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Evaluation of impact of fiber type and dosage rate on volumetrics and laboratory performance of asphalt mixtures

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EVALUATION OF IMPACT OF FIBER TYPE AND DOSAGE RATE ON VOLUMETRICS AND LABORATORY PERFORMANCE OF ASPHALT MIXTURES

by

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Dedications

I would like to dedicate this work to my father, my mother, my brother and both my sisters and their families. To everyone who was part of this journey. Thank you.

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Abstract

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2019-2020
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The purpose of this study is to evaluate the impact of fiber types, binder content, and dosage rates on the volumetric properties and laboratory performance of asphalt mixtures. One asphalt mixture (control) and four fiber types (Fiberglass, Basalt, Carbon, and Polyolefin/Aramid) were used to evaluate the impact of fiber types and dosage rates. Two mixing procedures for introducing fibers into asphalt mixtures were also evaluated: dry and proportional dispersion methods. To evaluate the impact of fiber types, 0.16% by total mix weight was used. Rutting, cracking, and durability performance tests were evaluated. Furthermore, using 0.15% and 0.3% fiber dosage rates, a novel experimental methodology was developed and implemented consisting of a volumetric mixture design and performance testing—(IDEAL-CT) and (APA)—to isolate the effects of fiber types and dosage rates from the effect of binder content. Results showed that 0.16% and 0.15% dosage rate had little to no impact on optimum binder content; whereas 0.3% dosage rate required an increase in binder content to meet volumetric requirements. Performance testing showed that 0.16% and 0.15% (regardless of fiber type) had little to no impact on cracking and rutting performance. All fiber types at 0.16% fiber dosage improved mixtures' durability. Using 0.3% dosage rate, only carbon fiber improved cracking performance without the use of additional binder.

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Chapter 1

Introduction

Background

Flexible pavements are commonly used for the construction of roadways and airports due to their cost effectiveness, recyclability, driving comfort, and low noise characteristics (Xiong et al., 2015). The estimated life of an asphalt pavement structure can be up to 20 years before the need for major rehabilitation or replacement of the asphalt pavement layer. In general, several factors influence the service life (or performance) of flexible pavements, and in particular, asphalt layers. These factors can be grouped into three classes: materials, traffic, and environment. For instance, the asphalt pavement layer is typically composed of high-quality aggregates and asphalt binders that are designed to properly resist various pavement distresses such as rutting and cracking. High traffic volumes, increased tire pressures, and freeze-thaw cycles are some examples of traffic and environmental factors that influence the performance of flexible pavements. In recent years, demand for long-lasting, high-performing flexible pavements and materials have increased. This is due to the limited maintenance budgets managed by State Departments of Transportation (State DOTs) and the condition of the transportation infrastructure in the nation; which was ranked as D+ (poor) according to the American Society of Civil Engineers (ASCE) (2). One potential approach for extending the service life of flexible pavements is incorporating performance enhancing additives such as fibers into the design of HMA.

Several research studies were conducted to evaluate the potential of using fiber additives to enhance the performance of HMA mixtures. (Kadolph et al., 2002) defined fibers used to reinforce asphalt mixtures as a natural or synthetic material that has a high length to width ratio. The addition of fibers into asphalt mixtures serves as a three-dimensional secondary reinforcement due to their adhesion with asphalt binders and the ability to interlock with aggregates. This in turn can strengthen asphalt mixtures and enhance their performance

Problem Statement

Researchers have conducted extensive studies to enhance mechanical and engineering properties of fiber-reinforced asphalt mixtures. Fiber types, dosage rates and fiber lengths were studied by researchers, agencies, and state DOTs on fiber-reinforced projects. However, the following points have not been considered in previous fiber-related studies:

- Previous studies of fiber-reinforced asphalts used conventional mixing methods to introduce fibers into the mixtures. Mixing methods that would result in minimum clumping and reduce changes in volumetrics have not been studied.
- Most studies did not account for mix design requirements (e.g. air void content%, Voids in Mineral Aggregate (VMA%), etc.) of the prepared fiber-reinforced asphalt mixtures.

Therefore, additional research should be conducted to extend the evaluation techniques of fiber-reinforcement. In addition, different compaction levels of fiber-reinforced asphalt mixtures representative of the level of traffic subjected on roadways or airfields should be considered.

Research Hypothesis

- A new mixing method can be followed to successfully produce minimum fiber clumping and dispersion variability when producing fiber-reinforced asphalt mixtures.
- A design approach can be successfully developed to evaluate the impact of fibers on laboratory asphalt mixture performance using rutting measures (i.e., APA rut depth and dynamic modulus |E*| at high temperatures), mix durability measurement (i.e. Cantabro durability), and cracking measures (i.e., cracking tolerance index (CT_{index})).

Significance of Study

This study is conducted to evaluate the impact of fibers types, fiber dosage rates and binder content on fiber-reinforced mix volumetric properties and laboratory performance, in terms of the rutting, durability, and cracking. The fiber-reinforced asphalt mixture is designed using Superpave mix design and performance tests specifications. If a new design/performance approach is found to be successful, the following benefits will be offered to Department of Defense (DoD):

- Improved service life of airfield pavements,
- Updated mixing method of fiber-reinforced asphalt mixtures,

- Updates to current specifications related to fiber-reinforced asphalt mixtures,
- Extension of the construction season: Fiber-reinforced asphalt pavement is possible in relatively cold regions,
- Extension of the pavement life cycle,
- Environmental and economic benefits such as less rehabilitation by enhancing pavement performance.

Goal & Objectives

The goal of this study was to evaluate the impact of mixing methods of fibers on the design and performance of asphalt mixtures. The study also aimed to evaluate the impact of fiber types, binder content, and dosage rates on volumetric properties and laboratory performance of asphalt mixtures. Specifically, parametric laboratory cracking, durability, and rutting performance testing were used to isolate the effects of fiber types and dosage rates from binder content on laboratory asphalt mixtures. The following objectives were established to accomplish the overall goal of this study:

- Conduct asphalt mix design using recommended and increased fiber dosage rates and different mixing methods.
- Assess the laboratory performance testing of mixtures using different fiber types and dosage rates and identify the impact of fiber types and dosage rates on mix design and performance.

- Compare rutting, durability and cracking performances of fiber-reinforced asphalt mixtures prepared at optimum binder contents and reduced binder content selecting four fiber types and two fiber dosage rates.

Research Approach

The approach utilized to meet the overall goal of this study consisted of the following tasks:

Task 1: Conduct a comprehensive literature review pertaining to fiber-reinforced asphalt mixtures by reviewing domestic and international previous fiber-related studies. This task will present the currently available general asphalt mix design procedures and laboratory mixing procedures for fiber-reinforced asphalt mixtures. In addition, the impact of fibers on asphalt mixtures' design properties, and the laboratory and field performance of fiber-reinforced asphalt mixtures will be assessed.

Task 2: Identify and select representative materials that will be used in preparing mixtures for the laboratory mix design of fiber-reinforced asphalt mixtures.

Task 3: Develop an experimental program that will:

- Determine the optimum method of introducing fibers into fiber-reinforced asphalt mixtures,
- Determine the impact of manufacturers' fiber dosage rate on asphalt mixtures' volumetric properties,

- Evaluate the laboratory performance of fiber-reinforced asphalt mixtures at the recommended dosage rate,
- Develop a design approach to isolate the effect of asphalt binder on laboratory performance of fiber-reinforced asphalt mixtures,
- Evaluate the impact of different fiber dosage rates on volumetric properties and laboratory performance of mixtures.

Task 4: Perform a statistical analysis to evaluate the impact of binder content, fiber types and dosage rates on the performance of fiber-reinforced asphalt mixtures.

Task 5: Develop recommendations for future studies.

Chapter 2

Literature Review

Introduction

In recent years, interest in fiber reinforcement of dense graded asphalt mixtures has increased with the goal of enhancing pavement performance. Fiber is a material that has a high length to width ratio (Kadolph et al., 2002). Fibers are mainly used in the manufacture of other materials and they have proven the ability to make materials stronger and obtain higher performance (Lavasani et al., 2015). Fibers are manufactured materials that can be broadly classified into three types depending on their base material: (i) natural fibers such as basalt, lignin, wood, minerals; (ii) semi-synthetic fibers like cellulose and rayon; and (iii) synthetic fibers such as metallic, carbon, fiberglass, aramid, silicon, polymer fibers, etc. Fibers are used in production of fiber-reinforced asphalt mixtures in order to enhance the overall performance of asphalt pavement (Lavasani et al., 2015; Mallick et al., 2017; Mahrez et al., 2010; Chen et al., 2009).

In this chapter, results of a comprehensive literature review for fiber-reinforced asphalt mixtures are provided. The following subsections presents a discussion about the use of fibers in asphalt mixtures, design of fiber-reinforced asphalt mixtures, and laboratory performance testing of fiber-reinforced asphalt mixtures.

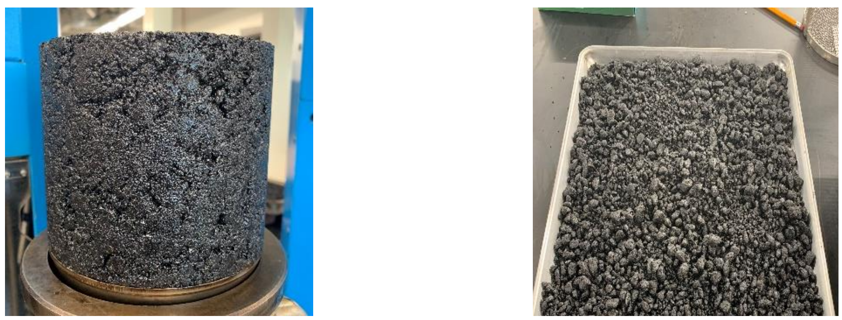
General Asphalt Mix Design Procedure

Superpave practice's gyratory compactors are being utilized widely due to the accurate compaction effort simulations in the laboratory. The Superpave mix design focuses on two main pavement distresses: permanent deformation caused by inadequate shear strength in the asphalt mix and low temperature cracking, which can be experienced when the tensile stress exceeds the tensile strength during asphalt pavement shrinkage. Asphalt mix design is the process of determining the optimum aggregates and asphalt binder combinations for specific asphalt mixtures (Asphalt Institute, 1997). Asphalt pavement mix design uses the physical (e.g. mass of specimen) and volumetric (e.g. volume of specimen) properties of the material. Both properties are utilized to convert weight to volume and vice versa, which have a significant relationship on the performance of asphalt mixtures (Mallick et al., 2017). Both heated aggregates and asphalt binder are placed in a mixer and mixed until aggregates become properly coated with asphalt binder. Figure 1 presents a graded aggregate and the asphalt binder prior to mixing.

Mixed samples are then placed in an oven and experience different aging according to (AASHTO R30). After aging, compacted and loose samples are both used to obtain the Bulk Specific Gravity of Asphalt Specimen (G_{mb}) (AASHTO T166 or AASHTO T331) and Maximum Specific Gravity of Asphalt Sample (G_{mm}) (AASHTO T 209 or ASTM D6857). Both compacted specimen and loose sample pictures can be seen in Figure 2.

(a) Asphalt binder (b) Graded aggregate blend

Figure 1. Materials Used in Asphalt Mixture' Sample Preparation



(a) Compacted Specimen (b) Loose Sample

Figure 2. Laboratory Asphalt Mixture Samples

The compacted and loose sample both have mass and volume that are directly correlated to mix design. Using G_{mb}, G_{mm} and G_{sb} (bulk specific gravity of aggregates) which was obtained previously, both Air Voids Content (AVC%) and Voids in Mineral Aggregate (VMA%) are calculated using equations 1 & 2. Several researches developed general mix design procedures that presented various AVC% and VMA% requirements. These procedures are discussed below.

$$Bulk\ Specific\ Gravity\ (Gmb) = \frac{Mass\ of\ Dry\ Sample}{SSD\ Specimen\ Mass - Specimen\ Mass\ Under\ Water} \quad (1)$$

$$Maximum\ Specific\ Gravity\ (Gmm) = \frac{Mass\ of\ Dry\ Sample}{Mass\ of\ Sample\ Under\ Water} \quad (2)$$

$$Air\ Void\ Content\ (AVC\%) = \frac{Gmm - Gmb}{Gmm} * 100 \quad (3)$$

$$Voids\ in\ Mineral\ Aggregates\ (VMA\%) = 1 - \frac{Gmb * (1 - Binder\ Content\ \%)}{Gsb} \quad (4)$$

Where:

SSD: Saturated Surface Dry

G_{sb}: Bulk Specific Gravity of Aggregates

Laboratory Mixing Procedures for Fiber-Reinforced Asphalt Mixtures

In literature, several different mixing procedures have been utilized to introduce fibers into the asphalt mixtures. Temperature and time are essential aspects related to field and laboratory asphalt mixing to ensure proper coating between aggregates and asphalt binder. Mixing procedure is even more critical for fiber-reinforced asphalt mixtures because it ensures adequate fiber distribution within the asphalt mixture and minimizes issues related to fiber-reinforcement (e.g. clumping and mix design requirements). Currently, no to limited studies compared different mixing procedures and stated the optimal method to introduce fibers into fiber-reinforced asphalt mixtures (Abtahi et al., 2013). The optimal mixing procedure will perform minimum clumping and more fiber distribution within the mixture (Tang et al., 2006). Methods of introducing fibers during the mixing process are described in the following subsections.

Dry mixing method. The dry mixing method is one of the most common methods used to introduce fibers during asphalt laboratory mixing procedures. This method consists of:

1. Aggregate and binder are heated between 10°C and 20°C above mixing temperature due to the fact that the addition of fibers will consume some time before beginning of mixing process.

2. Adding preheated aggregates and the full fiber dosage (not heated) into the mixing bowl.

3. Mix aggregate/fiber blend for specified time.

4. Asphalt binder is added to the blend.

5. Mix for additional time to obtain fiber-reinforced asphalt mixture.

Various studies used the dry mixing method to introduce fibers into asphalt mixture. (Mahrez et al., 2010) used dry mixing method to evaluate glass fiber used in a Stone Mastic Asphalt (SMA) graded blend. SMA is an aggregate blend with high coarse aggregate content and was chosen due to its suitability for heavy traffic roads and since aggregate have a majority in the blend, fibers with high dosage rates would have space within the mixture. In this study, glass fibers were blended with preheated aggregate and filler material before 80/100 penetration grade asphalt binder was added. The filler content was 2% by total weight of mixture and the mixing temperature for this test was reported to be 160°C and compaction temperature was reported to be 140°C.

Chen et al., 2009 also used the dry method to evaluate polyester, polyacrylonitrile, lignin, and asbestos fibers. Figure 3 presents pictures for each fiber evaluated by (Chen et al., 2009). Samples preparation followed the following procedure: fibers were mixed with aggregates for a period between 15 and 20 seconds, the blend was then heated to 175°C (10°C-20°C higher than mixing temperature (155°C)). Asphalt binder was heated to 160°C and added to the blend and mixed until obtaining a well coated and evenly distributed mixture. Finally, the asphalt mixtures were placed in a steel frame and compacted at 75 blows at a compaction temperature of 145°C to obtain Marshall specimens with measurements of 101.6 mm diameter and 63.5 mm height.

(a) Polyester Fiber

(b) Polyacrylonitrile Fiber

(c) Lignin Fiber

(d) Asbestos Fiber

Figure 3. Fibers used by (Chen et al., 2009)

Ye and Wu et al., 2009 also used the dry mixing method to evaluate cellulose fiber, polyester fiber and mineral fiber and their effect on dynamic response and fatigue properties of asphalt mixtures. In this study, fibers were blended with heated aggregates for about 30 seconds before adding the asphalt binders and mineral filler. (Guan et al., 2014) investigated the usability of brucite fiber in asphalt mixtures and compared it with the lignin fiber, basalt fiber and polyester fiber. Dry mixing method was also used in this study whereas fibers were blended with heated aggregate and filler material before the addition of asphalt binder.

Another study was performed by (Tapkin et al., 2009) were he used the dry method to evaluate Marshall stability, fatigue life and rutting resistance of Polypropylene-reinforced samples. In sample preparation, prior to the addition of asphalt binder to preheated aggregates, fibers were added to aggregates and mixed for 10 seconds. (Tapkin et al., 2009) reported that the mixing time can be increased until satisfactory samples are obtained.

Hejazi et al., 2008 also used the dry method on four fibers (glass, nylon 6.6, polypropylene, and polyester) to introduce two simple models for predicting fiber-reinforced behavior during longitudinal loads. During sample preparation, aggregates were heated for 16 hours at 170^{o}C, aggregates were blended with fibers and then asphalt binder (heated to 132^{o}C) was added. The mixing process began until proper aggregates coating with asphalt binder were obtained. More research studies in literature studied the effect of fibers on asphalt mixtures using the dry method (Mondschein et al., 2011; Modarres et al., 2014; Moghaddam et al., 2015; Soltani et al., 2015; Usman et al., 2016; Fakhri et al., 2017; Aliha et al., 2017; Dehghan et al., 2017; Klinsky et al., 2018; Shanbara et al., 2018)

Wet mixing method. The wet mixing method is also a common method utilized for introducing fibers into fiber-reinforced asphalt mixtures. The difference between dry and wet mixing method is instead of adding and mixing fibers along with aggregates before the addition of asphalt binder, fibers are mixed with the asphalt binder before adding the asphalt/fiber blend to heated aggregates.

Remadevi et al., 2014 utilized a wet mixing method to evaluate Polypropylene fiber. In sample preparation, fibers were added to heated asphalt binder at 160°C and stirred for five minutes. The asphalt/fiber blend was then added to aggregates which were heated also at 160°C and the full blend then was mixed for ten minutes to produce homogeneous specimen. Figure 4 presents the asphalt binder mixed with the Polypropylene fiber.

(a) Polypropylene Fiber Mixed with Asphalt Binder

(b) Adding the Blend to the Heated Aggregates

Figure 4. Sample preparation by (Remadevi et al., 2014)

Abtahi et al., 2013 evaluated both dry and wet mixing methods and used both methods to evaluate the addition of Polypropylene and glass fiber into asphalt mixtures. Sample preparation for Polypropylene was utilized using a wet mixing method and sample preparation for glass fiber was utilized using a dry mixing method. The wet mixing method was utilized for Polypropylene because that the melting temperature for Polypropylene is lower than the mixing temperature, this will lead to melting the fiber in asphalt binder and will result in changing the visco-elastic properties of asphalt binder and result a homogenous fiber distribution within the asphalt mixture. More recently, (Khabiri et al., 2016) also used both wet and dry mixing methods to evaluate which method was more efficient to evaluate both carbon and glass fibers. After using both approaches, Khabiri et al., 2016 reported that by visual comparison, the dry method resulted a better distribution within the asphalt mixture. The dry method was also more practical to use when fiber-reinforcing the asphalt mixtures. This is due to the fact that the dry mixing method performed better fiber distribution within the asphalt mixture. Better fiber distribution will assist the fiber-reinforced asphalt mixtures and clumping or not having a good fiber distribution will cause a reduction in performance.

Other mixing methods. Other studies used mixing methods different from wet and dry mixing methods to evaluate the addition of fibers into asphalt mixtures, these studies utilized these methods depending on the material and fibers used in their studies.

For instance, Guo et al., 2015 utilized a mixing method that contained wet mixing method and an additional procedure to introduce the fiber into the asphalt mixtures. This study evaluated the addition of diatomite powder and glass fibers into the asphalt mixture. For the addition of diatomite, wet mixing method was used where diatomite powder and asphalt binder were both heated at 135°C for four hours, both heated diatomite and asphalt binder were then placed in a speed shear mixer at a speed of 600 rounds/min. It is noted that this speed mixer was chosen mainly because using a low mixing speed made it difficult to perform an even dispersion of diatomite in the asphalt binder. The speed mixing process was performed for 15 minutes. It was also noted that diatomite particles were denser than the asphalt binder and settled during longer binder placement times. A second blending should be performed when modified asphalt binder was added prior to mixing. For asphalt specimen preparation, aggregates were heated at 170°C and placed in a mixing bowl, modified asphalt binder was added to the mixing bowl and both modified binder and aggregates were mixed for 90 seconds. The full glass fiber portion was then added to the mixture and mixed for another 90 seconds. Mineral filler was finally added, and an additional mixing process was performed for 90 seconds. (Guo et al., 2015) reported that the mixing time should not exceed six minutes to prevent binder aging.

A mixing method was proposed by Forta-Fi© to introduce the aramid and polyolefin fibers into the asphalt mixture. The entire laboratory sample preparation procedure for polyolefin-aramid (PFA) reinforced asphalt is provided in the literature (Forta, 2019). The aramid fiber portion which was weighted and pre-measured by the manufacture should be split into two equal portions and the aggregate blend is split into three equal portions. The mixing process begins by first placing one third of the preheated aggregate into the preheated mixing bowl. The first half portion of aramid fiber is added into the mixing bowl. The second third of the aggregate is then added followed by the second half of the aramid fibers. The remaining aggregate will be added along with asphalt binder. After the binder is added to the blend, full polyolefin fibers will follow the asphalt binder. Polyolefin fiber should melt within the binder due to having a melting temperature lower than mixing temperature.

Impact of Fibers on Asphalt Mixtures' Mix Design

Mix design requirements. Asphalt mix design is utilized as a laboratory procedure that uses several critical tests to make key characterizations of each trial asphalt blend to determine the optimum combination between aggregates and asphalt binder (Asphalt Institute, 2001; Roberts et al., 1991). Mix design requirements may be affected by the addition of new materials such as fibers into the asphalt mixture. More specifically, asphalt mix design requirements can be affected by either fiber dosage or fiber type.

It was found that mix design requirements were affected when Mahrez et al., 2010 evaluated different dosages of glass fiber (0.1%, 0.2%, 0.3% and 0.4% by total mix weight) in SMA blend and 80/100 penetration grade asphalt binder. Mahrez et al., 2010 reported that mix design requirements changed with the variation of fiber dosage. Unreinforced samples had an optimum binder content of 5.2% and for fiber dosages 0.1%, 0.2%, 0.3% and 0.4%, the study reported an increase of 0.1%, 0.2%, 0.5% and 0.6% in optimum binder content, respectively. Similar observations were made by Taherkhani et al., 2016 while evaluating effect of adding Nylon fibers and nanoclay to asphalt mixtures using the Marshall design method. Taherkhani et al., 2016 conducted asphalt mix designs on mixtures that contained no fiber and mixes with fiber dosages of 0.1%, 0.2%, 0.3% and 0.4% by percentage of total mix weight. The researchers found that optimum binder content increased when fibers were introduced to the asphalt mixtures. Binder content increased by 0.1%, 0.2%, 0.3%, and 0.4%, depending on fiber dosage rate. (Cleven et al., 2000) evaluated the use of carbon fibers in SMA mixtures and reported similar increases in binder contents due to fiber dosage. (Cleven et al., 2000) also reported that clumping issues were encountered during the mixing process of carbon fibers. The issue was minimized by increasing the mixing temperature and duration.

(Li et al., 2020) experienced change in optimum binder content when evaluating basalt fiber. In this study, two asphalt binder types were used (AC-13 and AC-20) to evaluate low-temperature cracking of fiber-reinforced asphalt mixtures. Fiber contents used in this study were reported to be 0.0% (control), 0.2%, 0.3%, 0.4%, and 0.5% by total weight of mixture. (Li et al., 2020) reported that the increase of fiber content caused increased air void content, which required increased binder content to meet required volumetric requirements. Similar findings in other studies are summarized in Table 1.

Table 1

Studies which required an increase in binder content as fiber content was increased

Study	Fiber Type tested	Mix Type	Mixing Process
Guan et al., 2014	Brucite Fiber	Marshall	Dry
Wu and Ye et al., 2008	Polyester Fiber	Dense graded	Fibers added slowly to mix for 2 hours
Kumar et al., 2016	Basalt and Cellulose fibers	SMA	Not mentioned

Park et al., 2015 utilized a unique approach to evaluate the impact of fibers on asphalt laboratory performance. The binder content was kept constant for the control and fiber-reinforced specimens while the fiber dosages and shapes of steel fiber were varied. Fiber dosages used for this study were 0.5%, 1.0% and 1.5% of fibers by volume of total mix. Park et al., 2015 reported that binder content should be increased for every increase in fiber dosage but maintained the same binder content for all fiber dosages. The reason behind maintaining the same binder content was to evaluate reinforcing effect of fibers and to focus mainly on the effect of fibers in mixtures. They also reported that if binder contents were adjusted, then the fiber reinforcement effects from the addition of fiber could not be distinguished from the effects of extra binder in asphalt mixture. The acceptable air void level was between 3% and 8%, whereas original mix design air voids was supposed to be (3.5% ± 0.5%). The change in fiber type also required changes in mix design requirements as reported by (Ye and Wu et al., 2009) while evaluating cellulose fiber, polyester fiber and mineral fiber and their effect on dynamic response and fatigue properties of asphalt mixtures. Fiber dosages of 0.3% (for cellulose fiber), 0.3% (for polyester fiber) and 0.4% (for mineral fiber) by the total weight of asphalt mixture were evaluated in this study. Optimum binder content for mixtures without fiber reinforcement was 4.8%. For asphalt mixtures containing cellulose fiber, polyester fiber and mineral fiber, optimum binder contents were reported to be 5.1%, 5.0% and 4.9%, respectively. Air void contents for all specimens were controlled at 3.0% by total volume of compacted asphalt specimens.

Clumping. Clumping is also one of the most common issues related to fiber-reinforcement asphalt mixtures. (Karleskint et al., 2012) identified clumping as a behavior of an individual's grouping close to each other. In fiber-reinforced asphalt mixtures, minimum clumping and homogenous distribution is required within the mixture mainly due to the fact that clumping will weaken the asphalt mixture and reduce the value of adding fibers into the asphalt mixture. Previous studies faced the issue of clumping while introducing fibers into fiber-reinforced asphalt mixtures. Dry mixing methods resulted in least amount of clumping. (Park et al., 2015) evaluated different dosages (i.e. 0.5%, 1.0% and 1.5% of fibers by volume of total mix) and different shapes of steel fibers. (Park et al., 2015) reported that 1.5% fiber dosage resulted in the most clumping for these fiber dosages, thus, additional mixing time was required to reduce clumping phenomenon. In another study, Moghadas Nejad et al., 2014 used different mixing blades to utilize addition of carbon fiber into the asphalt mixtures. Different fiber contents (i.e. 0.02%, 0.025% and 0.03% by weight of mixture) and fiber lengths (1 cm, 2 cm and 3 cm) were also evaluated to obtain optimum fiber dosage and length. Figure 5 presents mixing blades used in their study to evaluate carbon fiber reinforcement. Moghadas Nejad et al., 2014 reported that blade (e) resulted in minimum clumping among all mixing blades used in the study.

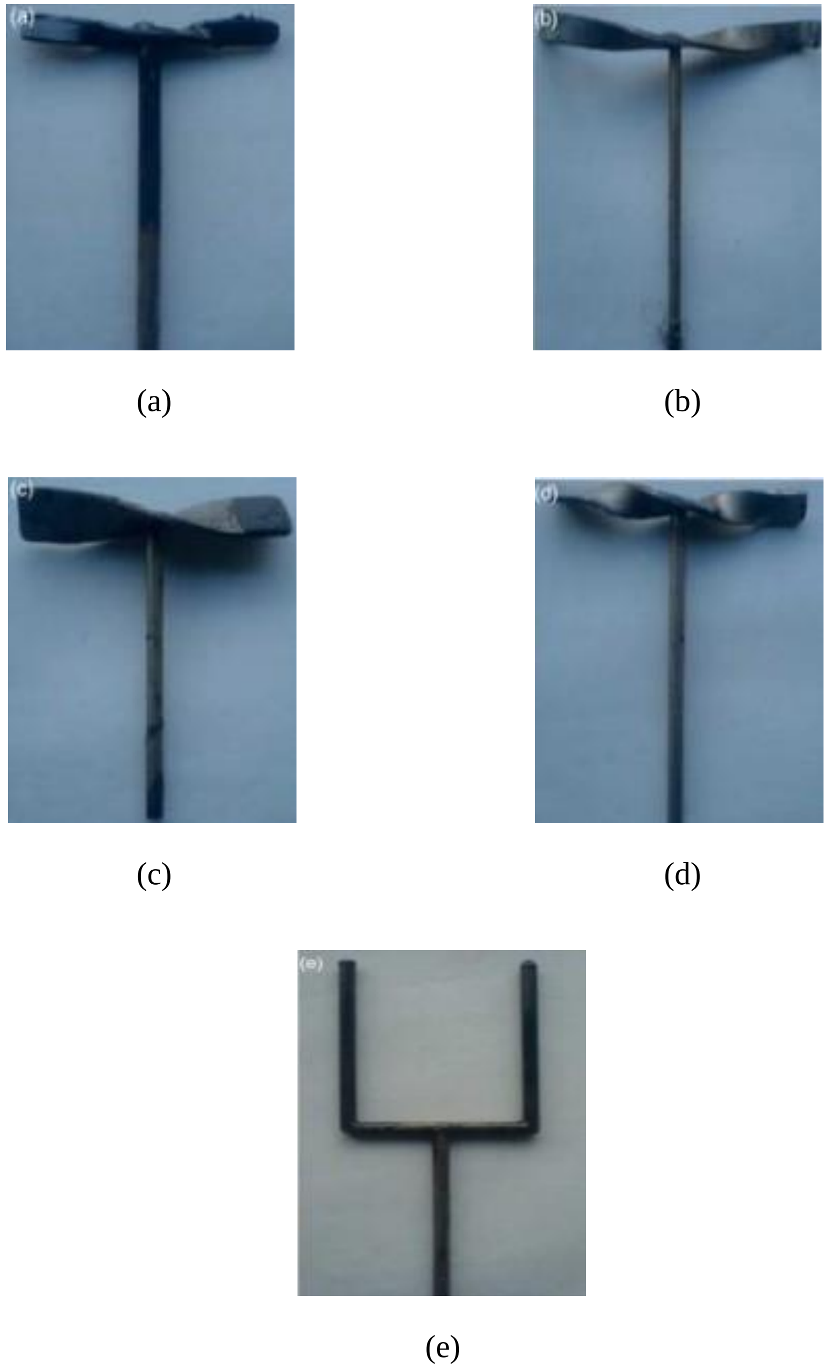


Figure 5. Mixing blades used by (Moghadas Nejad et al., 2014)

As mentioned before, in his master's thesis, Cleven et al., 2000 evaluated carbon fiber in SMA mixtures. In his study, Cleven et al., 2000 reported that he faced clumping issue when evaluating carbon fiber, he also reported that this issue was minimized when increasing mixing temperature and duration. It is noted that the clumping issue occurred while applying the dry mixing method when introducing fibers during this study. In an old study, Duszak et al., 1985 also reported that when evaluating polypropylene fiber, the clumping issue was observed while introducing fibers into asphalt mixtures. Duszak et al., 1985 reported that this issue was solved by increasing the mixing temperature by 10°C. The typical mixing temperature in the study was reported to be between 130°C and 145°C.

Laboratory Performance Testing on Fiber-Reinforced Asphalt Mixtures

The estimated life of an asphalt pavement structure can be up to 20 years before the need for major rehabilitation and replacement of the asphalt layer. In general, several factors influence the service life (or performance) of flexible pavements, and in particular, asphalt pavement layers. These factors can be grouped into three classes: materials, traffic, and environment-related factors. For instance, asphalt layer is typically composed of high-quality aggregates and asphalt binders that are designed to properly resist various pavement distresses (e.g. rutting, cracking, etc.). High traffic volumes, increased tire pressures, and freeze-thaw cycles are some examples of traffic and environmental factors that influence the performance of flexible pavements.

The main purpose of introducing fibers into the asphalt mixtures is to improve performance and extend pavement life. Summary of several different laboratory research studies on the use of fibers are presented in Table 2 and a detailed review of relevant selected studies are provided.

Table 2

Laboratory Studies on Fiber-Reinforced Asphalt Mixtures

Study	Fiber Type	Mix Type/s	Binder Type	Tests	Mixing Method	Fiber Dosage/s	Results
Lavasani et al., 2015	Rockwool and Polyester	HMA and SMA	60/70 penetration	resilient modulus and dynamic creep	Dry method	0.0% - 0.6% (0.1% increment)	Performance enhancement
Mahrez et al., 2010	Fiberglass	SMA	80/100 penetration	Marshall test, indirect tensile test	Dry method	0.2% by total mix weight	Enhanced resilient modulus and stiffness properties
Guan et al., 2014	Brucite, Lignin, Basalt and Polyester	AC-13 graded aggregates	AH-90	Marshall stability, wheel tracking test, low temperature bending and fatigue test	Dry method	Lignin 0.3%, basalt 0.30%, and polyester 0.25% (by total mix weight)	Performance enhancement
Tapkin et al., 2009	Polypropylene	Wearing coarse aggregate	50/70 penetration	Marshall design and optimum binder content	Wet process	0.3% by the aggregate weight	5.0% optimum binder content and 20% Marshall enhancement

Table 2 (Continued)

Study	Fiber Type	Mix Type/s	Binder Type	Tests	Mixing Method	Fiber Dosage/s	Results
Klinsky et al., 2018	Polypropylene and Aramid	Dense graded	PG 70-16	Rutting, resilient modulus, dynamic modulus, flow number, fatigue, and fracture energy test	Dry method	0.5 kg/metric ton of total mix weight	Enhanced rutting, raveling, fatigue and reflective cracking
Teherkhani et al., 2016	Nylon and Nanoclay	Dense graded	60/70 penetration	Marshall stability, resilient modulus, dynamic creep and fatigue life	Dry method	0.4% nylon with 7% nanoclay (by total mix weight)	Performance enhanced
Celauro et al., 2018	Basalt	HMA	50/70 penetration	Wheel tracking test	Dry method	0.3% by aggregate weight	Performance enhanced
Zhuang et al., 2019	Carbon	Porous asphalt mixture	PG 70-22ER	Hamburg wheel (Rutting)	Dry method	0.05% by total mix weight	Performance enhanced
Bahbahani et al., 2009	Cellulose and Rockwool	SMA	AC 60-70	Marshall stability, indirect tensile strength and flow parameters	N/A	0.3% and 0.4% cellulose and 0.4% mineral	Enhanced rutting

Table 2 (Continued)

Study	Fiber Type	Mix Type/s	Binder Type	Tests	Mixing Method	Fiber Dosage/s	Results
Davar et al., 2017	Basalt and Diatomite powder	HMA	PG 64-22	Bending beam fatigue, indirect tensile strength (ITS)	Dry method	0.3% by total mixing weight	Enhanced cracking at low temp.
Morea et al., 2018	Fiberglass	Dense graded	PG 64-16	Notched beam bending test	Dry method	0.4% by total mixing weight	Enhanced cracking
Kaloush et al., 2010	Polypropylene and Aramid	PHX C-3/4 (plant mix)	PG 70-10	Dynamic complex modulus, flow number, four-point bending beam fatigue and ITS	N/A	0.15% by total mix weight	Performance enhanced

As mentioned before, (Ye and Wu et al., 2008) faced some issues in mix design requirements, both Ye and Wu conducted two other studies related to fiber-reinforced asphalt mixtures. The first one (Ye and Wu et al., 2009) evaluated cellulose fiber, polyester fiber and mineral fiber and their effect on dynamic response and fatigue properties of asphalt mixtures. (Ye and Wu et al., 2009) reported that dynamic modulus and phase angle decreases. Also, polyester fiber provided improvement in fatigue resistance for asphalt mixture. Finally, it was reported that polyester fiber showed most positive effects regarding fatigue improvement of asphalt mixture. In the second study (Ye and Wu et al., 2007), cellulose fiber 0.3% fiber dosage, polyester fiber 0.3% fiber dosage and mineral fiber 0.4% fiber dosage by total mix weight were used. Dynamic modulus was evaluated at different temperatures and loading frequencies. Fatigue and rutting parameters of the asphalt mixture were used to study fatigue and rutting resistance properties. (Ye and Wu et al., 2007) reported that all dynamic moduli of asphalt mixtures containing different fibers increased at all testing temperatures and loading frequencies. Phase angles of fiber-reinforced asphalt mixtures were less than control mixture at low temperature, but higher at high temperatures. It was also reported that the master curves of fiber-reinforced asphalt mixtures have the same evolution trend with unreinforced mixtures. Also, fibers caused an increase in complex dynamic modulus |E*| within loading frequency range, especially at lower frequencies. Furthermore, fiber-reinforcement reduced loss of modulus of asphalt mixtures at medium temperatures which resulted an increase of flexibility of asphalt mixtures and an improvement of asphalt mixtures' fatigue resistance. Finally, when rutting parameters were evaluated, (Ye and Wu et al., 2007) reported that all fibers enhanced rutting performance. Cellulose fiber enhanced the mixture by 112%, polyester fiber by 114% and mineral fiber by 124%.

Recently, Ziari et al., 2019 evaluated the effect of synthetic Polyolefin-glass fibers on performance properties of asphalt mixtures. Tensile Strength Ratio (TSR), resilient modulus, modified Lottman, water boiling, dynamic creep, indirect tensile fatigue and Semi-Circular bending (SCB) fracture tests were evaluated in this study. They concluded that using 0.12% (of total mix weight) fiber dosage of polyolefin-glass fiber enhanced all aspects of asphalt mixtures. Polyolefin reinforcement also improved stiffness and elastic behavior of asphalt mixtures. Furthermore, glass fiber increased fatigue and cracking resistance of asphalt mixtures. Ziari et al., 2019 also reported that when up to 0.18% of fiber is used in mixture, enhancement in moisture resistance of mixtures occurred as TSR value improved by almost 10% and the number of stripped areas in the water boiling test decreased. In addition, when using 0.12% fiber content, fatigue resistance of mixtures improved. More significant improvement was observed at lower stress levels.

Lavasani et al., 2015 used Rookwool and Polyester to evaluate the resilient modulus and dynamic creep performance. Performance tests were conducted at testing temperature sweep of 5°C, 25°C, and 35°C. In this study, both control Hot Mix Asphalt (HMA) and SMA were used to evaluate different fiber types. Lavasani et al., 2015 reported that control mixtures showed improved mechanical performance in comparison with SMA mixtures in uniaxial resilient modulus and dynamic creep tests. It was also reported that adding both mineral and organic fibers to asphalt binder showed extreme enhancement in the mixtures’ properties.

Guo et al., 2015 evaluated the performance of diatomite and glass fiber on asphalt mixture. A wheel tracking test, low temperature indirect tensile test, indirect tensile fatigue test and indirect tensile stiffness modulus tests were evaluated in this study. Statistical analysis of variance (ANOVA) method and statistical regression were both used to evaluate the effects of adding diatomite and glass fiber on properties of asphalt mixtures. (Guo et al., 2015) reported significant impact was observed on rutting resistance of asphalt mixtures when using diatomite and glass fibers. It was also reported that diatomite fiber presented more significant rutting resistance than glass fiber. Overall, glass and diatomite fibers improved fatigue properties and fatigue cracking resistance of asphalt mixtures. Mixtures with glass and diatomite fibers had greater stiffness modulus and lower modulus than control mixtures when evaluated using temperatures below -10°C. Diatomite fiber had significant factor for stiffness modulus enhancement and glass fiber reduced stiffness modulus.

Abtahi et al., 2013 studied the effect of polypropylene and glass fibers. As mentioned in the mixing method section, they used dry mixing method for glass fiber and wet mixing method for polypropylene. Binder testing was performed on polypropylene modified asphalt which exhibited decreased penetration, reduced ductility and higher softening points compared to control (unmodified) asphalt binder. Performance testing was performed on a hybrid mix of polypropylene and glass fiber in comparison with a control mix. (Abtahi et al., 2013) reported that asphalt specimens that contained polypropylene had increased performance in Marshall Stability and AVC% in total mix and flow. Unit weight, on the other hand, tended to decrease compared with control samples. Mixtures with 6.0% Polypropylene fibers with 0.1% glass fibers showed the highest stability and above 25% improvement compared to control mixtures.

Field Performance of Fiber-Reinforced Asphalt Mixtures

Although several laboratory studies have been conducted on fiber-reinforced asphalt mixtures, few studies have investigated the use of fibers in field sections. (Maurer et al., 1989) studied field performance using fiber-reinforcing and reported that ease of placement varied considerably, and the experience of the contractor was a significant factor affecting both efficiency and adequacy of pavement placement. (Maurer et al., 1989) reported that pavement was more expensive and more difficult to construct. Data that was reported in this study were 8 months, 26 months and 44 months intervals. (Maurer et al., 1989) also reported that after 44 months, fiber-reinforcement did show enhanced cracking resistance. However, due to documented construction costs, none of the treatments used on this project were considered cost-effective and were not recommended.

Chen et al., 2015 evaluated the addition of glass fiber on field performance of fiber-reinforced asphalt mixtures. The study reported plant mixing procedure and construction method for glass fiber were similar to general asphalt pavement. After one year of constructing, Marshall stability, indirect tensile strength, and dynamic stability were evaluated. Chen et al., 2015 reported that the performance of Marshall stability was enhanced by 175% and indirect tensile strength was enhanced by 132% when fiber-reinforcing the asphalt pavement.

Cleven et al., 2000 went beyond laboratory performance asphalt testing and evaluated field performance of fiber-reinforced asphalt pavement sections using same carbon fiber. The section's construction confirmed that the mixing process of fiber-reinforced asphalt pavement should be a wet mixing method. The clumping issue was observed in the mixtures made from binder modified in the holding tank but the clumps were small and coated with asphalt binder and would be eliminated by increasing the mixing time or temperature. The dry mixing method was also evaluated by adding fibers to the pug mill and by visual inspection indicated more clumps were observed within the mixture. It is reported that each method had different effects on optimum fiber length. Also, the laboratory study indicated a longer optimum fiber length compared with the field optimum fiber length. Two different sections were constructed using two different performance graded binders (PG 52-28 and PG 58-28). Cleven et al., 2000 reported that fiber-reinforced pavement sections had increased performance in both stiffness and rutting performance. PG 52-28 presented more enhancement when fibers were added. It was also reported that the cost of carbon fibers does not justify their use in only lower quality asphalt mixtures.

Park et al., 2018 evaluated glass fiber using Accelerated Pavement Testing (APT) on modified SMA reinforced asphalt mixture. Heavy Vehicle Simulator (HVS) was used with an initial load of 4.1 ton applied, then it was increased gradually until it reached 6.15 ton and 8.2 ton. Park et al., 2018 studied two lateral profile measurement points and 690,000 ESALs loads were applied at 31.6°C for every mixture' pavement section. Lateral profiles of asphalt pavement were obtained by taking measurements at 1.0 cm intervals with reference to selected lateral profile points. The rut depth was calculated using derived lateral profile. Finally, plastic deformation resistance between modified SMA and glass fiber reinforced asphalt mixture was assessed. Hamburg wheel tracking and APT tests showed that plastic deformation resistance of glass fiber is higher than modified SMA mixture. It was also reported that fiber-reinforced pavement did cost more than unreinforced asphalt pavement.

Another study was conducted by Ohm et al., 2016 where he evaluated laboratory performance and field validity of glass fiber-reinforced asphalt mixtures. Unreinforced asphalt mixture and glass fiber-reinforced mixtures prepared with similar plant mixing and construction methods were paved in five locations in order to assess the field durability and applicability. Field cores were tested in the lab using the Marshall stability, indirect tensile strength, and dynamic stability tests. Findings showed that the glass fiber-reinforced asphalt mixtures presented better lab performances compared to the unreinforced asphalt pavement. The indirect tensile strength of glass fiber-reinforced asphalt pavement was 115% higher than that of unreinforced asphalt pavement. In addition to that, unreinforced pavement's Marshall stability was 128% less than that of glass fiber-reinforced. Dynamic stability of the glass-fiber-reinforced was 16,180 reps/mm and suggested high rut resistance may be expected. After one year, there were no noticeable cracks or deformation in the section. Lab tests and field surveys of five glass fiber-reinforced asphalt pavement sites resulted in superior performances compared to unreinforced pavement. The conclusion was that glass fiber-reinforcement is an alternative to polymer modified asphalt mixtures because it is a low-cost procedure. Field durability of fiber-reinforced asphalt pavement will be evaluated on the long term.

Summary of Literature Review

The following is a summary of the findings from the literature review:

- Dry mixing methods were more often recommended than wet mixing methods and were reported to result in a more uniform distribution of fibers within the asphalt mixture. Dry mixing methods also caused a reduction in the variability in performance testing of fiber-reinforced asphalt mixtures. These findings were also reported by other studies (Abtahi et al., 2010; Echols et al., 1989). Clumping is a common issue that occurs when using fiber-reinforced asphalt mixtures and a special procedure for introducing fibers into asphalt mixtures may be needed.

- There are limited studies that compared different mixing methods of fiber-reinforced asphalt mixtures to determine which method will be more suitable for incorporating fibers into fiber-reinforced asphalt mixtures. Thus, evaluating multiple methods is required for future researches. Also, there is a need to develop a method to introduce new material such as fiber into the asphalt mixtures, a method that would minimize clumping of fibers and enhance the overall performance of the mixtures.

The addition of fibers into the asphalt mixtures affect mix volumetrics. An increase in fiber dosage will increase the AVC% within asphalt mixtures which therefore will result the need of additional asphalt binder to obtain required mix design requirements.

- The usage of fibers in asphalt mixtures improved the overall performance of asphalt pavement mixtures, fiber reinforcement leads to minimization of distresses experienced by the asphalt pavement and extends the life cycle of asphalt pavement.

Chapter 3

Description of Fiber-Reinforced Asphalt Materials Used

In this chapter, a description of the materials developed as part of this study is presented. Moreover, this chapter provides a discussion of different fiber types, asphalt binder, aggregates and aggregate gradation used to evaluate the fiber-reinforced asphalt mixtures.

P-401 Asphalt Mixtures' Characteristics and Gradation

Dense-graded airfield mix was used for control mixtures (with no fiber reinforcement) and fiber-reinforced asphalt mixtures. The gradation was designed according to Superpave procedures and Federal Aviation Administration (FAA) P-401 specifications (FAA, 2018). FAA specifications were chosen due to local source availability of materials and its similarities with US Army Corps of Engineers (USACE) asphalt mix specifications for airfields.

Diabase aggregate type and one asphalt binder (polymer-modified PG 76-22) were used to prepare the selected dense graded control asphalt airfield mix. Figure 6 presents the control points for P-401 mixes along with the percent passing for the aggregate blend utilized in this study. The Nominal Maximum Aggregate Size (NMAS) in Figure 6 for the blend is 12.5 mm and is typically used as surface course. This aggregate gradation was selected from a previously FAA approved P-401 Job Mix Formula (JMF) obtained from a local contractor.

Superpave Gyratory Compactor (SGC) as per AASHTO T312 was used to prepare compacted asphalt mix specimens using selected aggregate gradation and selected asphalt binder at a design gyration level (N_{des}) of 50 gyrations (P-401 specifications). The mixtures were prepared using the selected aggregate blend (or gradation) at a limit minimum binder content of 5.0% by total mix weight binder content. The selected N_{des} represents the loading magnitude for aircraft loads less than 60,000 lbs. (or three million ESALs) (FAA, 2018). This design gyrations level takes into consideration future plans for evaluating full-scale fiber-reinforced flexible pavement sections using Heavy Vehicle Simulator (HVS). As seen in Figure 6, FAA's specifications require mixtures to meet a target air void content (AVC%) of 3.5 ± 0.5% and a 15% minimum Voids in Mineral Aggregate (VMA%) (FAA, 2018).

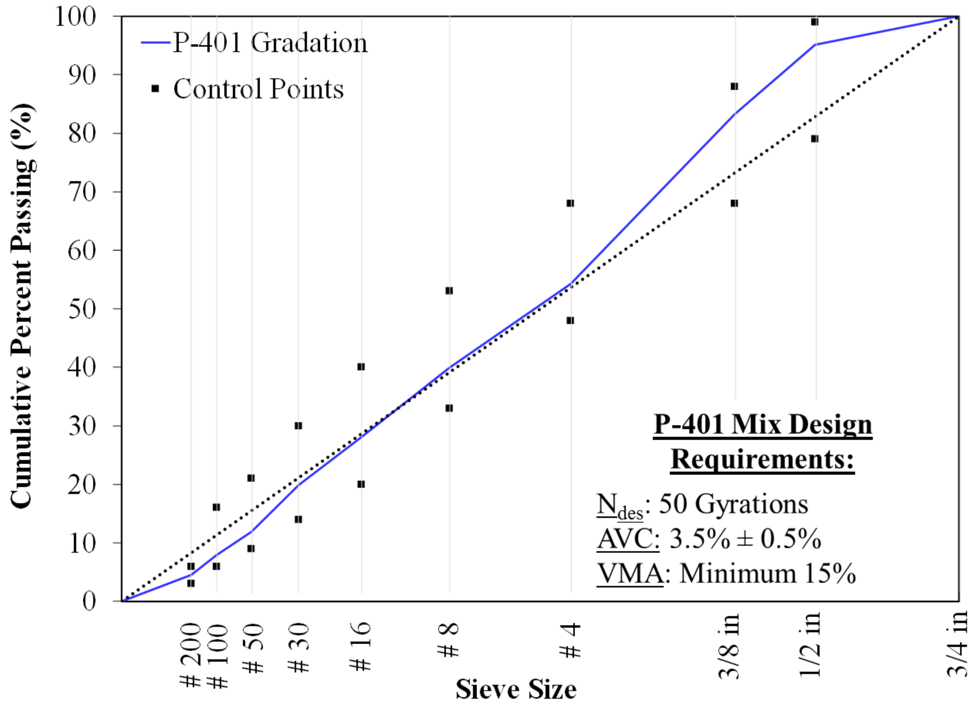


Figure 6. FAA P-401 Gradation.

Fibers

Four different fiber types were selected for fabrication of fiber-reinforced asphalt samples (i.e., reinforcing the control mix). Selected fibers varied in specific gravity, tensile strength, length, % absorption, decomposition and melting temperature, and the price of each fiber. Table 3 summarizes the properties of each fiber type. Images of each fiber type are provided in figure 7. These fibers were selected because of their high melting temperature points; therefore, this indicates that fibers did not melt when preparing and testing fiber-reinforced samples.

Table 3

Properties of Selected Fiber Types

Fiber Property	Fiberglass	Basalt	Carbon	Polyolefin/ Aramid (PFA)
Specific Gravity (g/cm^3) (ASTM D3800)	2.7	2.8	1.8	0.91/1.44
Tensile Strength (MPa) (ASTM D2256)	2000	2500	4137	483/3000
Length (mm) (ASTM D204 & ASTM D5103)	12	9	6	19
Absorption (%) (D5229/D5229M)	<1%	0%	Negligible	0%/ Negligible
Decomposition Temperature (ºC) (ASTM D7309)	>815	>1500	500	157/>450
Melting Temperature (ºC) (ASTM D276 & ASTM D7138)	1121	2500	1200	150/350
Price ($/lb.)	3.02	4.10	9.75	6.75

(a) Polyolefin

(b) Aramid

(c) Fiberglass

(d) Basalt

(e) Carbon

Figure 7. Images of each fiber type

Chapter 4

Impact of Fiber Types

In order to investigate the impact of fibers on fiber-reinforced asphalt mixtures, this study included two approaches to evaluate fiber-reinforced asphalt mixtures: impact of different fiber types and evaluating the impact of different fiber dosages. This chapter will contain the impact of fiber types including different mixing methods used to evaluate their effect on mix design requirements and clumping. Also, the experimental plan, mix design and performance tests results are discussed in this chapter.

Sample Preparation

This section consists of evaluating different mixing methods and finding recommended fiber dosage that would not affect mix design requirements and obtain minimum clumping. For sample preparation, the fibers were added at a dosage rate recommended by their respective manufacturer to evaluate the impact of fibers on the overall asphalt mix design and performance. Two methods were utilized to introduce fibers and produce fiber-reinforced asphalt mixes; the first is conventional "dry" method while the second is the "proportional dispersion" method which was developed in this study.

The dry mixing procedure was used in this study to replicate the process at the plant level where the fibers are directly added to the aggregate mixing drum. In the dry method, the fiber dosage prepared for making the asphalt sample was first added into hot aggregates at 340°F (15°F above mixing temperature). The blend of fibers and aggregates was mixed using a mixer for 60 seconds to distribute the fibers into aggregate structure.

Asphalt binder was then added into fiber-aggregates blend and mixing continued for a minimum of 120 seconds or until a complete coating is observed.

Although the dry mixing method was recommended by previous studies, a new mixing method “proportional dispersion” was developed in this study to evaluate the addition of fibers into the asphalt mixtures, this method was developed to proportionally introduce fibers into the asphalt mix instead of adding the full portion. Also, mixing the fibers “dry” with the aggregates may result in damaging the fibers and change their form due to the friction between fibers and aggregates which was addressed in this method by introducing fibers after aggregates were coated with asphalt binder. In “proportional dispersion” method, fiber dosage was first divided into four equal portions. Similar to the method of fabricating traditional asphalt specimens in the laboratory, preheated aggregates and asphalt binder were both added into the mixing bowl and mixing process began. After approximately 30 seconds after starting the mixing process, aggregates become fully coated by asphalt, the first portion of fibers was spread in the mixing bowl. Mixing continued for 15 seconds after which the mixing process stopped to add the second portion of fiber dosage. This process was repeated (every 15 seconds) until all fiber portions were added into the mixer. After the final fiber portion was added (approximately two minutes have passed), mixing continued for a minimum of 60 seconds or until full aggregate coating with fibers was observed. This mixing procedure was designed to replicate the plant level by adding fibers through spray bars. Figure 8 presents pictures of dry and proportional dispersion methods.

(a) Dry mixing method

(b) Proportional dispersion mixing method

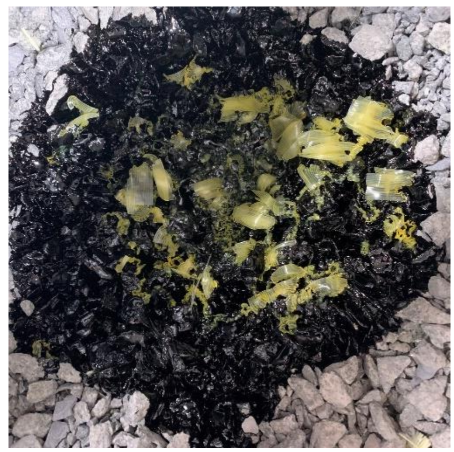
Figure 8. Images of the dry mixing method and the proportional dispersion mixing method.

Regarding the mix of polyolefin and aramid (PFA) fibers, PFA-reinforced asphalt mixtures specimens were formed according to the manufacturer's procedures. This was the case because these fibers were mixed at proprietary proportions that was not reproducible in the laboratory. The entire laboratory sample preparation procedure for PFA-reinforced asphalt mixtures was provided in literature (FORTA, 2019). The mixing process started by layering down aggregates and aramid fiber, asphalt binder was then placed into the mixing bowl followed by the full dosage of polyolefin. The addition of polyolefin fibers will result in melting the fibers within the blend. The melting process is due to a lower melting temperature (315°F) of polyolefin fibers than that of mixing temperature (325°C). Figure 9 presents pictures of PFA mixing process.

(a) Aggregate/Aramid layering

(b) Addition of asphalt binder

(c) Addition of Polyolefin



(d) Melting of Polyolefin

Figure 9. Images of PFA Mixing Method

Laboratory Experimental Plan

An extensive testing program was developed to evaluate the mix design and laboratory performance of fiber-reinforced asphalt mixtures. Table 4 presents the testing plan completed in this study. As be seen from Table 4, the testing program aimed to evaluate the effect of fiber type on asphalt mixture performance, including: the Asphalt Pavement Analyzer (APA), Flow Number (FN), Dynamic Complex Modulus (|E*|), Indirect Tensile Strength Cracking Index (IDEAL-CT), and Cantabro Durability (CD) tests.

Table 4

Mixing Methods and Performance Tests Experimental Plan

Factor	Test Temperature	Fibers Evaluated	Dosage Rates*	Number of samples
		Impact of Fiber Types		
Mixing Method: Dry vs. Proportional Dispersion	325°F Mixing 315°F Compaction	Basalt, Carbon and Fiberglass	0.16%	60 (30 G_{mb} + 30 G_{mm})
Mixing Method: FortaFi®		PFA	0.05%	
Cracking Performance: IDEAL-CT	25°C	All four fibers	Both fiber dosages	15 (3 per fiber + 3 for control)
Rutting Performance: APA	64°C	All four fibers	Both fiber dosages	30 (6 per fiber + 6 for control)
Durability Performance: CD	25°C	All four fibers	Both fiber dosages	15 (3 per fiber + 3 for control)
Mix Characteristics Performance: DCM	4.4, 21.1, 37.8, & 54°C	All four fibers	Both fiber dosages	15 (3 per fiber + 3 for control)
Rutting Performance: FN	54°C			
Total:				135 Samples

*Dosage rates are percentage of total mix weight

As described previously, different mixing procedures are commonly used to prepare fiber-reinforced asphalt mixtures with no consensus on the best method to utilize for consistency. Thus, the testing program also facilitates determining the most effective method for producing fiber-reinforced asphalt mixes. A brief description of each performance test is provided in the following subsections.

Dynamic complex modulus (|E*|). The Dynamic Complex Modulus test was conducted to characterize linear viscoelastic properties of fiber-reinforced asphalt mixtures at varying temperatures and loading frequencies. The test was conducted according to AASHTO T378. The test was performed at temperatures of 4.4°C, 21.1°C, 37°C, and 54°C. At each temperature, a sinusoidal stress load is applied at frequencies of 0.1Hz, 0.5Hz, 1Hz, 5Hz, 10Hz, and 25 Hz. The magnitude of the applied stress was controlled to ensure that the resulting strain did not exceed 150 $\mu\varepsilon$; thus, not damaging the samples and maintaining the behavior of asphalt specimen in linear viscoelastic range. Using time-temperature superposition, a dynamic modulus master curve was developed at a reference temperature of 21.1°C. Three cylindrical specimens (or replicates), each being 170 mm in height and 150 mm in diameter with starting AVC% 8.0% ± 0.5%, cored to reduce diameter to 100 mm and 150 mm in height, were prepared for control and four fiber-reinforced asphalt mixtures. The samples were cored and cut from Superpave Gyratory Compactor (SGC) compacted samples to meet a target 7.0% ± 0.5% air voids.

Flow number (FN) or repeated load permanent deformation. The Flow Number test was conducted to characterize rutting resistance of fiber-reinforced asphalt mixtures. The test was conducted according to AASHTO T378. The test was performed at a temperature of 54°C (130°F) by applying a 0.1 second haversine load pulse followed by a 0.9 seconds rest period (one loading cycle). Loading is repeated for several hundred cycles (or until the sample fails) to determine the cumulative permanent deformation and number of cycles to failure (beginning of tertiary flow, or FN). Higher flow number values for asphalt mixtures are desirable as that is an indication of high resistance to rutting. Three replicates at a target AVC% of 7.0% ± 0.5% were tested per specimen. It is noted that the specimens prepared for |E*| were utilized to conduct the FN test after completing all required |E*| testing.

Asphalt pavement analyzer (APA). The Asphalt Pavement Analyzer (APA) test was also conducted to evaluate the rutting susceptibility of fiber-reinforced asphalt mixtures according to AASHTO T340 standards. The test was performed at a temperature of 64°C using APA machine and configured to apply 444.8 N (100-lb) wheel force applied on top of a 6.89 kPa (100 psi) pressurized hose that is placed on top of the samples. The test was conducted until a total of 8,000 loading passes are applied on the samples. An average rut depth value per specimen is typically reported after applying 8,000 cycles using APA machine. Lower rut depth values are desirable as that provides an indication of low mix rutting susceptibility. Three APA specimens (one sample composed of two SGC compacted samples having a diameter of 150 mm and a height of 75 mm) were tested per mix. Samples were compacted to a target 7.0% ± 0.5% air voids.

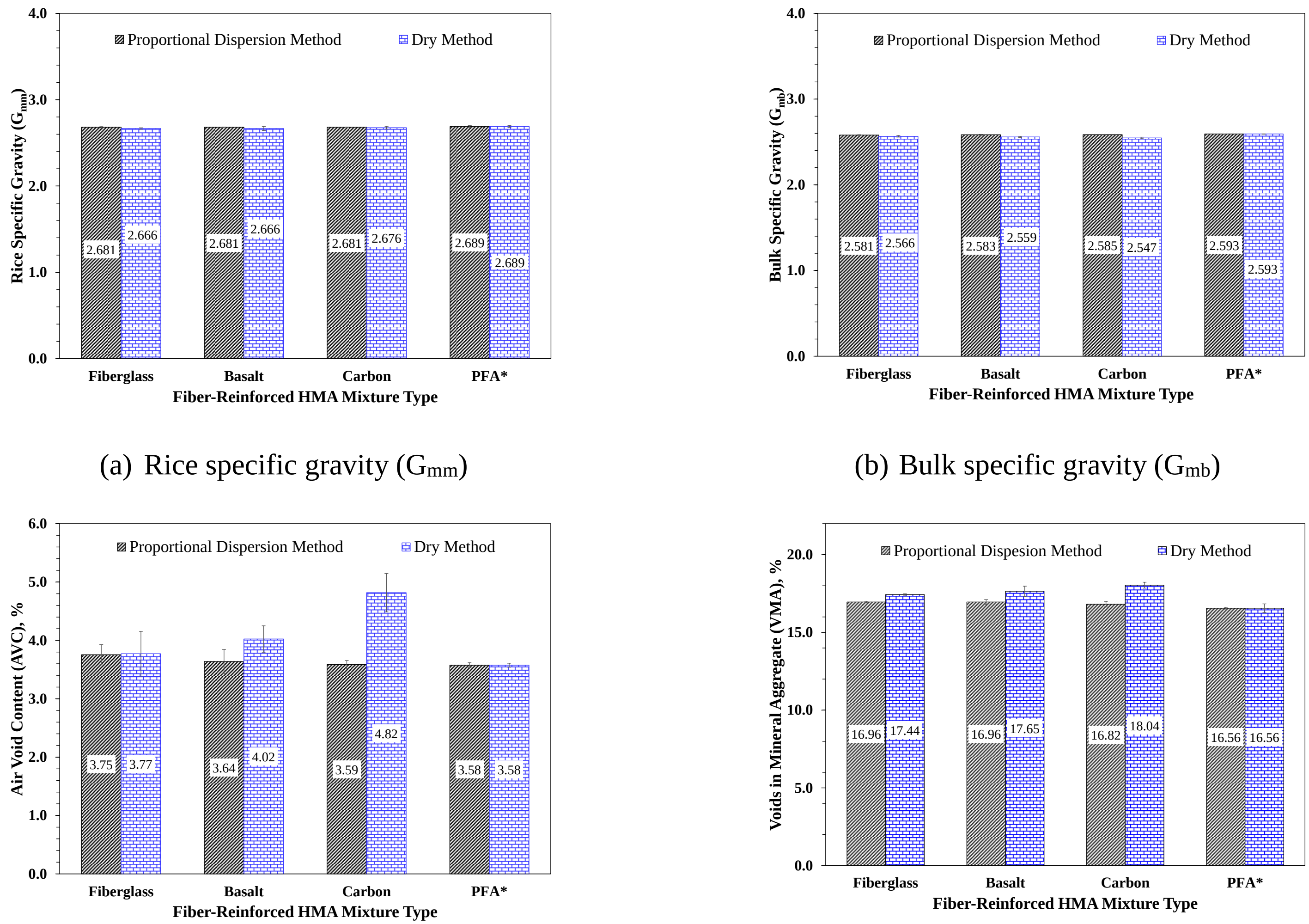
Indirect tensile strength cracking index (IDEAL-CT). Cracking sensitivity of fiber-reinforced asphalt mixtures was characterized using Indirect Tensile Strength Cracking Index (IDEAL-CT) test performed at intermediate temperatures (i.e., 25°C) according to ASTM D8225 where higher cracking tolerance index (CTindex) values indicate better cracking performance. The test was conducted over load displacement application rate of 50 mm/min (2 in/min) on specimens located in ITS loading jig. Having 150 mm diameter with 62.0 mm ± 1.0 mm height, three specimens were tested for each fiber type, fiber dosage and binder content. The control specimens were compacted using Superpave gyratory compactor (SGC) to 7.0% ± 0.5% target air voids. Previous studies have shown that IDEAL-CT index is sensitive to asphalt properties and volumetric changes.

Cantabro durability test. The durability (or resistance to breaking down) of fiber-reinforced asphalt mixtures was evaluated using Cantabro Durability test performed according to AASHTO TP 108 standards. In general, Cantrabro Loss is defined as percent abrasion loss of compacted asphalt mix samples using Los Angeles Abrasion (LA Abrasion) machine. Specimens for this test were compacted at the design number of 50 gyrations to a target height of 115 ± 5 mm. Three replicates per mix were tested with each sample separately subjected to a total of 300 revolutions at a speed of 30 – 33 revolutions per minute in the LA Abrasion machine. Percent materials loss was determined based on the before and after test sample weights. Lower percent materials loss values indicate that asphalt mixtures are more durable (more resistant to breaking down under loading). These conclusions were also found in other researches (Alvarez et al., 2011).

Impact of Mixing Methods and Fiber Types on Asphalt Mixtures' Volumetrics

In the mix design phase, two different mixing procedures were used to evaluate the addition of fibers into the fiber-reinforced asphalt specimens; the first method is called the "dry" mixing method and the second method is called "proportional dispersion" method. Fibers were evaluated using both these mixing methods at a dosage rate of 0.16% for (carbon, basalt and fiberglass) and at a dosage rate of 0.05% for (aramid and polyolefin) blend. Both of these dosages are by total mixing weight which was recommended by each fiber's manufacture.

For this study, the binder content remained the same for the control and all fiber-reinforced asphalt samples (5.3% by total mix weight). Using both dry and proportional dispersion mixing procedures and the manufacturer fiber dosage rates, mix design properties (rice specific gravity (G_{mm}), bulk specific gravity (G_{mb}), air void content (AVC%), and Voids in Mineral Aggregate (VMA%) and four different fiber types were evaluated. An average of three replicates for control and each fiber types were evaluated to obtain asphalt mix design. Results of mix design study for each fiber-reinforced asphalt mixture are presented in Figure 10. The error bars in all graphs that contain error bars are presented at 95% confidence level. The asterisk in Figure 10 denotes no change in the mixing procedure due to the specific laboratory procedure recommended for PFA (FORTA, 2019).



(a) Rice specific gravity (G_{mm})

(b) Bulk specific gravity (G_{mb})

(c) Air void content (AVC%)

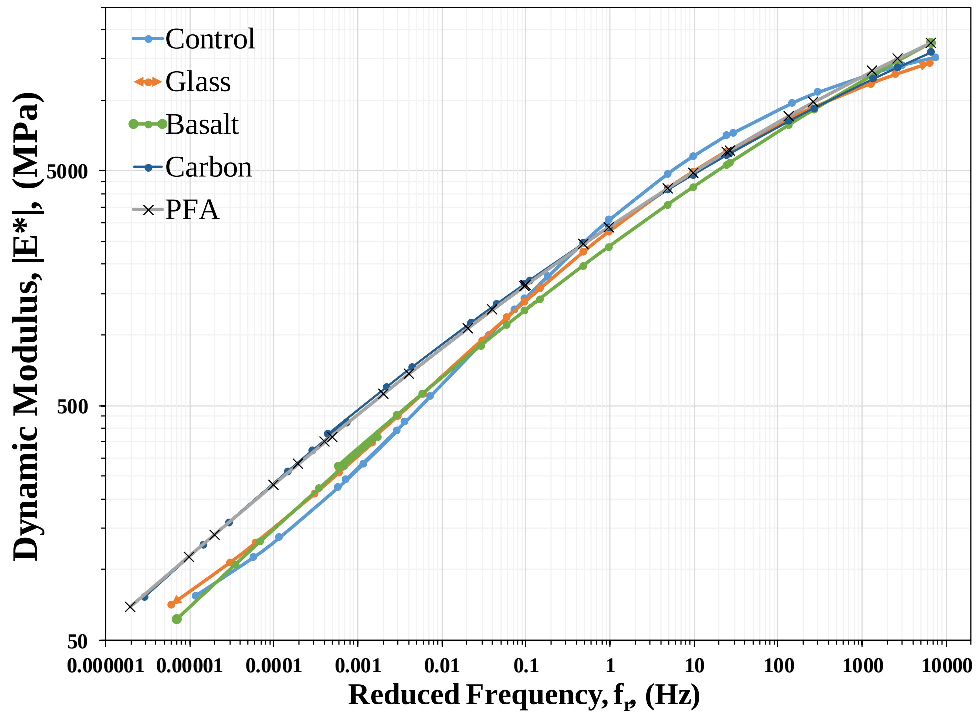
(d) Voids in Mineral Aggregate (VMA%)

Figure 10. Results of the mix design for fiber-reinforced hot mix asphalt mixtures using the proportional dispersion and dry mixing methods

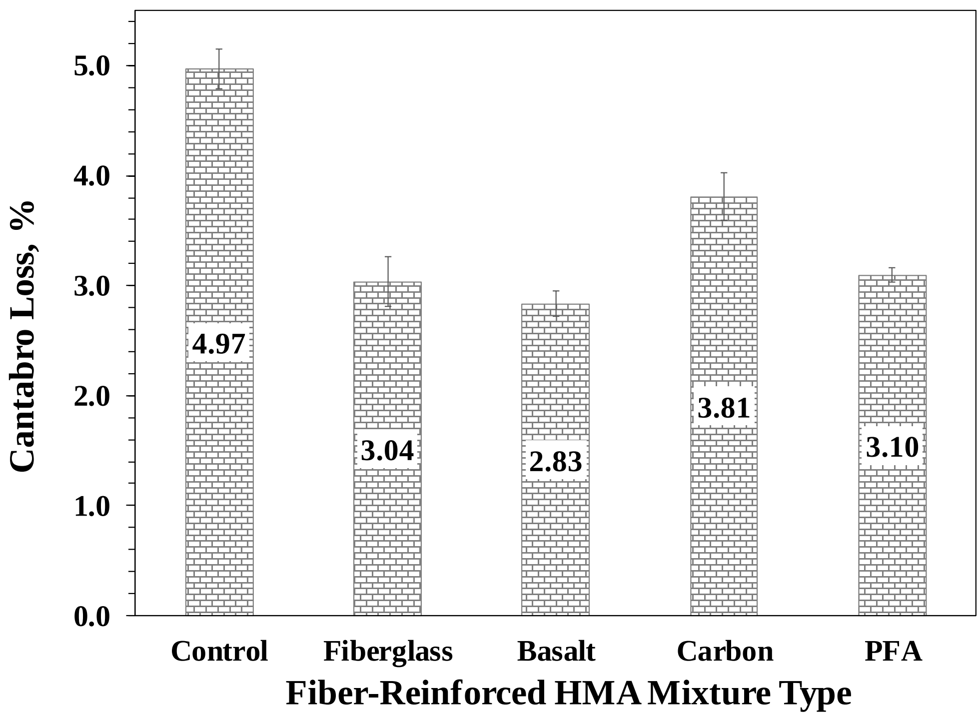
As can be seen from Figure 10, when using proportional dispersion method and at a fiber dosage of 0.16% for basalt, fiberglass, and carbon or 0.05% for PFA, the addition of fibers did not change optimum binder content for asphalt mixtures. Control and all fiber types are within the FAA specifications for a P-401 mix at an optimum binder content of 5.3% using proportional dispersion method. It is noted that FAA's P-401 specifications of binder content should be between 5.0% and 7.0% (of total mixing weight), These results agree with findings from previous research study that showed no impact of fibers on the asphalt mixture' mix design requirements (Bayomy et al., 2016). When using the dry mixing procedure, two fiber types (carbon and basalt) were not within FAA specifications for the P-401 asphalt mix. Therefore, changes to the asphalt mix design will be required and additional asphalt binder would be necessary to achieve required volumetric measurements. It also appears that in figure 10c, with only a 0.02% difference in air void content, the fiberglass fiber type was the least impacted by the difference in both mixing procedures. Therefore, for fiberglass fiber, the impact of mixing procedure on the overall mix design is minimal. It can also be observed from Figure 10 that the dry mixing procedure has greater variability in mix design measurements compared to the proportional dispersion method. The inconsistency in measurements can especially be observed in G_{mb} and G_{mm} (Figure 10a and 10b) in which the fiberglass, basalt, and carbon all had greater variability when using the mixing method over proportional dispersion method. This finding may be attributed to changes in the way the fibers breakdown during dry mixing process with aggregate blend. Images of the fibers during each mixing procedure were presented in sample preparation section (Figure 8.) As can be seen in Figure 8, fibers, by visual inspection, break down when using the dry mixing procedure, and have a more variable distribution than in the proportional dispersion method. This may lead to differences in coating of aggregates with asphalt binder, resulting in reduced Rice specific gravity values (Figure 10a) and higher air void contents (Figure 10c). Therefore, based on better consistency during mix design analysis, proportional dispersion method is recommended for laboratory production of fiber-reinforced asphalt mixtures and was used for all performance tests performed in this study.

Laboratory Performance Results

Mix characteristics and durability. Figure 11 presents laboratory test results on the evaluation of fiber's impact on asphalt mix characteristics (|E*| master curves shifted to a reference temperature of 21.1^{o}C) and durability (Cantabro loss values) for all five asphalt mixtures. As can be seen from Figure 11a, |E*| values for all fiber-reinforced asphalt mixtures were similar to or slightly lower than control mixture at higher frequencies. Findings from DCM indicate that fiber types show little impact on cracking performance of asphalt mixtures. In contrast, however, at lower frequencies, two fiber types, Carbon and PFA, showed greater |E*| values compared to unreinforced (control) and remaining fiber-reinforced asphalt mixtures. This finding gives the indication that the use of Carbon and PFA in asphalt mixtures have the potential to improve the rutting resistance of asphalt mixtures. Furthermore, control mixtures presented slightly more sensitivity with frequency (or temperature) change than fiber-reinforced specimens. These findings can be found in Figure 11a where the control mix had steeper slope in comparison to the fiber-reinforced mixtures.



(a) |E*| master curves

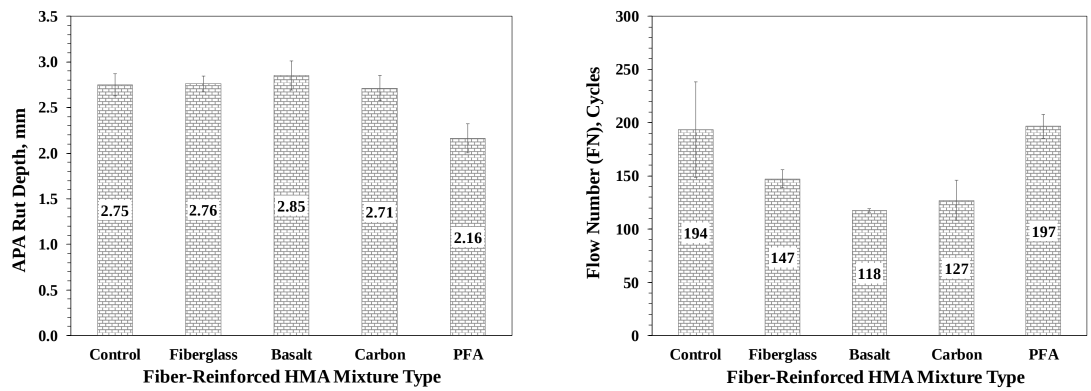


(b) Cantabro loss

Figure 11. Results of a) Dynamic Complex Modulus (DCM) and b) Cantabro Durability

With respect to mix durability (Figure 11b), high Cantabro loss percentages (4.97%) were observed for control asphalt specimens compared to Fiberglass (3.04%), Basalt (2.83%), Carbon (3.81%) and PFA (3.10%). For Cantabro loss test, the use of fibers in asphalt mixtures resulted in an average 1.78% improvement. Basalt fiber presented the best durability performance with Cantabro loss percentage of 2.83% (an enhancement of 2.41% over control asphalt specimens). The addition of Fiberglass and PFA also improved durability performance in comparison with control asphalt mixture with Cantabro loss values of 3.04% and 3.10%, respectively. Overall, it can be concluded from Figure 10b that the use of fibers can improve the durability of asphalt mixtures.

Rutting susceptibility performance. The APA rut depth results and FN cycles to failure are presented in Figure 12. As can be observed from Figure 12a, a slight improvement of the measured APA rut depth was observed with the use of PFA-reinforced asphalt. PFA-reinforced asphalt specimens showed slight improvement with a decrease in APA average rut depth of 0.6 mm. These results agree with findings obtained in DCM test in which PFA-reinforced asphalt mixtures appeared to have greater |E*| values at low frequencies. No impact was observed in APA rut depth for Fiberglass, Basalt, and Carbon as all were within an average of 0.1 mm compared to control asphalt specimens. Considering inconsistency between samples, it appears from Figure 11a that the use of fibers may not impact the APA rutting performance. Regarding FN presented in Figure 12b, a greater dissimilarity in rutting performance was observed between each asphalt mixture considered in this study. FN test results conflict with APA test results. The FN results showed the highest rut depth in unreinforced asphalt specimens. This finding conflicts with |E*| and APA test results found in this study and further in-depth study on each laboratory test is required to determine their applicability for fiber-reinforced asphalt mixtures. These findings are due the difference in standard error between rutting tests, this may result in conflicting findings between different tests.



(a) APA rut depth (b) Flow number (FN) values

Figure 12. Rutting performance test results; a) APA results and b) Flow Number results.

Strength and cracking resistance. Cracking tolerance indices (CT_{index}) for the control and fiber-reinforced asphalt mixtures are presented in Figure 13. Little to no impact from the use of fiber on the strength and cracking performance of asphalt mixtures was observed. CT_{index} showed a slight increase in average cracking resistance when using fibers in asphalt mixtures and the difference is not significant as indicated by the error bars. This increase may be associated with the variability of the test and not the result of fiber modification. Therefore, based on the results observed in Figure 13, no enhancement was observed when comparing control with fiber-reinforced asphalt mixtures regarding cracking resistance of asphalt mixtures. This finding agrees with the DCM test results presented previously (Figure 11a).

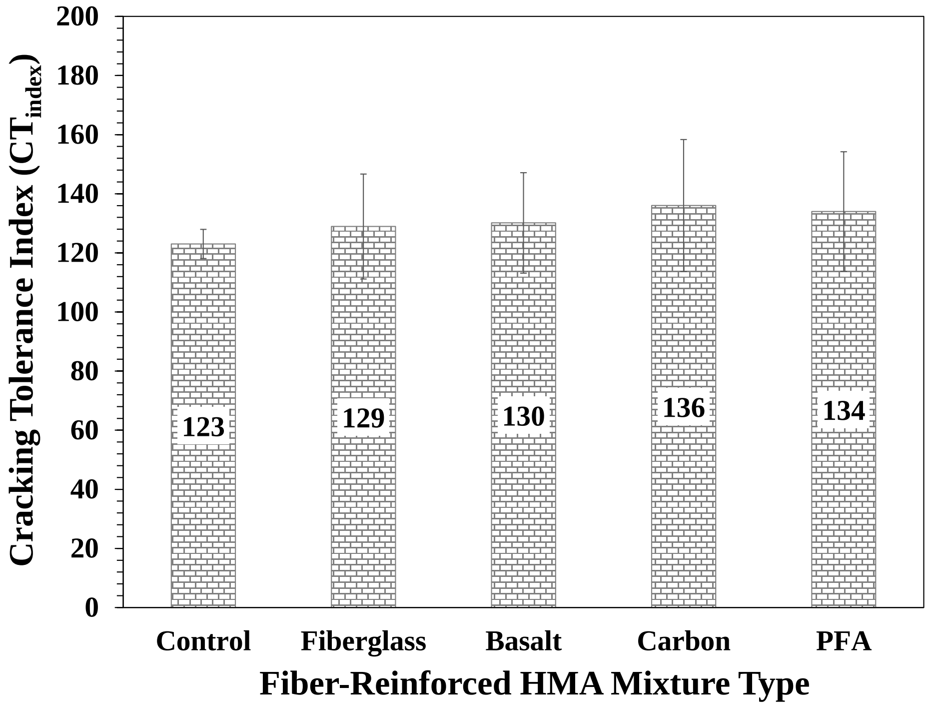


Figure 13. Cracking performance test results.

Statistical analysis using analysis of variance (ANOVA) and tukey post-hoc. Statistical analyses were conducted to compare the statistical significance in performance observed between control and fiber-reinforced asphalt samples. Consequently, Analysis of Variance (ANOVA) was conducted. ANOVA was conducted at 95% confidence level (p-value <= 0.05 indicate significant impact) to evaluate the statistical significance between control and at least one fiber type. Additionally, Tukey Post-Hoc analysis was performed on control and all fiber-reinforced asphalt mixtures to further investigate the statistical significance between control and each fiber type specifically. Table 5 presents the ANOVA and post-Hoc results for performance tests conducted in this study.

As can be seen from Table 5, ANOVA results indicate no significant impact on cracking performance (IDEAL-CT p-value = 0.987 > 0.05). Post-Hoc analysis supports this by having all sigmoid values for all fiber types > 0.05. This further supports the observation made previously regarding impacts of fibers on cracking performance.

Table 5 also shows that the use of fibers had a significant impact rutting resistance of asphalt mixtures (APA rut depth p-value = 0.006). These results indicate that there was a significant difference (reduction in rutting) between at least one of the fiber-reinforced asphalt rut depth values and unreinforced (control) asphalt mixture. Furthermore, Post-Hoc analysis shows that PFA was the fiber that actually had a significant impact on APA rut depth (sigmoid value of 0.030). Flow Number (FN) statistical analysis showed no significant impact was observed between control and all fiber-reinforced asphalt mixtures (p-value = 0.175 and sigmoid values between 0.359 and 1.000 > 0.05). This supports the conflictive results shown in the data analysis of the FN test.

Cantabro durability test had a statistically significant difference among the mixtures (p-value = 0.000). Post-Hoc also supports these findings by having a sigmoid value of 0.000 for basalt, fiberglass and PFA and 0.018 for carbon all being lower than 0.05 which indicates significant impact for all fiber types when comparing to the control mixtures.

Table 5

Statistical Analysis for Impact of Fiber Types

Cantabro			IDEAL-CT		
Analysis of Variance (ANOVA)					
p-value			*p-value*		
0.000*			*0.987*		
Tukey's HSD Post-Hoc Analysis					
Control vs Fiber		*Sig.*	*Control vs Fiber*		*Sig.*
Control vs	Basalt	***0.000****	Control vs	Basalt	0.980
	Carbon	***0.018****		Carbon	0.985
	Fiberglass	***0.000****		Fiberglass	0.999
	PFA	***0.000****		PFA	0.992
APA Rut Depth			Flow Number (FN)		
Analysis of Variance (ANOVA)					
p-value			*p-value*		
0.006*			*0.175*		
Post-Hoc					
Control vs Fiber		*Sig.*	*Control vs Fiber*		*Sig.*
Control vs	Basalt	0.985	Control vs	Basalt	0.359
	Carbon	1.000		Carbon	0.377
	Fiberglass	1.000		Fiberglass	0.683
	PFA	***0.030****		PFA	1.000

*Statistically significant at a 95% confidence level.

Chapter 5

Impact of Fiber Dosage Rates

The evaluation of the effect of impact of fiber types, dosage rates, and binder content on volumetric properties and laboratory performance of asphalt mixture is presented in this chapter. The following subsections contain information on the fibers used, the experimental plan, results of mix design, and performance tests. This section will also provide a better understanding and an overall approach to evaluate interaction between fibers and asphalt binder and their impacts on asphalt mixture performance.

Material and Experimental Plan Used to Evaluate the Impact of Fiber Dosages

To evaluate the impact of different fiber dosage rates, three different fiber types—basalt, fiberglass, and carbon—were used to produce fiber-reinforced asphalt mixture specimens. PFA fiber as was not evaluated in this section because PFA has a different fiber dosage and mixing procedure than basalt, fiberglass and carbon fibers. Fiber properties were discussed previously in chapter 3 (Table 3.) The same aggregate type and gradation curve (diabase and FAA P-401) were used to evaluate the impact of fiber dosage rates on mix volumetrics and performance of asphalt mixtures. Furthermore, the same asphalt binder PG 76-22 was also used to evaluate fiber-reinforced asphalt mixtures. However, while obtaining PG 76-22 asphalt binder from the manufacturer, the new asphalt binder was a little different from previous asphalt binder used to evaluate impact of fiber types. To evaluate the difference between the previous and new asphalt binder, Dynamic Complex Modulus (DCM) was performed on asphalt samples using the new asphalt binder with the same gradation and binder content (i.e. 5.3% by total mix weight). The results were compared with previous asphalt binder and are presented in Figure 14.

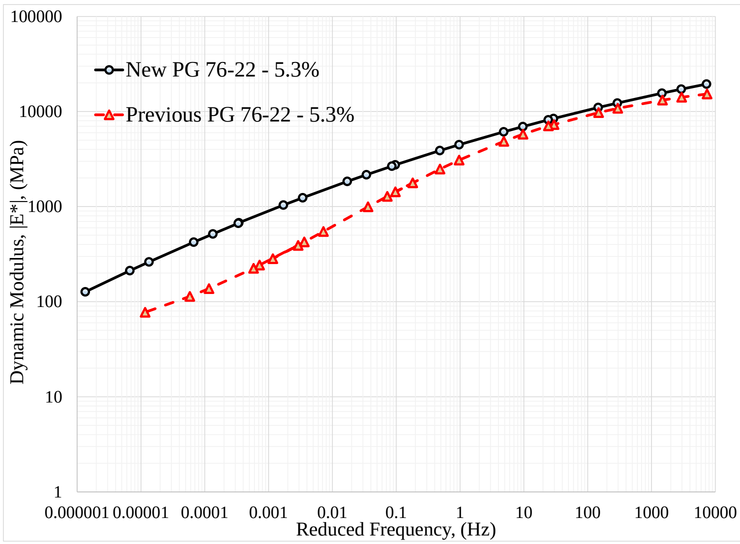


Figure 14. DCM comparison between previous and new PG 76-22 asphalt binder

As can be seen from Figure 14, |E*| for the new PG 76-22 asphalt binder was higher than previous PG 76-22 asphalt binder. This finding indicates the new PG 76-22 is stiffer than the previous PG 76-22 asphalt binder. Both PG 76-22 asphalt binders obtained from the manufacturer presented different rotational viscosity values. The rotational viscosity for the previous asphalt binder was 1.100/0.287 Pa-s whereas the new asphalt binder had 1.500/0.425 rotational viscosity. This indicates the new PG 76-22 asphalt binder has more rotational stiffness than the previous PG 76-22 asphalt binder. These findings agree with DCM results for both PG 76-22 asphalt binders. This results in more asphalt binder required to meet Superpave mix design requirements (i.e. 3.5% ±

0.5% AVC%). The framework for conducting mix design and performance evaluation for different fiber dosage rates is presented in Figure 15.

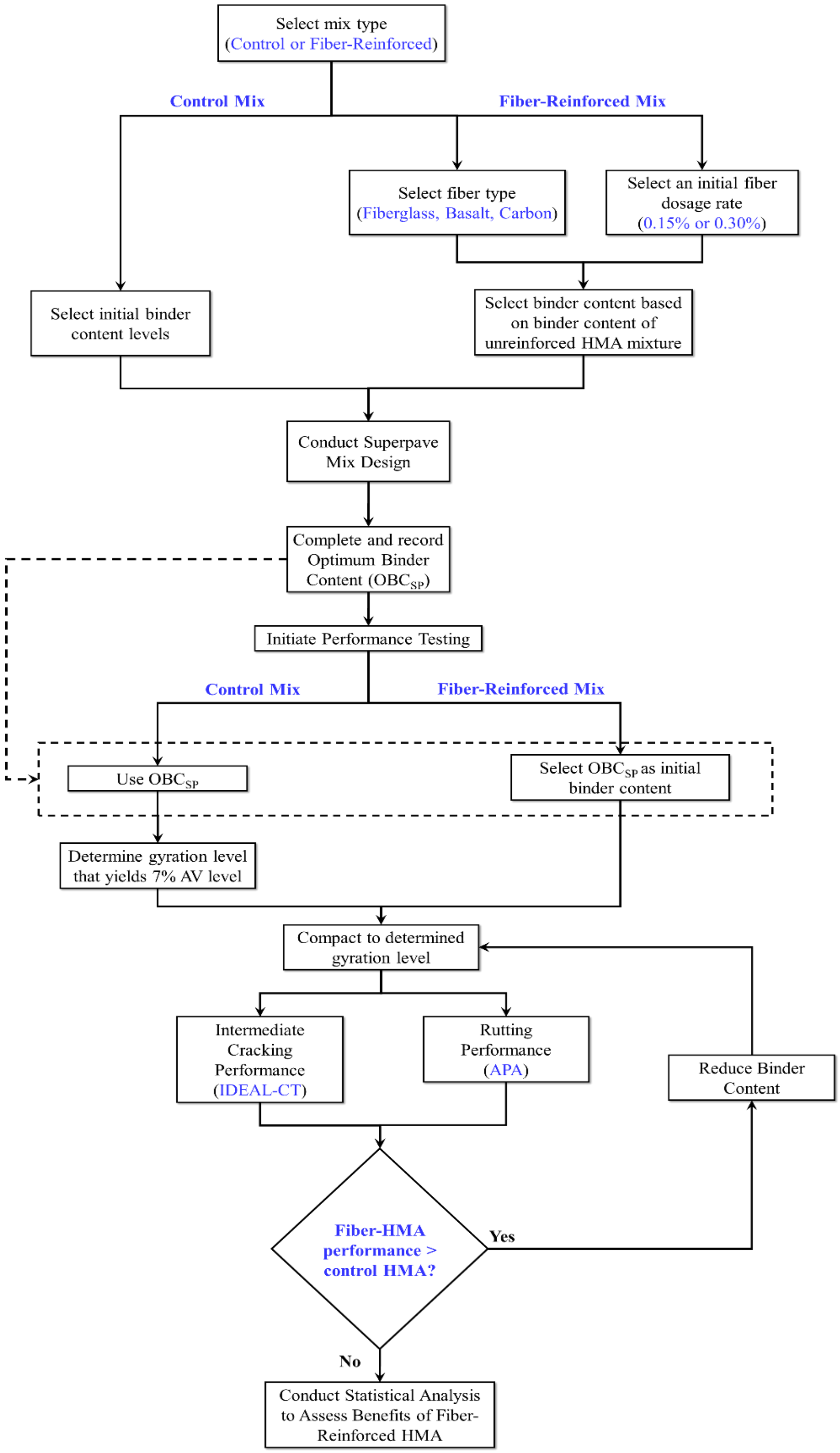


Figure 15. Experimental framework for developing performance-related mix design process for fiber-reinforced asphalt mixtures

Mixing Procedure and Experimental Plan

Fiber-reinforced asphalt mixtures were prepared following the fiber dispersion method. This method was selected because it showed greater consistency during mix design of fiber-reinforced asphalt mixtures compared to conventional dry laboratory mixing procedures presented in Chapter 4. The process is summarized as follows

1. Add heated aggregates to mixing bowl.

2. Add asphalt binder and mix for 30 seconds (until aggregates are coated with asphalt binder).

3. Add fibers every 15 seconds while mixing four separate times (60 seconds total).

4. Mix entire mix (aggregate, binder, and all fibers) for 90 seconds. (total mixing time should not exceed three minutes).

For the laboratory experimental plan, cracking and rutting performance tests were performed to evaluate the impacts of fiber types, dosage rates, and binder contents on asphalt performance. A common issue, however, when evaluating the performance of fiber-reinforced asphalt mixtures with high dosage rates is that these mixtures also require additional asphalt binder to meet volumetric requirements (Li et al., 2020; Cleven et al., 2000; Mahrez et al., 2010; Teherkhani et al., 2016; Park et al., 2015) and there is no clear methodology to separate the effects of fiber and binder on performance. For that reason, in this study a parametric performance evaluation of fiber-reinforced asphalt mixtures at varying binder contents was conducted to allow for better understanding of the interaction between fiber and binder content.Table 6 presents the testing plan performed on unreinforced and fiber-reinforced asphalt mixes. Binder contents were varied between 5.0% to 5.6% and 5.7% to 6.3% for dosage rates of 0.15% and 0.30%, respectively.

Table 6

Performance Experimental Plan for Impact of Fiber Dosage

Mix Types	**Fiber Dosage Rates, %**[1]	**Fibers**		**Number of replicates**
Mix Design	0.15, 0.30	Control, Basalt, Fiberglass, and Carbon		42 (21 G_{mb} and 21 G_{mm})
Mix Types	**Fiber Dosage Rates, %**[1]	**Binder Content Levels, %**[1]	**Performance Test**	**Number of replicates**
Control (Co)	-	5.6	APA	162 (6 for each mix combination & 6 for control)
Basalt (B)	0.15	5.0, 5.2, 5.4, 5.6, OBC		
Fiberglass (FG)			IDEAL-CT	81 (3 for each mix combination & 3 for control)
Carbon (Ca)	0.30	5.7, 5.9, 6.1, 6.3, OBC		
Total:				285 Samples
Grand Total: (With 135 samples in the previous chapter)				**420 Samples**

[1]Percent by total mix weight

Additional binder contents were also included in the experimental plan when Optimum Binder Content (OBC)—determined from asphalt mix design—did not fall within the considered binder content ranges. Indirect Tensile Strength Cracking Index

(IDEAL-CT) and Asphalt Pavement Analyzer (APA) tests were performed to evaluate cracking and rutting performance of fiber-reinforced asphalt mixtures, respectively.

Superpave Mix Design Results

Results from the mix design of asphalt mixtures are shown in Table 7.

Table 7

Mix Design Results

Mix ID	P_b (%)	G_{mb}	G_{mm}	G_{sb}[1]	AVC (%)	VMA (%)	V_{be} (%)	V_{ba} (%)	V_b (%)
Co/0.0/5.6	5.6	2.593	2.681	2.941	3.3	16.8	13.5	0.6	14.1
B/0.15/5.8	5.8	2.573	2.671	2.941	3.7	17.6	13.9	0.6	14.5
B/0.3/6.3	6.3	2.537	2.638	2.941	3.8	19.2	15.4	0.2	15.6
FG/0.15/5.6	5.6	2.584	2.682	2.941	3.7	17.1	13.5	0.7	14.2
FG/0.3/6.3	6.3	2.560	2.635	2.940	3.4	18.5	15.7	0.1	15.8
Ca/0.15/5.6	5.6	2.584	2.684	2.938	3.7	17.1	13.4	0.8	14.2
Ca/0.3/6.5	6.5	2.541	2.635	2.935	3.6	19.3	15.7	0.5	16.2

[1]Bulk specific gravity of the aggregate blend (G_{sb}) varied due to different fiber densities and dosage rates.

The control mixture required 5.6% binder content to meet all mix design requirements including 3.5% ± 0.5% AVC% and 15.0% minimum VMA%). For fiber-reinforced asphalt mixes with a fiber dosage of 0.15% by total mixture weight, there was a slight increase in optimum binder content of 0.2%. In the case of carbon and fiberglass, optimum binder content did not require any adjustment, and basalt required a slight increase in binder content (0.2% by total mix weight) to meet mix design requirements.

This was expected as this dosage rate is recommended by manufacturers based on its low impact on gradation evaluated in chapter 4.

In the case of higher fiber dosages (0.3% of total mix weight), major changes in binder content were necessary to meet mix design requirements. Basalt and fiberglass required similar increase in required optimum binder content of 0.7% (from 5.6% to 6.3%); whereas carbon fiber required an increase in binder content of 0.9% (from 5.6% to 6.5%). These results agree with findings highlighted previously from literature in which increased dosage rates require additional binder (Li et al., 2020; Cleven et al., 2000; Mahrez et al., 2010; Teherkhani et al., 2016; Park et al., 2015). Further, it can also be seen from Table 7 that all fiber types with 0.15% fiber dosage rate, had similar volumes of effective and absorbed binder (V_{be} and V_{ba}, respectively) compared to the control asphalt mixture. In contrast, the use of 0.3% fiber dosage resulted in higher V_{be}, but similar levels of V_{ba}.

The findings at the 0.3% dosage rate was unexpected as the current assumption is that additional fibers would require (or absorb) more binder in the mixing process due to fiber coating and absorption (Cleven et al., 2000). However, Table 7, highlights that the same amount of binder was absorbed regardless of the type and/or amount of fibers (within the ranges considered in this study). One potential reason for the need of additional binder content at higher fiber dosage rates could be due to an increase in specimen volume (hereinafter referred to as reflecting height) after 24 hours of cooling at room temperature.

Reflecting Height

While producing mix design specimens, it was observed that the height of each fiber-reinforced asphalt mixture specimen was increasing during cooling time after compaction. This was discovered by comparing final height during compaction recorded by Superpave Gyrator Compactor (SGC) and a height measurement using calipers 24 hours after compaction. Figure 16 presents reflecting height measurements for control and fiber-reinforced asphalt mix design specimens. As can be seen from Figure 16a, the addition of 0.15% by total mix weight had a similar reflecting height compared to control with an increase of 0.0 mm to 0.2 mm in specimen height, depending on fiber type. Similarly, for these specimens, there was minimal impact on the binder content needed to meet mix design requirements (Table 7). When adding 0.3% fiber dosage, however, all fiber-reinforced asphalt mixes had higher reflecting heights compared to control. Basalt and fiberglass had reflecting heights of 1.0 mm and 0.8 mm, respectively, which translated to an increase in binder content (Pb) of 0.7%. Carbon fiber had the greatest reflecting height of 2.4 mm, which also required the greatest increase in binder content (Pb) of 0.9%.

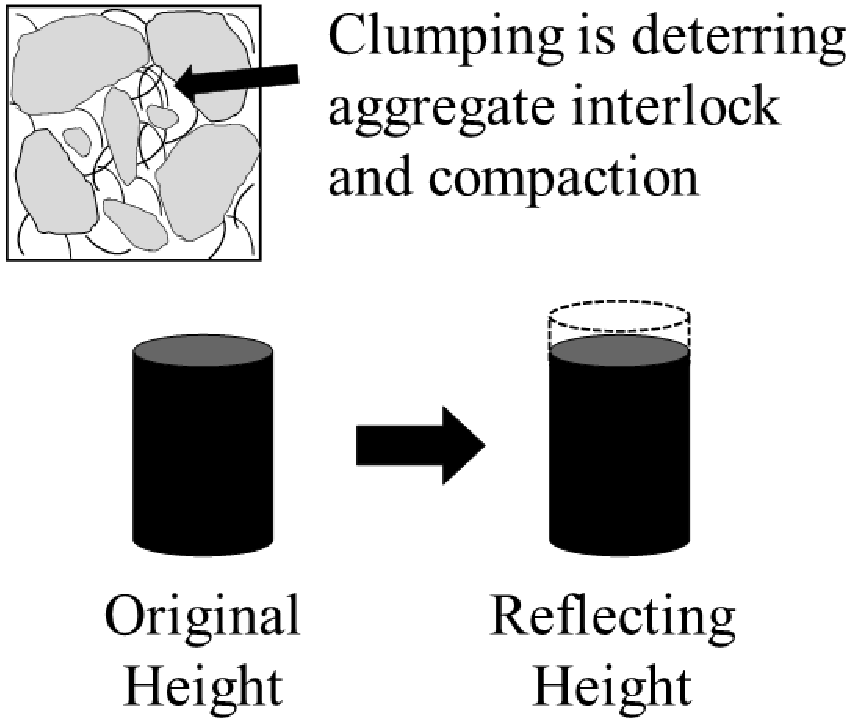


Figure 16. Clumping interlock inside asphalt specimen and rebounding height of asphalt mixtures.

Reflecting heights presented in Figures 16 and 17 highlight an overall resistance to aggregate compaction and interlock. In this phenomenon, it is believed that the internal forces within mix force an expansion in specimen immediately after compaction load is removed. These internal forces may be a result of bending or clumping of fibers between aggregate particles, which hinder aggregate compaction and interlock. Figure 16 presents an illustration of this behavior at micro- and macro-structural levels. Thus, because the specimen volume increases after compaction, more binder is needed to fill these newly developed voids to meet mix design requirements. Results of reflecting height are presented in Figure 17.

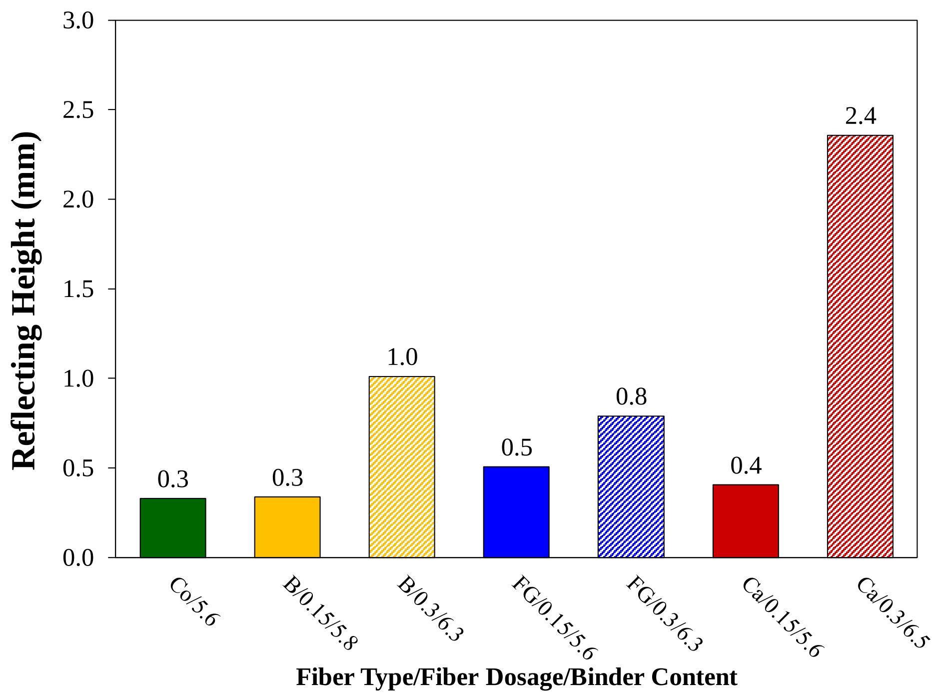
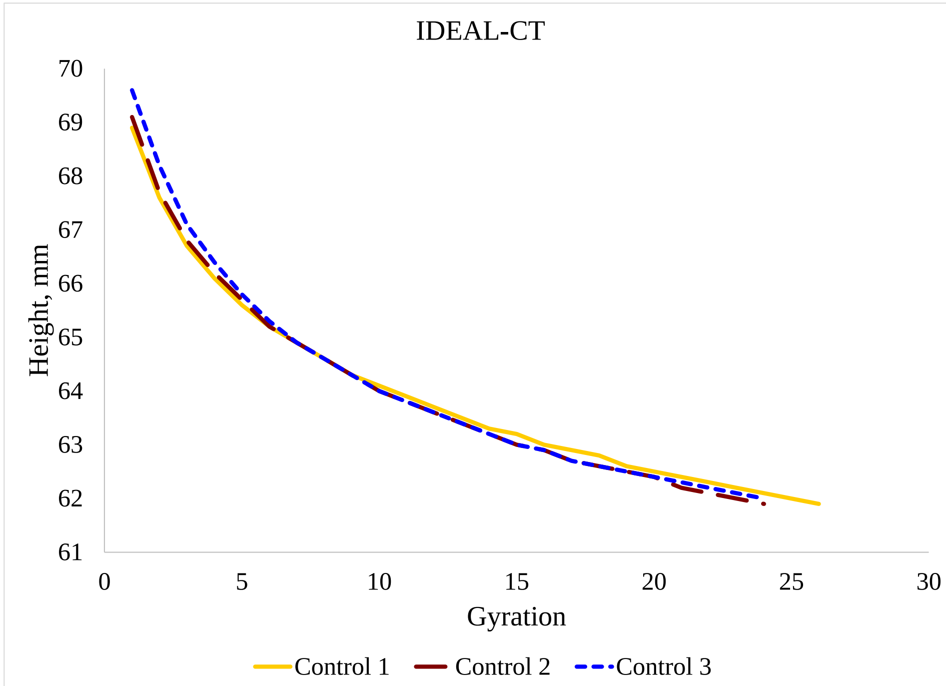


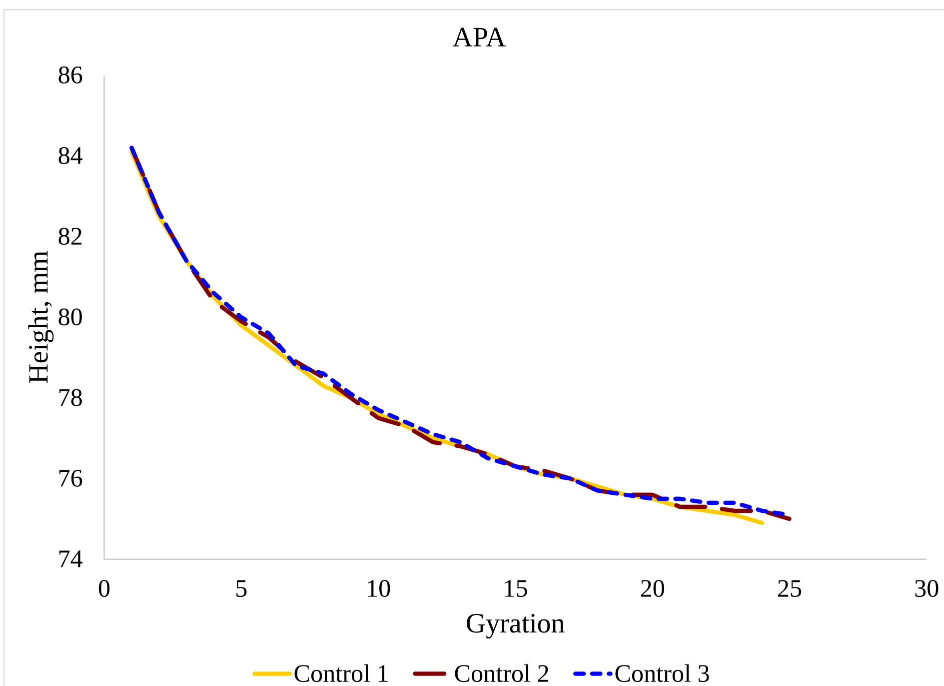
Figure 17. Mix design reflecting height results.

Selection of Compaction Effort

As seen in Figures 16 and 17, reflecting height poses a challenge to conventional volumetric properties and air void measurements of fiber-reinforced asphalt mixtures. This is especially true when evaluating the performance of asphalt mixtures, where air void level is typically kept consistent (e.g. 7.0% ± 0.5%) to represent field compaction density. In this study, however, due to the reflecting heights and varying binder content for each asphalt mixture, the air void level could not be held constant for every mix combination that was tested. Therefore, before evaluation of the performance of fiber-reinforced asphalt mixtures, a standard level of compaction effort was determined to fabricate all fiber-reinforced asphalt performance specimens based on the unreinforced asphalt mixture. For this purpose, the number of gyrations ($N_{performance}$) was determined using the data collected and recorded by the Superpave gyratory compactor presented in Figure 18. For this study, $N_{performance}$ was selected to be 25 based on the $N_{performance}$ required for control specimens to reach an air void level of 7.0% ± 0.5% and was kept constant for all performance tests and asphalt mixtures considered in this study.



(a) IDEAL-CT



(b) APA.

Figure 18. Height vs gyration level for the control fiber-reinforced mixtures

Laboratory Performance Results and Discussion

As shown in Table 7, the laboratory experimental plan included IDEAL-CT and APA to evaluate cracking and rutting performance of fiber-reinforced asphalt mixtures, respectively. The discussion of each test focuses primarily on two major comparisons: (i) fiber-reinforced asphalt mixtures at optimum binder content and (ii) fiber-reinforced asphalt mixtures at the optimum binder content of the control asphalt mixture (5.6%). The first comparison highlights the impact of fibers using conventional volumetric design, whereas the second comparison isolates the impact of fibers (from asphalt binder) on laboratory performance. Figures 19, 20, and 21 presents CT_{index} for basalt, fiberglass and carbon mix combinations, respectively. Additionally, because air void contents were not controlled due to the reflecting heights, control specimens were prepared at two different AVC levels (7% and 10%) to evaluate the sensitivity of the test to air voids and provide a benchmark for comparisons.

Impact of fiber type and dosage rate on asphalt cracking performance. This section contains two sections of evaluation: comparison between fiber-reinforced asphalt mixtures at optimum binder content (OBC), and comparison between fiber-reinforced asphalt mixtures at control binder content (5.6%). These two-way evaluations were performed to separate the assessment between the effect of fiber types, dosage rates, and binder content of fiber reinforced asphalt mixtures.

Comparison between fiber-reinforced asphalt mixtures at optimum binder content (OBC). As can be seen in Figure 19, the control mixes exhibited CT_{index} values of 266, whereas basalt fibers measured showed an improved in CT_{index} with values of 405 and 472 for fiber dosages of 0.15% and 0.3% at optimum binder content, respectively. Fiberglass fibers (Figure 20) did not show an improvement at 0.15% dosage rate and optimum binder content compared to control with a CT-index value of 212 but did shown an improvement at 0.30% with a CT_{index} value of 413. Carbon fibers (Figure 21) followed a similar trend to fiberglass fibers, in which there was little impact at 0.15% dosage rate with a CT_{index} of 324 and a larger impact at 0.30% dosage rate with a CT_{index} of 765. From Figures 19, 20, and 21, it can be seen that the dosage rate of 0.30% had higher CT_{index} values compared to the CT_{index} values at 0.15% dosage rate. This may have been the case due to the increased amount of fiber (increase in dosage rate of 0.15%) or increase in binder content (between 0.7% and 0.9%). Therefore, as mentioned previously, comparison of cracking performance at similar binder contents to the control (5.6%) will provide a better understanding of interaction between fibers and binder and their impact on cracking performance.

Comparison between fiber-reinforced asphalt mixtures at control binder content (5.6%). As can be seen from Figure 19, when using basalt fibers at similar binder content to control (5.6%) there was little impact on CT_{index}. In fact, the CT_{index} ¬for basalt-reinforced asphalt mixtures with dosage rates of 0.15% (B/0.15/5.6) and 0.30% (B/0.30/5.7) were 235 and 337, respectively. Similar observations to the basalt fibers were observed when using fiberglass fibers (Figure 20). When using fiberglass fibers at dosage rates of 0.15% (FG/0.15/5.6) and 0.30% (FG/0.3/5.6), the CTindex was 212 and 360, respectively. Compared to the control mixture with CT_{index} of 266, both basalt and fiberglass-reinforced asphalt mixtures (Figures 19 and 20) saw slight improvements in CT_{index} at the 0.30% dosage rate, but no impact at 0.15% dosage rate. In contrast to basalt and fiberglass fibers, carbon fibers (Figure 21), at dosage rates of 0.15% (Ca/0.15/5.6) and 0.30% (Ca/0.3/5.7) showed improvement in cracking resistance with CT_{index} values of 324 and 484, respectively. Thus, carbon fibers show improvement in CT_{index} regardless of dosage rate. Interestingly, carbon fibers reached an average air void level of 11.4% (holding compaction effort constant), but still had greater CT_{index} values (484) compared to control (266).

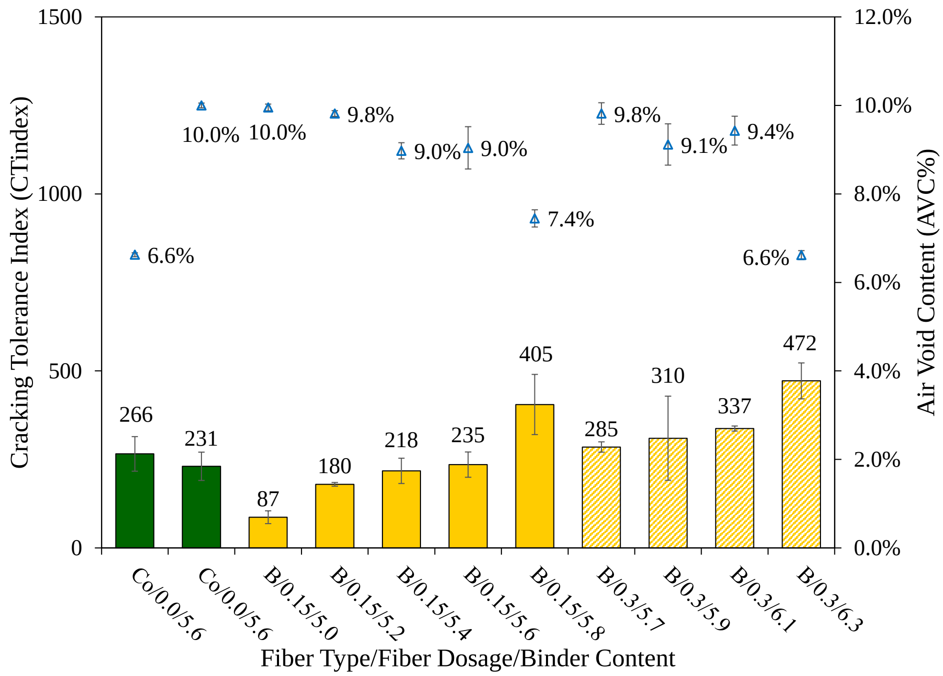


Figure 19. IDEAL-CT laboratory test results for basalt asphalt mix combinations

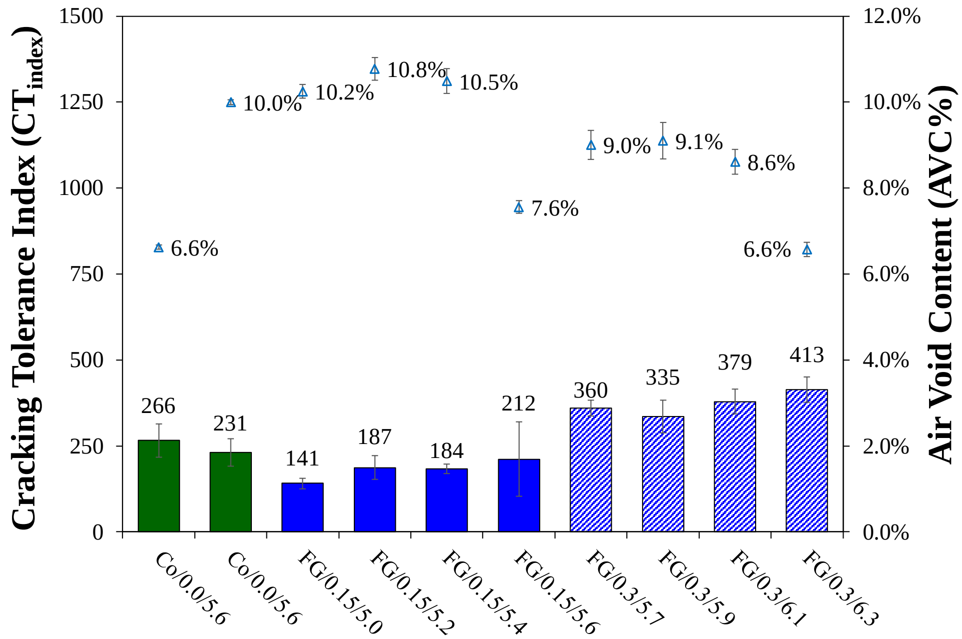


Figure 20. IDEAL-CT laboratory test results for Fiberglass asphalt mix combinations

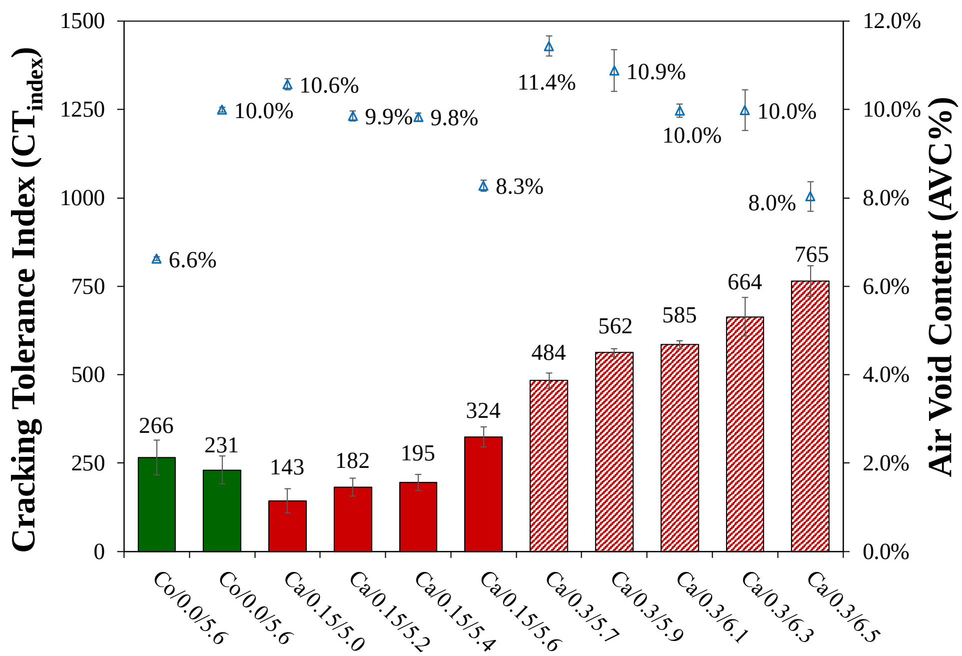


Figure 21. IDEAL-CT laboratory test results for carbon asphalt mix combinations

Impact of fiber type and dosage rate on asphalt rutting performance.

Comparison between fiber-reinforced asphalt mixtures at optimum binder content (OBC). When comparing rutting performance at 0.15% dosage rate and OBC, basalt (Figure 22), fiberglass (Figure 23), and carbon (Figure 24) had APA rutting depths of 5.24 mm, 4.20 mm, and 4.69 mm, respectively. In comparison to control (APA rut depth of 4.18 mm), all fiber types at 0.15% dosage rate had relatively little impact on APA rutting performance. When using fibers at 0.30% dosage rate and OBC, basalt, fiberglass, and carbon-reinforced asphalt mixtures showed APA rut depths of 6.46 mm, 6.45 mm, and 7.27 mm. In comparison to the control mix, the 0.30% dosage rate exhibited much greater APA rut depths with increases in APA rut depth of 2.3 mm (basalt and fiberglass) to 3.1 mm (carbon). One reason for this finding is due to the fact that the fiber-reinforced asphalt mixtures at 0.30% dosage had higher OBC than the control and asphalt mixtures using 0.15% dosage rate.

Comparison between fiber-reinforced asphalt mixtures at control binder content (5.6%). As mentioned previously, direct comparisons of each mix combination at the control binder content (5.6%) provide a clearer understanding of the impact of fibers within each asphalt mixture. Fiber mixes prepared with 0.15% dosage rate had OBC similar to 5.6% and, as mentioned previously, had little impact on the APA rut depth. When evaluating each fiber at the 0.30% fiber dosage rate and 5.7% binder content, the APA rut depth for basalt, fiberglass, and carbon was 5.88 mm, 5.82 mm, and 6.64 mm, respectively. These rut depths were slightly lower compared to the rut depths measured at OBC. Although the rut depths decreased compared to OBC, the APA rut depths were greater than the control mix with increases in APA rut of 1.7 mm (basalt and fiberglass) and 2.46 mm (carbon). Furthermore, the basalt fibers at 5.7% binder content had reduced rutting performance. Thus, it can be seen from Figures 22, 23, and 24 that the use of 0.3% fiber dosages (regardless of fiber type) negatively impacted the rutting performance of asphalt mixtures.

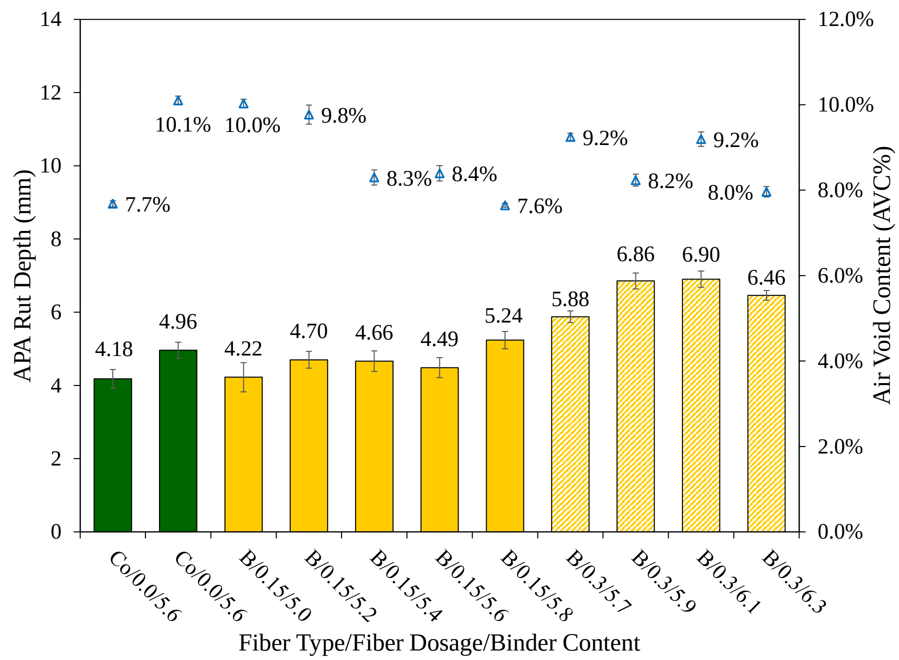


Figure 22. APA laboratory test results for basalt asphalt mix combinations

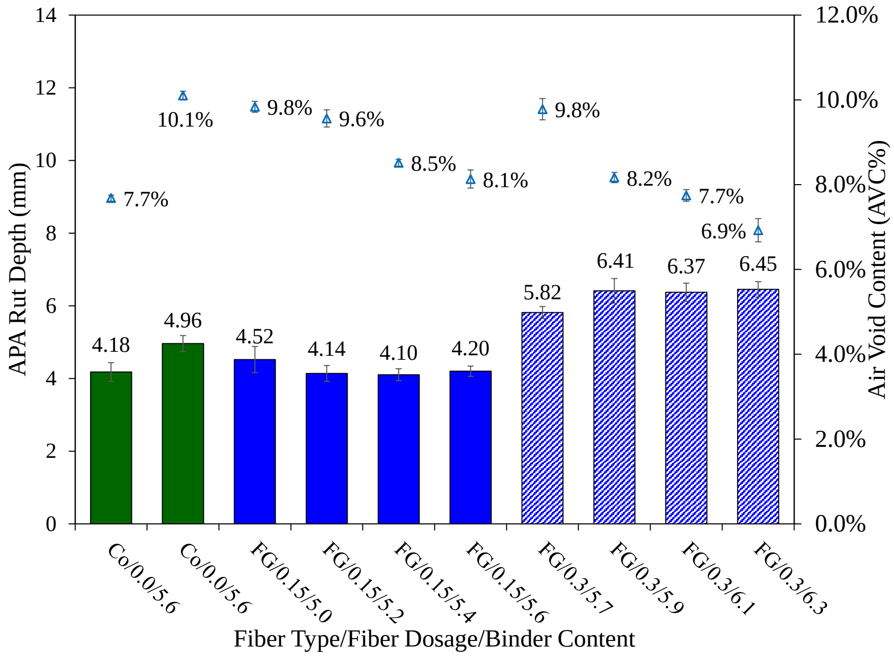


Figure 23. APA laboratory test results for fiberglass asphalt mix combinations

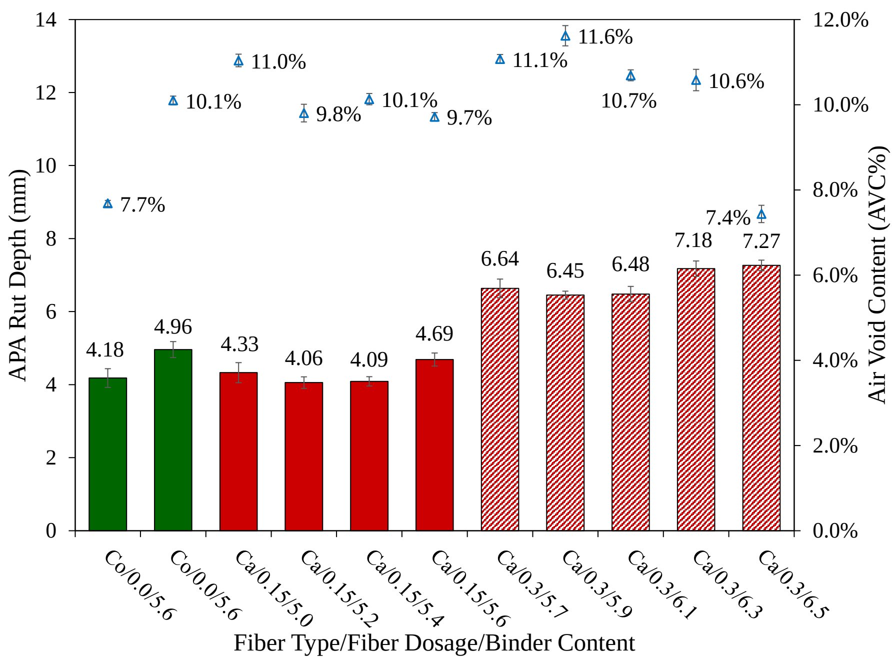


Figure 24. APA laboratory test results for carbon asphalt mix combinations

Statistical analysis. Statistical analyses were performed to compare laboratory performance (cracking and rutting) of control and fiber-reinforced asphalt mixtures. An Analysis of Variance (ANOVA) was conducted with a Tukey's Honestly Significant Difference (HSD) post-hoc analysis to investigate the statistical difference between control and each fiber type and dosage rate. Both statistical tests were performed at a 95% confidence level (p-value <= 0.05 for a significant difference). Table 8, and 9 presents the results of statistical analysis for IDEAL-CT and APA performance tests, respectively. As can be seen from Table 8, ANOVA test indicated a significant impact between for each fiber type with p-values less than 0.05. Although, ANOVA tests indicated a significant impact, Tukey's HSD post-hoc analysis allows for direct comparison between unreinforced and fiber-reinforced asphalt mixes. The post-hoc analysis identified that a fiber dosage rate of 0.15% does not significantly impact cracking performance regardless of fiber type. This finding is justified as similar findings have been observed in literature for comparable mixes and fiber types. At an increased dosage rate of 0.30%, however, a statistically significant impact was observed for basalt and carbon fibers. When using basalt fibers at a dosage rate of 0.30%, a statistically significant improvement was observed at optimum binder content with a p-value of 0.044. Although an improvement was observed under this mix combination, this mix also had more binder than control (unreinforced) asphalt mix. Thus, it is inconclusive whether the increase in cracking performance was due to fibers or increased binder content. In contrast to basalt fibers, carbon fibers (at a dosage rate of 0.30%) showed a statistically significant improvement in cracking performance was observed at all binder contents between 5.7% and 6.5%. These results more conclusively identify that the use of carbon fibers at higher dosage rates can improve cracking performance of asphalt mixtures. It is also noted that there was no mix combination using fiberglass fibers that resulted in a statistically significant improvement in cracking performance.

Table 9 presents the ANOVA and post-hoc analysis for APA rutting test. A statistical significance was observed for each fiber type indicating that measured rutting was statistically significant for at least one testing combination. Post-hoc analysis show that 0.15% fiber dosage rate had no statistical impact on rutting performance compared to the control asphalt mixture, regardless of fiber type. Furthermore, the use of fibers with a 0.3% dosage rate had a statistical significance in rutting performance compared to the control asphalt mixture, regardless of fiber type and binder content. As mentioned previously and shown in Figure 22, 23, and 24, this statistically significant finding was due to the negative effects of fibers on rutting performance of the asphalt mixture. Therefore, no combination of fiber types, dosage rates, and binder content considered in this study statistically improved the rutting performance.

Table 8

Statistical Analysis on Cracking Performance Test Results.

Cracking Performance Comparison using IDEAL-CT					
Control vs Basalt		Control vs Carbon		Control vs Fiberglass	
Analysis of Variance (ANOVA)					
p-value		*p-value*		*p-value*	
*0.000**		*0.000**		*0.001**	
Tukey's HSD Post-Hoc Analysis					
Fiber Dosage Rate: 0.15%					
Binder Content	***Sig.***	**Binder Content**	***Sig.***	**Binder Content**	
5.0%	0.090	5.0%	0.323	5.0%	0.430
5.2%	0.838	5.2%	0.770	5.2%	0.878
5.4%	0.998	5.4%	0.895	5.4%	0.855
5.6%	1.000	5.6%^{SP}	0.963	5.6%^{SP}	0.993
5.8%^{SP}	0.301	-	-	-	-
Fiber Dosage Rate: 0.30%					
5.7%	1.000	5.7%	***0.025****	5.7%	0.748
5.9%	0.999	5.9%	***0.001****	5.9%	0.752
6.1%	0.969	6.1%	***0.001****	6.1%	0.544
6.3%^{SP}	***0.035****	6.3%	***0.000****	6.3%^{SP}	0.237
-	-	6.5%^{SP}	***0.000****	-	-

Table 9

Statistical Analysis on Rutting Performance Test Results.

Rutting Performance Comparison using APA					
Control vs Basalt		Control vs Carbon		Control vs Fiberglass	
Analysis of Variance (ANOVA)					
p-value		*p-value*		*p-value*	
*0.000**		*0.000**		*0.000**	
Tukey's HSD Post-Hoc Analysis					
Fiber Dosage Rate: 0.15%					
5.0%	1.000	5.0%	1.000	5.0%	1.000
5.2%	0.911	5.2%	1.000	5.2%	1.000
5.4%	0.943	5.4%	1.000	5.4%	1.000
5.6%	0.998	5.6%[SP]	0.761	5.6%[SP]	1.000
5.8%[SP]	0.108	-	-	-	-
Fiber Dosage Rate: 0.30%					
5.7%	***0.000****	5.7%	***0.000****	5.7%	***0.000****
5.9%	***0.000****	5.9%	***0.000****	5.9%	***0.000****
6.1%	***0.000****	6.1%	***0.001****	6.1%	***0.000****
6.3%[SP]	***0.000****	6.3%	***0.000****	6.3%[SP]	***0.000****
-	-	6.5%[SP]	***0.000****	-	-

*Denotes statistically significant condition at 95% confidence level/
[SP] Optimum binder content

Chapter 6

Summary of Findings, Conclusions, Recommendations & Future Work

Summary of Findings

The goal of this study was to evaluate the impact of different fiber types and dosage rates on asphalt mix design properties and laboratory performance. To evaluate the impact of fiber types, four different fiber types (fiberglass, basalt, carbon, and polyolefin/aramid blend) were used throughout the study. The dosage rate used was 0.16% by total mix weight which was recommended by the manufacturer. Furthermore, two different mixing procedures—proportional dispersion and dry method—were used during the asphalt mixtures' mix design process to determine the method with least variability. A laboratory experimental plan was also adopted to evaluate the performance of fiber-reinforced asphalt mixtures. Five different performance tests were adopted in the laboratory experimental plan to investigate the impact of fiber types on performance of fiber-reinforced asphalt mixtures.

Three of these fibers (fiberglass, basalt, and carbon) were used to evaluate the impact of fiber dosage rates on mix volumetrics and the overall performance of asphalt mixtures. In addition, two different fiber dosage rates—0.15% and 0.3% by total mix weight—and varying binder contents—from 5.0% to 6.5%--were used to determine the effect of different fiber dosages on volumetrics and performance of fiber-reinforced asphalt mixtures. Two performance tests (IDEAL-CT for cracking and APA for rutting performance) were used to evaluate the impact of fiber dosage of fiber-reinforced asphalt mixtures. Based on the laboratory experimental results and the subsequent statistical analyses, the following conclusions were drawn:

- The dry mixing procedure exhibited less consistency, in comparison to the proportional dispersion method, and showed higher variability in measured volumetric properties (i.e., G_{mb} and G_{mm}) of fiber-reinforced mixtures.
- For 0.16% and 0.05% fiber dosages, $|E^*|$ values at the high frequency (10 Hz and higher) for unreinforced and all fiber-reinforced asphalt mixtures were similar. At low frequencies (less than 10 Hz), the Carbon and PFA-reinforced asphalt mixtures had greater $|E^*|$ values than all other asphalt mixtures; indicating the potential for better rutting performance using these fiber types and dosage rates.
- The use of 0.16% and 0.05% fiber dosage rates improved the overall asphalt mix durability with an average improvement of 1.78% in Cantabro loss values. The basalt fiber type showed the best durability performance with a Cantabro loss value of 2.83%.
- Fiber dosage rate of 0.15%, and 0.16% by total mix weight (for basalt, fiberglass, and carbon) and 0.05% by total mix weight (for PFA fibers) had little to no impact on volumetrics. Fiber dosage rate of 0.30%, however, required an increase of 0.5% to 0.7% in binder content to meet mix design requirements depending on the fiber type.
- Increases in specimen height (referred to as reflecting height) were observed in fiber-reinforced asphalt mixtures 24 hours after specimen compaction. Fiber dosage rate of 0.30% resulted in the greatest reflecting heights varying between 0.8 mm and 2.4 mm, on average, depending on the fiber type.

- Fiber dosage rate of 0.15%, 0.16%, and 0.05% showed no improvement in CT_{index} for all fiber types when reinforcing asphalt mixtures. ANOVA and post-hoc results supported these findings by showing no statistically significant difference in CT_{index}.
- Fiber dosage rate of 0.30% dosage rate showed an improvement in CT_{index} for basalt and carbon fibers. ANOVA and post-hoc results identified that basalt fibers improved CT_{index} at the mix design binder content; whereas carbon fibers improved CT_{index} at all binder contents. No improvement in CT_{index} was found for fiberglass fibers.
- All fiber types at 0.15%, and 0.16% dosage rates exhibited similar APA rut depths compared to the control specimens. PFA reinforced mixtures with fiber dosage of 0.05% by total mix weight had the highest rutting resistance (lowest APA rut depth values) with an average rut depth of 2.163 mm (an improvement of 0.6 mm over the unreinforced asphalt mixture). Furthermore, APA rut depth increased for all fiber types when used at 0.30% dosage rate to an average rut depth of 6.55 mm. ANOVA and post-hoc found that all fiber types negatively impacted the APA rut depth when used at 0.30% dosage rate.

Conclusions and Recommendations

Based on the findings from this study, the following conclusions can be found:

- **Different Mixing Methods**: The use of proportional dispersion method showed less variability compared to traditional dry mixing method, Therefore, the proportional dispersion method is recommended in future production of fiber-reinforced asphalt laboratory mixtures

- **Fiber Dosage & Optimum Binder Content**: Use of all fibers at 0.16%, 0.15% and 0.05% dosages had little to no impact on optimum binder content, as compared to the control. Higher dosages, however, required greater binder contents to meet air void specifications.
- **Fiber Type & Laboratory Performance:** Carbon fibers were the only fiber type that showed an improvement in cracking resistance, particularly at dosage rates of 0.30%. PFA showed an ability to improve rutting resistance at 0.05% fiber dosage.
- **Reflecting Height & Volumetric Properties:** Fiber-reinforced asphalt mixtures exhibited changes in specimen height causing higher air void contents. Thus, performance testing at different binder contents using a constant compaction effort (such as number of gyrations) was the only method capable of isolating the benefits of using fibers in asphalt mixtures.
- **Mix Design Methods for Fiber-Reinforced Asphalt Mixtures:** Reflecting height observed in fiber-reinforced asphalt mixtures posed unique challenges with using conventional volumetric approaches to design fiber-reinforced asphalt mixture. Further, it was observed from the performance testing that the benefits of fiber were able to offset the additional air in some cases. Therefore, alternative mix design approaches, such as a hybrid approach (both volumetric- and performance-based), are necessary to design fiber-reinforced asphalt mixtures.

Future Work

Future research can include the development of a unique mix design approach for fiber-reinforced asphalt mixtures that consider the impacts of fiber on air void measurements and laboratory. The design approach must include a consistent level of compaction (i.e. number of gyrations) rather than conventional air void measurements due to reflecting heights. Beyond mix design, an investigation of the long-term cracking performance is necessary to explore the impacts of oxidation on fiber-reinforced asphalt mixtures. Full-scale testing and life-cycle cost analysis will also be beneficial to better understand the monetary benefits of including fibers in asphalt mixtures.

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