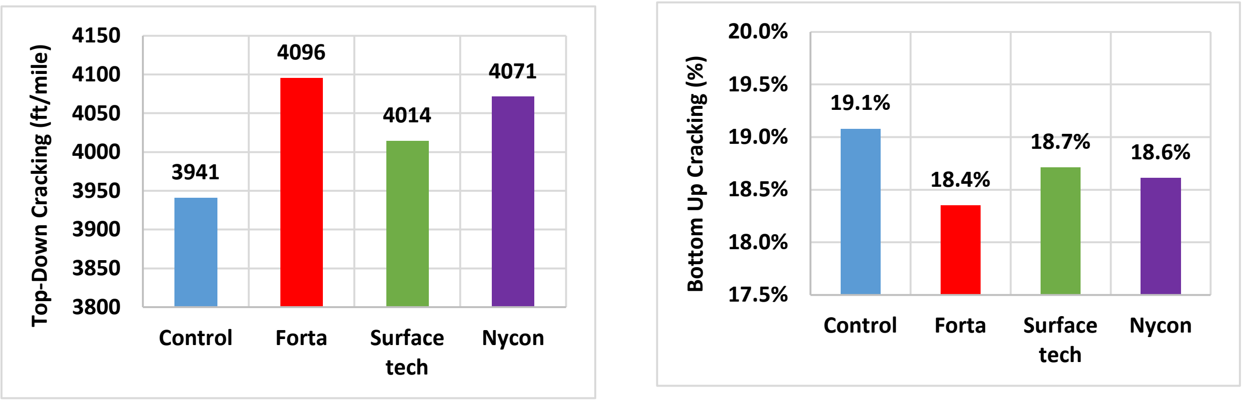
Figures 25a through 25f present the predicted rut depths, top-down fatigue cracking, bottom-up fatigue cracking, and thermal cracking, and IRI results of the control and fiber pavements, respectively. The predicted rut depths of the asphalt layers after 20 years indicated that the control mix had a rut depth slightly higher than the others, and all the fiber mixes had the same level of rutting. This is due to the rutting model for asphalt layers in AASHTOWare Pavement ME Design being based on the dynamic modulus values, and since there was no significant difference among fiber mixes modulus values at high temperature there was no difference in performance. Figures 25c and 25d present the predicted top-down and bottom-up fatigue cracking results, respectively. The same trend of the fiber mixes can be seen in the bottom up cracking. Again, these outcomes are due to the fact that the top-down and bottom-up fatigue cracking models in AASHTOWare Pavement ME Design are based on the dynamic modulus. High modulus values of an asphalt mix lead to less fatigue cracking in this model. Forta Fi fibers showed poor resistance to thermal cracking compared to the other mixes, as shown in Figure 25e. This may be due to the low m-values of the creep compliance (which describes the ability to relieve stress), which is similar to the m-values for the creep stiffness of binder in Superpave binder specifications. In AASHTOWare Pavement ME Design, the thermal cracking model is based on IDT strength, creep compliance, and the slope of the creep compliance master curve.

Generally, the predicted performance follows the material properties measured in the laboratory after considering traffic and climate. This result makes sense, because the distress models are based on these material properties and the traffic and climate conditions are kept the same for pavements with different Fibers. In addition, because this study used nationally calibrated distress models, the absolute values for predicted distresses may not be representative of true pavement performance without the local calibration of these models. However, the ranking of the performance of the four different pavements should hold true.



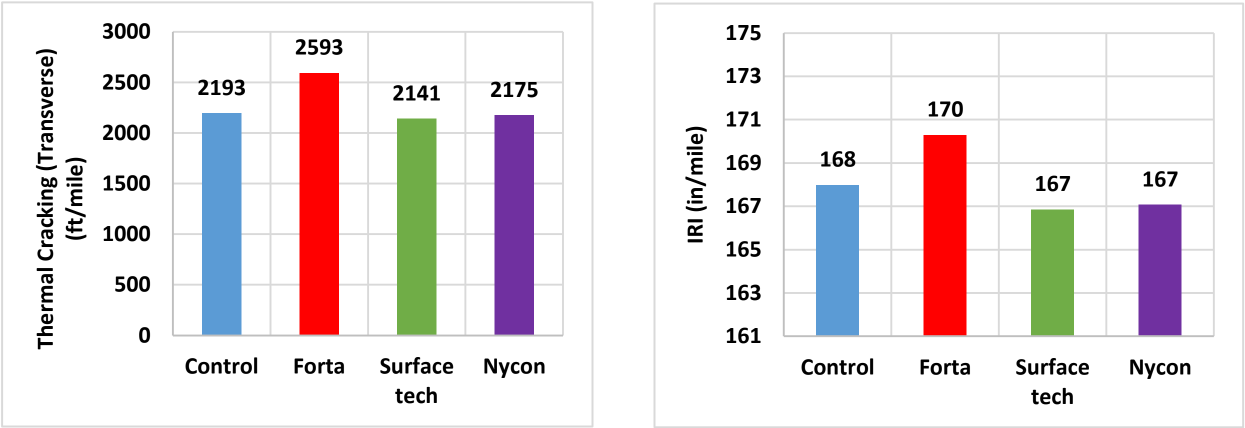
(a) Total Rut depth (in.)

(b) AC Rut depth (in.)



(c) Top-Down cracking (ft/mi)

(d) Bottom Up cracking (%)



(e) Thermal cracking (ft/mi)

(f) IRI (in/mile)

Figure 25. (a) to (F) AASHTOWare Pavement ME Predicted Distresses of the Fiber Pavements

Chapter 6
Summary, Conclusion and Recommendation

Summary

Project Description

This research project was developed mainly to evaluate the effectiveness of using fibers to improve performance of the Hot-Mix Asphalt (HMA). The Idaho Transportation Department (ITD) adopted the rehabilitation project at US-30 east of Montpelier, to build three sections modified with fibers and compare it to a control section with unmodified mix. The scope of this lab research was limited to evaluate the properties of the laid mixes using standard lab testing methods. Three different fibers were used to modify the HMA overlay mix. Fibers were provided by three vendors representing three different types of fibers. Aramid and Polyolefin fibers was provided by Forta Fi Corporation. Wax treated aramid fibers that is referred to as ACE fibers was provided by Surface-Tech., Inc., and glass fibers Type E was provided by Nycon Corporation.

The project HMA mix design was developed at NCAT, Auburn University, Alabama following the ITD specification of SP5. The mix contained 47% RAP of the exiting roadway. Mix design Job-Mix-Formula (JMF) was developed for the unmodified control mix.

Fiber contents and method of addition of fibers to the mix was controlled and performed by each vendor. Based on vendors' recommendations, the added fiber contents (by weight of mix) were 1 lb/ton, 1/3 lb/ton and 3 lb/ton for Forta Fi, ACE and Glass fibers respectively. The fibers were injected in a hot mix asphalt plant at the inlet of the RAP to the plant drum dryer "dry mixing" then blended with the binder and aggregates. The mix design of the fiber-modified mixes followed the original unmodified control mix. It was assumed that the fibers would not affect the volumetric mix design.

Lab Testing Program

The research team evaluated the laboratory performance of these mixes in terms of rutting resistance, fatigue cracking resistance, and low temperature thermal cracking resistance.

For rutting, the tests performed were the Flow Number (FN), Hamburg Wheel Tracking (HWT) and the Asphalt Pavement Analyzer (APA). Potential of the mix to resist fatigue was evaluated using the Fracture Work Density measured at the Indirect Tension Test (IDT) at normal temperature (68 °F) as well as the Semi-circular bending test of notched samples to determine the fracture parameter (Jc). Resistance to low temperature cracking was evaluated by the IDT as well but at low temperature (14 °F). Furthermore, an attempt to evaluate the degree of fiber dispersion in each mix using X-ray Tomography was made, but it did not reveal any meaningful results due to the fact that the size of fibers were too small and could not be seen in the x-ray images.

The research team also utilized the AASHTOWare Pavement ME Design software to evaluate, predict and compare performance of the fiber-modified HMA mixes. The team compiled and measured material properties, pavement structure, climate, and traffic data to derive the inputs for the mechanistic-empirical analysis. ITD designed and provided all the pavement structures. We compared all the predicted pavement distresses at 90 percent reliability over a design life of 20 years.

Remarks and Observations at Construction Site

Based on the observations during the construction of the test sections at the project site, the research team noted that fiber feeding was controlled by representatives of the vendors. Fibers were blown into the plant at the inlet of RAP feeder to the drum dryer of the mix plant. The research team observed in several instances that the fibers clumped and were blown as balls into the feeder. It is essential for the fibers to be randomly well distributed in the mix. The clumping of fibers would have produced non-homogenous fiber-modified mixes that could lead to loss the benefits of using them. Therefore, it is critical to develop some sort of a quality control test to monitor the distribution of the fibers during the production.

Modeling of Fiber-Modified Mixes

Different models that simulate the behavior of fibers in Portland cement concrete were reviewed. These models aim to determine the role of fibers on the tensile stress-strain response and the fracture toughness of the composite. In the case of a fiber reinforced Asphalt mixture, it is essential to use stress-strain data from experimental testing. This is mainly because of the difficulty in modeling the randomness in the orientation of fibers in FE model. The test data in this report was not sufficient to develop a numerical or analytical model that can describe a realistic behavior of the fibers in the Asphalt mixture. Several variables including fiber type and content should be considered to understand the effect of fibers in the mechanical properties of the mix.

Long-Term Monitoring of Field Performance

As mentioned earlier that the main goal of the project was to evaluate the mixes as they perform in the field under real traffic and climatic conditions. Therefore, ITD is planning to monitor the performance of the project sections over a number of years as Phase 2 of the project. It is anticipated that the long-term performance task will take five or more years to be able to observe significance difference among the constructed sections. When the long-term performance task is completed by ITD, its results will be analyzed and reported.

Conclusions of Lab Test Results

Based on the results of this lab research, the following conclusions are drawn:

Density analysis of field cores as well as reproduced lab specimens from loose plant mixes revealed that the addition of fibers did not alter the mix design volumetric properties.

Rutting resistance as measured by Flow Number, APA and Hamburg Wheel Track tests of the fiber mixes were comparable to the control mix. The rutting performance did not improve regardless of the type of fiber added. Statistical analysis confirmed that there was no significant difference in the rutting performance for the investigated mixes. It is to be noted that we did not vary fiber content since it was controlled by the vendors.

For the fatigue cracking resistance, as measured by both the Fracture Work Density (FWD) and the fracture parameter Jc, fibers did not add any extra cracking resistance as was reported in previous studies. The reason could be related to the behavior and the orientation of the fibers inside the mix. In other words, the fibers did not experience any tensile stress until the pavement experience excessive stresses that lead to cracking of the mix.

At low temperatures, the fracture work densities of the fiber mixes were statistically comparable to the control mix and had no significant difference. The expected advantage of the fibers in resisting cracking was not observed.

Lab results of rutting, and cracking evaluations were confirmed by the rutting and cracking distresses from the AASHTOWare Pavement ME Design software.

Recommendations

During the lab study, the research team identified few gaps that would need further consideration to better evaluate the effectiveness of adding fibers to HMA. Some of these factors include:

1. More than one mix needs to be investigated. For example, the nominal max size of the mix and aggregate gradation may have an effect on the outcome performance of the fiber-modified mixes.
2. The fiber contents adopted in this study were suggested by the vendors. A study is needed to optimize on the fiber content of each type and its relation to the mix gradation and size.
3. The mix adopted in this study has a relatively high RAP content. It was not clear whether this high RAP has altered the effect of fibers. Therefore, more analysis is needed for mixes with only virgin aggregates to isolate the RAP factor.
4. There is a great need for a field quality control test to measure the uniformity of fiber distribution and injection to the mix plant.

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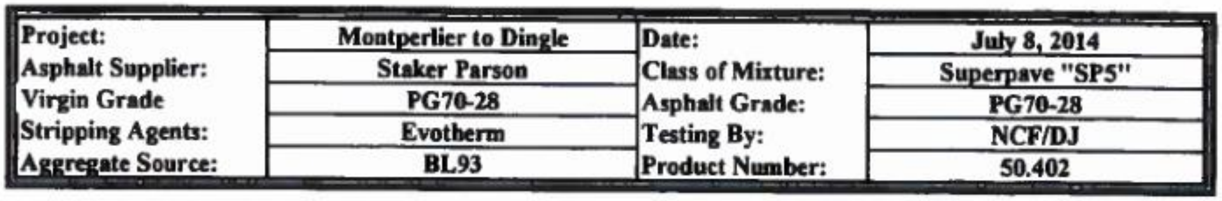
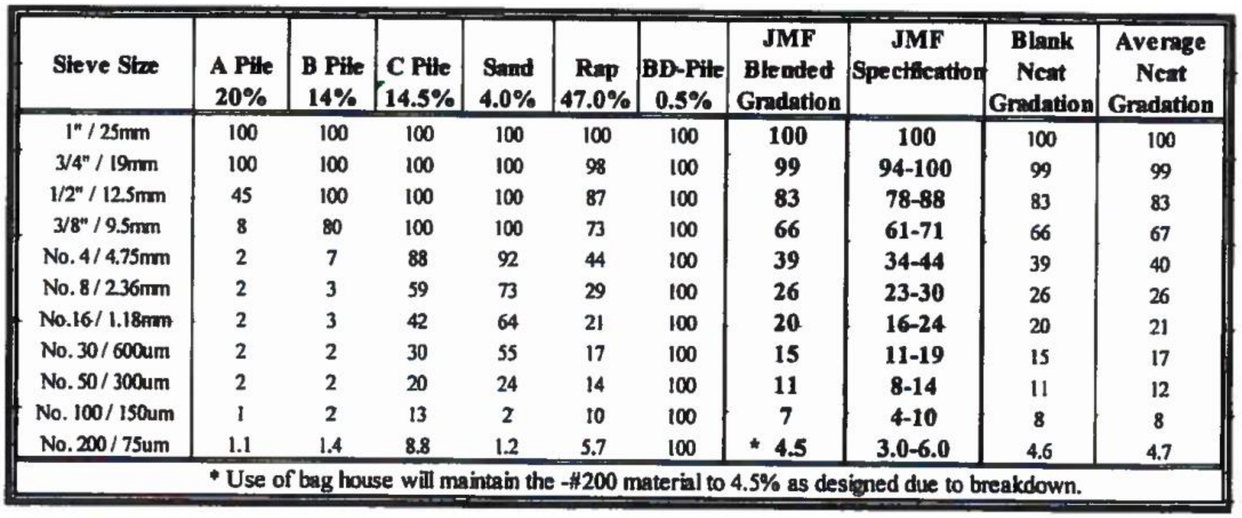
Appendix A
Approved Project Mix Design



Project:	**Montperlier to Dingle**	**Date:**	**July 8, 2014**
Asphalt Supplier:	**Staker Parson**	**Class of Mixture:**	**Superpave "SP5"**
Virgin Grade	**PG70-28**	**Asphalt Grade:**	**PG70-28**
Stripping Agents:	**Evotherm**	**Testing By:**	**NCF/DJ**
Aggregate Source:	**BL93**	**Product Number:**	**50.402**

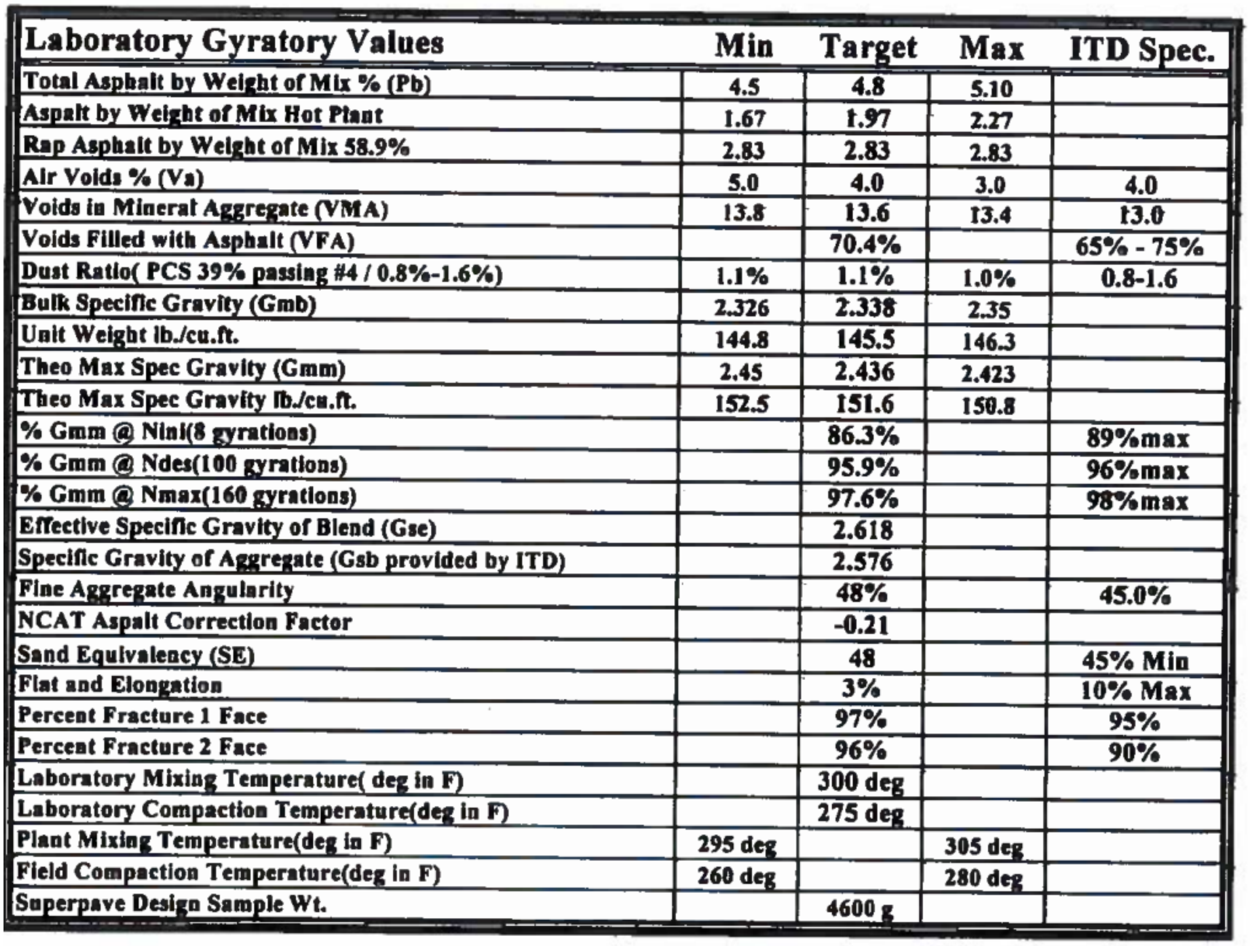
Figure 26. Selected PG grade for the ITD Superpave SP5



Sieve Size	A Pile 20%	B Pile 14%	C Pile 14.5%	Sand 4.0%	Rap 47.0%	BD-Pile 0.5%	JMF Blended Gradation	JMF Specification	Blank Ncat Gradation	Average Ncat Gradation
1" / 25mm	100	100	100	100	100	100	**100**	**100**	100	100
3/4" / 19mm	100	100	100	100	98	100	**99**	**94-100**	99	99
1/2" / 12.5mm	45	100	100	100	87	100	**83**	**78-88**	83	83
3/8" / 9.5mm	8	80	100	100	73	100	**66**	**61-71**	66	67
No. 4 / 4.75mm	2	7	88	92	44	100	**39**	**34-44**	39	40
No. 8 / 2.36mm	2	3	59	73	29	100	**26**	**23-30**	26	26
No.16 / 1.18mm	2	3	42	64	21	100	**20**	**16-24**	20	21
No. 30 / 600um	2	2	30	55	17	100	**15**	**11-19**	15	17
No. 50 / 300um	2	2	20	24	14	100	**11**	**8-14**	11	12
No. 100 / 150um	1	2	13	2	10	100	**7**	**4-10**	8	8
No. 200 / 75um	1.1	1.4	8.8	1.2	5.7	100	*** 4.5**	**3.0-6.0**	4.6	4.7

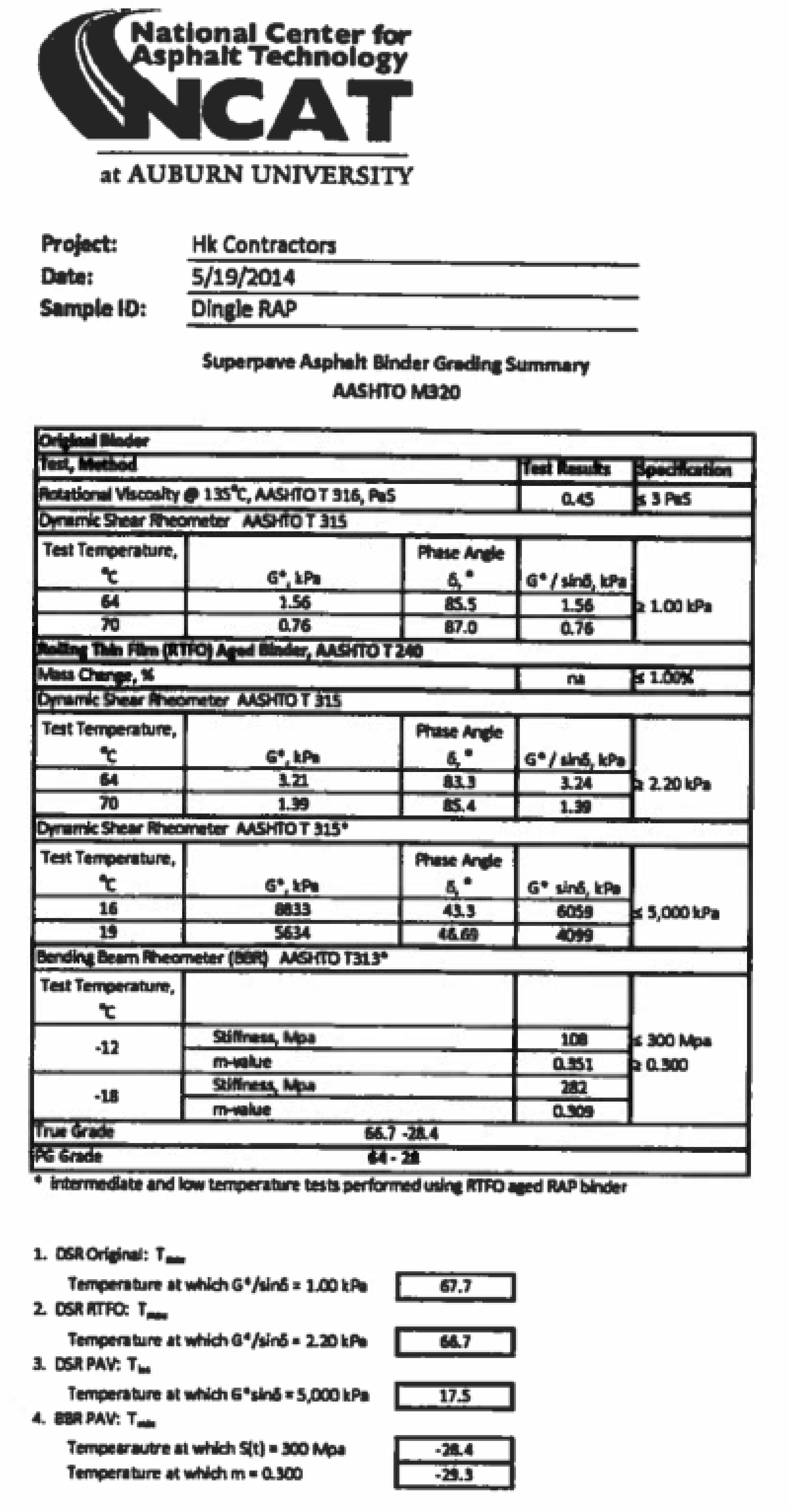
*** Use of bag house will maintain the -#200 material to 4.5% as designed due to breakdown.**

Figure 27. Aggregate Gradation Data



Laboratory Gyratory Values	Min	Target	Max	ITD Spec.
Total Asphalt by Weight of Mix % (Pb)	4.5	4.8	5.10	
Aspalt by Weight of Mix Hot Plant	1.67	1.97	2.27	
Rap Asphalt by Weight of Mix 58.9%	2.83	2.83	2.83	
Air Voids % (Va)	5.0	4.0	3.0	4.0
Voids in Mineral Aggregate (VMA)	13.8	13.6	13.4	13.0
Voids Filled with Asphalt (VFA)		70.4%		65% - 75%
Dust Ratio(PCS 39% passing #4 / 0.8%-1.6%)	1.1%	1.1%	1.0%	0.8-1.6
Bulk Specific Gravity (Gmb)	2.326	2.338	2.35	
Unit Weight lb./cu.ft.	144.8	145.5	146.3	
Theo Max Spec Gravity (Gmm)	2.45	2.436	2.423	
Theo Max Spec Gravity lb./cu.ft.	152.5	151.6	150.8	
% Gmm @ Nini(8 gyrations)		86.3%		89%max
% Gmm @ Ndes(100 gyrations)		95.9%		96%max
% Gmm @ Nmax(160 gyrations)		97.6%		98%max
Effective Specific Gravity of Blend (Gse)		2.618		
Specific Gravity of Aggregate (Gsb provided by ITD)		2.576		
Fine Aggregate Angularity		48%		45.0%
NCAT Aspalt Correction Factor		-0.21		
Sand Equivalency (SE)		48		45% Min
Flat and Elongation		3%		10% Max
Percent Fracture 1 Face		97%		95%
Percent Fracture 2 Face		96%		90%
Laboratory Mixing Temperature(deg in F)		300 deg		
Laboratory Compaction Temperature(deg in F)		275 deg		
Plant Mixing Temperature(deg in F)	295 deg		305 deg	
Field Compaction Temperature(deg in F)	260 deg		280 deg	
Superpave Design Sample Wt.		4600 g		

Figure 28. Job Mix Formula (JMF)



National Center for Asphalt Technology
NCAT
at AUBURN UNIVERSITY

Project: Hk Contractors
Date: 5/19/2014
Sample ID: Dingle RAP

Superpave Asphalt Binder Grading Summary
AASHTO M320

Original Binder				
Test, Method			**Test Results**	**Specification**
Rotational Viscosity @ 135°C, AASHTO T 316, PaS			0.45	≤ 3 PaS
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, °C	G*, kPa	Phase Angle δ, °	G* / sinδ, kPa	
64	1.56	85.5	1.56	≥ 1.00 kPa
70	0.76	87.0	0.76	
Rolling Thin Film (RTFO) Aged Binder, AASHTO T 240				
Mass Change, %			na	≤ 1.00%
Dynamic Shear Rheometer AASHTO T 315				
Test Temperature, °C	G*, kPa	Phase Angle δ, °	G* / sinδ, kPa	
64	3.21	83.3	3.24	≥ 2.20 kPa
70	1.39	85.4	1.39	
Dynamic Shear Rheometer AASHTO T 315*				
Test Temperature, °C	G*, kPa	Phase Angle δ, °	G* sinδ, kPa	
16	8833	43.3	6059	≤ 5,000 kPa
19	5634	46.69	4099	
Bending Beam Rheometer (BBR) AASHTO T313*				
Test Temperature, °C				
-12	Stiffness, Mpa		108	≤ 300 Mpa
	m-value		0.351	≥ 0.300
-18	Stiffness, Mpa		282	
	m-value		0.309	
True Grade	66.7 -28.4			
PG Grade	64 - 28			

* Intermediate and low temperature tests performed using RTFO aged RAP binder

1. DSR Original: T_{max}
   Temperature at which G*/sinδ = 1.00 kPa: 67.7
2. DSR RTFO: T_{max}
   Temperature at which G*/sinδ = 2.20 kPa: 66.7
3. DSR PAV: T_{int}
   Temperature at which G*sinδ = 5,000 kPa: 17.5
4. BBR PAV: T_{min}
   Tempearautre at which S(t) = 300 Mpa: -28.4
   Temperature at which m = 0.300: -29.3

Figure 29. Superpave Asphalt Binder Grading Summary

Appendix B
Laboratory Performance Test Data

Table 7. Averaged Dynamic Modulus Test Results of Fiber Mixes

Temp. (°F)	Frequency (Hz)	Control Mix			Fort Fi Mix			Surface Tech Mix			Nycon Mix		
		Modulus (ksi)	SD	COV (%)	Modulus (ksi)	SD	COV (%)	Modulus (ksi)	SD	COV (%)	Modulus (ksi)	SD	COV (%)
40	25	2268	93.58	4.13	2241	122.83	5.48	2305	83.38	3.62	2342	209.8	8.96
40	10	2059	85.04	4.13	2052	105.12	5.12	2099	74.18	3.53	2141	197.3	9.22
40	5	1896	78.51	4.14	1905	100.08	5.25	1950	78.48	4.03	1948	165.7	8.50
40	1	1505	59.57	3.96	1551	85.23	5.50	1584	84.24	5.32	1605	155.9	9.72
40	0.5	1345	49.71	3.70	1399	80.97	5.79	1428	87.16	6.10	1403	127.0	9.05
40	0.1	979	37.15	3.80	1058	60.63	5.73	1073	77.29	7.20	1024	118.8	11.61
70	25	984	27.24	2.77	1057	51.43	4.87	1061	79.62	7.51	1084	110.3	10.18
70	10	795	16.56	2.08	874	43.67	5.00	875	67.68	7.74	881	93.1	10.56
70	5	665	14.74	2.22	742	37.15	5.00	744	64.69	8.69	746	80.5	10.78
70	1	402	12.38	3.08	468	21.89	4.67	470	55.03	11.71	465	62.4	13.41
70	0.5	320	11.75	3.67	379	17.95	4.74	379	52.33	13.79	373	57.3	15.38
70	0.1	168	7.18	4.28	204	10.41	5.12	200	41.73	20.87	201	43.5	21.66
100	25	266	8.72	3.28	316	11.68	3.69	311	43.64	14.03	307	46.0	14.99
100	10	190	7.01	3.70	226	6.53	2.89	220	37.85	17.19	218	37.9	17.37
100	5	138	5.65	4.09	165	4.61	2.79	160	32.59	20.37	158	31.0	19.60
100	1	60	2.96	4.93	73	2.60	3.57	70	17.81	25.38	71	18.4	25.79
100	0.5	41	2.23	5.37	51	2.00	3.92	49	13.06	26.72	50	13.8	27.36
100	0.1	20	5.64	27.80	22	0.66	2.94	22	5.37	24.69	23	6.0	26.00
130	25	77	8.58	11.21	98	8.94	9.10	93	8.02	8.67	88	13.0	14.75
130	10	49	5.33	10.91	59	13.91	23.48	56	7.42	13.13	51	10.1	19.64
130	5	37	7.25	19.51	43	5.06	11.88	37	5.08	13.58	34	7.0	20.38
130	1	16	3.71	23.91	18	1.76	9.85	16	1.37	8.76	16	6.0	38.15
130	0.5	11	2.68	24.48	13	1.16	8.97	11	0.69	6.06	13	2.2	17.55
130	0.1	6	1.31	22.57	7	0.34	4.58	6	0.27	4.22	7	1.0	13.26

Table 8. Multiple Comparisons of Fiber -reinforced Mixes for Dynamic Modulus at 70F and 1 Hz test by ANCOVA Analysis (p-value)

Mixes		(p-value) of E*
C	**F**	0.002*
	S	0.053
	N	0.095
F	**C**	0.002*
	S	0.959
	N	0.923
S	**C**	0.053
	F	0.959
	N	0.909
N	**C**	0.095
	F	0.923
	S	0.909

Note: C: Control mix, F: FORTA mix, N: NYCON mix and S: SURFACETECH mix
#*: means p-value is less than 0.05

Table 9. Flow Number Test Results of Fiber Mixes

Mixes		Flow Numbers	Avg. Flow Numbers	Standard Deviation	COV (%)
C	1	1534	1891	966.86	51.12
	2	1154			
	3	2986			
F	1	2823	2079	744.00	35.78
	2	2080			
	3	1335			
S	1	2442	2415	573.98	23.77
	2	2975			
	3	1828			
N	1	2050	2453	361.58	14.74
	2	2749			
	3	2560			

Note: C: Control mix, F: Forta Fi mix, N: Nycon mix and S: Surface Tech mix

Table 10. Multiple Comparisons of Fiber-reinforced Mixes for Flow Number Test by ANCOVA Analysis (p-value)

Mixes		**(p-value) of FN test**
C	**F**	0.803
	S	0.465
	N	0.399
F	**C**	0.803
	S	0.570
	N	0.478
S	**C**	0.465
	F	0.570
	N	0.927
N	**C**	0.399
	F	0.478
	S	0.927

Table 11. Multiple Comparisons of Fiber-reinforced Mixes for HWT Final Rut Depth by ANOVA Analysis (p-value)

Mixes		**(p-value) Of Rut Depth**
C	**F**	0.366
	N	0.064
	S	0.140
F	**C**	0.366
	N	0.202
	S	0.459
S	**C**	0.140
	F	0.459
	N	0.519
N	**C**	0.064
	F	0.202
	S	0.519

Table 12. Fracture Work Density for IDT Test at 68°F

Mixes		Fracture Work Density (psi)	Average (psi)	Standard Deviation (psi)	COV (%)
C	1	17.42	16.39	0.97	5.93
	2	16.26			
	3	15.49			
F	1	16.02	16.38	1.00	6.13
	2	15.60			
	3	17.51			
S	1	20.29	18.53	1.57	8.49
	2	18.05			
	3	17.26			
N	1	14.30	15.83	2.48	15.63
	2	18.69			
	3	14.51			

Table 13. Vertical Failure Deformation for IDT Test at 68°F

Mixes		Vertical Failure Deformation (inch)	Average (inch)	Standard Deviation (inch)	COV (%)
C	1	0.0739	0.0639	0.0088	13.75
	2	0.0596			
	3	0.0580			
F	1	0.0643	0.0651	0.0011	1.69
	2	0.0648			
	3	0.0663			
S	1	0.0700	0.0681	0.0037	5.43
	2	0.0704			
	3	0.0638			
N	1	0.0576	0.0663	0.0075	11.31
	2	0.0697			
	3	0.0714			

Table 14. IDT Strength for Mixes at 68°F

Mixes		IDT Strength (psi)	Average (psi)	Standard Deviation (psi)	COV (%)
C	1	339	273	58.79	21.53
	2	255			
	3	225			
F	1	304	284	18.44	6.49
	2	279			
	3	268			
S	1	297	295	11.70	3.96
	2	306			
	3	283			
N	1	241	274	61.89	22.59
	2	345			
	3	235			

Table 15. Multiple Comparisons of Fiber-reinforced Mixes for Fracture Work Density at Intermediate Temperature by ANCOVA Analysis (p-value)

Mixes		(p-value) of Fracture Work Density
C	**F**	0.759
	N	0.748
	S	0.129
F	**C**	0.759
	N	0.533
	S	0.219
S	**C**	0.748
	F	0.533
	N	0.079
N	**C**	0.129
	F	0.219
	S	0.079

Table 16. Multiple Comparisons of Fiber-reinforced Mixes for Vertical Failure Deformation at Intermediate Temperature by ANCOVA Analysis (p-value)

Mixes		(p-value) of Vertical Failure Deformation
C	F	0.567
	N	0.559
	S	0.397
F	C	0.567
	N	0.996
	S	0.792
S	C	0.559
	F	0.996
	N	0.783
N	C	0.397
	F	0.792
	S	0.783

Table 17. Multiple Comparisons of Fiber-reinforced Mixes for IDT Strength at Intermediate Temperature by ANCOVA Analysis (p-value)

Mixes		(p-value) of Failure Deformation
C	F	0.396
	N	0.847
	S	0.452
F	C	0.396
	N	0.494
	S	0.896
S	C	0.452
	F	0.896
	N	0.571
N	C	0.847
	F	0.494
	S	0.571

Table 18. Jc Test Results of Fiber Mixes

Mixes		Jc (psi)	Average Jc (psi)	Standard Deviation (psi)	COV (%)
C	1	2.428	2.041	0.487	23.84
	2	1.355			
	3	2.341			
F	1	3.534	2.058	1.098	53.34
	2	1.737			
	3	0.903			
S	1	2.970	2.120	0.674	31.78
	2	2.793			
	3	1.446			
N	1	2.311	2.463	0.804	32.63
	2	3.514			
	3	1.563			

Table 19. Multiple Comparisons of Fiber-reinforced Mixes Jc at Intermediate Temperature by ANCOVA Analysis (p-value)

Mixes		(p-value) of Jc
C	**F**	0.985
	S	0.574
	N	0.560
F	**C**	0.985
	S	0.725
	N	0.696
S	**C**	0.574
	F	0.725
	N	0.940
N	**C**	0.560
	F	0.696
	S	0.940

Table 20. Fracture Work Density for IDT Test at 14°F

Mixes		Fracture Work Density (psi)	Average (psi)	Standard Deviation (psi)	COV (%)
C	1	12.43	11.81	2.00	16.90
	2	9.58			
	3	13.42			
F	1	14.77	11.62	2.74	23.56
	2	10.32			
	3	9.79			
S	1	9.31	11.19	3.85	34.46
	2	8.63			
	3	15.62			
N	1	12.33	12.46	0.76	6.10
	2	13.28			
	3	11.78			

Table 21. Multiple Comparisons of Fiber-reinforced Mixes for Fracture Work Density at Low Temperature by ANCOVA Analysis (p-value)

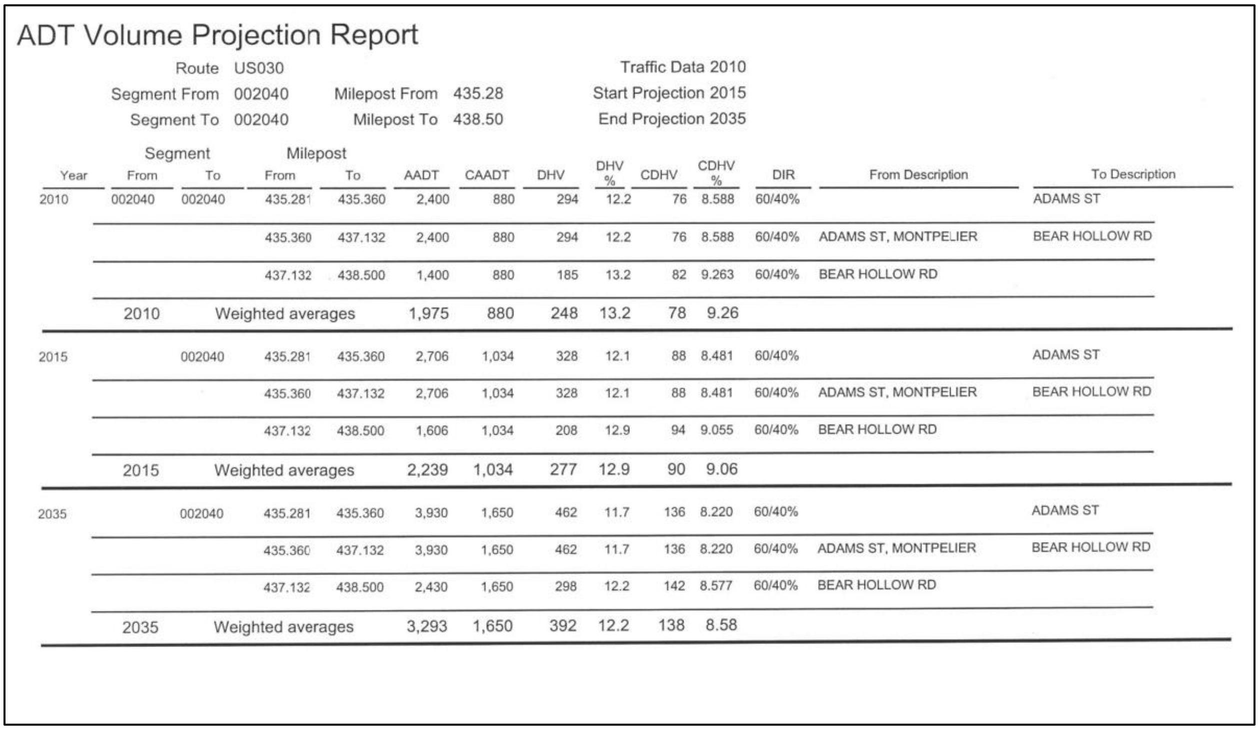
Mixes		(p-value) of Vertical Failure Deformation
C	**F**	0.646
	N	0.223
	S	0.734
F	**C**	0.646
	N	0.113
	S	0.905
N	**C**	0.223
	F	0.113
	S	0.134
S	**C**	0.734
	F	0.905
	N	0.134

Table 22. Multiple Comparisons of Fiber-reinforced Mixes for Creep Compliance at Low, Intermediate and High Time-Temperature Level by ANCOVA Analysis (p-value)

Mixes		(p-value) of Creep Compliance at Low Level	(p-value) of Creep Compliance at Intermediate Level	(p-value) of Creep Compliance at High Level
C	**F**	0.409	0.101	0.865
	N	0.773	0.172	0.255
	S	0.419	0.828	0.774
F	**C**	0.409	0.101	0.865
	N	0.577	0.735	0.306
	S	0.970	0.138	0.653
N	**C**	0.773	0.172	0.255
	F	0.577	0.735	0.306
	S	0.612	0.232	0.168
S	**C**	0.419	0.828	0.774
	F	0.970	0.138	0.653
	N	0.612	0.232	0.168

Appendix C
AASHTOWare Pavement ME Design Inputs

This Appendix presents data that were used for AASHTOWare Pavement ME Design. Some data, e.g. asphalt layer properties, were measured directly in the lab. However, other data, such as Traffic, Pavement structure, Layers properties, and project location were provided by the Idaho Transportation Department.

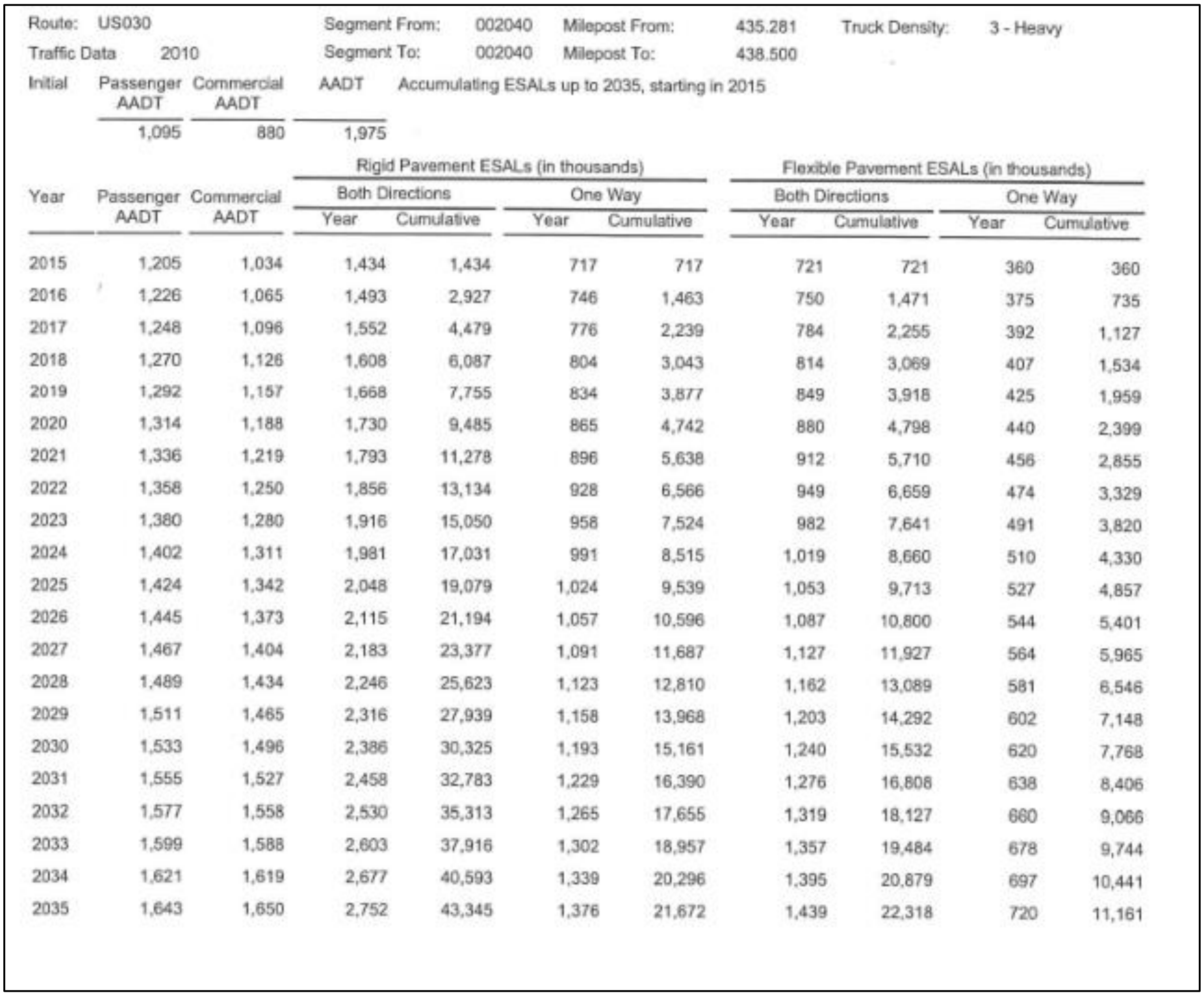


ADT Volume Projection Report

Route US030
Segment From 002040
Segment To 002040
Milepost From 435.28
Milepost To 438.50
Traffic Data 2010
Start Projection 2015
End Projection 2035

	Segment		Milepost										
Year	From	To	From	To	AADT	CAADT	DHV	DHV %	CDHV	CDHV %	DIR	From Description	To Description
2010	002040	002040	435.281	435.360	2,400	880	294	12.2	76	8.588	60/40%		ADAMS ST
			435.360	437.132	2,400	880	294	12.2	76	8.588	60/40%	ADAMS ST, MONTPELIER	BEAR HOLLOW RD
			437.132	438.500	1,400	880	185	13.2	82	9.263	60/40%	BEAR HOLLOW RD	
	2010	Weighted averages			1,975	880	248	13.2	78	9.26			
2015		002040	435.281	435.360	2,706	1,034	328	12.1	88	8.481	60/40%		ADAMS ST
			435.360	437.132	2,706	1,034	328	12.1	88	8.481	60/40%	ADAMS ST, MONTPELIER	BEAR HOLLOW RD
			437.132	438.500	1,606	1,034	208	12.9	94	9.055	60/40%	BEAR HOLLOW RD	
	2015	Weighted averages			2,239	1,034	277	12.9	90	9.06			
2035		002040	435.281	435.360	3,930	1,650	462	11.7	136	8.220	60/40%		ADAMS ST
			435.360	437.132	3,930	1,650	462	11.7	136	8.220	60/40%	ADAMS ST, MONTPELIER	BEAR HOLLOW RD
			437.132	438.500	2,430	1,650	298	12.2	142	8.577	60/40%	BEAR HOLLOW RD	
	2035	Weighted averages			3,293	1,650	392	12.2	138	8.58			

Figure 30. AADT Volume Projection Report



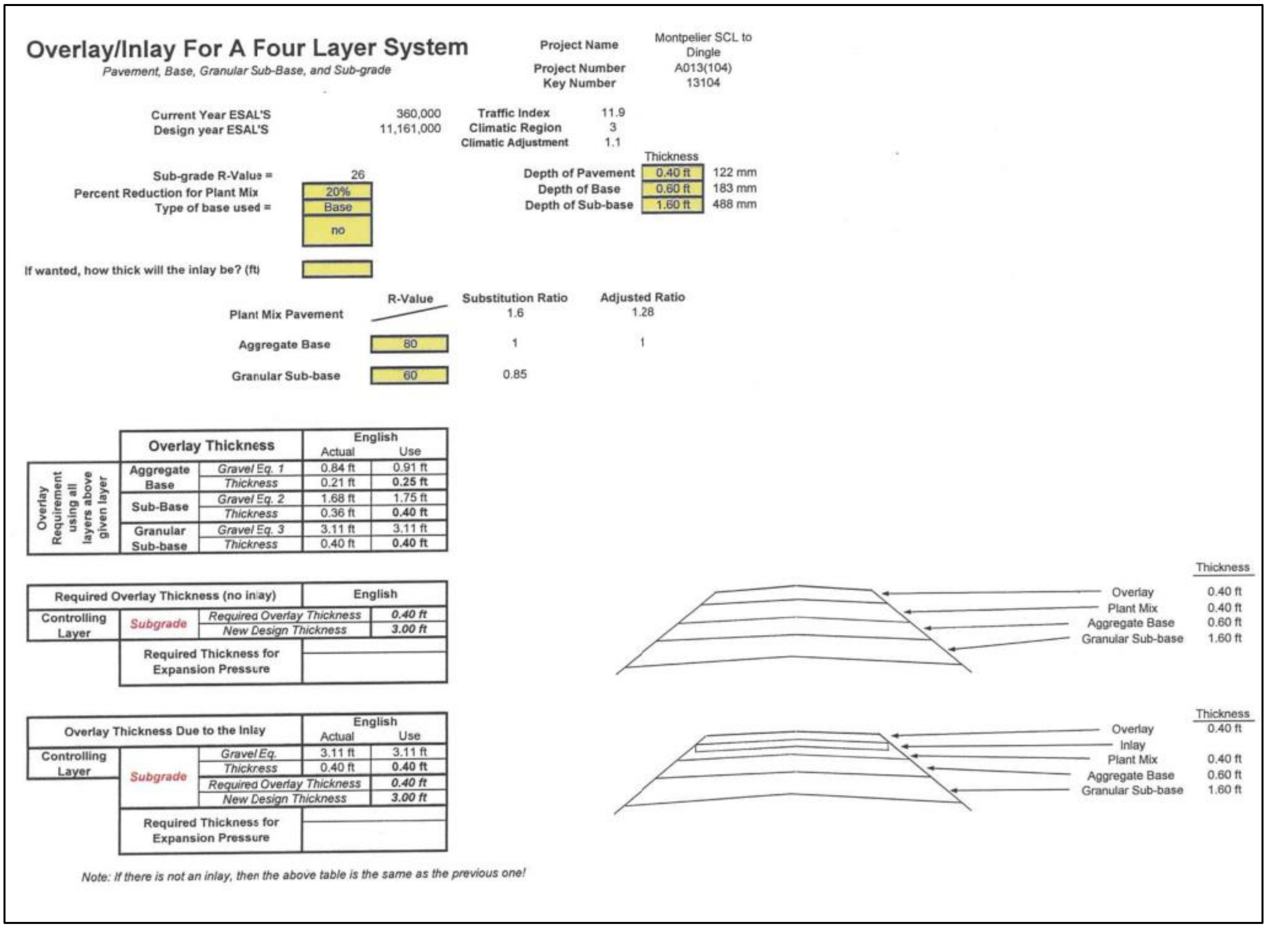
Route: US030 Segment From: 002040 Milepost From: 435.281 Truck Density: 3 - Heavy
Traffic Data 2010 Segment To: 002040 Milepost To: 438.500

Initial	Passenger AADT	Commercial AADT	AADT
	1,095	880	1,975

Accumulating ESALs up to 2035, starting in 2015

			Rigid Pavement ESALs (in thousands)				Flexible Pavement ESALs (in thousands)			
Year	Passenger AADT	Commercial AADT	Both Directions		One Way		Both Directions		One Way	
			Year	Cumulative	Year	Cumulative	Year	Cumulative	Year	Cumulative
2015	1,205	1,034	1,434	1,434	717	717	721	721	360	360
2016	1,226	1,065	1,493	2,927	746	1,463	750	1,471	375	735
2017	1,248	1,096	1,552	4,479	776	2,239	784	2,255	392	1,127
2018	1,270	1,126	1,608	6,087	804	3,043	814	3,069	407	1,534
2019	1,292	1,157	1,668	7,755	834	3,877	849	3,918	425	1,959
2020	1,314	1,188	1,730	9,485	865	4,742	880	4,798	440	2,399
2021	1,336	1,219	1,793	11,278	896	5,638	912	5,710	456	2,855
2022	1,358	1,250	1,856	13,134	928	6,566	949	6,659	474	3,329
2023	1,380	1,280	1,916	15,050	958	7,524	982	7,641	491	3,820
2024	1,402	1,311	1,981	17,031	991	8,515	1,019	8,660	510	4,330
2025	1,424	1,342	2,048	19,079	1,024	9,539	1,053	9,713	527	4,857
2026	1,445	1,373	2,115	21,194	1,057	10,596	1,087	10,800	544	5,401
2027	1,467	1,404	2,183	23,377	1,091	11,687	1,127	11,927	564	5,965
2028	1,489	1,434	2,246	25,623	1,123	12,810	1,162	13,089	581	6,546
2029	1,511	1,465	2,316	27,939	1,158	13,968	1,203	14,292	602	7,148
2030	1,533	1,496	2,386	30,325	1,193	15,161	1,240	15,532	620	7,768
2031	1,555	1,527	2,458	32,783	1,229	16,390	1,276	16,808	638	8,406
2032	1,577	1,558	2,530	35,313	1,265	17,655	1,319	18,127	660	9,066
2033	1,599	1,588	2,603	37,916	1,302	18,957	1,357	19,484	678	9,744
2034	1,621	1,619	2,677	40,593	1,339	20,296	1,395	20,879	697	10,441
2035	1,643	1,650	2,752	43,345	1,376	21,672	1,439	22,318	720	11,161

Figure 31. Projected Equivalent Single Axle Loading of the Project



Overlay/Inlay For A Four Layer System

Pavement, Base, Granular Sub-Base, and Sub-grade

Project Name Montpelier SCL to Dingle
Project Number A013(104)
Key Number 13104

Current Year ESAL'S 360,000
Design year ESAL'S 11,161,000

Traffic Index 11.9
Climatic Region 3
Climatic Adjustment 1.1

Sub-grade R-Value = 26
Percent Reduction for Plant Mix 20%
Type of base used = Base
no

If wanted, how thick will the inlay be? (ft)

	Thickness	
Depth of Pavement	0.40 ft	122 mm
Depth of Base	0.60 ft	183 mm
Depth of Sub-base	1.60 ft	488 mm

	R-Value	Substitution Ratio	Adjusted Ratio
Plant Mix Pavement		1.6	1.28
Aggregate Base	80	1	1
Granular Sub-base	60	0.85	

	Overlay Thickness		English	
			Actual	Use
Overlay Requirement using all layers above given layer	Aggregate Base	*Gravel Eq. 1*	0.84 ft	0.91 ft
		Thickness	0.21 ft	**0.25 ft**
	Sub-Base	*Gravel Eq. 2*	1.68 ft	1.75 ft
		Thickness	0.36 ft	**0.40 ft**
	Granular Sub-base	*Gravel Eq. 3*	3.11 ft	3.11 ft
		Thickness	0.40 ft	**0.40 ft**

Required Overlay Thickness (no inlay)			English
Controlling Layer	*Subgrade*	*Required Overlay Thickness*	***0.40 ft***
		New Design Thickness	***3.00 ft***
	Required Thickness for Expansion Pressure		

Overlay Thickness Due to the Inlay			English	
			Actual	Use
Controlling Layer	*Subgrade*	*Gravel Eq.*	3.11 ft	3.11 ft
		Thickness	0.40 ft	**0.40 ft**
		Required Overlay Thickness		***0.40 ft***
		New Design Thickness		***3.00 ft***
	Required Thickness for Expansion Pressure			

Note: If there is not an inlay, then the above table is the same as the previous one!

	Thickness
Overlay	0.40 ft
Plant Mix	0.40 ft
Aggregate Base	0.60 ft
Granular Sub-base	1.60 ft

	Thickness
Overlay	0.40 ft
Inlay	
Plant Mix	0.40 ft
Aggregate Base	0.60 ft
Granular Sub-base	1.60 ft

Figure 32. Pavement structure Design of the test sections

Table 23. Traffic Input Data for the Project

Initial Two-Way AADTT	1034
Number of Lanes in Design Direction	1
Percentage of Trucks in Design Direction (%)	61
Percentage of Trucks in Design Lane (%)	100

Table 24. Monthly Adjustment Factors (MAF) for North Mixes

	Vehicle Class									
	4	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
January	0.261	0.776	0.844	0.632	0.457	1.005	0.886	0.632	1.333	1.104
February	0.417	0.792	0.724	0.632	0.519	1.078	0.886	0.632	1.333	1.254
March	0.313	0.857	0.724	0.632	0.561	1.125	0.818	0.632	1.333	1.045
April	0.417	0.890	0.784	0.632	0.685	1.078	0.852	1.263	1.333	0.955
May	0.470	0.976	0.965	0.947	0.872	1.059	1.023	0.632	1.333	0.716
June	1.096	0.586	0.724	0.947	0.830	0.447	0.648	1.263	0.444	0.388
July	2.922	1.389	1.749	2.526	1.889	1.041	1.295	1.895	0.889	0.896
August	2.452	1.291	2.111	2.211	1.806	1.064	1.159	1.895	0.889	0.896
September	2.191	1.335	1.508	1.579	1.599	1.157	1.193	1.263	0.444	1.015
October	0.626	1.156	0.603	0.316	1.287	1.040	1.261	1.263	0.889	1.284
November	0.470	1.052	0.603	0.316	0.893	1.036	1.023	0.632	0.889	1.194
December	0.365	0.901	0.663	0.632	0.602	0.870	0.955	0.000	0.889	1.254

Table 25. Vehicle Class Distribution for North Mixes

	Vehicle Class									
	4	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
AADTT Distribution by Vehicle Class (%)	2.15	21.28	1.90	0.36	5.51	61.01	3.43	0.19	0.27	3.91

Table 26. Number of Axles per Truck Class for North Mixes

Vehicle Class	Axle Type			
	Single	Tandem	Tridem	Quad
4	1.59	0.34	0.00	0.00
5	2.00	0.00	0.00	0.00
6	1.00	1.00	0.00	0.00
7	1.00	0.22	0.83	0.10
8	2.52	0.60	0.00	0.00
9	1.25	1.87	0.00	0.00
10	1.03	0.85	0.95	0.26
11	4.21	0.29	0.01	0.00
12	3.24	1.16	0.07	0.01
13	3.32	1.79	0.14	0.02

Table 27. Complex Shear Modulus and Phase Angle of PG 70-28 Binder Used

PG 70-28		
Temp. (°F)	G* (psi)	Delta (°)
40	1,445.15	58.22
70	273.56	59.61
100	16.11	61.85
130	1.94	67.88

Table 28. Tensile Strength at 14 F (psi)

Control	730.14
Forta	705.70
Surface Tech	689.59
Nycon	726.76

Table 29. Avg. Creep Compliance of Control Mix (1/psi)

time (S)	-4°F	14°F	32°F
1	2.34292E-07	3.11519E-07	4.64867E-07
2	2.4551E-07	3.28663E-07	5.18723E-07
5	2.57697E-07	3.56704E-07	5.98653E-07
10	2.68573E-07	3.83264E-07	6.90494E-07
20	2.81021E-07	4.14287E-07	8.11314E-07
50	2.99141E-07	4.64419E-07	1.03319E-06
100	3.18799E-07	4.97916E-07	1.25197E-06

Table 30. Avg. Creep Compliance of Forta Fi Mix (1/psi)

time (S)	-4°F	14°F	32°F
1	2.24E-07	2.64E-07	4.08E-07
2	2.25E-07	2.74E-07	4.37E-07
5	2.45E-07	2.98E-07	5.06E-07
10	2.52E-07	3.17E-07	5.84E-07
20	2.62E-07	3.34E-07	6.91E-07
50	2.84E-07	3.62E-07	8.44E-07
100	2.99E-07	3.85E-07	1.03E-06

Table 31. Avg. Creep Compliance of Surface Tech Mix (1/psi)

time (S)	-4°F	14°F	32°F
1	2.19E-07	3.04E-07	4.8E-07
2	2.31E-07	3.19E-07	5.37E-07
5	2.43E-07	3.45E-07	6.38E-07
10	2.55E-07	3.69E-07	7.41E-07
20	2.66E-07	4.14E-07	8.7E-07
50	2.81E-07	4.64E-07	1.11E-06
100	2.93E-07	5.34E-07	1.36E-06

Table 32. Avg. Creep Compliance of Nycon Mix (1/psi)

time (S)	-4°F	14°F	32°F
1	2.37E-07	3.09E-07	4.6E-07
2	2.47E-07	3.2E-07	5.11E-07
5	2.58E-07	3.44E-07	5.82E-07
10	2.71E-07	3.72E-07	6.62E-07
20	2.79E-07	4.07E-07	7.74E-07
50	3.01E-07	4.52E-07	9.67E-07
100	3.16E-07	5.08E-07	1.17E-06