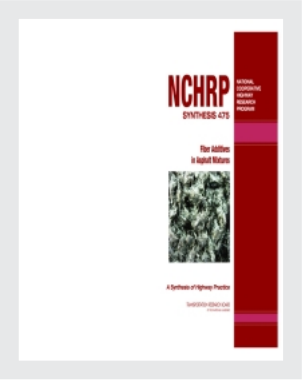

Fiber Additives in Asphalt Mixtures

DETAILS

50 pages | 8.5 x 11 | PAPERBACK
ISBN 978-0-309-27177-6 | DOI 10.17226/22191

AUTHORS

Rebecca S. McDaniel

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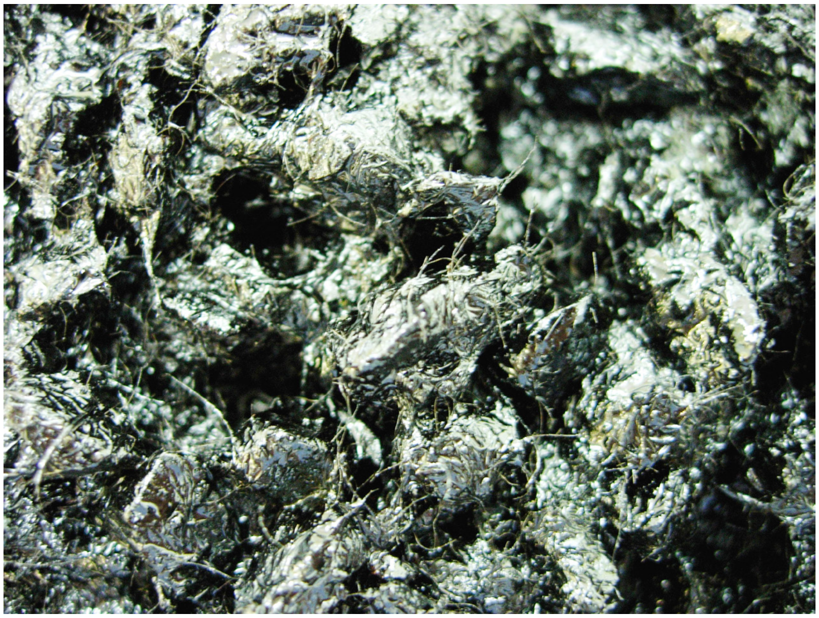
Fiber Additives in Asphalt Mixtures



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Fiber Additives in Asphalt Mixtures

A Synthesis of Highway Practice

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Rebecca S. McDaniel
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NCHRP SYNTHESIS 475
Project 20-05 (Topic 45-15)
ISSN 0547-5570
ISBN 978-0-309-27177-6
Library of Congress Control No. 2015932061

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are available from:

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Cover figure: Close-up of polymer fibers in a stone matrix asphalt mixture. Photo by: Krzysztof Blazejowski.

FOREWORD

Highway administrators, engineers, and researchers often face problems for which information already exists, either in documented form or as undocumented experience and practice. This information may be fragmented, scattered, and unevaluated. As a consequence, full knowledge of what has been learned about a problem may not be brought to bear on its solution. Costly research findings may go unused, valuable experience may be overlooked, and due consideration may not be given to recommended practices for solving or alleviating the problem.

There is information on nearly every subject of concern to highway administrators and engineers. Much of it derives from research or from the work of practitioners faced with problems in their day-to-day work. To provide a systematic means for assembling and evaluating such useful information and to make it available to the entire highway community, the American Association of State Highway and Transportation Officials—through the mechanism of the National Cooperative Highway Research Program—authorized the Transportation Research Board to undertake a continuing study. This study, NCHRP Project 20-5, "Synthesis of Information Related to Highway Problems," searches out and synthesizes useful knowledge from all available sources and prepares concise, documented reports on specific topics. Reports from this endeavor constitute an NCHRP report series, *Synthesis of Highway Practice*.

This synthesis series reports on current knowledge and practice, in a compact format, without the detailed directions usually found in handbooks or design manuals. Each report in the series provides a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems.

PREFACE

By Donna L. Vlasak
Senior Program Officer
Transportation
Research Board

The report documents the current state of the practice regarding the use of fiber additives in asphalt mixtures. It outlines the many types of fibers that have been used, their properties and how they are tested, mix design tests for fiber mixes, the types of applications in which fibers have been used, and lab and performance of fiber mixes. This synthesis can aid state asphalt engineers and researchers on the use of fibers.

A literature review and detailed survey responses from 48 of 50 state agencies, yielding a response rate of 96%, are provided. Also, six case examples offer more detailed information on the use of fibers.

Rebecca S. McDaniel, Purdue University, West Lafayette, Indiana, collected and synthesized the information and wrote the report. The members of the topic panel are acknowledged on the preceding page. This synthesis is an immediately useful document that records the practices that were acceptable with the limitations of the knowledge available at the time of its preparation. As progress in research and practice continues, new knowledge will be added to that now at hand.

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Note: Many of the photographs, figures, and tables in this report have been converted from color to grayscale for printing. The electronic version of the report (posted on the web at www.trb.org) retains the color versions.

FIBER ADDITIVES IN ASPHALT MIXTURES

SUMMARY

This synthesis explores the state of knowledge and state of the practice regarding the use of fiber additives in asphalt mixtures. It outlines the many types of fibers that have been used, their properties and how they are tested, mix design tests for fiber mixes, the types of applications in which fibers have been used, and lab and field performance of fiber mixes, among other topics.

The information in this synthesis was gathered through a thorough review of the available U.S. and international literature. In addition, a survey of U.S. and Canadian state/provincial agencies was conducted to determine the current status of fiber asphalt use. The U.S. state response rate to the survey was 96.0% (48 of 50). Numerous international asphalt engineers and researchers were contacted by e-mail to gather information on the use of fibers and on current international research.

About 28 states report using fiber in asphalt mixes. By far the majority of the use is in stone matrix asphalt (SMA) and open-graded or porous friction courses (OGFCs/PFCs) to control draindown of the binder from the mix. In the past, fibers were used in dense-graded mixes in some states, but that usage has decreased in the past 20 years or so. Use of SMAs and porous mixes is also on the decline in some states because of the high costs, but that situation is fluid and subject to change.

A wide variety of fiber types has been used in asphalt mixtures, including cellulose, mineral, synthetic polymer, and glass fibers, as well as some less common fiber types. Recycled fiber materials—such as newsprint, carpet fibers, and recycled tire fibers—have also been used. These different types of fibers have benefits and disadvantages that make them better suited for some applications than others. For example, cellulose is not strong in tension, but it is absorbent and holds asphalt, therefore it is well-suited to reducing draindown in open-graded mixes but not for reinforcing dense-graded concrete. Also, because of the different applications, sources, and types of fibers, test methods used to characterize them vary.

Typically, asphalt mixtures with fibers are designed using the same procedures as conventional mixtures. The only common addition is the use of a draindown test for SMA and OGFC mixes. Some types of fibers, particularly those that are highly absorptive or have a high surface area, require increased binder contents, which may improve mix durability but also may increase costs. Fiber quality is ensured through supplier certification in most states where fiber properties are specified.

Mixture production and pavement construction are also typically similar to conventional construction practices. The only difference in mix production equipment is the presence of a mechanism to introduce fibers into the asphalt mix plant. This may be accomplished by blowing loose or pelletized fibers into a drum mix plant (typically through the reclaimed asphalt pavement collar) or by adding premeasured, meltable bags of fibers into the pug mill

or weigh hopper on a batch plant. There are other, less common methods as well. Handling and storing fibers properly at the production facility are important to ensure the success of the fiber addition.

A great deal of research has been conducted over nearly 50 years on the use of fibers in asphalt. Much of this research has focused on the laboratory and field behavior of fiber-modified asphalt binders and mixtures. The results of the research have been mixed, especially regarding the use of fibers in dense-graded mixtures. In some cases, fibers have reportedly improved the rutting and cracking tendencies of binders and dense mixes; in other cases, there has been no significant improvement. Generally, fibers appear to be more effective at improving the performance of marginal or lower-quality mixtures. Fibers have rarely been detrimental to performance in dense mixes, but if they do not improve performance, they may not be cost-effective. In SMA and OGFC mixes, fibers have clearly been shown to reduce draindown and are commonly used, although alternative materials—such as polymer-modified binders and recycled asphalt shingles—can be used.

The survey results in chapter three show that 30 of 50 states currently allow or require the use of fibers in some asphalt mixtures. By far the most common use is in SMA and OGFC mixes. A few other states indicated that they would use fibers but are currently not constructing SMAs or OGFCs. For SMAs and OGFCs, the use of cellulose or mineral fibers is typical. The few current applications of fibers in dense-graded mixes use various synthetic polymer fibers. Information on the cost-effectiveness of the use of fibers in different applications is almost nonexistent.

The use of fibers internationally is quite similar to that in the United States; that is, the use of cellulose or mineral fibers in gap- and open-graded mixtures is routine in many countries. There appears to be growing interest in developing parts of the world in using locally available plant-based materials—such as coconut, jute, hemp, and sisal—as sources of fibers; this allows the benefits of fibers to be taken advantage of economically while creating a market for locally produced materials.

Case examples of the use of fibers in asphalt by local and state agencies are provided in chapter four. The first case example outlines the common questions an agency might face when it considers the possibility of using fibers. The second describes the history of one agency that used large quantities of fibers in the past to reinforce dense-graded mixtures but has reduced usage drastically after making other changes in its mix design procedures and specifications. A third case example describes another agency's path toward implementing fibers in open- and gap-graded mixtures, and the contractors' experiences as they began using the materials. The last two case examples highlight ongoing research efforts; one in a state with little to no prior experience with the use of fibers in asphalt and the other in a state that uses fibers extensively in SMA and OGFC, and is exploring using them in dense-graded mixtures as well.

The information reported here shows a number of gaps in the state of knowledge. Information to address these gaps was found to be lacking or inconsistent. Although the use of fibers to reduce draindown in gap- and open-graded mixes is quite well established and clearly successful, the effects of using fibers for other reasons are less clear. Research is needed to determine or clarify the following:

- Cost-effectiveness of fiber mixes;
- Use of mechanistic-empirical pavement design with fiber-reinforced mixtures;
- Standardized guidance on production and construction of fiber mixes;
- Fiber quality and interactions;
- Test methods to verify the presence and distribution of fibers;
- Health, safety, and environmental issues;

- Performance mechanisms and material characteristics with different types of fibers, perhaps through a comprehensive performance study; and
- Potential impacts on recycled materials.

Overall, the reported success of fiber-reinforced asphalt mixtures is quite promising. Their use in open- and gap-graded mixtures is well established. Opportunities exist to increase the use of fibers in other applications, provided their benefits can be clearly and consistently demonstrated. Additional guidance on mixture and pavement design, critical fiber properties, and the cost-effectiveness of fibers in different applications could make this sometimes overlooked tool a more widely used method to improve pavement performance.

CHAPTER ONE

INTRODUCTION

Fibers have been used to reinforce paving materials for many decades in various parts of the world. Their use in stone matrix asphalt and porous or open-graded mixtures to prevent draindown of the binder from the aggregate particles is very common. Less common is the use of fibers in dense-graded mixtures to increase stability (reduce rutting) and improve resistance to cracking. Cracking of asphalt pavements appears to be an increasing concern in many states, so identification of a potential tool to reduce cracking could be very beneficial. This synthesis is intended to explore past and current use of fibers in asphalt mixtures.

Many types of fibers are available for incorporation into asphalt paving mixtures. Cellulose and mineral fibers are commonly used in gap-graded stone matrix asphalt (SMA) and open-graded or porous mixtures. Polypropylene and polyester fibers were previously used in dense-graded mixtures and are still used to some extent. Various polymers, steel wool, and other fibers are also sometimes added to asphalt mixtures. The relative benefits and issues with these various types of fibers are not well documented. The appropriate specifications and material characteristics to ensure the best performance in different climates, under different traffic loadings, and in different applications are also not widely recognized.

This synthesis assembles and summarizes the available literature on asphalt mixtures with fiber additives. Agencies were surveyed to determine their current and past use of fibers in asphalt, their testing and mix design procedures, performance history, and other information. In particular, the synthesis panel examined the following:

- Types of fibers (e.g., materials, dimensions, applications, sources);
- Specifications, test methods, and acceptance criteria;
- Fiber quality, interactions, and supply issues;
- Health, safety, and environmental issues;
- Use of fibers in both experimental and routine construction;
- Mix design, production, placement, and acceptance issues/resolutions;
- Factors that affect performance (e.g., climate, traffic, application, fiber type);
- Performance mechanisms/material characteristics;
- Costs/benefits; and
- Impact on recycled materials.

The use of fibers in specialty mixes (such as cold mix or curb mixes) and in spray-applied pavement preservation treatments is not considered; however, if an agency mentioned such applications in its comments, the comments have been included in the summary response tables.

BACKGROUND

The use of fibers in asphalt mixes dates back many decades. Or longer: Button and Epps (1981) maintain that the earliest use of fibers in asphalt was the use of straw in ancient Egyptian building specifications. In the United States, asbestos fibers were used as early as the 1920s (Serfass and Samanos 1996), and this usage continued until the 1960s, when health and environmental concerns put an end to it (Busching et al. 1970). Cotton fibers were used in the 1930s (Busching et al. 1970), but they tended to degrade over time (Freeman et al. 1989). Since then many types of fibers have been used in various applications and different parts of the world. Fibers were reportedly used to provide the following benefits (Busching et al. 1970; Peltonen 1991):

- Increased tensile strength resulting in increased resistance to cracking,
- Reduced severity of cracking when it did occur,
- Increased fatigue resistance,
- Increased rutting resistance as a result of lateral restraint within the mixture,
- Increased abrasion resistance,
- Higher asphalt contents leading to increased durability, and
- Potential lower life cycle costs arising from longer service life.

Early applications were in dense-graded mixtures. Beginning in 1991, the first SMA mixtures were placed in the United States after more than 30 years of successful use in Europe (Cooley and Brown 2001). These mixes were designed in Europe mainly to resist studded tire wear but were found to be highly resistant to permanent deformation as well. Usage in the United States increased rapidly: by 1997 more than 140 SMA projects across the country were evaluated by the National Center for Asphalt Technology (NCAT) (Cooley and Brown 2001). These mixes generally used cellulose or mineral fibers to help hold the asphalt binder in the gap-graded aggregate structure; that is, to prevent draindown of the binder.

Fibers are also used in open-graded friction courses (OGFCs) or porous asphalt mixes to prevent draindown. These mixes have open-graded aggregate structures and high air voids to create stone-on-stone contact to resist rutting, reduce noise (McGhee et al. 2013), reduce splash and spray, and improve friction (Watson et al. 1998).

In summary, there are two main uses for fibers: (1) to prevent draindown in gap- and open-graded mixes, and (2) to strengthen dense-graded asphalt mixes to resist rutting and cracking. These uses plus other potential benefits and applications of the use of fibers are explored in this synthesis.

SYNTHESIS APPROACH

A variety of approaches was used to collect the information presented in this synthesis. The first was a comprehensive literature search performed using the TRID database, Google, and Compendex. Pertinent references were also provided by some of the survey respondents, the panel members, and others. The references were reviewed and categorized as to the topics they addressed (e.g., performance, testing, types of fibers). More than 100 references were identified and reviewed. Information on past research and practices from this literature review is presented in chapter two.

The second approach was aimed at getting a picture of the current state of the practice. A Qualtrics electronic survey was developed and distributed to all 50 states in the United States. Responses were received from 48 states for a response rate of 96.0%. The responses are summarized in chapter three. A copy of the survey, list of agencies responding to the survey, and tabulations of survey responses are provided in the appendices. Chapter three also includes a summary of some international experience with the use of fibers in asphalt mixes gleaned from interviews and e-mail with personal contacts.

Following up on the initial survey, selected organizations were interviewed by phone or questioned by e-mail to elicit additional information. These follow-up interviews provided the basis for the case examples in chapter four.

Finally, on the basis of the literature review, survey responses, and interviews, topics that need additional research were identified. This list and the conclusions drawn from the synthesis are presented in chapter five.

CHAPTER TWO

LITERATURE REVIEW: USE OF FIBER ADDITIVES IN ASPHALT MIXTURES

This chapter summarizes the findings of the literature review on the use of fibers in asphalt mixtures. The findings are grouped by fiber materials, summarizing the types of fibers used and their typical properties; methods of testing fibers and the significance of those tests; mix design, production, and construction of fiber-reinforced mixtures; laboratory and field performance of fiber-reinforced dense-graded mixtures and open- or gap-graded mixtures; and the cost-effectiveness of the use of fibers.

FIBER MATERIALS AND MIXTURES

It is generally understood that asphalt is strong in compression and weak in tension (Busching et al. 1970). Adding fibers with high tensile strength can help increase the tensile strength of a mixture. In theory, stresses can be transferred to the strong fibers, reducing the stresses on the relatively weak asphalt mix. To effectively transfer stresses, there must be good adhesion between the fiber and the asphalt binder; a greater surface area on the fibers can aid this adhesion. In addition, the fiber needs to be uniformly dispersed in the mixture to avoid stress concentrations (Busching et al. 1970). If the primary reason for adding fibers is to reduce binder draindown, high strength is not required; fibers that will absorb or retain binder are used in these applications. The properties that affect fiber performance, how those properties are measured, and the types of fibers used are described in this section.

Types of Fibers

Many types and forms of fibers have been used in asphalt mixtures, either experimentally or routinely. Cellulose, mineral, and polymer fibers are the most common. The most commonly used types of fibers and their reported benefits and disadvantages are summarized in Table 1.

Cellulose: Cellulose fibers are plant-based fibers obtained most commonly from woody plants, although some are obtained from recycled newspaper. These fibers tend to be branching with fairly high absorption; it is this nature that helps cellulose fibers hold on to high binder contents in mixtures. Cellulose fibers can be provided in loose form or in pellets.

Mineral: Either naturally occurring fibers, such as asbestos (chrystolite), or manufactured mineral fibers can be used. Mineral fibers (also called mineral wool or rock wool) are manufactured by melting minerals then physically forming fibers by spinning [similar to making cotton candy (Science Channel n.d.)] or extruding. Minerals used to create mineral fibers include slag or a mixture of slag and rock (U.S. EPA 1995; Brown et al. 1996), basalt (Morova 2013), brucite (Guan et al. 2014), steel (Garcia et al. 2009, 2012 a and b, 2013 a and b; Serin et al. 2012), and carbon (Clevin 2000; Liu and Shaopeng 2011; Khattak et al. 2012, 2013; Yao et al. 2013). Carbon fibers and steel fibers (or steel wool) have been used in some fairly exotic ways to produce electrically conductive asphalt that can be used for deicing (Garcia et al. 2009, 2012 a and b, 2013 a and b) or to heal microcracks (Gallego et al. 2012; Liu et al. 2012; Garcia et al. 2012a, 2013a; Dai et al. 2013). Steel fibers have been used for research purposes, but because they corroded upon exposure to water, they were not effective in the long term (Freeman et al. 1989; Putnam 2011). Asbestos fibers were the first type of fiber used in hot mix asphalt; they were used from the 1920s (Serfass and Samanos 1996) until the 1960s when environmental and health issues curtailed the use of asbestos (Busching et al. 1970).

Synthetic polymer fibers: The most commonly used polymer fibers are polyester, polypropylene, aramid, and combinations of polymers. Other fibers include nylon, poly para-phenyleneterephthalamide, and other less commonly used materials. Different polymers have different melt points, which need to be considered when adding to hot mix asphalt. Production of synthetic fibers typically involves drawing a polymer melt through small holes. Fibers can be bundled together into yarn (although yarn is not typically used today in asphalt concrete) (Busching et al. 1970). Reportedly, aramid fibers contract at high temperatures, which helps resist pavement deformation (Kaloush et al. 2010).

Other plant-based fibers: These have been used in more limited areas. They may be derived from woody fibers (such as jute, flax, straw, and hemp), leaves (such as sisal), and seeds; or they may be fruit fibers, such as coir, cotton, coconut, or palm (Cleven 2000; Oda et al. 2012; Das and Banerjee 2013; Qiang et al. 2013; Abiola et al. 2014; Do Vale et al. 2014; Muniandy et al. 2014).

Glass fibers: These have not been reported often in the literature but appear to have desirable properties, including

TABLE 1
REPORTED BENEFITS AND DISADVANTAGES OF COMMON FIBER TYPES

Fiber Type	Reported Advantages	Reported Disadvantages
Cellulose	• Stabilizes binder in open- and gap-graded stone matrix asphalt (SMA) mixtures. • Absorbs binder, allowing high binder content for more durable mixture. • Relatively inexpensive. • May be made from a variety of plant materials. • Widely available. • May be from recycled materials such as newsprint.	• High binder absorption increases binder cost. • Not strong in tensile mode.
Mineral	• Stabilizes binder in open- and gap-graded SMA mixtures. • Not as absorptive as cellulose. • Electrically conductive fibers have been used for inductive heating for deicing purposes or to promote healing of cracks.	• Some may corrode or degrade because of moisture conditions. • May create harsh mixes that are hard to compact and may be aggressive, causing tire damage if used in surfaces.
Polyester	• Resists cracking, rutting, and potholes. • Increases mix strength and stability. • Higher melting point than polypropylene. • High tensile strength.	• Higher specific gravity means fewer fibers per unit weight added. • Cost-effectiveness not proven/varies.
Polypropylene	• Reduces rutting, cracking, and shoving. • Derived from petroleum, so compatible with asphalt. • Strongly bonds with asphalt. • Disperses easily in asphalt. • Resistant to acids and salts. • Low specific gravity means more fibers per unit weight added.	• Lower melting point than some other fiber materials requires control of production temperatures. • Begins to shorten at 300°F. • Cost-effectiveness not proven/varies.
Aramid	• Resists cracking, rutting, and potholes. • Increases mix strength and stability. • High tensile strength. • May contract at higher temperature, which can help resist rutting.	• Cost-effectiveness not proven/varies.
Aramid and polyolefin	• Controls rutting, cracking, and shoving. • Combines benefits of aramid and polyolefin (polypropylene) fiber types.	• Cost-effectiveness not proven/varies.
Fiberglass	• High tensile strength. • Low elongation. • High elastic recovery. • High softening point.	• Brittle. • Fibers may break where they cross each other. • May break during mixing and compaction. • Cost-effectiveness not proven/varies.

Source: Literature review.

high tensile modulus (~60 GPa), low elongation (3%–4%), high elastic recovery (100%), and high softening point (815°C). They are, however, brittle and must be handled carefully during construction (Abtahi et al. 2013).

Waste or recycled fibers: The increasing importance of sustainability in construction has led to increased interest in reusing materials that would otherwise be disposed of, including waste fibers from a variety of sources. Putnam, for example, has explored the possibility of reusing waste carpet fibers and tire fibers from the auto manufacturing industry, with favorable results in terms of increased mixture toughness, permanent deformation, and moisture resistance (Putnam and Amirkhanian 2004). Chowdhury et al. (2005) investigated the use of fibers from recycled tires and found that they performed well, especially in reducing draindown.

The advantages of natural fibers include low cost, acceptable strength and mechanical properties, and sustainability. One disadvantage is their tendency to absorb moisture, which can cause them to swell (Table 1) and can interfere with bonding of hydrophobic asphalt with the moisture-laden fiber. Natural fibers can also degrade at high temperatures or moisture conditions. Compatibility of the fiber and the asphalt can be improved with various surface treatments. Overall, however, it appears that some natural fibers, such as jute and sisal, can be used to replace synthetic fibers in asphalt mixes (Abiola et al. 2014).

Fibers come in various forms in addition to loose and pelletized cellulose fibers. Fibers can be short and randomly oriented, long and unidirectional, tufts, or woven (Abiola et al. 2014). (Woven fabrics are not the focus of this synthesis.)

The individual types of fibers can have various structures and cross-sections. Chen and Xu used scanning electron microscopy to investigate the structure of some fibers, including asbestos, lignin (cellulosic), polyacrylonitrile, and polyester. They found that the synthetic fibers had "antenna features" at their ends that helped anchor them in the binder phase, creating a stronger network within the binder. The asbestos fibers had a smooth texture and a thin diameter, yielding a large surface area. The cellulosic fiber had a rough texture, and the diameter varied along the length of individual fibers. All the fibers were found, in this laboratory study, to increase binder stiffness, rutting resistance, and flow resistance. The asbestos and cellulosic fibers absorbed more binder (Chen and Xu 2010).

Surface coatings are frequently applied to fibers during production for various reasons. Some reduce static, while others help with the manufacturing and packaging processes. Excess static can make handling and mixing fibers difficult. Some coatings, such as stain-resistant coatings used for carpet fibers, may not be compatible with asphalt binder. In a study by Putnam (2011), one fiber source was used with different binder grades and sources to explore issues related to the compatibility of the binder and the fiber coating. In another part of the study, one binder was used with polyester fibers with different coatings. The research revealed that different binder (crude) sources had different compatibilities with fiber finishes. Chromatography testing suggested that the fiber coating could affect the absorption of different fractions of the binder, particularly lighter fractions. The study also found that different finishes can affect binder properties, particularly tensile properties. However, the amount of finish applied to a fiber did not cause any significant differences (Putnam 2011).

Methods of Testing Fibers and Fiber Mixtures

The methods of testing fibers have largely come from the textile industry and may vary for different types of fibers because of their historical use. Properties of interest include the dimensions of the fibers, ash content, shot content, and properties related to compatibility with asphalt. For use on open- and gap-graded mixtures, the effects of the fibers on binder draindown are of primary interest; several variations of a draindown test are in common use. Mixtures are also frequently tested for abrasion resistance in the Cantabro test.

The physical dimensions of the fibers are important because they can affect how well the fibers can disperse and interact with the other components of the mixture. For example, the lengths of the fibers can be modified to relate to the maximum aggregate size in the mixture; smaller aggregate sizes may use shorter fibers. Long fibers may be difficult to mix uniformly into the mixture in the lab or plant because they can get tangled and clump together (Tapkin et al. 2009, 2010; Do Vale et al. 2014). Sieve analysis is also sometimes used to characterize fiber size. This analysis can be performed using wire mesh screens or a device called an Alpine Air Jet Sieve, which fluffs the fiber and sieves it using a vacuum. The denier of a fiber is a measure of its fineness; it is an artifact of the textile industry. The denier is the weight in grams of 9,000 m of fiber. Fine silk fibers have a denier of 1.0. The denier relates to the surface area of fiber, which in turn is related to the potential asphalt demand and holding power in a mixture.

The ash content is a measure of the organic content of plant-based fibers and is, therefore, a method of ascertaining that the fiber is organic. A small amount of fiber is heated to burn off the organic material. The remaining ash is the nonvolatile portion. ASTM D128 includes an ash determination procedure that is sometimes cited in organic fiber specifications.

The shot content is a parameter frequently specified for mineral fibers. When mineral fibers are produced, there may be small globules of mineral material called shot. These globules do not contribute fibrous material, so the amount is typically limited. To determine the shot content, the fibers are placed in a nest of sieves and shaken in a shaker machine or by hand to separate the fibers (which are retained on the sieves) from the shot (which passes through). Shot content limits in specifications also report the applicable sieve size used to separate the fibrous and shot material. ASTM C1335 is one method used to measure the shot content.

The compatibility and binding of organic fibers with asphalt binder are usually controlled by properties of the fiber, including pH, oil absorption, and moisture content. These properties are less often specified for synthetic fibers, which are sometimes petroleum based and therefore assumed to be compatible with asphalt. [However, some coatings that can be applied to fibers may not be compatible with the binder (Putnam 2011).] The pH is typically measured by soaking fiber in distilled water, then measuring the pH of the water with a pH meter. The oil absorption is an indication of the compatibility of the fiber with asphalt and is determined, usually, by suspending a measured amount of fiber in mineral spirits for a short time (typically 5 minutes), removing the fiber from the mineral spirits and shaking it to remove excess mineral spirits on the surface, then measuring the change in mass of the fiber. Oil absorption is reported in terms of how many times the mass of fiber is absorbed; for example, it may be specified that the fiber absorb five times its own mass.

Gap- and open-graded mixes (SMA and porous) are generally tested to determine the percentage binder draindown. There are various methods for measuring this property. Stuart and Malmquist (1994) compared three test methods. The same compaction temperature was used in all three cases; this was 170°C, which is a common German plant discharge temperature.

- The German draindown test involves placing about 1 kg of mixture in a glass beaker after mixing, then covering the beaker with foil and holding it in an oven at the compaction temperature for 60 ± 1 min. Then the beaker is turned over, allowing the mix to fall into a tared bowl. The difference in the mass before and after storage, expressed as a percentage of the original mass of the mixture, is the draindown loss. The maximum allowable loss using this method is 0.3%.
- The FHWA draindown test also involves holding a sample of mix at the compaction temperature for 60 ± 1 min. In this method, however, about 1 kg of mix is placed in a 2.36-mm sieve set on top of a bowl. After storage at the compaction temperature, the difference in the mass of the bowl reflects the mass lost through draindown. This difference, expressed as a percentage of the original mass of the mixture, is the percentage loss.
- A third draindown test was developed by FHWA for open-graded friction courses. As with the other tests, 1 kg of mix is held for an hour at the compaction temperature, but in this case the mix is spread in a Pyrex pie plate before putting it in the oven. The mix is allowed to cool after the storage period, then the pie plate is turned over or inspected from below to determine how much binder has accumulated on the bottom of the plate. Five standard photographs illustrate different degrees of draindown; a visual comparison to these photos is used to assess draindown tendencies of the subject mix. Figure 1 shows three images used by the South Carolina DOT to illustrate below optimum, optimum, and above optimum binder contents for open-graded mixtures from its draindown test (SCDOT SC-T-91).

FIGURE 1 Example of images demonstrating binder contents from draindown test (*Source*: South Carolina DOT, Test Method SC-T-91).

The Austroads draindown test method is similar to the German method in that 1 kg of mix is placed in a tared glass beaker, then held for 60 ± 1 min before the beaker is turned upside down, allowing the mix to fall out. In the Austroads method, the oven temperatures are specified according to the mix type (open-graded or SMA) and whether or not a modified binder is used; the specified temperatures range from 160°C for an unmodified OGFC to 185°C for a modified SMA. In addition, a supplementary procedure can be used with polymer-modified binders if the amount of binder remaining in the beaker is more than 0.3% of the original mass of the mix. This procedure involves using a solvent to wash the residue from the beaker through a tared 0.600-mm sieve to determine whether a significant amount of the fine aggregate particles was trapped in the modified binder adhering to the beaker (Austroads 2006).

As part of an effort to refine the mix design process for OGFC mixtures, Watson et al. (2003) explored various test methods and sample preparation techniques using mineral fiber with three different binder grades, modified and unmodified. The mineral fiber was added at 0.4% based on the total mass of the mix. Watson et al. (2003) compared the use of two different-sized sieves (4.75 mm and 2.36 mm) for the draindown test based on AASHTO T 305-97, because they suspected that the 4.75-mm sieve was too large for some finer OGFCs, allowing stone loss. Another modification was weighing the basket after removing the mixture to measure any asphalt remaining in the basket.

The draindown testing was performed on mixes with PG (performance grade) 64-22 with and without mineral fiber, polymer-modified PG 76-22 with and without fiber, and rubber-modified PG 76-34 with fiber. The presence of fibers in the mix was the most significant factor related to the amount of draindown. Fibers reduced draindown dramatically: mixes without fibers had draindown amounts as high as 3%; adding only 0.4% fiber could reduce the draindown to minimal amounts. Adding the mass of asphalt clinging to the basket did not significantly affect the draindown estimate for the mixes tested. Both sieve sizes were found to be acceptable, but the 2.36-mm sieve had a lower standard deviation in the results.

AASHTO T 305, Determination of Draindown Characteristics in Uncompacted Asphalt Mixtures, is now the most widely accepted test method in the United States for determining draindown (survey results). Similar to the methods discussed earlier, the difference in mass before and after oven storage is used to determine draindown. In this method, however, the mix is held in a woven wire basket, allowing the binder to drain off through the wire. Figure 2 illustrates this test in progress.

Another test that is commonly used, particularly with open-graded mixtures, is the Cantabro test. In this test, compacted mixture specimens are tumbled in a Los Angeles abrasion test drum, without the steel balls used in the LA abrasion test. The change in mass before and after testing is an indication of the durability of the mixture. Fibers have been reported to improve this durability in some cases (Lyons and Putnam 2013). Watson et al. (2004) confirmed the suitability of the Superpave gyratory compactor to prepare specimens for Cantabro testing in place of the Marshall compacted specimens originally used.

Attempts to test fibers as part of the binder phase have been fraught with difficulty. The binders with fibers tend to crawl out of rolling thin film oven bottles during conditioning (Brown et al. 1996). In addition, in fabricating samples for bending beam rheometer or direct tension testing, it is difficult to get smooth samples with uniformly distributed fibers (Ayesha Shah, Purdue University communication, June 15, 2014).

FIGURE 2 Draindown test in progress (*Source*: WSDOT).

One recurring question from agencies is whether there is a test to detect the presence and uniformity of the distribution of fibers (Austroads 2007). Fibers may be visible in the mix, as illustrated in Figure 3, but this is not a quantifiable means of determining the presence of fibers. Comparisons of reported maximum specific gravity values reported in the literature for fiber-modified and control mixtures show that the values are not significantly different and cannot be used to detect the presence of fibers. Sometimes the presence of fibers can be detected using a solvent extraction and sieve analysis; fibers typically remain on the sieves. However, it can be difficult to determine whether the required amount of fibers has been added because of the small amounts of fiber per ton and the small size of the extraction sample. Also, this method does not assess the uniformity of distribution.

Huang and White compared three fiber extraction techniques to assess the fiber content in Indiana mixtures with polypropylene fibers. The first technique used trichloroethylene to wash the asphalt binder and fiber from the mixtures, then the solvent was filtered to separate the fiber. Some fines were also removed in the process, so the material on the filter was ashed, which removed the fiber. Fiber content was determined on the basis of the difference in mass before and after ashing. The second procedure used water to float the fiber (and some fines) from the aggregate remaining after extraction using ASTM D2172. Ashing was again used to remove the fibers from the fines so that the weight of fibers could be determined. The final technique used sieve analysis (ASTM C136-84a) to remove fibers from the aggregate remaining after extraction using D2172. The fibers were caught on the sieves. As in the previous methods, ashing was used to separate the fiber and fine aggregates. Each method has its uses, depending on the kind of information needed. The first method would be an easy way to determine fiber content only. The second method also allows determination of binder content, while the third would be useful if aggregate gradation is needed (Huang and White 1996).

FIGURE 3 Fibers visible in mixture clinging to shovel (*Source*: PennDOT).

Research under way in Idaho will explore the use of X-ray computed tomography to compare the distribution of fibers in laboratory and field samples (see the case example in chapter four that describes ongoing research on fibers in dense-graded asphalt).

MIX DESIGN WITH FIBERS

Little appears in the literature regarding mix design procedures with fibers. When the topic is mentioned, it is usually as a brief introduction to sample preparation as part of a larger study. In general, mix design proceeds as usual with the addition of a draindown test (see state specifications and test methods in chapter three).

Over time, the appropriate fiber content to use in a given mixture type may become almost standard for certain fiber types; for example, 0.3% by weight of mix is a very common addition rate for cellulose fibers in SMA. However, use of too high a fiber content may make compaction more difficult, leading to higher air void contents in laboratory- or field-compacted mixtures (Serin et al. 2012; Crispino et al. 2013; Morova 2013). Chowdhury et al. (2005) found that using 1% of 6-mm-long recycled tire fibers stiffened SMA and porous mixes too much and made the mixes more susceptible to cracking.

Binder contents are frequently higher in fiber mixes, especially with more absorbent cellulose or other plant-based fibers (Busching et al. 1970; Button and Hunter 1984; Toney 1987; Freeman 1989; Fortier and Vinson 1998; Cooley et al. 2003; Chen et al. 2009; Gibson et al. 2012). Absorption is a beneficial property to some extent because it allows for increased binder or mastic contents in the mixtures, which can aid durability, especially for gap- and open-graded mixes. Excessive absorption, however, may lead to expensive mixes. In addition to higher absorption, fibers may have high surface areas that need to be coated with asphalt.

In a 2012 FHWA report, Gibson et al. summarized the results of a previous study comparing polymer-modified and a fiber-reinforced dense hot mix. The optimum asphalt contents for the various mixes are shown in Table 2. Work conducted by FHWA under NCHRP 90-07 demonstrated the increase in binder content associated with the use of fibers. Optimum binder contents were determined at 4% air voids at 75 gyrations in the Superpave gyratory compactor at a fixed compaction temperature of 140°C. Table 2 shows that the fiber mix had an optimum binder content 0.5% to 1.0% higher than the polymer-modified mixes and 0.8% higher than the unmodified control section (Gibson et al. 2012).

TABLE 2
OPTIMUM BINDER CONTENTS FROM FHWA STUDY

Modifier	Optimum Binder Content (%)
Terpolymer	4.4
Ethylene vinyl acetate (EVA)	4.4
SBS-LG	4.5
SBS radial grafted	4.6
Ethylene styrene interpolymer	4.6
Air-blown asphalt	4.8
Chemically modified crumb rubber	4.9
Unmodified PG 70-22	4.6
Unmodified PG 70-22 with 0.3% polyester fiber (by aggregate mass)	5.4

Source: Gibson et al. (2012).

PRODUCTION, CONSTRUCTION, AND ACCEPTANCE OF FIBER MIXTURES

Production of fiber mixes can be accomplished in different ways. Fibers can be added to the liquid binder in a process called wet-mixing or can be added to the aggregate in a dry-mixing procedure (Abiola et al. 2014). Fibers are often blown into the hot mix plant to help ensure uniform distribution (Figure 4) but are sometimes added to the plant in bags (Figure 5). Fibers can be added to drum plants through the reclaimed asphalt pavement collar, where they can be mixed with aggregate before the binder is added (Ryan Barborak, TxDOT communication, Sept. 2, 2014). In batch plants, fibers are added to the weigh hopper or pugmill (Shoenberger 1996; Watson et al. 1998). The addition rate must be coordinated with the plant production rate (metered) to ensure that consistent mix is produced (Schmiedlin 1998).

(*a*) (*b*) (*c*)

FIGURE 4 One example of blowing fibers into drum plant: (*a*) fiber hopper, (*b*) blowing equipment, (*c*) feeding fibers through RAP collar (*Source*: PennDOT).

FIGURE 5 Adding fibers in premeasured bags at a batch plant (*Source*: R.S. McDaniel).

Clumping of fibers in the mixture was reported in both the literature and the survey results. Figures 6 and 7 show examples of clumps of fibers found during and after mix compaction. Keeping the fibers dry is reportedly important to help prevent clumping and clogging of fiber injection equipment. In many cases, clumps can also be avoided by increasing the mixing time (Watson et al. 1998; Cleven 2000), which is more easily accomplished in a batch plant. With some of the more brittle fiber types—such as steel wool and glass fibers—increasing the mixing time may cause the fibers to break, resulting in shorter fibers (Garcia et al. 2012a). In some cases, clumps of fibers have been observed when mix is discharged from the plant, but by the time mix is transferred into a silo, into haul trucks, and through a material transfer device, the clumps have dissipated (Nelson Gibson, FHWA communication, Aug. 25, 2014).

FIGURE 6 Fiber clump (*Source*: PennDOT).

FIGURE 7 Clump of fibers on surface of compacted mat (*Source*: PennDOT).

Plant temperature also needs to be controlled to prevent thermal degradation of the fibers. Polypropylene fibers, for example, melt at a lower temperature than polyester fibers (163°C vs. 249°C), so more control of production temperatures is needed. This would be less of an issue with warm mix asphalt (WMA), but there are few examples of using fibers at WMA temperatures.

Fiber mixes have also been reported to be "stickier" than some other mixes and may make hand work more difficult. For example, a dense mix with ¼-in.-long polyester fibers reportedly stuck to pneumatic tired rollers, hand tools, rakes, and other equipment (Toney 1987). On the positive side, some polymer fiber mixes have demonstrated a reduced tendency to segregate, presumably because of their stickiness and the fiber network (Jiang and McDaniel 1992).

Few additional mixture tests were cited in the literature for routine production control or acceptance; conventional tests were generally found to be adequate. Of course, many additional types of tests have been performed for research purposes, as will be outlined in reference to specific projects later in this chapter. Busching et al. (1970) cautioned that testing fiber mixtures in compression only will not adequately characterize the mixture properties; some sort of cracking or flexural testing is also needed.

PERFORMANCE OF FIBER MIXTURES

Most of the literature reviewed for this synthesis was related to the performance of fiber mixes in the laboratory or the field. Individual projects compared different types of fibers in a variety of applications. Some of the most pertinent references are summarized here. (See the Bibliography for related literature not cited in this report.)

Use of Fibers in Dense-Graded Mixtures

In 1974, a badly cracked section of continuously reinforced concrete in Indiana was overlaid with approximately 2 in. of asphalt binder and 2 in. of surface. Six years later, the overlay was seriously deteriorated and needed to be overlaid again. At that time (October 1980), the Indiana Department of Highways (DOH, now Transportation) decided to place a test section of overlay containing polypropylene fibers to determine what benefits, if any, the fibers could provide. The 2-in. overlay was placed over the existing pavement (without milling). The fiber mix was placed in about 990 ft of the passing lane and an adjacent 550 ft of the travel lane. The remainder of the travel lane did not include fibers and served as the control. The fibers were added into the batch plant at a rate of 6 pounds per ton of mix (0.3%) (Galinsky 1984).

After 2.5 years, the control section was exhibiting more than twice the amount of cracking observed in the fiber section and the cracks were of much greater severity [moderate to high severity, as defined in the *Distress Identification Manual* (FHWA 2003)]. Those cracks that did appear in the fiber section were less than 1/32 inch in width and had very little secondary cracking (braiding). Cracks in the control section were about ¼ in. wide, with some as wide as 3/8 in. or more. Significant secondary cracking was also observed. The control section was also "severely deformed" with ruts as deep as 2¼ in. Rut depths in the fiber section were all less than 3/8 in. and averaged about 1/8 in. (Galinsky 1984). On the basis of the performance of the fiber mix, the Indiana DOH began using polypropylene fibers in more situations.

In 1985, a new researcher visited the site of the experimental overlay to check on its condition after another year had passed. In May 1985, the control section had deteriorated to the point of functional failure. The rutting was severe, more than 2.5 in., and extreme plastic deformation (shoving) was seen. The extremely rough profile could have caused a loss of control of a vehicle, possibly throwing it into a bridge railing just south of the control section. The profile was so bad that truck drivers familiar with the roadway would merge into the passing lane to avoid the short control section (McDaniel 1985).

The test section, on the other hand, had minimal rutting and no shoving. Cracks formed in the control section were numerous, wide and braided. Fewer, tighter cracks were observed in the fiber section, with very little braiding. Some cracks in the control section stopped at the joint and did not propagate into the test section, despite being quite severe. Because of the hazardous condition of the control section, a letter was sent to the district engineer and immediate action was taken to mill off and replace the control section (McDaniel 1985).

Jiang and McDaniel (1992) evaluated the 8-year field performance of various thicknesses of asphalt overlays with and without cracking and seating the existing concrete and with and without polypropylene fibers in the intermediate and base layers of the overlays. The fibers were 10 mm long and added at 0.3% by weight of the mixture. They found that adding fibers to the base and intermediate layers of the conventionally overlaid section did not reduce cracking, because the cracking was mainly reflective cracking caused by substantial vertical and horizontal movements of the underlying concrete. However, the use of fibers did delay and reduce cracking on the cracked and seated sections. There was no apparent difference between the cracked and seated sections with fibers in the base versus the base and intermediate layers, suggesting that use of fibers in the base alone was effective at reducing cracking. Rutting was not severe on any of the sections but was lower on the sections with fibers.

A later study in Indiana compared the field performance of seven asphalt additives or modifiers. In this case, polyester fibers were used in an asphalt overlay over jointed concrete pavement. The fibers were 6.35 mm long, added at a rate of 0.3% by weight of the mix, and dry mixed for 30 s, then wet mixed for 35 s in a batch plant. The other modifiers were various polymers, gelled asphalt, and crumb rubber. This study evaluated the ability of these modifiers to control both rutting and cracking. The styrene butadiene rubber (SBR), polymerized asphalt cement (PAC), and asphalt rubber mixtures were the most effective in terms of resisting cracking. Polyester fibers also performed well but had slightly more cracking than the top-tier performers. None of the mixes—not even the control section—demonstrated significant rutting under heavy interstate traffic. This finding suggested that additives were not necessary to achieve good performance; attention to detail and good construction practices could be sufficient (McDaniel 2001; McDaniel and Shah 2003).

Maurer and Malasheskie (1989) compared the field performance of four fabric interlayers, one fiber-reinforced asphalt interlayer (stress-absorbing membrane interlayer, or SAMI), and a fiber-reinforced asphalt overlay to a control section with an unreinforced overlay. The objective was to identify treatments that could reduce reflective cracking in asphalt overlays. (For the purposes of this synthesis, this review will focus on the comparison of the fiber-reinforced SAMI and the fiber overlay to the control section.) The fiber-reinforced overlay consisted of a 38-mm wearing course with the addition of 0.3% (by weight of mix) polyester fiber. This treatment was included in the study because, if it performed as well as or better than the other treatments, it would be easier to implement and construct at a lower cost (Maurer and Malasheskie 1989).

Test sections were constructed in 1984 on a principal arterial highway in Pennsylvania that exhibited a stable base in most areas and surface block cracking. The dense-graded mixes were produced in a batch plant. The underlying pavement was mostly portland cement concrete, except for a section in the center of the roadway that had previously held a trolley line and was paved with asphalt when the trolley was abandoned (Maurer and Malasheskie 1989).

The fiber-reinforced SAMI was applied full-width as an alternative to placing paving fabrics. The membrane consisted of AC-20 with the addition of proprietary fibers at a rate of 6.0% by weight of asphalt along with an adhesion promoter (2.0% by weight of asphalt). The manufacturer used specialized equipment to heat, blend, and place the membrane. The paving contractor applied a layer of stone cover after membrane installation. Construction issues caused significant delays, especially on the first day of membrane placement. The issues included suspected contamination of the AC-20, steam from water in the adhesion promoter, and difficulty controlling the membrane application (Maurer and Malasheskie 1989).

The fiber overlay consisted of a standard Pennsylvania Department of Transportation (PennDOT) surface mix with the addition of 0.35% fiber, equivalent to 3 kg of fiber per tonne of mix. The polyester fibers, in bags, were added to the batch plant at the beginning of the dry mix cycle. No construction difficulties or need for extra manpower were encountered in placing this material (Maurer and Malasheskie 1989).

After 44 months in service, the fiber-reinforced overlay was outperforming all the other treatments, with less reflective cracking (a reduction of more than 50% compared with the control). The fiberized membrane was the second most effective, with a reduction of 46.4% relative to the control. All the treatments provided some reduction in reflective cracking. Life cycle cost analysis, however, showed that the increased construction costs could not be justified at the time. In conclusion, the 1989 report recommended none of the treatments for implementation because of their lack of cost-effectiveness, but it did recommend that the test sections be revisited in 3 years to verify the life cycle (Maurer and Malasheskie 1989).

Huang and White (1996) tested cores and slabs taken from polypropylene fiber-modified asphalt overlays in the state of Indiana. At the time of the research, the Indiana Department of Transportation (INDOT) used fibers extensively in overlays, a practice that had been shown to be effective at reducing reflective cracking over cracked and seated pavements and concrete pavements undersealed with asphalt. A total of 33 test sections were constructed on two high-traffic roadways in 1990. These test sections were cored, and slabs were cut for lab testing. In addition to control sections without fibers, the test sections included varying amounts of fibers in different pavement layers (Huang and White 1996).

Testing included fatigue testing of beams cut from the pavement slabs and complex modulus testing on cores. In addition, bulk-specific gravities, maximum specific gravities, and sieve analyses were performed on samples from the pavements. The sieve analysis results (determined using the third testing method described earlier) showed that the actual fiber contents in the plant-produced mixes varied from the target values in most cases, probably owing to difficulties in feeding the fiber into the mixture at the discharge chute. The contents varied by 4% to 43% from the target; in most cases the fiber content was low, but in one case it was nearly 22% higher than designed (Huang and White 1996).

The aggregate gradations and asphalt contents for all of the mixes, with and without fibers, were within specifications, but the field densities were low. The air void contents of the fiber mixes were higher than those of the controls, suggesting that the fibers made compaction more difficult (Huang and White 1996).

Beam fatigue testing showed that the use of fiber extended the fatigue life of the overlays by as much as two times. Dynamic modulus testing results from one project indicated that the presence of fibers decreased the modulus but did not affect the phase angle (Huang and White 1996).

A study by the Oregon DOT reported on 10-year performance of fiberized and polymer-modified test sections placed in 1985 after the application of more than 1.5 to 1.7 million equivalent single-axle loads. Additives were placed in the dense-graded top course (38 to 51 mm thick) over an unmodified base course (102 to 114 mm) over an existing pavement with severe alligator and thermal cracks. One section included polypropylene fibers and another included polyester fibers, both with AC-20 binder. There were two control sections and six sections with mixtures incorporating various anti-strip and polymer additives. Both fiber sections were comparable to the controls, with average rut depths of 13 to 16 mm. The polypropylene fibers performed much better than the control in terms of block cracking, while the polyester fibers performed better than the control. The polypropylene fiber had no block cracking, and the polyester had block cracking over less than 10% of the travel lane. The control section exhibited block cracking over between 30% and 50% of the travel lane. The fiber sections performed comparably to the controls in fatigue cracking (Edgar 1998).

The Pennsylvania DOT was experiencing rutting problems on asphalt roadways in the 1980s, so it embarked on a field evaluation to explore various modification techniques that could improve the rutting performance. Anderson et al. (1999) reported on the 10-year performance of test sections constructed on I-80. Retained samples of the component materials were tested using the new Superpave protocols as well (Anderson et al. 1999).

The field test sections included an unmodified control, four different polymer-modified binders [polyethylene, ethylene vinyl acetate (EVA), styrene butadiene styrene (SBS), and styrene butadiene (SB)], Gilsonite, and polyester fibers. The test sections consisted of an overlay over jointed concrete pavement. The modifiers were placed in the 63.5-mm-thick intermediate course and the 38-mm-thick surface course but not in the 75-mm-thick base course. The mixes were designed under the Marshall mix design procedure (Anderson et al. 1999).

The fibers were added at 0.280% by weight of the mix into the mixing chamber of the batch plant during the dry mixing period. The dry mixing time was increased by 10–15 s to ensure that the fibers were uniformly distributed. No construction problems were noted (Anderson et al. 1999).

The researchers attempted to add the fibers to the binder and test in the dynamic shear rheometer (DSR) and bending beam rheometer (BBR) but experienced great difficulty in preparing the specimens and ensuring that the fibers were well dispersed in them. This testing was abandoned and not reported (Anderson et al. 1999).

Loose samples of some of the modified mixes, including the fiber mix, had been collected during construction. These retained samples were reheated and used to compact gyratory specimens for testing in the Superpave shear tester (SST) and the indirect tensile (IDT) tester. IDT testing indicated that the tensile strengths of all of the modified mixes were similar, with the two mixes with polymer-modified binders being slightly stronger than the Gilsonite and fiber mixes [3.5 vs. 3.4 MPa (510 vs. 490 psi), respectively]. The critical cracking temperatures for the fiber mix and the SB mix, however, were about 3°C cooler than for the Gilsonite and EVA-modified mixes (Anderson et al. 1999).

SST testing showed that the fiber mix had the third highest modulus, after the Gilsonite and EVA mixes. The frequency sweep and phase angle data suggested that the fiber and SB mixes would perform best in terms of fatigue cracking. The field performance confirmed this, as the fiber and SB test sections exhibited less severe fatigue cracking than the Gilsonite and EVA (Anderson et al. 1999).

Field performance showed that all the modified mixes performed well in terms of rutting; the control section also performed well, but had more rutting than the modified sections. The fiber mix did not show any secondary cracking around the sawn and sealed joints after 8 years. The Gilsonite section, in particular, showed excessive raveling and was replaced by PennDOT after 9 years. Top-down longitudinal cracking was observed in three sections but not in the fiber-reinforced section (Anderson et al. 1999).

In a laboratory study at Clemson University, continuous polyester fibers from roofing manufacturing trim waste were shredded to two lengths [6.35 mm and 12.7 mm (1/4 in. and ½ in.)] in a paper shredder to see whether they could be used as a replacement for other fibers in dense asphalt mixtures. The indirect tensile strength and moisture sensitivity of mixtures with these fibers at different addition rates (0.35% and 0.50% by weight of the mix) were evaluated (Anurag et al. 2009).

The optimum asphalt content of the fiber mixes was higher than that of the control mix because additional binder was needed to coat the high surface area of the fibers. The air voids and voids in mineral aggregate (VMA) of the fiber mixes were also higher than those of the control. Marshall stability and flow values increased with the addition of fibers. The tensile strength, tensile strength ratio, and toughness of the fiber mixes were higher than those of the control. The shorter fibers at the higher addition rate (6.35 mm at 0.50%) were found to perform best in this study (Anurag et al. 2009).

Kaloush et al. (2010) compared the performance of a dense asphalt mixture containing 1 lb/ton of polypropylene and aramid fibers to a control mixture without fibers. The plant-produced mixes, from a paving project in Tempe, Arizona, were sampled for later testing at Arizona State University using current characterization tests.

Overall, the fiber-reinforced mixture outperformed the control mixture, specifically:

- The fiber mix exhibited higher peak stress and higher residual energy in triaxial shear testing compared with the control mix. This was attributed to the reinforcement effect of the fibers and greater resistance to shear failure and rutting.
- The fiber mix demonstrated flow numbers 15 times greater than the control mixture in the repeated load permanent deformation test. The results suggested that the fiber mix could store more energy than the control, which again indicated greater resistance to permanent deformation.
- In the dynamic modulus test, the fiber mix developed higher moduli than the control mix at all temperatures and frequencies, though the difference between the mixes was greater at high temperatures than at low temperatures. At high temperatures, the effects of the aggregate and fiber structure dominated over the binder properties, which were dominant at lower temperatures. Since the two mixes contained the same binder, differences were lessened at low temperatures.
- The fatigue testing results were mixed depending on strain level and temperatures. At 40°C the fiber mix had a longer fatigue life, but at 70°C the fatigue lives of the two mixes were similar. At 100°C and high strain levels, the control mix had higher fatigue life; at lower strains, the fiber mix was superior. This behavior was explained by comparing the tensile strength of the fibers with the bonding strength between the fiber and the binder; at high temperatures, the strength of the bond determined the reinforcing effectiveness.
- Indirect tensile testing at low temperatures (0°C, -10°C, and -20°C) indicated that the fiber mix would be more resistant to thermal cracking, with a strength 1.5 times greater than the control. In addition, the fiber mix demonstrated higher fracture energy, which relates to reduced thermal cracking.
- Fracture mechanics analysis (C*-integral) indicated that the fiber mix would be much more resistant (40 times more) to crack propagation than the control. It was noted that the control samples tended to split open during testing while the fiber-reinforced samples did not (Kaloush et al. 2010).

Overall, the lab characterization tests generally showed that the fiber mix would perform better than the control in resisting permanent deformation and thermal cracking, and would sometimes perform better in fatigue. The applicable test results were used as inputs into the *Mechanistic-Empirical Pavement Design Guide* (MEPDG) software to estimate the effects on pavement performance under different traffic conditions and in different pavement layer thicknesses. Using the MEPDG to simulate the effects of different layer thicknesses, the researchers estimated that the control mix would need to be placed 2 in. thicker than the fiber mix (5.5 vs. 3.5 in. for the assumed conditions) to resist an equivalent amount of rutting (such as 0.4 in.) to develop. The fatigue analysis showed that the fiber mix would experience less fatigue cracking, though the difference in cracking varied depending on the layer thickness (Kaloush et al. 2010).

After 2 years in the field, the control sections had "about three times the amount of low-severity cracking" as the fiber sections (Kaloush et al. 2010).

A study by Xu et al. (2010) compared the laboratory performance of four fiber types (polyester, polyacrylonitrile, lignin, and asbestos) to a control with no fibers. The polyacrylonitrile, lignin, and asbestos fibers were added at 0.3% by mass of the mix; the polyester fiber was used at varying contents from 0.20% to 0.50% to evaluate the effect of addition rate on performance. Dense mixes were evaluated in terms of rutting, flexural strength and strain, fatigue, tensile strength, and resistance to freeze-thaw cycles. All four fibers reduced rutting in a one-fourth scale accelerated loading test, but the polymer fibers reduced it the most (19% and 32% at 2,500 cycles for the polyacrylonitrile and polyester, respectively, compared with 8.4% and 11.4% for the lignin and asbestos). Fibers also improved the flexural strength and ultimate strain at 0°C and -10°C. The lignin and asbestos fibers had slightly better performance than the synthetic fibers, probably because of their high surface areas and branched structure. Similarly, all the fibers increased the fatigue life of the mixture, with the polyacrylonitrile, polyester and asbestos performing better than the lignin (Xu et al. 2010).

The polymer fibers also resulted in the greatest improvement in indirect tensile strength. After freezing and thawing, however, these fiber mixes were only slightly stronger than the control. The asbestos and lignin fiber mixes actually had strengths lower than the control after freezing and thawing. The relatively poor performance after freezing and thawing may be related to higher air void contents in these mixes (Xu et al. 2010).

Bennert (2012), in a study for the New Jersey DOT, compared the performance of plant-produced mixtures with and without a combination of polyolefin and aramid fibers. Both mixtures were produced in the same batch plant on the same day using the same mix design; the 9.5-mm surface mix was designed for a traffic volume of 3 to 10 million equivalent single-axle load with 5.9% PG 64-22 binder. The mixtures were characterized using dynamic modulus (AASHTO TP 79), flow number (AASHTO TP 79), beam fatigue (AASHTO T 321), and cycles to failure in the overlay tester (TxDOT TEX-248F).

Somewhat surprisingly, the results showed that the mixture without fibers had a much higher high temperature modulus than the mix with fibers—as much as two to three times higher. The mixture without fibers was only slightly stiffer than the fiber mix at low temperature. Analysis of the mixture phase angle from the same tests showed that the mix without fibers was more elastic than the fiber mix. Similarly, the flow number tests showed that the mixture without fibers had a greater resistance to rutting than the fiber mix, evidenced by exhibiting about five times the cycles to 5% strain (2,124 vs. 427). The beam fatigue test, which relates to the initiation of cracking, showed that the two mixtures had nearly identical resistance. The overlay test results, on the other hand, showed that the fiber mix had much greater resistance to crack propagation than the mix without fibers (174 cycles to failure vs. 6 cycles) (Bennert 2012).

Since the mixture testing results were somewhat unexpected, the binders from the dynamic modulus samples were extracted, recovered, and tested in the dynamic shear rheometer (DSR) and multiple stress creep recovery (MSCR) tests to explore the possibility that differences in the binders were influencing the mixture results. The high performance grades of the binders (AASHTO M 320) were very comparable, with that from the no-fiber mix being slightly higher than that from the fiber mix (68.8°C vs. 67.4°C). The recoverable strain from the MSCR test (AASHTO TP 70) was almost four times greater for the no-fiber mix than for the fiber mix at 58°C and almost nine times greater at 64°C, despite the fact that both mixes reportedly contained the same PG 64-22 binder. This indication of much greater elasticity of the binder in the no-fiber mixture could help to explain some of the differences in mixture behavior; it led to the speculation that the binder used in the mix without fibers may have had some contamination with a polymer-modified binder. A small amount of polymer could increase the elasticity of the binder and mixture, leading to higher stiffness and improved rutting resistance (Bennert 2012).

In another study, Bennert also compared the performance of a conventional 12.5-mm mixture produced for the New Jersey DOT with a similar mix containing aramid and polyolefin fibers, both using a PG 64-22 binder. Plant-produced mixes were sampled and tested in the laboratory (Bennert, n.d.). Dynamic modulus testing (AASHTO TP 79) of the plant-produced mixtures showed that the two mixes had similar stiffnesses at all frequencies. The fiber-reinforced mixture had slightly better resistance to rutting in the asphalt pavement analyzer (AASHTO T 340) than the control (2.70 vs. 3.14 mm). Likewise, results of testing in the repeated load flow number test (AASHTO TP 79) also showed slightly better performance for the fiber mix (959 vs. 747 cycles) (Bennert n.d.).

On the other hand, overlay test results [according the NJDOT B-10 overlay test for determining crack resistance of hot mix asphalt (HMA)] showed that the mix without fibers had a statistically significant greater resistance to crack propagation than the fiber mix after both short-term (194 vs. 129 cycles) and long-term (179 vs. 118 cycles) aging. The short-term aging was plant aging during construction; the long-term aging was in the laboratory according to AASHTO R 30. The beam fatigue test yielded similar behavior. The reason the mix without fibers performed better in fatigue than the reinforced mix is unknown, but it is possible that the addition of fibers reduced the effective asphalt content of the mix (Bennert n.d.).

The FHWA included a polyester-fiber-reinforced test section in a study comparing the performance of modified and unmodified binders using the accelerated loading facility (ALF) to test fatigue and rutting resistance. The ultimate goal was to explore candidate binder tests to improve the performance grade specifications, especially regarding testing modified binders. This ALF study tested PG 70-22 (unmodified control), Arizona wet process crumb rubber (CR-AZ), catalytically air-blown binder, styrene butadiene styrene with ~3% linearly grafted styrene SBS polymer by weight (SBS-LG), terminal blend CR (CR-TB) (5.5% rubber plus 1.8% SBS), terpolymer (Elvaloy with 0.4 % polyphosphoric acid), PG 70-22 with polyester fiber, and SBS 64-40 (approximately 3.5% SBS in a soft-base asphalt). Dense-graded Superpave 12.5-mm mixtures with these binders were produced in a drum plant. The optimum asphalt content for the control mix was 5.3%, so the binder content was fixed at 5.3% for all the mixes except the Arizona CR, which is a gap-graded mix and has a binder content of 7.1%. This mix also had different aggregates, which may have contributed to the much higher binder content. The following are additional details about the mixes, test sections, and their performance:

- The Arizona CR was placed at 50 mm over 50 mm of PG 70-22 mix. The control and other modified mixes were placed at 100 mm. Thicker 150-mm sections were placed using the control, two SBS-modified, air-blown, and terpolymer mixes for comparison of the effects of lift thickness.
- The maximum specific gravity of all the mixes was comparable (2.699 to 2.705) with the exception of the gap-graded mix, suggesting that the presence of a small amount of polyester fiber does not affect specific gravity.
- Loading was applied with the ALF device at a temperature of 64°C. The fiber mix withstood 125,000 wheel passes and reached a maximum rut depth of 12.50 mm. Rutting on the other 100-mm sections exceeded 12.50 mm in less than 50,000 wheel passes (with the exception of the CR-TB, for which testing stopped after 50,000 passes at a rut depth of 9.06 mm). The differences were not statistically significant except for the CR-TB; that is, the fiber performed similarly to SBS-LG, CR-AZ, control, and air-blown binders. It performed better than terpolymer.
- The temperature was increased to 74°C and a different location was loaded. In this case, the fiber mix performed better than all the sections except the linearly grafted SBS and the CR-TB. Rutting in the fiber section was similar at the two different temperatures.
- In terms of fatigue cracking, the fiber section performed second best after the Arizona CR, followed by the terminal blend CR, as measured by percentage of area cracked and cumulative crack length.
- The fiber section was "very resistant to fatigue cracking." It performed second only to CR-AZ as measured by load passes to surface crack initial, load passes to 25 mm cumulative crack, and load passes to 25% cracked area.
- Laboratory fatigue testing results did not match the field performance of the fiber mix.
- The authors concluded that the fiber mix demonstrated "very good fatigue cracking resistance … in the dense-graded mixture reinforced with polyester fibers. The fatigue cracking of this section was measurably better than those of the polymer-modified section even though a less-resistant unmodified asphalt binder was used in the mix. This was the second most effective performer of its thickness group behind the composite, gap-graded crumb rubber asphalt pavement. The presence of fiber had no significant beneficial or negative impact on rutting performance" (pp. 229–230).

A 2009 paper reporting on the same experiment indicated that when microcracks appeared on the surface of the ALF section with fibers, they did not coalesce into a larger crack as was seen in the other sections (Kutay et al. 2009).

In a study of materials from Cyprus, polypropylene (PP) and glass fibers were used together in dense-graded hot mix asphalt. The authors reported that a previous study compared the performance of different types of fibers and concluded that glass and PP fibers outperformed polyester and nylon fibers. Therefore, they decided to try combining the two in this study. The concept was that the PP fiber would become "tacky around its melting point" to improve bonding and the glass fibers would provide a high stiffness. The PP fibers were blended into the liquid asphalt and the glass fibers were added to the aggregates; both fibers were 12 mm in length. The binder and aggregates were then mixed and specimens were prepared in the Superpave gyratory compactor (Abtahi et al. 2013).

The content of PP fibers was 2%, 4%, and 6% by weight of the binder. These contents were combined with 0.00%, 0.05%, 0.1%, and 0.2% glass fibers by weight of the aggregate. For the PP in binder, softening point, penetration, and ductility tests were also performed. As the PP fiber content increased, the penetration and ductility decreased and the softening point increased (Abtahi et al. 2013).

Marshall stability tests were performed on the mixtures with PP and glass fibers (as well as mix with no fibers and with PP alone). As the PP content increased, the stability increased and flow decreased at each glass fiber addition rate. The addition of glass fibers at 0.05% and 0.1% increased the stability and decreased flow, but less improvement was seen when the glass fiber content increased to 0.2% (Abtahi et al. 2013).

In terms of volumetric properties, increasing the fiber content increased the voids in the total mix and decreased the voids filled with asphalt, hence the VMA also increased. There was a decrease in unit weight of the mix with increasing fiber content. The optimum combination found in this study was 6% PP with 0.1% glass fibers. The stability for the combination was 25% higher than that for the unmodified control. The decrease in voids filled with asphalt was considered to be a benefit that would help the mix resist flushing in hot climates, where significant expansion of the binder would occur (Abtahi et al. 2013).

Fibers in Stone Matrix Asphalt and Open-Graded Asphalt Mixes

Stone matrix asphalt mixtures are gap-graded mixtures in which the voids in the mineral aggregate are mostly filled with asphalt mastic (binder, filler, and sometimes fibers). Open-graded mixtures, as their name implies, have open void space, which allows water to flow into and out of the mixture; therefore, these mixes are also called porous asphalt or permeable asphalt mixes. The main purpose of using fibers in these mixes is to control binder draindown; both will be discussed in this section.

Stuart and Malmquist (1994) summarized the properties and purported benefits of using SMAs fairly early in the U.S. usage of this type of mix, after about 20 had been placed in the United States. On the basis of previous European experience with this type of mix in surface courses, it was expected that SMAs would perform better in terms of rutting under heavy traffic. These mixes are gap-graded with high coarse aggregate, binder, and mineral filler contents. Because of the lack of intermediate aggregates in the mixture, stabilizers are typically added to help retain the binder in the mixture; that is, to prevent draindown during production, transport, and laydown (Stuart and Malmquist 1994).

Stuart and Malmquist reported on a study to evaluate the effects of different types of stabilizers in SMA, including loose cellulose fibers, pelletized cellulose fibers, loose rock wool fibers, and two polymers with AC-20 binder. Six stabilizers were evaluated in terms of their effects on mixture resistance to rutting, low temperature cracking, aging, and moisture damage, as well as draindown. Three of these stabilizers (one fiber and two polymers) were also used to construct an SMA surface on US-15 in Maryland. The two loose cellulose fibers evaluated were of domestic origin, while the pelletized cellulose and the rock wool were European. Because the SMA technology had been introduced to the United States from Europe, many of the early projects involved European stabilizers (Stuart and Malmquist 1994).

The mixes were designed using the Marshall mix design with 50 blows per face. Then the mixes were evaluated in terms of draindown (by three methods: German, FHWA, and "pie plate"); resistance to rutting (three methods); resistance to low temperature cracking (two methods); resistance to aging (short- and long-term); and resistance to moisture damage (three methods) (Stuart and Malmquist 1994).

The four fiber mixes evaluated in this study exhibited similar low amounts of draindown, but the polymer-modified mix had relatively high amounts of draindown and did not pass the German and open-graded friction course draindown tests. On the basis of the initial results, one loose cellulose and one loose rock wool fiber were dropped from further testing because they were expected to perform similarly to the remaining loose cellulose and pelletized cellulose fiber in the study (Stuart and Malmquist 1994).

There were no significant differences in the resistance to rutting of the remaining two fiber and two polymer-modified mixes as measured by the Georgia loaded wheel test, the French pavement rutting test, and the gyratory testing machine. Similarly, there were no significant differences in the low temperature cracking resistance. The two polymer-modified mixes demonstrated less age hardening than the fiber mixes but were not effective at controlling draindown. It was noted that none of the actual mixes placed on US-15 exhibited any draindown during construction, despite the fact that the two polymers did drain down in the lab; the discrepancies between testing and performance were reported to be "difficult to explain." After 18 months in the field, all the SMA sections were performing without noticeable distress (Stuart and Malmquist 1994).

Brown et al. (1996) conducted a laboratory study of mortars for SMA mixtures using different fine aggregate types, two mineral fillers, modified and unmodified asphalts, and three types of fibers—cellulose, rock wool, and slag wool. The goals were to determine whether Superpave PG binder tests could be used to characterize SMA mortars and to determine how the components of the mortar affect performance. Fine mortar was defined as the binder plus stabilizer, mineral filler, and aggregate that passed through the 75-µm (#200) sieve and was considered for testing as a binder under the performance grade system. The total mortar was also tested in some cases; it included the fine mortar plus aggregates that passed through the 2.36-mm (#8) sieve. The fibers were added at 1.9% to 3.0% by weight of the mortar, which would be typical of the fiber content in the mortar fraction of SMAs (Brown et al. 1996).

Limited testing showed that fibers did not have a great effect on either the DSR or BBR results of the fine mortar. Cellulose stiffened the mortar slightly, but the rock and slag wools did not. There were difficulties in conducting the testing, such as mortars crawling out of the rolling thin film oven bottles, mortars not flowing in the pressure aging vessel pans, and complications in molding BBR and direct tension specimens (Brown et al. 1996).

The results of testing both the total mortar and the fine mortar indicated that most of the stiffening came from the mineral filler; the fibers did little to stiffen the mortar at most temperatures. However, at high temperatures, such as those encountered during production and placement, the fibers did stiffen the mortar appreciably. This high temperature effect is credited with reducing the draindown during construction and may be the main reason to use fibers in SMA (Brown et al. 1996).

In tests at the Nantes, France, test track, porous asphalts with mineral, glass, and cellulose fibers retained their high void content better than unmodified and polymer-modified overlays. In another experiment at Nantes, a very thin fiber-modified overlay showed excellent resistance to reflective cracking from an underlying fatigued pavement (Serfass and Samanos 1996).

The authors identified the following benefits provided by the use of fibers:

- Fixing the asphalt binder in the mix and preventing draindown;
- Reinforcing the mastic (binder plus fibers); and
- Reducing temperature susceptibility of the mastic because of the 3D network created.

These benefits enable asphalt mixes to be designed that are rich in bitumen and therefore have increased durability, resistance to aging, resistance to fatigue and thermal cracking, and high stability (Serfass and Samanos 1996).

Watson et al. (1998) summarized the Georgia DOT's (GDOT's) history of using open-graded friction courses. GDOT had used OGFCs for decades before banning them in 1982 after numerous problems with draindown, oxidation, raveling, and stripping of the pavement layer under the OGFC. Beginning in 1993, GDOT began using a modified 12.5-mm OGFC that included polymer-modified binder, fibers, and hydrated lime placed at 41 to 50 kg/m2 (75 to 90 lb/yd2). The use of polymer-modified binder and fibers reportedly allowed the buildup of thicker films coating the aggregates, which reduced weathering and early oxidation. Hydrated lime was added to both the OGFC and the underlying layers to prevent stripping.

Mineral fibers were used at about 0.4% by weight of the mix to prevent binder draindown and increase mix strength. They also reportedly worked with the modified binder to increase film thickness; calculated film thicknesses in OGFCs with fibers were about 400% greater than those in conventional dense-graded mixes and about 30% to 40% greater than in previous OGFCs. Similar mixes are still routinely used in Georgia.

A paper in 2000 by Cooley et al. compared the performance of cellulose with mineral fibers in OGFC. Cooley et al. credited a 1998 survey by Kandhal and Mallick as one impetus for their study; that survey reportedly revealed that many states specified mineral instead of cellulose fibers in OGFCs because of concerns that the cellulose would absorb water and cause moisture-related damage to the pavement. Cooley et al. conducted a field inspection of a 6-year-old Georgia DOT trial project that showed no significant performance differences between sections with cellulose and those with mineral fibers in terms of surface texture, rutting, cracking, and raveling.

Cores from the field sections were tested for permeability; the cores with cellulose and cellulose with polymer-modified binder had the highest permeabilities, but the differences were not statistically significant. Differences in water absorption into Marshall compacted specimens did not appear to be significantly different for the cellulose and mineral fiber specimens, though the loose cellulose mixes did have the highest absorption. Mixes with loose cellulose, two cellulose pellets (pelletized with 34% and 20% asphalt), and mineral fibers did not perform differently in terms of tensile strength ratio (TSR). No visual stripping was observed in any of the mixes. Submerged asphalt pavement analyzer (APA) rut depths were low, but the loose cellulose mix did have lower rutting (5.2 mm at 8,000 cycles compared with 7.6 mm for the mineral fiber). The authors concluded that cellulose was as effective as mineral fibers and no moisture problems should be expected because of the use of cellulose.

In another study, Watson (2003) inspected 13 SMA projects in five states after 5 to 10 years in service. On the basis of visual examination, he concluded that SMAs with fiber and unmodified binder performed as well as SMAs with polymer-modified binder. The types of fibers were not identified, but they probably included cellulose and possibly mineral fibers.

Putnam and Amirkhanian (2004) compared the laboratory performance of cellulose, polyester (recycled raw materials), scrap tire, and waste carpet fibers (nylon) in an SMA with a PG 76-22 binder and granite aggregate. The waste carpet fibers were in the form of tufts of fibers and were added at 0.3% for each fiber type. An optimum asphalt content was determined for each mix. The synthetic fibers had lower optimum asphalt content than the cellulose because they were less absorptive. The mixes were evaluated in terms of draindown (AASHTO T 305), moisture sensitivity (ASTM

D4867 modified), and rut testing (APA). Draindown was determined at the optimum asphalt content and at higher contents to see how well the fibers could stabilize an excess amount of binder (Putnam and Amirkhanian 2004).

The different types of fibers were equally able to prevent draindown at the optimum asphalt content. At higher binder contents, however, cellulose performed most effectively, followed by polyester, tire, and carpet fibers (the last two were comparable). The high stabilizing capacity of the cellulose was attributed in part to its higher absorption compared with the synthetic fibers (Putnam and Amirkhanian 2004).

Although there were no significant differences in the wet or dry strengths of the fiber-reinforced mixes and the TSR values were all in excess of the minimum required, the cellulose fiber resulted in a lower mix toughness. The authors commented that the synthetic fibers would therefore be expected to bridge cracks better than the cellulose and might have a stronger bond with the asphalt binder (Putnam and Amirkhanian 2004).

There were no significant differences in the ability of the fiber-reinforced mixes to resist rutting in the APA (Putnam and Amirkhanian 2004).

Hassan et al. (2005), in a study for Oman, explored the effects of 6-mm-long cellulose fibers (0.4% by weight of mix), SBR-modified binder (4% SBR), and a combination of fibers and SBR compared with a control with no additives. The study found that the polymer was more effective at resistance to raveling in the short term, while both polymer and fibers improved the long-term resistance (resistance in an aged condition). Fibers reduced draindown more than polymer alone.

Tayfur et al. (2007) compared the performance of unmodified and modified SMAs for their resistance to permanent deformation using indirect tensile strength, static and repeated creep, and wheel-tracking tests. The modifiers included granular amorphous polyalphaolefin, cellulose fibers, polyolefin, bituminous cellulose fiber, and styrene butadiene styrene. The researchers found that all the modified mixes had higher tensile strengths than the unmodified control, with the polyolefin and SBS having the highest tensile strengths. The SBS mixes had the greatest resistance to permanent deformation in the wheel-tracking test; the fiber mixes had some of the highest deformations in this test. The SBS mixes also had the highest resilient modulus among the modified mixes; the control had the highest resilient modulus at 5°C but not at 25°C or 40°C. Overall, the SBS mix performed most effectively; the fiber mixes did not perform particularly well (Tayfur et al. 2007).

As the importance of sustainability has increased in roadway construction, it has also become an important consideration in airfield construction. Stempihar et al. (2012) conducted a lab and field study to explore the feasibility of using fiber-reinforced porous asphalt mixtures for airfield pavements. The addition of fibers was considered a potentially sustainable paving practice because they might improve the performance of the pavement. Airfield pavements in cool climates need to be able to withstand heavy loads from aircraft, extreme variations in temperatures, and snow plowing in winter; fibers could potentially help with all these issues. An increase in service life would also increase sustainability by reducing carbon emissions from maintenance and reconstruction, and from production of new paving materials. Use of recycled or waste fibers would also increase sustainability (Stempihar et al. 2012).

This study compared the laboratory performance of fiber-reinforced asphalt concrete (FRAC) mixture samples from a paving project at the Jackson Hole Airport (JAC) in Jackson, Wyoming, with a control mixture without fibers. The control mix was reproduced in the laboratory using the same materials from a mix that was placed at the Sheridan County Airport (SHR) in Sheridan, Wyoming. The mixtures were evaluated in terms of dynamic modulus, fatigue, indirect tension, and Cantabro mass loss. A blend of polypropylene and aramid fibers was added to the batch plant at a rate of 1 lb/ton (0.5 kg/MT). The fibers were added to the hopper after the bag house so they would not be pulled into the bag house. Both mixtures used a PG 64-34 binder and similar binder contents (5.70% at JAC and 5.6% at SHR) and were open-graded mixes with a maximum aggregate size of 19 mm, conforming to the FAA P-402 porous friction course specification control points. The JAC mixture also included 0.75% hydrated lime (Stempihar et al. 2012).

Confined dynamic modulus testing according to AASHTO TP 62-03 showed that the FRAC was significantly stiffer than the SHR mixture at higher temperatures, which should represent increased rutting resistance. There were no substantial differences in the dynamic moduli at lower temperatures (Stempihar et al. 2012).

Beam fatigue testing (AASHTO T 321-03) showed that the fiber mix performed better in fatigue than the control mix at strain levels of 400 μm and 600 μm, but the performance was similar at 800 μm (Stempihar et al. 2012).

Tensile strength testing was conducted on the mixtures at 0°C, 10°C, and 21.1°C according to AASHTO TP 9-02. The FRAC outperformed the control in terms of tensile strength, energy at fracture, and total energy. The authors noted that "although the specimen cracks, the fibers hold the specimen together, which requires more energy for the asphalt sample to fail" (Stempihar et al. 2012, p. 64).

Finally, the Cantabro mass loss of the two mixtures was compared. In this test, specimens 100 mm (4 in.) in diameter and 63.5 mm (2.5 in.) tall were tumbled in an LA abrasion drum (without the steel balls) for 300 revolutions. The difference in mass before and after testing is used to determine the percentage mass loss. The mixes performed similarly in this test, with mass losses of only 2.6% and 3.7% for the fiber and control mixes, respectively (Stempihar et al. 2012).

The authors also examined the sustainability of fiber mixes through the estimated CO2 equivalent emissions. The emissions during construction of fiber-reinforced or -nonreinforced mixes would be similar, so any overall differences would arise from a difference in the service lives of the pavements or a difference in thickness. The use of fibers was estimated to result in an increase in the service life and could yield a 33% decrease in CO2 emissions, depending on the extent of the increase (Stempihar et al. 2012).

A cost estimate was also developed: the cost of adding the fibers was estimated to be approximately 11% in this case. For this to be cost-effective, the equivalent uniform annual cost was determined for the JAC and SHR mixes. The typical service life of an open-graded mix was assumed to be about 8 years. If the use of fibers increased the service life from 8 to 8.9 years, the additional cost of the fibers could be justified (Stempihar et al. 2012).

The authors concluded that the use of fibers in airfield pavements is feasible and offers the potential for increased service life under heavy loading and high tire pressures (Stempihar et al. 2012).

Lyons and Putnam (2013) compared the laboratory performance of cellulose fibers, CR-modified asphalt, and SBS-modified asphalt in porous asphalt mixtures. They found that the addition of fibers and polymers led to reductions in the porosity and permeability of the porous mixtures. However, it also led to improvements in draindown, abrasion resistance (Cantabro), and indirect tensile strength. Cellulose and crumb rubber were most effective at reducing draindown compared with the unmodified control. Crumb rubber and a combination of cellulose fibers with SBS-modified binder were most effective at improving the abrasion resistance of the mixtures. Finally, cellulose did not have a significant effect on tensile strength, but SBS and crumb rubber did lead to increased strength (Lyons and Putnam 2013).

Do Vale et al. (2014) studied the effects of using coconut fibers in SMA. The northeastern part of Brazil is a leading producer of coconuts. They found that the addition of cellulose and coconut fibers increased the TSR. But SMA mixes with coconut fibers did not perform as well in fatigue as mixes with cellulose or no fiber. This was possibly because the high absorption of the coconut fiber increased the stiffness of the mix. The researchers also noted that long coconut fibers were difficult to mix with the aggregate and could have lowered the strength of the mix by interfering with aggregate interlock. Work using shorter coconut fibers was planned.

Discussion of Performance of Fiber-Reinforced Mixtures

The literature survey on the performance of fiber-reinforced mixtures shows that the results are mixed. The use of fibers is not reported to cause any performance problems, provided the mix design, fiber dosage, and mix production are adequate. In some cases, fibers are reported to improve cracking or rutting resistance; in others they appear to have no effect. There are many possible explanations for these apparent discrepancies, including differences in the materials used in different studies, construction or laboratory mix preparation issues, and natural variability. Work by Cleven (2000) suggests an additional explanation.

Cleven reported that the use of fibers may have a greater impact on the performance of marginal or low-quality mixtures. His findings showed that fibers did not affect low temperature cracking resistance until the binder began to fail. When cracking began to develop in the binder, the fibers were mobilized and helped reduce the cracking (Cleven 2000). This conclusion is supported by Kutay et al. (2009), who observed that when cracking initiated in the ALF fiber section, the fibers helped reduce the severity of the cracking. A paper by Gibson and Li (2015), also using the FHWA ALF, showed that fiber-reinforced mix performs better in fatigue than polymer-modified mix at high strain levels, but not at lower strain levels.

These observations might also explain some of the seemingly disparate results reported in the literature. For example, the Indiana test section placed in 1980 exhibited much better rutting and cracking resistance than the control section without fibers (Galinsky 1984; McDaniel 1985). The severe rutting and cracking in the control section, however, showed that the control mixture was not of sufficient quality to withstand the interstate traffic loadings applied. Later, when fibers were added to a much more visible and closely controlled study in Indiana (McDaniel 2001; McDaniel and Shah 2003), all the mixes, including the unmodified control, performed very well for more than 10 years under interstate traffic loadings. Adding fibers or a variety of polymer binders to a high-performing mixture did not have as great an impact on performance.

COSTS AND BENEFITS OF FIBER ADDITIVES IN ASPHALT MIXTURES

Some of the cited studies demonstrate the benefits of using fibers, including these:

- Reduced draindown in open- and gap-graded mixtures,

- Increased resistance to rutting and cracking,
- Improved durability, and
- Increased toughness and stability.

However, documented benefit–cost ratios or cost-effectiveness studies are lacking in the literature. Only the study by Stempihar et al. (2012) included a cost estimate. As previously reported, the cost for the fiber mix in that study was about 11% higher than the cost for the control mix. This increased cost could be justified by an increase in the service life of 0.9 to 1.1 years.

CHAPTER THREE

SURVEY RESULTS: CURRENT U.S. AND INTERNATIONAL EXPERIENCE

This chapter presents the results of the survey of U.S. states, summarizing their experiences with the use of fibers in asphalt mixes. It also summarizes the information that has been gathered on fiber use in other countries. See the appendices for a copy of the survey, a list of those who completed it, and the tabulated survey responses.

U.S. SURVEY RESULTS

An electronic survey was distributed to all 50 states in April 2014. Responses were received from 48 states, for a response rate of 96.0%. The survey responses are summarized here.

Of the two states that did not respond to the survey, an online search of their specifications and special provisions found that one (Massachusetts) does not mention fibers in its documents, so it appears they do not currently use fibers in asphalt. The other state (Vermont) does include fibers in its specifications but only for asphalt curb mixtures, so, again, it is likely that their experience is limited. The District of Columbia had been identified in a 2011 AASHTO Subcommittee on Materials survey (Nelson Gibson, FHWA communication, Nov. 1, 2013) as not using fibers in asphalt.

Figure 8 lists the states that responded and the status of their use of fibers. Montana responded that it does not allow fibers but pointed out that its specifications are silent on the matter, so contractors would presumably have the option to use them if they felt the need. West Virginia has been open to vendors demonstrating their products but has not yet implemented the use of fibers. Hawaii does not routinely use fibers, but the state placed one SMA project with fibers in 2004 and another in 2014.

Of the states that do use fibers, by far the most common applications are in stone matrix asphalt and porous mixes (open-graded or porous friction courses) (see Table 3). Fibers are used in these mixtures to prevent draindown of the asphalt binder from the mixture. Eleven states use fibers in both SMA and porous mixes; 12 use them in SMA only; and eight use them only in porous mixes. This likely reflects the types of mixes used in those states. For example, so far North Carolina has used fibers only in porous mixes; the state has a draft specification for SMA but has not yet placed any. In addition to preventing draindown (cited by 27 of the states that use fibers), there are a few other reasons to use fibers. Georgia, Oklahoma, Tennessee, and Virginia also use them to reduce rutting and cracking. Idaho uses them only on an experimental basis to reduce rutting and cracking. New Hampshire uses fibers to reduce cracking and draindown, while Ohio uses them to reduce rutting and draindown. Maryland indicated that fibers allow more binder in the mix, while Oklahoma says they allow more mastic. Washington State has had limited experience with fibers, having used them on only a few SMA projects.

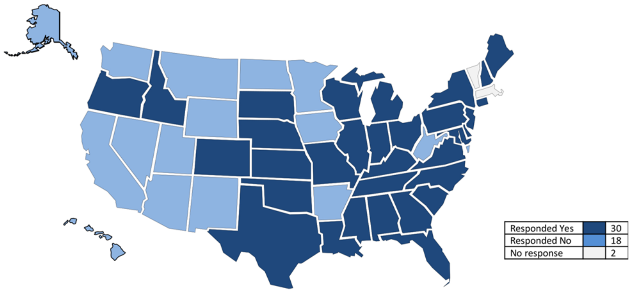

FIGURE 8 State responses to "Does Your Organization Currently Specify or Allow the Use of Fibers in Asphalt Mixes?" (*Source*: Survey responses).

TABLE 3
STATES AND PROVINCES INDICATING USE OF FIBERS IN VARIOUS APPLICATIONS

Application	States and Provinces Indicating Use
SMA or gap-graded mixes	AL, CO, CT, IL, KS, KY, MI, MO, OH, PA, SD, WI
Porous or open-graded mixes	CT, FL, ME, NC, NH, NY, OR, SC
Both SMA and open-graded friction course (OGFC)	DE, IN, GA, LA, MD, MS, NJ, OK, TN, TX, VA
Dense-graded hot mix asphalt overlays	ID
Other applications	• CT – cold mix • NH – curb mixes • OH – supplemental spec for districts desiring to use fibers • PA – curb mixes • VA – thin hot mix overlays and stabilized mixtures

Source: Survey responses.

Three states reported using fibers in the past but not currently. New Mexico used them in SMA but has not placed any SMA since at least 2000. Arizona also formerly used fibers in SMA but is not currently placing SMAs. PennDOT reported past use and is studying the potential of using fibers again through 12 pilot projects. Several states report declining use, as indicated in Table 2. In most cases, this is because of a decrease in the amount of premium surface (SMA and porous) being placed under reduced budgets. In other cases, such as Illinois, other materials are being used in lieu of fibers.

Table 4 shows the approximate annual tonnage of asphalt being placed in the states that use fibers and responded to the question. The tonnage varies greatly depending on the size of the program, number and size of projects with the mix types using fibers, and availability of alternative methods to reduce draindown.

TABLE 4
STATE ESTIMATES OF ANNUAL TONNAGE CONTAINING FIBERS

State	Approximate Annual Tonnage Containing Fibers (tons)
CT	1,500
DE	20,000
FL	500,000
GA	208,586
ID	Very few currently
IL	Minimal with use of reclaimed asphalt shingles (RAS) and ground tire rubber (GTR)
KS	10,000
KY	50,000–100,000
ME	Less than 1,000
MD	In 2012, 396,379; in 2013, 10,212
NC	60,000 tons
NH	Less than 5,000
NJ	100,000
NY	Less than 2,000 for DOT work
OH	Less than 10,000
OK	20,500
OR	Currently under 500; before 2009, approximately 30,000
SC	Approximately 250,000 OGFC per year
SD	100,000–150,000
TN	2012, 197,000 OGFC; 2013, 197,000 OGFC; no SMA for last 4-5 years
TX	700,000
AL, IN, LA, WI	Unknown or unavailable without research

Source: Survey responses.

Some states require the use of fibers and others allow it. For example, Kansas reported that it currently requires cellulose or mineral fibers in SMA but is considering removing that requirement as long as a draindown limit is met. Illinois allows the use of fibers, but the amount actually used is limited because the state also allows the use of reclaimed asphalt shingles (RAS) and ground tire rubber, which also control draindown. North Carolina also allows RAS to prevent draindown in OGFCs. New York allows the fibers "if needed." Ohio has had success with polymer-modified binders to reduce draindown in many districts. Ohio also has a supplemental specification for fibers that can be used at a district's option to produce a rut-resistant mix for high-stress applications. Ohio reports that in high-strength mixes with high crushed aggregate contents, fibers can actually reduce strength by interfering with aggregate interlock, though they do improve lower-strength mixes. Oklahoma is allowing the use of a warm mix technology (Evotherm) on one SMA project in lieu of fibers.

Only Idaho currently reports using fibers in dense-graded asphalt overlays to reduce rutting and cracking. One project has been completed, and research is under way to compare the field performance of three brands of fibers.

In addition to using fibers in SMA and porous mixes, Virginia uses them in thin asphalt surfaces and stabilized mixtures. Connecticut uses fibers in cold mix in addition to SMAs. New Hampshire reports using fibers in curb mixes, and the Vermont specifications indicate that it does too.

Most of the states that use fibers in SMA and porous mixtures allow either cellulose or mineral fibers. Table 5 summarizes the reported fiber types specified or allowed. Florida's specifications allow the use of either cellulose or mineral, but the agency reports that the vast majority of the use is of mineral fibers. Georgia uses synthetic polymer fibers (polyethylene and poly para-phenylene terephthalamide) experimentally. Pennsylvania does not currently use fibers routinely but is researching the use of aramid and polyethylene fibers in 12 pilot projects. Indiana used to use large quantities of polymer fibers in dense-graded mixes but now uses limited quantities of cellulose or mineral fibers in SMAs (see chapter four for details).

Asked to name any additional tests, specifications, mix designs, or acceptance criteria required for fibers or fiber mixes, six states said they did not require anything additional: Connecticut, Idaho, Indiana, Louisiana, Mississippi, and Oklahoma. The remaining 22 states that use fibers do have some additional requirements, most often a maximum limit on draindown. More details are provided in the following section on state specifications and test methods.

No states reported having any safety or health issues when fibers are used. Almost all said they rely solely on the Material Safety Data Sheet/Safety Data Sheet.

Nine states reported that they have conducted or are conducting research into the use of fibers in asphalt. The completed reports were included in the literature review presented in chapter two. As indicated previously, Idaho and Pennsylvania have ongoing research efforts in this regard. Alaska is considering an experimental use of fibers in pavement preservation in 2014 or 2015.

TABLE 5
TYPES OF FIBERS SPECIFIED OR ALLOWED BY STATES

State	Fiber Types Specified or Allowed
AL	Polymer, cellulose, mineral
CT	Polymer
DE	Cellulose, mineral
FL	Cellulose, mineral
GA	Cellulose, mineral, polymer (experimentally)
ID	Polymer
IL	Cellulose, mineral
IN	Cellulose, mineral
KS	Cellulose, mineral
KY	Cellulose, mineral
LA	Cellulose, mineral
ME	Cellulose, mineral
MD	Polymer, cellulose, mineral
MI	Cellulose
MS	Cellulose, mineral
MO	Cellulose, mineral
NY	Polymer, mineral
NH	Polymer (polyester)
NJ	Cellulose, mineral
NC	Cellulose, mineral
OH	Polymer, cellulose, mineral
OK	Cellulose
OR	Cellulose, mineral
PA	Cellulose
SC	Cellulose, mineral
SD	Cellulose
TN	Cellulose
TX	Cellulose, polymer
VA	Cellulose, polymer
WI	Polymer, cellulose

Source: Survey responses.

Life cycle cost analyses or benefit–cost ratios for the use of fibers are almost nonexistent. Very few states report having any such data available. Oregon said it essentially eliminated the use of OGFCs in 2008 after an evaluation revealed that the life cycle costs were not favorable; the use of fibers immediately dropped. Oregon's response mentioned the possibility of using more fibers in the future because the state is considering increasing the use of porous asphalt to reduce water runoff from the pavement.

South Carolina is the only state to mention constructability issues with fiber mixes in its survey response, though other states are known to have encountered difficulties. South Carolina respondents indicated that the service life of OGFC mixes has been less than expected, which they attribute, in part at least, to mix consistency and constructability issues. They have experimented with using warm mix technology (Evotherm) and ground tire rubber to control draindown without fibers in hopes of improving uniformity and constructability.

Alabama reports that it is currently updating its specifications to allow reclaimed asphalt shingles (RAS) in place of fibers in SMA mixes. RAS contains fibrous materials from the backing material on the shingles; it also includes a stiff asphalt binder, which may help to reduce draindown.

STATE SPECIFICATIONS AND TEST METHODS

One survey question asked whether the agencies have any specifications, test methods, mix design methods, or acceptance criteria for fibers or fiber-modified mixtures. A total of 22 states reported having specifications or test methods specific to fibers or fiber-reinforced asphalt mixes. Most require a maximum allowable draindown, typically no more than 0.3% by weight of the mix. AASHTO T 305 is frequently cited as the test method used; Kansas and South Carolina have their own draindown test methods, which are similar to the other methods.

Table 6 is a summary of the properties specified by agencies that have particular requirements for fiber mixes. The specifications are very similar. Requirements for cellulose fibers typically include fiber length, sieve analysis, ash content, pH, moisture content, and oil absorption. The requirements for mineral fibers sometimes specify the mineral types that can be used (virgin basalt, diabase, and slag, most often) and usually include length, thickness, and shot content. The limits placed on these properties are also fairly standard, though there are some deviations.

For cellulose fibers, the fiber length and thickness relate to the ability of the fibers to reinforce the binder or mixture. The length and the percentage that passes specific sieve sizes are typically determined using one of two methods, the Alpine method or the sieve analysis method. Both are described in chapter two, in the section on methods of testing fibers and fiber mixtures. In either case, the percentage of fibers by mass that pass the specified sieve size is determined. The pH, oil absorption, and moisture content all relate to the bond of the fiber and asphalt. The pH must be compatible with the binder. The cellulose fiber absorbs oil (typically five times the mass of fiber) to retain binder and ensure good adhesion. And the moisture content is limited to avoid adding water to the mix and interfering with the bonding of the fiber and binder. Similar requirements frequently apply to cellulose pellets, with additional limitations on pellet size and binder penetration.

TABLE 6
SPECIFIED FIBER PROPERTIES REPORTED BY STATES/PROVINCES

State	Fiber Types Specified or Allowed
AL	Draindown (AASHTO T 305)
DE	Cellulose: ash content (D1282); pH, moisture content, and length (AASHTO MP 8). Mineral (from virgin basalt, diabase, slag, or other silaceous rock): length and thickness (MP 8), shot content (ASTM C612).
FL	Mineral (from virgin basalt, diabase, or slag) with cationic sizing agent for dispersal and adhesion: specified length, thickness, shot content (ASTM C612). Cellulose: length, sieve analysis (Alpine or Ro-Tap methods), ash content, pH, oil absorption, moisture content. Certified test results required for each batch.
GA	Draindown, wet mixing time. Polymer: limit on unseparated fibers, length, form, specific gravity, tensile strength, melt temperature, acid/alkali resistance, packaging. Cellulose: ash content, pH, moisture contents. Cellulose pellets: pellet diameter, binder type, and content. Mineral (from virgin basalt, diabase, slag, or other silicate rock): shot content.
IL	Sieve analysis, length, ash content, pH, oil absorption, moisture content, shot content/gradation.
KS	Draindown (KT-63).
KY	Reference AASHTO M325 for design of SMA. Material certification to verify cellulose or mineral fibers. Dosage rate specified.
MD	Draindown, percent stabilizer.
ME	Cellulose: Alpine sieve analysis, ash content, pH, oil absorption, moisture content. Mineral: dosage rate, length, thickness, shot content.
MO	Draindown (AASHTO T 305).
NH	Polyester fibers from Qualified Products List, uniformly distributed in dry mix at ~0.25% of total batch weight.
NJ	Mineral or cellulose fibers conforming to AASHTO MP 8. Dosage rate specified. Fibers must be dispersed uniformly and proportioned to within ±10% of required rate. Certification required. Manufacturer's representative present for first day of production.
NY	Mineral: length, thickness, shot content.
OH	For SMA–cellulose: length, sieve analysis (Alpine or Ro-Tap), ash content pH, oil absorption, moisture content. Cellulose pellets: cellulose fiber requirements above, pellet size, binder penetration. Mineral (from virgin basalt, diabase or slag with cationic sizing agent for dispersal and adhesion): length, thickness, shot content, degradation. For supplemental specification for rut-resistant mix: polyester or polypropylene from Qualified Products List: denier, length, crimps, tensile strength, specific gravity, melt temperature, certified test results.
ON	Cellulose: sieve analysis (Alpine or mesh screen), length, ash content, pH, oil absorption, moisture content. Mineral: sieve analysis, length, shot content. Draindown for SMA.
OR	Mineral: mineral (from virgin basalt, diabase or slag): dosage rate, length, minimum and maximum thickness, shot content (ASTM C612). Cellulose: dosage rate, length, gradation (Alpine or mesh screen), ash content, pH, oil absorption, moisture content.
SC	Draindown (SC-T-90, SC-T-91).
SD	Draindown (at design and once a day during production). Cellulose: length, sieve analysis (Alpine), ash content, pH, oil absorption, moisture content.
TN	Draindown (T 305).
TX	Draindown.
VA	Cellulose or mineral with supplier's certification of properties and documented success in similar applications.
WI	Draindown.

Source: Survey responses.

For mineral fibers, the length and thickness are typically specified for the same reasons as they are for cellulose, but different test methods have historically been used. Thickness is determined by examining 200 fibers under a microscope. The fiber length is determined using a Bauer McNett fractionation; this process disperses the fibers in water so they can be sieved. In addition, the shot content is usually controlled. This property is a measure of nonfibrous materials contained in the fiber and is determined as the percentage that passes two small sieve sizes (typically 0.250 mm and 0.063 mm). Besides draindown, no additional tests are required for fiber mixes.

INTERNATIONAL EXPERIENCE

Two survey responses were received from Canadian provinces. Manitoba reported that it does not use fibers in asphalt. Ontario does use fibers in SMA mixes and some trial mixes. In the trial mixes, the purpose of the fibers is to help resist cracking over jointed concrete. Five trial sections were constructed in 2007 to compare the performance of a control section without fibers to four test sections with varying combinations of polymer-modified binder and polyethylene terephthalate (PET) fibers. The properties required of the fibers in Ontario are listed in Table 6.

Aside from the Canadian experience, much of the other information on international use of fibers was obtained through the literature review. As noted in the Introduction, fibers were typically used in European stone matrix asphalts. When that technology was introduced to the states, the use of fibers was included. These were typically cellulose and mineral fibers, as they are today. The origin of the use of fibers in dense-graded mixes is harder to determine. There were some early reports of this type of application, but it was limited. Much of this experience is apparently in the United States.

Although cellulose, mineral, and synthetic fibers are widely used in developed nations in Europe and North America, there has been quite a bit of work in developing countries to make use of locally available, plant-based fibers. This is a more economical practice and provides a market for local materials. The types of plant-based fibers that have been studied for use in asphalt mixes include coconut (Oda et al. 2012; Do Vale et al. 2014), sisal (Oda et al. 2012), hemp (Abiola et al. 2014), jute (Das and Banerjee 2013), straw (Qiang et al. 2013), and sisal oil palm (Muniandy et al. 2014).

To supplement the literature review and obtain current information on fiber use internationally, individuals working in asphalt research and teaching or in asphalt mixture production/construction were contacted by e-mail. The responses obtained from these contacts are summarized in Table 7. These responses confirm that international use of fibers is predominantly in SMA and porous asphalt mixtures, and that the most widely used fiber is cellulose.

TABLE 7
COMMENTS ON FIBER USAGE IN OTHER COUNTRIES/REGIONS

Country/Region	Comments
Australia/New Zealand	Cellulose fibers used in SMA, typically at 0.3% by mass of total mix. Other fibers, including fiberglass, rockwool, polyester and natural wool, are suitable for use but rarely used because cellulose is more cost-effective.
Brazil	SMA mixes require fibers, which are typically cellulose. SMA mixes are not widely used, perhaps <4,000 km total. There have been a few applications of microsurfacing with glass fibers.
Finland	Uses cellulose fibers in SMA. Does not use porous mixtures because of studded tire wear.
Germany	Continues to use fibers in SMA. One major supplier precoats cellulose fibers with binder to pelletize the fibers and aid in dispersion in the mix plant.
Israel	Netivei Israel, the national roads company, requires cellulose or mineral fiber in SMA and porous mixtures.
Other Middle Eastern Countries	No known use of fibers. Iran has used some SMA and porous asphalt, but typically uses SBS or crumb rubber to limit draindown.
Poland	Not used routinely. One company in Poland does use synthetic fibers in cold mix. Other European use is of fibers in SMA; about 99% of the fibers used are cellulose. Some European companies with operations in Poland (and other European countries) have researched the use of fibers within the past 10 years or so, but current coordinated European research efforts (Framework Programs for Research and Technological Development and COST, European Cooperation in Science and Technology) are not addressing fibers in asphalt. There is a Polish patent for a process using fibers from waste tires, but there has been no practical application to date. There has been research on the use of polymer fibers in high-stiffness modulus base layers for heavy traffic applications.
Spain	Cellulose fibers are used in high binder content mixes to prevent draindown, but this is a limited application used mainly for airports. Spain rarely uses SMA. There has been some research on use of steel fibers for heating and self-healing asphalts.
U.K. and Northern Ireland	Cellulose fibers are used in SMAs to prevent draindown.

Source: E-mail communications.

CHAPTER FOUR

CASE EXAMPLES

This chapter presents five case examples of agencies and their use of fibers. The first example is of an agency that is contemplating the use of fibers but has no previous experience. This example is intended to illustrate the types of questions an agency might have regarding the use of this technology. The second case example is of a state that has had a dramatic change in the use of fibers over time. The third case example describes the evolution of specifications for fiber mixes and the experiences of contractors. The fourth case example summarizes an ongoing research effort by a state with little previous use of fibers in asphalt. The fifth case example is of a state that has used fibers extensively in SMA and porous mixes and is now exploring the possibility of using a different type of fiber in dense-graded mixes.

CASE 1. AGENCY CONSIDERING USE OF FIBERS

This case example is offered as an illustration of the types of questions an agency might have when considering requiring or allowing the use of fibers in asphalt mixtures. Erie County, New York, is considering that possibility to help asphalt pavements better withstand the rigors of their environment. Erie County, where Buffalo is located, experiences substantial lake-effect snowfall and very cold winter weather. Cracking is a frequent distress in asphalt pavements, so fiber reinforcement could be a good tool to have available. However, the county lacks experience with fibers.

County officials are seeking information on the types of fibers that have been used and are currently available. They also wonder which applications are most suitable for fibers, which pavement layers would benefit most, and which distress types fibers can address effectively. The performance of fiber mixes is an obvious area of interest. Officials are particularly interested in cases where fibers have been used under environmental conditions similar to their own (wet freeze).

If the county decides to use fibers, it will need guidance on how to specify the fibers and mixtures, whether the type of mix design (Marshall or Superpave) makes a difference, and whether they will have to make changes to the mix design. Other questions include the typical dosage of fibers and whether it varies depending on fiber type.

Moving on to construction, concerns include how to introduce the fibers into the mixture and whether that varies for different types of fibers. The types of equipment needed to uniformly disperse the fibers, where to introduce the fibers, and impacts on production time are also issues to consider. Officials wonder if they will have to make any changes to the construction process, procedures or equipment, and about the effects of fibers on constructability. Of course, cost is also an issue.

To the extent that information could be obtained on these issues, answers to these questions have been sought as this synthesis was prepared.

CASE 2. AGENCY WITH VARYING FIBER USAGE

On the basis of research in the early 1980s which showed that fiber-reinforced asphalt surfaces experienced greatly reduced rutting and cracking, the Indiana Department of Transportation (INDOT) made extensive use of fibers in asphalt in the 1980s and very early 1990s. At the time, cracking and seating concrete pavements, followed by an asphalt overlay, was a standard rehabilitation technique in the state. For several years, INDOT required the use of polypropylene fibers in these dense-graded overlays. Both cracking and seating and the use of fibers were intended to reduce reflective cracking, which was a common problem. Fibers also helped reduce rutting, another major problem.

A 1989 study by El-Sheikh and Sudol found that cracking and seating reduced reflective cracking, compared with the control, by 75% after 5 years. Sections with fibers in the overlay over cracked and seated pavements showed a reduction in transverse cracking of 85%. In addition, fibers improved pavement strength (measured by falling weight deflectometer testing) by 15% compared with sections without fibers (El-Sheikh and Sudol 1989). Reduced rutting was also observed on this project and in previous trials (Galinsky 1984; McDaniel 1985). On the basis of this and other research, INDOT began specifying the use of fibers in all dense-graded overlays over cracked and seated pavements, and in some other overlays as well. Anecdotally, it was estimated that Indiana used more fibers in asphalt mixes than the next four states combined, but this has not been documented.

Reportedly, problems began to develop in the late 1980s or early 1990s when INDOT loosened its specifications to allow more types of fibers, including waste carpet fibers, with reduced controls on their content or coatings. Construction problems with clumping of fibers began to appear.

Shortly after the problems began to increase, INDOT implemented the new Superpave binder and mixture specifications. Under this system, it was difficult to quantify the effects of using fibers. Attempts to test the fibers as a binder modifier were ineffective because of severe difficulties in preparing the specimens for testing; the fibers could not be uniformly dispersed in poured binder specimens. Attempts to cut binder specimens from sheets of fiber-reinforced binder were also unsuccessful, as the specimen geometry and smooth edges could not be ensured. Tests of fiber-reinforced mixtures in the Superpave shear tester and the indirect tensile (IDT) tester, according to AASHTO TP 7 and TP 9, were also unsuccessful. It was speculated at the time that the tests were not sensitive enough to detect the contributions of the fibers. Superpave provided a means for the state to use polymer-modified binders for high-volume roadways; these were expected to help reduce both rutting and cracking. In addition, changes in the mix designs and aggregate requirements helped to greatly reduce the occurrence of rutting. Given these performance benefits, it was hard to justify the added cost of using fibers in Superpave mixes; consequently, the use of fibers in the state dropped dramatically.

There was an increase in fiber usage in the late 1990s when the state began using SMA surfaces widely. In these mixes, however, cellulose or mineral fibers were used instead of polymer fibers. The high cost of SMAs during hard economic times led to a decrease again in fiber use. SMAs are making a small comeback in the state, so fiber usage may see an uptick.

Virginia is another state that has seen ups and downs in fiber usage. McGhee et al. (2013) reported that Virginia had used open-graded friction courses but experienced various problems so discontinued their use in the late 1980s. Draindown was frequently observed and led to the pavement being underasphalted; these pavements often suffered durability problems leading to early failure. Those OGFCs that did not experience draindown reportedly developed black ice in some conditions, leading to safety concerns. Finally, OGFCs were linked to increased moisture damage of the underlying layer, which resulted in failures deeper in the pavement that were more difficult and expensive to repair. New generation OGFCs used polymer-modified binders and fibers to prevent draindown. Higher void contents were also maintained with these mixes, so they could dissipate sound energy, making the pavements quieter. [Virginia had a legislative mandate to explore options for quieter pavements (McGhee et al. 2013).]

CASE 3. CONTRACTORS' EXPERIENCES WITH FIBERS IN ASPHALT MIXTURES

In the 1980s and 1990s, the Florida Department of Transportation (FDOT) used an open-graded friction course, designated FC-2, to provide a high-friction, drainable surface for high-speed, multilane roadways to reduce hydroplaning. This open-graded mixture used a 3/8-in. nominal maximum aggregate size and, initially, an unmodified AC-30 asphalt binder. Later, 12% asphalt rubber was added to the AC-30 (Cunagin et al. 2014) to increase the binder content (and film thickness) without creating a draindown problem.

This surface type tended to have a relatively short service life and typically failed because of raveling of aggregate from the surface. The raveling was attributed to the open-graded structure of the mix, a low binder content, and the resulting thin binder film. The open structure of the mix allowed oxygen to enter the pavement and accelerate oxidation and embrittlement of the binder. The use of an unmodified binder was also a contributing factor, but the use of rubber-modified asphalt did not entirely solve the problems with this mix; relatively thin lifts and low tack coat application rates also aggravated performance problems.

The development of a new mixture specification implemented in 2000 was motivated by the problems with earlier friction courses and the Georgia DOT's success with modified OGFCs. The resulting FC-5 surface course uses a ½-in. nominal maximum aggregate size and modified binder—either the same asphalt rubber or a PG 76-22 polymer modified binder. In addition, cellulose or mineral fibers are required to stabilize the asphalt binder and prevent excessive draindown. The fiber rate is specified at 0.4% for mineral fibers and 0.3% for cellulose fibers (Cunagin et al. 2014).

FDOT's pavement management system data show that the implementation of the FC-5 specification increased the median service life of the surface to 15 years, compared with 12 years for the FC-2. Although fibers presumably contributed to the increase in the life of the surface, other changes made at the same time also contributed. These include a heavier tack coat, thicker lifts, higher production and placement temperatures, and more polymer-modified binder (Cunagin et al. 2014). Nonetheless, the use of this fiber-reinforced material has resulted in better durability of the surface, and its use is expected to continue.

When the FC-5 specification was implemented, contractors in Florida had to adjust to adding fibers to the mixtures. There were a number of issues in the beginning. Owing to a patent issue, there was initially only one supplier for the fibers. This caused occasional supply shortages, which eventually led some contractors to stockpile fibers so they would be available when needed. The expiration of a patent on the fibers allowed other suppliers to enter the market, which increased the supply and led to lower prices through competition. Today, supply issues are a thing of the past (Jim Musselman, FDOT correspondence, Aug. 29, 2014).

Another problem in the early days of implementation was with clumping of the fibers during mix production. Some contractors reported more clumping problems with certain sources of fibers; with multiple suppliers, these sources can usually be avoided. Storing the fibers properly and keeping them dry are also credited with resolving a number of the clumping problems. Although the FDOT specifications allow the use of either cellulose or mineral fibers, the majority of contractors use mineral fibers. Cellulose fibers require about 0.3% to 0.5% additional binder compared with mineral fibers and, because binder is included in the mix price, result in a higher mix cost for the contractors (Jim Musselman, FDOT correspondence, Aug. 29, 2013).

The addition of fibers also meant retrofitting some asphalt plants and renting or buying the equipment to blow in the fibers. While most contractors initially rented the equipment, most of them have now purchased it; it is routinely used, so owning is more cost-effective than renting. In one case, for example, the cost to rent was $7,000 per month and the purchase price was $75,000, so the payback period was quite short (Jim Musselman, FDOT correspondence, Aug. 29, 2013).

The example of the Florida DOT and its contractors shows that issues can arise when fiber use begins, but that with attention to detail and experience with the product the issues can be addressed and overcome.

CASE 4. ONGOING RESEARCH ON FIBERS IN DENSE-GRADED ASPHALT

As the survey results show, nearly all the current use of fibers in asphalt in the United States is in open-graded or SMA mixtures. The Idaho Transportation Department (ITD) provides an example of an agency that is currently researching the use of fibers in dense-graded asphalt. (Others include the Pennsylvania DOT, Ontario Ministry of Transportation, and some local agencies.)

Fibers are being investigated to determine their effectiveness at reducing rutting and cracking, as ITD continues its efforts to reduce costs and prolong pavement life. In addition to comparing the laboratory performance of the fiber mixes, the research effort will assess the mixture properties needed as inputs to the mechanistic-empirical pavement design software. A later phase of the project is intended to monitor the field performance for a period after construction (University of Idaho 2015).

Three test sections incorporating different fibers and one control section were constructed on US-30 in August 2014. This highway carries heavy truck traffic near the border with Wyoming, which has caused rutting. Cracking of the existing pavement was also observed. The existing pavement was milled 122 mm (0.4 ft) before the new overlay was placed in two 61-mm (0.2-ft) lifts. Fibers were added to both lifts in the test sections without increasing the binder content. The milled material was reused in the new mixtures (Mike Santi, ITD communication, Aug. 29, 2013; University of Idaho 2015).

The mix design was performed without fibers, which were later added at the drum mix plant. The mix incorporated a high reclaimed asphalt pavement content of 47% by mass of mix with a binder replacement value of about 54%. The fibers under study include aramid (0.35 lb/ton), fiberglass (3 lb/ton), and a blend of polypropylene and aramid (1 lb/ton). The fibers were blown into the plant along with the reclaimed asphalt pavement through the vendors' equipment, which was calibrated to inject the required amount of fibers (Mike Santi, ITD communication, Aug. 29, 2013; University of Idaho 2015).

The laboratory evaluation of the mixtures will include the following:

- Gyratory stability analysis using the Superpave gyratory compactor;

- Dynamic modulus testing in indirect mode at a range of temperatures (-20°C, -10°C, 0°C, 10°C, 20°C, and 30°C) and frequencies (0.1, 1, 5, 10, 20 Hz) to assess stiffness;
- Flow number testing to evaluate resistance to permanent deformation;
- Creep compliance testing to evaluate thermal cracking;
- Fatigue analysis using the fracture work density concept;
- Transverse cracking analysis, also based on fracture work density;
- Asphalt pavement analyzer (APA) testing to evaluate permanent deformation;
- Performance prediction using mechanistic-empirical pavement design software from AASHTO; and
- X-ray tomography to explore the distribution of fibers through the mix.

The testing and analysis will be done by the University of Idaho and Washington State University, with the exception of the APA testing, which will be conducted by ITD (University of Idaho 2015).

The X-ray tomography results may be of particular interest because of ongoing and widespread concerns about the uniformity of fiber dispersion during construction. A researcher present during construction of the Idaho test sections noted that some of the fibers, which were visible through clear tubes leading into the plant, did not flow uniformly into the plant but rather agglomerated into a ball that was pushed through the tube. It is currently unknown whether the fibers were then uniformly distributed during the mixing process (Fouad Bayomy, University of Idaho correspondence, Aug. 28, 2013).

Fibers have been promoted in Idaho and elsewhere as a means to reduce layer thicknesses and thereby reduce costs. The current study is not evaluating reduced thickness, though this is a possibility in the future (Mike Santi, ITD correspondence, Aug. 29, 2013).

Regarding the use of fibers to reduce pavement thickness, the Asphalt Pavement Association of Oregon (APAO) has recently prepared a position paper urging agencies to treat the use of fibers as an experimental technology. APAO recommends that control sections be placed on projects incorporating fibers to expand the range of materials and conditions (e.g., traffic, climate, pavement structure) in which fibers are used to develop a clearer understanding of their effects on performance. Although APAO supports the use of proven technologies, its position is that the benefits of fibers, especially for reducing pavement thickness, have not yet been proven (APAO position paper).

CASE 5. STATE WITH HIGH FIBER USAGE RESEARCHING OTHER APPLICATIONS

Texas
Department
of Transportation

The Texas Department of Transportation (TxDOT) uses large quantities of fiber-reinforced SMA and PFC every year—about 700,000 tons of fiber mix annually. This is about 40% more fiber mix than Florida uses and three to five times more than other high-use states such as Georgia, South Carolina, and Tennessee. Texas uses cellulose and mineral fibers in these applications.

In 2013, TxDOT began placing test sections around the state to evaluate the use of fibers in dense-graded surface mixes to control cracking. There is some concern that some of the DOT mixes might be too stiff, and cracking has been observed, so the department is interested in exploring options to reduce cracking and increase the service lives of its asphalt surfaces.

The test sections reflect a variety of climates and traffic conditions to determine whether fibers are beneficial in various settings. The test sections include 1 lb of blended polyolefin and aramid fibers per ton of hot mix. They also include unmodified control sections. In addition to exploring the field performance of these mixes, two other questions are being investigated: Are there differences between lab and plant mixing when fibers are used? Are the tests used in Texas—including IDT testing, the Hamburg tester, and the overlay tester—applicable to fiber mixes? There is a concern in Texas, as elsewhere, that some laboratory tests might not accurately reflect the effects of fiber reinforcement.

No construction difficulties were reported during construction of the test sections.

In the coming years, the results of this research will likely be of interest to other agencies that have expressed some of the same concerns about field performance and laboratory testing of fiber mixes.

CHAPTER FIVE

CONCLUSIONS

This synthesis compiles available information on the use of fibers in asphalt mixtures. It outlines the many types of fibers that have been used, their properties and how they are tested, mix design tests for fiber mixes, the types of applications in which fibers have been used, and lab and field performance of fiber mixes, and other topics.

The information in this synthesis was gathered through a thorough review of the available U.S. and international literature. In addition, a survey of U.S. and Canadian state/provincial agencies was conducted to determine the current status of fiber asphalt usage. The U.S. state response rate to the survey was 96.0% (48 of 50).

About 30 states report using fiber in asphalt mixes. By far the majority of the use is in stone matrix asphalt (SMA) and open-graded or porous friction courses (OGFC or PFC) to control draindown of the binder from the mix. In the past, fibers were frequently used in dense-graded mixes in some states, but that usage has decreased in the past 20 years or so, though interest appears to be increasing again. The use of SMAs and porous mixes is also on the decline in some states because of the high cost, but that situation is fluid and subject to change.

Cellulose and mineral fibers are most commonly used in SMA and porous mixes in the United States. The use of synthetic polymer fibers is less common but perhaps increasing. There is also interest in using recycled or waste fibers, provided they can perform as well as virgin fibers.

Of the states that use fibers, most do not routinely require any additional tests or changes to the mix design procedures, with the exception of adding a draindown test for open- or gap-graded mixes. Fiber quality is ensured through supplier certifications in most states in which fiber properties are specified. Because some fibers are absorbent or have large surface areas to coat with binder, the binder contents in fiber mixes may need to be increased, which can have beneficial effects on durability but might increase mix costs. Mix production and placement are largely unchanged, except that some means of introducing the fibers into the mix plant is required. If the fibers are properly stored and handled, construction issues can usually be minimized.

Research into the use of fibers in asphalt has been extensive over the past 4 to 5 decades. Studies of the laboratory and field performance of fiber-reinforced dense-graded mixtures, however, have yielded mixed results. In some cases, the fibers improved performance, especially in terms of rutting and cracking resistance; in other cases, the fibers have not resulted in significant performance improvements. It appears that fibers might be more effective in marginal or lower-quality mixtures that are prone to rutting and cracking. The benefits of fibers for reducing draindown in gap- and open-graded mixes are more clearly defined in the literature, which may explain their common use in those mixes.

The use of fibers internationally is quite similar to that in the United States; that is, cellulose or mineral fibers are routinely used in gap- and open-graded mixtures. Fibers are less commonly used in dense-graded mixes, but when they are used, synthetic polymer fibers are most prevalent. There appears to be growing interest in using locally available plant-based materials—such as coconut, jute, hemp, and sisal—as sources of fibers in developing parts of the world.

Case examples of the use of fibers in asphalt by local and state agencies are provided in chapter four. These case examples include the following:

- Common questions an agency might have when it is considering the possibility of using fibers;
- An agency that saw a great decrease in the use of fibers as they implemented new mix design procedures and specifications;
- An agency's and its contractors' experiences with the implementation of fibers in open- and gap-graded mixes;
- An ongoing research project being conducted by a state with little previous experience with the use of fibers in asphalt; and
- Another ongoing research effort in a state that uses fibers extensively in SMA and OGFC and is exploring their use in dense-graded mixtures as well.

On the basis of the information reported here, a number of gaps in the state of knowledge have been identified. Research is needed to clarify or document the cost-effectiveness of using different types of fibers in different applications; how to characterize fiber mixes for mechanistic-empirical pavement design; best practices for production and construction of fiber mixes; critical fiber characteristics to ensure quality; test methods to verify the presence and distribution of fibers; health, safety, and environmental issues with the use of different types of fibers; performance mechanisms of different types of fibers (perhaps through a comprehensive performance study); and the future recyclability of fiber mixes and effects on use with recycled materials.

In summary, some uses of fibers in asphalt mixtures are well established and successful. Opportunities exist to use fibers in other applications to extend pavement service lives and improve the level of service, but more research is needed to ensure that those potential benefits are consistently realized.

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Serfass, J.P. and J. Samanos, "Fiber-Modified Asphalt Concrete Characteristics, Applications and Behavior," *Journal of the Association of Asphalt Paving Technologists*, Vol. 65, 1996, pp. 193–230.

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Stempihar, J.J., M.I. Souliman, and K.E. Kaloush, "Fiber-Reinforced Asphalt Concrete as Sustainable Paving Material for Airfields," *Transportation Research Record: Journal of the Transportation Research Board, No. 2266*, Transportation Research Board of the National Academies, Washington, D.C., 2012, pp. 60–68.

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Tapkin, S., A. Çevik, and Ü. Uşar, "Prediction of Marshall Test Results for Polypropylene Modified Dense Bituminous Mixtures Using Neural Networks," *Expert Systems with Applications*, Vol. 37, 2010, pp. 4660–4670.

Tapkin, S., Ü. Uşar, A. Tuncan, and M. Tuncan, "Repeated Creep Behaviors of Polypropylene Fiber-Reinforced Bituminous Mixtures," *Journal of Transportation Engineering*, Vol. 135, 2009, pp. 240–249.

Tayfur, S., H. Ozen, and A. Aksoy, "Investigation of Rutting Performance of Asphalt Mixtures Containing Polymer Modifiers," *Construction and Building Materials*, Vol. 21, 2007, pp. 328–337.

Toney, C.A., *Fiber Reinforced Asphalt Concrete Pavements—City of Tacoma*, Report No. WA-RD 133.1, Washington State Department of Transportation, Olympia, 1987.

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Watson, D.E., Updated Review of Stone Matrix Asphalt and Superpave Projects," *Transportation Research Record: Journal of the Transportation Research Board, No. 1832*, Transportation Research Board of the National Academies, Washington, D.C., 2003, pp. 217–223.

Watson, D.E., L.A. Cooley, Jr., K.A. Moore, and K. Williams, "Laboratory Performance Testing of Open-Graded Friction Course Mixtures," *Transportation Research Record: Journal of the Transportation Research Board, No. 1891*, Transportation Research Board of the National Academies, Washington, D.C., 2004, pp. 40–47.

Watson, D., A. Johnson, and D. Jared, "Georgia Department of Transportation's Progress in Open-Graded Friction Course Development," *Transportation Research Record 1616*, Transportation Research Board, National Research Council, Washington, D.C., 1998, pp. 30–33.

Watson, D.E., K.A. Moore, K. Williams, and L.A. Cooley, Jr., "Refinement of New-Generation Open-Graded Friction Course Mix Design, *Transportation Research Record: Journal of the Transportation Research Board No. 1832*, Transportation Research Board of the National Academies, Washington, D.C., 2003, pp. 78–85.

Xu, Q., H. Chen, and J. Prozzi, "Performance of Fiber Reinforced Asphalt Concrete Under Environmental Temperature and Water Effects," *Construction and Building Materials*, Vol. 24, 2010, pp. 2003–2010.

Yao, H., Z. You, L. Li, S.W. Goh, C.H. Lee, and Y.K. Yap, "Rheological Properties and Chemical Analysis of Nanoclay and Carbon Microfiber Modified Asphalt with Fourier Transform Infrared Spectroscopy," *Construction and Building Materials*, Vol. 38, 2013, pp. 327–337.

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This review of the literature concludes that fibers are promoted for use in asphalt for three main reasons: to improve the mechanical properties of the mix, to allow electrical conductivity of the mixes, and to provide a market for waste fibers.

Arabani, M., S.M. Mirabdolazimi, and A.R. Sasani, "The Effect of Waste Tire Thread Mesh on the Dynamic Behavior of Asphalt Mixtures," *Construction and Building Materials*, Vol. 24, 2010, pp. 1060–1068.

The use of waste tire cord mesh was investigated in this study, which found that the tire thread mesh could be used effectively to improve the cracking resistance of asphalt mixtures. The stiffness, rutting resistance, and fatigue resistance of mixtures with tire thread mesh was found to be higher than the control mix without the fiber.

Austroads, *Review of Stone Mastic Asphalt Design Concepts*, AP-T138-09, 2009.

This document provides a good summary review of materials and mix designs for SMA. The information on fibers is minimal, however.

Chan, S., B. Lane, T. Kazmierowski, and W. Lee, "Pavement Preservation: A Solution for Sustainability," *Transportation Research Record: Journal of the Transportation Research Board, No. 2235*, Transportation Research Board of the National Academies, Washington, D.C., 2011, pp. 36–42.

The Ministry of Transportation of Ontario (MTO) compared the effectiveness of various pavement preservation techniques, including fiber-modified chip seals known as FiberMat. Chopped fiberglass fibers are added to a polymer-modified emulsion used to construct a chip seal. The fibers are intended to help reduce reflective cracking of a new overlay. At the time of this report, the method was relatively new to MTO.

Chen, J.-S., W. Hsieh, and M.-C. Liao, "Evaluation of Functional Properties of Porous Asphalt Pavements Subjected to Clogging and Densification of Air Voids," *Transportation Research Record: Journal of the Transportation Research Board, No. 2369*, Transportation Research Board of the National Academies, Washington, D.C., 2013, pp. 68–76.

This study from Taiwan compared the performance of porous asphalt pavement with nonmodified binder, polymer-modified binder, and highly modified binder. The nonmodified and polymer-modified mixtures contained hydrated lime and cellulose fibers. The overall performance of the mixture with highly modified binder was found to be superior to that of the other two mixtures.

Chen, J.-.S, Y.-C. Sun, M.-C. Liao, and C.-C. Huang, "Effect of Binder Types on Engineering Properties and Performance of Porous Asphalt Concrete," *Transportation Research Record: Journal of the Transportation Research Board, No. 2293*, Transportation Research Board of the National Academies, Washington, D.C., 2012, pp. 55–62.

Compared three binder types [conventional, polymer-modified, and high-viscosity (HV)] for use in porous asphalt. Included cellulose fibers at 0.3% of the mass of the total mixture with the conventional and polymer-modified binders (not with HV). Adding fibers to the conventional and polymer-modified binders greatly reduced draindown. The HV material performed comparably without fibers. Use of polymer binder plus fibers reduced abrasion loss in the Cantabro test compared with mixes without fibers and conventional binder with fibers. Addition of fibers had a small positive impact on indirect tensile strength, resilient modulus, and wheel tracking rut depth. Use of fibers decreased the permeability slightly.

Ferrotti, G., E. Pasquini, and F. Canestrari, "Experimental Characterization of High-Performance Fiber-Reinforced Cold Mix Asphalt Mixtures," *Construction and Building Materials*, Vol. 57, 2014, pp. 117–125.

This study looked at the use of fibers in cold mix for patching purposes.

Garcia, A., J. Norambuena-Contreras, M.N. Partl, and P. Schuetz, "Uniformity and Mechanical Properties of Dense Asphalt Concrete with Steel Wool Fibers," *Construction and Building Materials*, No. 43, 2013, pp. 107–117.

This paper is related to other work by the same authors. The conclusion is that long, thin fibers tend to clump, whereas short, thick fibers do not. Steel wool fibers are also damaged (shortened) during mixing. Improvements in raveling resistance and flexural strength were not observed when steel wool fibers were used in dense asphalt concrete.

Goh, S.W., M. Akin, Z. You, and X. Shi, "Effect of Deicing Solutions on the Tensile Strength of Micro- or Nano-Modified Asphalt Mixture," *Construction and Building Materials*, Vol. 25, 2011, pp. 195–200.

This study looked at the effects of deicing chemicals on the moisture sensitivity of asphalt mixtures containing carbon microfibers or nano-clay. Both materials were observed to reduce the moisture sensitivity of the mixtures.

Kabir, M.S., W. King, Jr., C. Abadie, P. Icenogle, and S.B. Cooper, Jr., "Louisiana's Experience with Open-Graded

Friction Course Mixtures," *Transportation Research Record: Journal of the Transportation Research Board, No. 2295*, Transportation Research Board of the National Academies, Washington, D.C., 2012, pp. 63–71.

Open-graded friction courses containing styrene butadiene styrene (SBS) and cellulose performed well in this field and laboratory study.

Lui, Q., E. Schlangen, A. Garcia, and M. van de Ven, "Induction Heating of Electrically Conductive Porous Asphalt Concrete," *Construction and Building Materials*, Vol. 24, 2010, pp. 1207–1213.

This paper is related to other TU Delft work on induction heating. It compares steel wool with steel fibers and determines that 10% steel wool (type 000) by volume of asphalt is the optimal addition to porous asphalt concrete.

Lui, Q., E. Schlangen, and M. van de Ven, "Induction Healing of Porous Asphalt," *Transportation Research Record: Journal of the Transportation Research Board, No. 2305*, Transportation Research Board of the National Academies, Washington, D.C., 2012, pp. 95–101.

This paper relates to other work at TU Delft on induction heating. This study suggests that the use of induction heating can help delay the onset of raveling of porous asphalt.

Liu, X. and S. Wu, "Study on the Graphite and Carbon Fiber Modified Asphalt Concrete," *Construction and Building Materials*, No. 25, 2011, pp. 1807–1811.

This study evaluated mechanical and electrical properties of asphalt concrete modified with the addition of graphite and carbon fibers.

Liu, Q., S. Wu, and E. Schlangen, "Induction Heating of Asphalt Mastic for Crack Control," *Construction and Building Materials*, Vol. 41, 2013, pp. 345–351.

This paper is related to the other induction papers from TU Delft (Garcia et al.).

Prowell, B., "Design, Construction, and Early Performance of Hot-Mix Asphalt Stabilizer and Modifier Test Sections," *Transportation Research Record: Journal of the Transportation Research Board, No. 1767*, Transportation Research Board, National Research Council, Washington, D.C., 2001, pp. 7–14.

This study compared coarse-graded Superpave mix designs with modified binders to 75-blow dense-graded Marshall mixes. The Marshall mixes included the control with AC-30 and two fiber-modified mixes with AC-20—one with polyester and the other with polypropylene fibers. After 45 months in service, all the sections were resistant to rutting, fatigue, and thermal cracking. The fiber sections were performing comparably to the polymer-modified sections. The author suggested that the use of fibers might be an effective treatment in situations such as intersections at which a highly rut-resistant mixture is needed.

Tapkin, S., "Optimal Polypropylene Fiber Amount Determination by Using Gyratory Compaction, Static Creep and Marshall Stability and Flow Analyses," *Construction and Building Materials*, Vol. 44, 2013, pp. 399–410.

This study looked at using gyratory compaction to prepare 100-mm-diameter specimens of fiber mix for testing in static creep, Marshall stability, and flow. The conclusions were that 100-mm-diameter specimens could be prepared in the gyratory that were suitable for subsequent mix testing as long as the aggregate was smaller than 2.54 cm.

Wu, S., G. Liu, L.-T. Mo, Z. Chen, and Q.-S. Ye, "Effect of Fiber Types on Relevant Properties of Porous Asphalt," *Transactions of Nonferrous Metals Society of China*, Vol. 16, 2006, pp. 791–795.

This study looked at cellulose and polyester fibers in porous mixtures, including the use of X-ray computerized tomography to examine the microstructure of the fiber and the skeleton of the porous asphalt. The results showed that fibers stabilize and thicken the binder film around the aggregates and lead to slight improvements in the strength of the porous mix.

Wu, S., Q. Ye, and N. Li, "Investigation of Rheological and Fatigue Properties of Asphalt Mixtures Containing Polyester Fibers," *Construction and Building Materials*, Vol. 22, 2008, pp. 2111–2115.

This study evaluated the performance of polyester fibers on binder and mixture properties and concluded that polyester fiber increases the viscosity of the binder, especially at low temperatures, and improves the fatigue behavior of the mixtures, especially at lower stress levels.

Xu, T., H. Wang, Z. Li, and Y. Zhao, "Evaluation of Permanent Deformation of Asphalt Mixtures Using Different Laboratory Performance Tests," *Construction and Building Materials*," Vol. 53, 2014, pp. 561–567.

This study used a partial triaxial test to evaluate the rut resistance of mixtures containing polyester fibers in the laboratory. The authors concluded that fibers can improve the permanent deformation behavior of asphalt mixtures.

Ye, Q., S. Wu, and N. Ling, "Investigation of the Dynamic and Fatigue Properties of Fiber-Modified Asphalt Mixtures," *International Journal of Fatigue*, Vol. 31, 2009, pp. 1598–1602.

This study compared the performance of mixtures containing cellulose, polyester, and mineral fibers in the Superpave simple performance tester. The findings suggest that fiber-modified mixtures had lower stiffness and more flexibility than the control mixture without fibers. The findings also suggest that the fiber mixes will have improved fatigue performance. The polyester fiber provided the most improvement in fatigue resistance.

Yoo, P.J. and K.-H. Kim, "Thermo-plastic Fiber's Reinforcing Effect on Hit-Mix Asphalt Concrete," *Construction and Building Materials*, Vol. 59, 2014, pp. 136–143.

This study investigated the behavior of asphalt mixtures containing recycled polyethylene terephthalate (PET) fibers. These extruded fibers can have different surface textures, depending on the extrusion nozzle used.

APPENDIX A

Survey Questionnaire

THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine
National Academy of Sciences
National Academy of Engineering
Institute of Medicine
National Research Council

TRB
Transportation Research Board

Default Question Block

Your cooperation in gathering information on the use of fiber additives in asphalt mixtures will be greatly appreciated. To ensure we have complete information, a few questions require an answer; other answers are requested, but not required.

Please complete this questionnaire by March 21, 2014. If you prefer, you may respond to these questions by phone. To do so, please contact Becky McDaniel, the consultant for this project, either by email at rsmcdani@purdue.edu or by phone at 765-463-2317, ext 226, to arrange a date and time.

[Notes in brackets show survey logic embedded in the online questionnaire.]

First, please provide your contact information, so that we know who is responding to this survey.

What is your name?

What is your position/title?

What organization/agency do you work for? (Required field)

May we contact you for more information?

○ Yes; please provide your phone number and email address.

○ Please contact this person instead (please provide name, phone number and/or email address).

○ No.

Does your organization currently specify or allow the use of fiber additives in asphalt mixtures? (Required field)

- ○ Yes, currently use/allow,
- ○ No.
- ○ Not sure.

[If no is selected, skip next two questions.]

In which application(s) do you specify/allow the use of fibers in asphalt mixtures?

Approximately how many tons of asphalt mix containing fibers are used each year?

Did your organization use fibers in the past and discontinue use in some or all applications?

- ○ Yes.
- ○ No.
- ○ Not sure.

[If No is selected, then skip to "Do you have any additional information?"]

Why are fibers no longer used in those applications?

What types of fibers does/did your organization specify or allow for various applications? (Click all that apply.)

	Specify/Require	Allow
Polymer (polyester. polypropylene, other)	☐	☐
Cellulose	☐	☐
Mineral	☐	☐
Unspecified	☐	☐
Other	☐	☐

Why does/did your organization use fibers? (Click all that apply.)

- ○ To prevent binder draindown.
- ○ To improve cracking resistance.
- ○ To improve rutting resistance.
- ○ Other

Does your organization have any specifications, test methods, mix design methods or acceptance criteria for fibers or fiber-modified mixtures?

- ○ Yes.
- ○ No.

[If No is selected, then skip next two questions.]

Please provide a link of email copies to rsmcdani@purdue.edu

Which properties do you measure/control?

Are you aware of/does your organization practice or enforce any safety/health/environmental restrictions when fibers are used in asphalt mixtures?

- ○ Yes; if so, please specify.
- ○ No.
- ○ Rely on manufacturers' recommendations (MSDS or SDS).

Does your organization have any current or completed research or performance histories on fiber-modified asphalt mixtures?

- ○ Yes.
- ○ No.

[If No is selected, then skip next question.]

If yes, please provide reference or contact person.

Does your organization have information on costs (initial or life cycle) of fibers or benefit:cost ratios for fiber-modified mixtures?

- ○ Yes.
- ○ No.

[If No is selected, then skip next question.]

Is there someone we could contact for more information? (Please provide name and contact information.)

Do you have any additional information, current or historical, that you would like to share? If yes, please outline the information below or provide links or contact information for more detail.

This completes the survey. Thank you for your time and information.

APPENDIX B

Survey Respondents

Title	Agency
Asphalt Group Supervisor	West Virginia DOT
Assistant Materials and Tests Engineer	Alabama DOT
State Pavement Engineer	Alaska DOT&PF
State Construction Engineer	Arizona DOT
Materials Engineer	Arkansas State Highway and Transportation Department
Senior Transportation Engineer	California DOT
Asphalt Program Manager	Colorado DOT
Transportation Supervising Engineer	Connecticut DOT
Hot Mix Supervisor	Del DOT Materials and Research
State Bituminous Materials Engineer	Florida DOT
State Bituminous Construction Engineer	Georgia Department of Transportation—Office of Materials and Testing
Engineer	Hawaii DOT
State Materials Engineer	Idaho Transportation Department
HMA Operations Engineer	Illinois DOT
Policy Engineer	Illinois DOT Bureau of Local Roads and Streets
Materials Engineer	Indiana DOT
Bituminous Engineer	Iowa DOT
Materials Field Engineer	Kansas DOT
Engineer-in-Training II, Asphalt Mixtures Section, Division of Materials	Kentucky Transportation Cabinet
Materials Engineer	Louisiana DOTD
Materials Engineer	Maine DOT
Surfacing Materials Engineer	Manitoba Infrastructure and Transportation
Chief, Asphalt Technology Division	MD State Highway Administration
HMA Operations Engineer	Michigan DOT
Assistant Chief Engineer—Operations	Mississippi DOT
Field Materials Engineer	Missouri DOT
Mix Design Specialist	Mn/DOT
Testing Engineer	Montana DOT
Principal Materials Engineer	Nevada DOT
Civil Engineer 3 (Materials)	New York State DOT
Chief of Materials Technology	NHDOT
Manager, Bureau of Materials	NJDOT
State Asphalt Engineer for NMDOT	NMDOT
State Asphalt Materials Engineer	North Carolina DOT
Materials and Research Engineer	North Dakota DOT
Asphalt Materials Engineer	Ohio DOT
Bituminous Engineer	Okla. DOT
Head, Bituminous Section	Ministry of Transportation, Ontario
Pavement Quality & Materials Engineer	Oregon DOT
Research Project Manager	PennDOT
Civil Engineer (Materials & Quality Assurance)	Rhode Island DOT
Asphalt Materials Manager	SCDOT Office of Materials and Research
Bituminous Engineer	South Dakota DOT
State Asphalt Pavement Engineer	Tennessee DOT
State Bituminous Engineer	Texas DOT
Engineer for Asphalt Materials	Utah DOT Materials Division

Table continued on p. 47

Table continued from p. 46

Title	Agency
Assistant State Materials Engineer	Virginia DOT
Assistant State Materials Engineer	Washington State DOT
Materials Lab Supervisor	Wisconsin DOT
State Materials Engineer	Wyoming DOT

APPENDIX C

Tabulated Survey Responses

1 Does your organization currently specify or allow the use of fibers in asphalt mixes?

TABLE C1
DOES YOUR ORGANIZATION CURRENTLY SPECIFY OR ALLOW THE USE OF FIBERS IN ASPHALT MIXES?

Yes	No
AL, CO, CT, DE, FL, GA, ID, IL, IN, KS, KY, LA, MD, ME, MI, MS, MO, NC, NH, NJ, NY, OH, OK, ON, OR, SC, SD, TN, TX, VA, WI	AK, AR, AZ, CA, CO, HI, IA, MI, MN, MT, ND, NM, NV, PA, RI, UT, WA, WV, WY

2. In which applications do you specify/allow the use of fibers in asphalt mixtures?

TABLE C2
IN WHICH APPLICATIONS DO YOU SPECIFY/ALLOW THE USE OF FIBERS IN ASPHALT MIXTURES?

State/ Province	SMA or Gap-Graded	Porous or Open-Graded	Both SMA and Porous	HMA Overlays	Other
AL	•				
CO	•				
CT		•			Cold mix
DE			•		
FL		•			
GA		•			
ID					HMA overlays
IL	•				
IN			•		
KS	•				
KY	•				
LA			•		
MD			•		
ME		•			
MI	•				
MO	•				
MS			•		
NC		•			Has SMA spec, but has not placed any.
NH		•			Curb mixtures
NJ			•		
NY		•			
OH	•				Supplemental spec for districts desiring to use.
OK			•		
ON	•				Have specified on trial mixes designed to better resist cracking.
OR		•			
SC		•			
SD	•				
TN			•		
TX			•		
VA			•		Thin HMA overlays, stabilized mixtures
WI	•				

3. Approximately how many tons of asphalt mix containing fibers are used each year?

-- No response.

TABLE C3
APPROXIMATELY HOW MANY TONS OF ASPHALT MIX CONTAINING FIBERS ARE USED EACH YEAR?

State/Province	Approximate Tonnage	Comment
AL		Not tracked.
CO	—	
CT	1,500	
DE	20,000	
FL	500,000	
GA	208,586	
ID		Unknown. Very few.
IL		Minimal with current use of RAS and GTR.
IN		Unknown.
KS	10,000	
KY	50,000–100,000	
LA		Not available.
MD	500,000	
ME	<1,000	
MI	—	
MO	396,379 in 2012; 10,212 in 2013	
MS	—	
NC	60,000	
NH	<5,000	
NJ	100,000	
NY	<2,000	
OH	<10,000	
OK	20,500	
ON	Average 10,000 per year 2010–2013; 60,000 in 2014	SMA pause lifted for 2014.
OR	Under 500	Before 2009, approx. 30,000.
SC	250,000	
SD	100,000–150,000	
TN	135,000 in 2013; 197,000 in 2012	In OGFC. No SMA placed for last 4–5 yrs.
TX	700,000	
VA	—	
WI	Unknown	

4. Did your organization use fibers in the past and discontinue use in some or all applications? (Asked only of states that do not currently use fibers.)

TABLE C4

DID YOUR ORGANIZATION USE FIBERS IN THE PAST AND DISCONTINUE USE IN SOME OR ALL APPLICATIONS?

State/Province	No	Yes	Not sure	Comments
AK	•			
AR	•			
AZ		•		Fibers were used in SMA to prevent draindown but not currently using SMA.
CA			•	
HI	•			
IA	•			
MB	•			
MN	•			
MT	•			
ND	•			
NM		•		Used to use in SMA but have not placed SMA since at least 2000.
NV	•			
PA		•		Researching use of fibers through 12 current pilot projects (polyester and aramid).
RI	•			
UT	•			
WA	•			
WV	•			
WY	•			

Asked only of states that indicated they do not currently use fibers.

5. What types of fibers does/did your organization specify or allow for various applications? (Click all that apply.)

TABLE C5

WHAT TYPES OF FIBERS DOES/DID YOUR ORGANIZATION SPECIFY OR ALLOW FOR VARIOUS APPLICATIONS?

State/Province	Fiber Types Specified	Fiber Types Allowed	Comments
AL		Polymer, cellulose, mineral	
CT		Polymer	Unspecified fibers required
DE		Cellulose, mineral	
FL	Cellulose, mineral		
GA		Cellulose, mineral	Polymer (experimentally)
ID	Polymer		
IL	Cellulose, mineral	Cellulose, mineral	
IN		Cellulose, mineral	
KS	Cellulose, mineral		
KY	Cellulose, mineral		
LA		Cellulose, mineral	
MD		Polymer, cellulose, mineral	
ME	Cellulose, mineral		
MI	Cellulose		
MO	Cellulose, mineral		
MS	Cellulose, mineral		
NC	Cellulose, mineral		
NH	Polymer (polyester)		
NJ	Cellulose, mineral		
NY		Polymer, mineral	
OH	Polymer	Cellulose, mineral	
OK	Cellulose		
ON	Cellulose, mineral	Cellulose, mineral, manufactured shingle material	Polyethylene terephthalate
OR		Cellulose, mineral	
SC	Cellulose, mineral	Cellulose, mineral	
SD	Cellulose		
TN	Cellulose	Cellulose	
TX	Cellulose	Polymer, cellulose	
VA	Cellulose	Polymer	
WI		Polymer, cellulose	

6. Why does your organization use fibers? (Click all that apply.)

TABLE C6
WHY DOES YOUR ORGANIZATION USE FIBERS?

State/ Province	To Prevent Draindown	To Improve Cracking Resistance	To Improve Rutting Resistance	Other
AL	•			
CO	•			
CT	•			
DE	•			
FL	•			
GA	•	•	•	
ID		•	•	
IL	•			
IN	•			
KS	•			
KY	•			
LA	•			
MD	•	•	•	Allows more binder in mix
ME	•			
MI	•			
MO	•			
MS	•			
NC	•			
NH	•	•		
NJ	•			
NY	•			
OH	•		•	
OK	•	•	•	Increase mastic content
ON	•	•		
OR	•			
SC	•			
SD	•			
TN	•	•	•	
TX	•			
VA	•	•	•	
WI	•			

7. Does your organization have any specification, test methods, mix design methods, or acceptance criteria for fibers or fiber-modified mixtures?

TABLE C7
DOES YOUR ORGANIZATION HAVE ANY SPECIFICATION, TEST METHODS, MIX DESIGN METHODS, OR ACCEPTANCE CRITERIA FOR FIBERS OR FIBER-MODIFIED MIXTURES?

Yes	No
AL, DE, FL, GA, IL, KS, KY, MD, ME, MO, NC, NH, NJ, NY, OH, ON, OR, SC, SD, TN, TX, VA, WI	CT, ID, IN, LA, MS, OK

8. Which properties do you measure/control?

TABLE C8

WHICH PROPERTIES DO YOU MEASURE/CONTROL?

Yes	No
AL	Draindown (AASHTO T 305).
DE	Cellulose: ash content (D1282); pH, moisture content, and length (AASHTO MP 8). Mineral (from virgin basalt, diabase, slag, or other silaceous rock): length and thickness (MP 8), shot content (ASTM C612).
FL	Mineral (from virgin basalt, diabase, or slag) with cationic sizing agent for dispersal and adhesion: specified length, thickness, shot content (ASTM C612). Cellulose: length, sieve analysis (Alpine or Ro-Tap methods), ash content, pH, oil absorption, moisture content. Certified test results required for each batch.
GA	Draindown, wet mixing time. Polymer: limit on unseparated fibers, length, form, specific gravity, tensile strength, melt temperature, acid/alkali resistance, packaging. Cellulose: ash content, pH, moisture content. Cellulose pellets: pellet diameter, binder type and content. Mineral (from virgin basalt, diabase, slag, or other silicate rock): shot content.
IL	Sieve analysis, length, ash content, pH, oil absorption, moisture content, shot content/gradation.
KS	Draindown (KT-63).
KY	Reference AASHTO M325 for design of SMA. Material certification to verify cellulose or mineral fibers. Dosage rate specified.
MD	Draindown, percent stabilizer.
ME	Cellulose: Alpine sieve analysis, ash content, pH, oil absorption, moisture content. Mineral: dosage rate, length, thickness, shot content.
MO	Draindown (T 305).
NC	Mineral (from virgin basalt, diabase, or slag) with cationic sizing agent for dispersal and adhesion: specified length, thickness, shot content (ASTM C612), degradation (GDT-124/McNett fractionation). Cellulose: Fiber length, sieve analysis (Alpine or Ro-TAP method), ash content, pH, oil absorption, moisture content, degradation. Cellulose pellets: 50/50 blend of cellulose fiber and asphalt binder; fiber to conform to cellulose requirements above, pellet size, asphalt penetration.
NH	Polyester fibers from Qualified Products List, uniformly distributed in dry mix at ~0.25% of total batch weight.
NJ	Mineral or cellulose fibers conforming to AASHTO MP 8. Dosage rate specified. Fibers must be dispersed uniformly and proportioned to within ±10% of required rate. Certification required. Manufacturer's representative present for first day of production.
NY	Mineral: length, thickness, shot content.
OH	For SMA–cellulose: length, sieve analysis (Alpine or Ro-Tap), ash content, pH, oil absorption, moisture content. Cellulose pellets: cellulose fiber requirements above, pellet size, binder penetration. Mineral (from virgin basalt, diabase, or slag with cationic sizing agent for dispersal and adhesion): length, thickness, shot content, degradation. For supplemental specification for rut-resistant mix: polyester or polypropylene from Qualified Products List: denier, length, crimps, tensile strength, specific gravity, melt temperature, certified test results.
ON	Cellulose: sieve analysis (Alpine or mesh screen), length, ash content, pH, oil absorption, moisture content. Mineral: length, thickness, shot content.
OR	Mineral: mineral (from virgin basalt, diabase, or slag): dosage rate, length, minimum and maximum thickness, shot content (ASTM C612). Cellulose: dosage rate, length, gradation (Alpine or mesh screen), ash content, pH, oil absorption, moisture content.
SC	Draindown (SC-T-90, SC-T-91).
SD	Draindown (at design and once a day during production). Cellulose: length, sieve analysis (Alpine), ash content, pH, oil absorption, moisture content.
TN	Draindown (T 305).
TX	Draindown.
VA	Cellulose or mineral with supplier's certification of properties and documented success in similar applications.
WI	Draindown.

9. Are you aware of/does your organization practice or enforce any safety/health/environmental restrictions when fibers are used in asphalt mixtures?

TABLE C9

ARE YOU AWARE OF/DOES YOUR ORGANIZATION PRACTICE OR ENFORCE ANY SAFETY/HEALTH/ENVIRONMENTAL RESTRICTIONS WHEN FIBERS ARE USED IN ASPHALT MIXTURES?

Yes	No	Rely on Manufacturers' Recommendations
None	CT, KS, KY, MD, ME, NH, OK, ON, SD, TN, VA, WI	AL, DE, FL, GA, ID, IL, IN, LA, MO, MS, NC, NJ, NY, OH, ON, OR, SC, TX

10. Does your organization have any current or completed research of performance histories on fiber-modified asphalt mixtures?

TABLE C10

DOES YOUR ORGANIZATION HAVE ANY CURRENT OR COMPLETED RESEARCH OF PERFORMANCE HISTORIES ON FIBER-MODIFIED ASPHALT MIXTURES?

Yes	No
FL, GA, ID,* MD, MO, NJ, ON	AL, CT, DE, IL, IN, KS, KY, LA, ME, MS, NC, NH, NY, OH, OK, OR, SC, SD, TN, TX,VA, WI

11. Does your organization have information on costs (initial or life cycle) of fibers or benefit–cost ratios for fiber-modified mixtures?

TABLE C11

DOES YOUR ORGANIZATION HAVE INFORMATION ON COSTS (INITIAL OR LIFE CYCLE) OF FIBERS OR BENEFIT–COST RATIOS FOR FIBER-MODIFIED MIXTURES?

Yes	No
SD	AL, CT, DE, IL, IN, KS, KY, LA, ME, MS, NC, NH, NY, OH, OK, OR, SC, SD, TN, TX,VA, WI

12. Do you have any additional information, current or historical, that you would like to share? (Asked of all.)

TABLE C12
DO YOU HAVE ANY ADDITIONAL INFORMATION, CURRENT OR HISTORICAL, THAT YOU WOULD LIKE TO SHARE?

State/ Province	Comment
AK	We are experiencing shorter than normal life expectancy out of our OGFC pavements. We have experimented using WMA (Evotherm) and GTR to remove fibers from OGFC pavements to improve mixture consistency and overall constructability of these pavements. We have also looked into possibly using a finer 9.5 mm gradation using 789 stone in lieu of the 12.5 mm design using mostly # 7 stone to improve durability.
CO	The only fibers currently allowed are in our SMA mix, to prevent draindown.
FL	We have only ever used fibers in open-graded friction courses, with the purpose to reduce binder draindown. We have been using them since the late 1990s. While our specifications allow either mineral or cellulose fibers, about 99% of our experience is with mineral fibers.
HI	We have used fibers in SMA mixes—one project in 2004 and one paving in a couple of months.
LA	Fibers have been found to be useful for the purpose specified, preventing draindown.
MI	We require cellulose fibers in our gap-graded mixture (SMA). In other mixes we do not allow.
MO	In reference to the question regarding current and completed research, please see the following. We have a few early reports looking at the implementation of the stone mastic asphalt mixtures which incorporated fibers.
MT	When I say we “don’t allow” I mean our specification is silent. We don’t have any language allowing or prohibiting fibers.
NC	NCDOT does also allow the use of recycled asphalt shingles in OGFC strictly to control asphalt draindown. If the mixture can meet draindown specifications with the sole use of shingles, no fibers are needed.
NJ	Can provide research reports regarding plant produced mixtures—data generated based on laboratory testing and comparisons with nonfiber mixture on same job. (Tom Bennert)
OH	SS 826 has been in existence for over 20 years. Some requirements in it are a result of learning what does not work. Most districts do not specify 826 because of the availability of PG modified binders that work well in most instances. In addition, we have had mixed success with 826 fiber mixes. What we found is that in high crush aggregate mixes the fibers can fall between aggregate particles, actually preventing aggregate lock. For lesser strength mixes, fibers do help though.
OK	We are allowing an SMA to use Evotherm rather than cellulose fibers for one project. I added 0.3% cellulose fibers to an OGFSC design for the NCAT Test Track section E1. The intent is to allow more binder to increase the mastic. A SCDOT method was used to determine binder content of 7.1%. FHWA formula for our average specific gravity results in binder contents of 5.7%–5.8% for traditional OGFSC.
ON	We experimented with the addition of 1%–2% asbestos fibers in the mid-70s, but discontinued the use due to health and safety issues. Adopted SMA as a premium wearing course in 2002, allowing mineral and cellulose fibers. The addition of roof shingle tabs (which was also a source of fiber) was permitted. SMA quantities were around 75–100 K tonnes. The use of SMA was paused in 2006/07 due to early age friction issues. It has now been reinstated. Other fibers have been trialed, including polymer and PET fibers in Superpave 19.0 and SMA to evaluate mitigation of reflection cracking from the underlying concrete pavement. Performance is being monitored.
OR	The use of open-graded mixes in Oregon was all but eliminated after examining life cycle cost for open-graded mixtures in 2008. As this was the only mixture [in which] Oregon was using fibers, their use has also significantly been reduced. There may be an increase in the future of porous asphalt use for runoff mitigation, which may lead to an increase in the use of fibers again.
PA	We are going to summarize testing results by the end of 2014; I can provide them when we have them.
SC	We are experiencing shorter than normal life expectancy out of our OGFC pavements. We have experimented using WMA (Evotherm) and GTR to remove fibers from OGFC pavements to improve mixture consistency and overall constructability of these pavements. We have also looked into possibly using a finer 9.5mm gradation using 789 stone in lieu of the 12.5mm design using mostly # 7 stone to improve durability.
WA	Our only experience with fibers (cellulose) has been on a couple of SMA trial projects constructed several years ago
WV	We have been open to vendors showing us the products but have not implemented the use of fiber in our asphalt mixes.

Abbreviations used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation

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ISBN: 978-0-309-27177-6
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