FIBRA

Fostering the implementation of fiber-reinforced asphalt mixtures by ensuring its safe, optimized and cost-efficient use

Deliverable 2.1

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Executive summary

The growing demand for transportation in the world and the importance of Infrastructure-based economic development require affordable, eco friendly, uptodate, and practical methods to improve asphalt pavement. In order to comply with these requirments, considerable research on new pavement materials such as fiber-reinforced asphalt mixtures is needed to develop and advanced the current road engineering.

Over the last decades, the application of fibers in pavement have been considered and used to improve mechanical performance of asphalt mixture. More recently, newer type of fibers were investigated with the objective of reinforce asphalt materials to face the more extreme climatic events, high traffic volumes, and seismic-waves action.

This document provides a literature review focusing on the modification of asphalt materials through the inclusion of different types of fibers. This report covers the use of fiber materials in asphalt binder and mixtures. Mechanical properties of different types of fibers (polymer, carbon, aramid, geogrid and glass, cellulose, and fabric fibers) and their reinforcing and stabilizing effects on pavement performance are presented. This document is divided into four parts:

- CHAPTER 1 provides an introduction to the asphalt materials and fibers modification;
- CHAPTER 2 briefly presents the type of fibers and mixing process;
- CHAPTER 3 details the mechanical properties of fiber-modified asphalt materials;
- CHAPTER 4 discusses the economic and environmental benefits of fiber modified asphalt materials.
- CHAPTER 5 deals with the selections of the fiber and includes a multicriteria decision making methodology, an environmental evaluation and an economic analysis of a pre-defined list of fibers.

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1 Introduction

Asphalt pavements represent an important asset for the economic prosperity and everyday life of both developed and developing countries. As traffic volume continues to grow it is recognized that asphalt binders and mixtures with enhanced characteristics are needed to guarantee the durability of the functional performance of transportation infrastructures. Pavement design can be a complex process due to the wide range of potential aggregates, binders and mixtures types available, all with the ultimate objective of building asphalt pavements that have sufficient load bearing capacity, high resistance to deformation, and long service life. With the continuous reduction in the budgets allocated for road maintenance, lifetime and performance of road pavements may be significantly affected, eventually limiting their capacity to resist to common distresses such as rutting, fatigue failure (Figure1) and thermal cracking among others (Lancaster, 2016).

Figure 1. Typical cracking observed on an asphalt pavement surface layer. (Koch and Brilakis, 2011)

Commonly, when an asphalt binder or mixture does not meet the climate, traffic, and pavement structure requirements, modifications are used to improve the material properties (Kim, 2008). Generally, polymers and fibers have been successfully used as alternative modifications (Rahnama, 2009; Wu, et al., 2008). Although the most popular asphalt binder modification technique is polymer modification, it has also been reported that fibers can be successfully used as modifiers (Airey, 2004; Yildirim, 2007). Reinforcing bituminous mixtures is one of the methods used to improve their tensile strength and engineering properties, especially when conventional mixes may not provide satisfactory performance (Bonica, et al., 2016).

The use of fiber reinforcement in asphalt materials for pavement application date back to the late part of the 1950s when asbestos was investigated as a potential solution (Hansen, et al., 1959). During the 1960s and the 1970s a number of continuous and particulate reinforcement where evaluated, including cotton and fiberglass (Busching, et al., 1970), while showing the potential for using polyester and polypropylene fibers (Brown, et al., 1977). Together with experimental studies, several field tests were also performed to verify the laboratory findings across the 1970s and 1980s (Finemore, 1979; Smith, et al., 1983) and to evaluate the actual cost-effective potential of fibers.

In the mid-1980s a comprehensive research effort was proposed to further investigate the use of different fibers in asphalt mixture (Button & Hunter, 1984). In this study, several types of fibers obtained from different manufacturers were first used for a large laboratory investigation and later, for a restricted number of materials, for field evaluation. The fibers used in this research were composed of “polypropylene, polyester, aramid, fiberglass, asbestos, a combination of polypropylene and aramid, and a fiber product consisting of cellulose, starch, and ash”. Specific attention was devoted to the mixing process to avoid potential clumps of fibers both at laboratory and plant level. Resilient modulus, indirect tension test, freeze-thaw cycles, flexural fatigue test, resistance to reflective cracking, direct tension-compression test, among others, were used to characterize the fiber reinforced mixtures. In addition, the experimental results were used as input in a computer software to predict the pavement performance. Finally, two field sections were prepared and monitored for 19 months. Opposing results were obtained from the field tests. At the production level, it was observed that fibers can be incorporated in the production with drum mixer or they can be pre-mixed with the binder. A significant recommendation from the authors of this work was devoted to the effective compaction effort that is needed to achieve an equivalent air voids content for conventional and fiber mixtures.

Over the years, different types of fibers were evaluated to produce fiber-reinforced asphalt materials in some cases addressed as fiber-reinforced asphalt mixture. For example, Chen et al. (2009) observed the addition of fibers such as polyester, polyacrylonitrile, lignin, and asbestos demand a larger amount of asphalt binder, while resulting in higher air voids, voids in mineral aggregate, and Marshall stability. The possibility of incorporating polypropylene, polyester fibers and polymers in the asphalt binder was addressed by Simpson & Mahboub (1994). The mixture prepared with the modified binder showed improved tensile strength and resistance to cracking. Additional research efforts were proposed to investigate the potential effects of fibers on the asphalt mixture response on a wide range of temperatures showing an overall beneficial impact on the material properties (Isacsson & Lu, 1995; Champion, et al., 2001; Tasdemir & Agar, 2007; Kaloush, et al., 2010). Some of the most common types of fibers that were used in combination with asphalt materials are shown in Figure 2.

Figure 2. Types of fibers. (Chen et al., 2009)

Liu et al. (2012) investigated the performance of Porous Asphalt (PA) Concrete with steel wool-reinforced fiber. The results indicated that the reinforced steel wool fiber has better performance in terms of permanent deformation ultimately leading to an increased durability of porous asphalt pavements. In addition, it was also observed that the healing potential of PA concrete can be enhanced when exploiting the induction heating properties of the wool fibers.

The combination of polymer modified binders and fibers was investigated in a recent research work by Ho et al. (2016) to produce fiber-reinforced polymer-modified asphalt mixture (FPMAC). Experimental and field tests were conducted on stone matrix asphalt (SMA) prepared with and without fibers consisting of a synthetic fiber blend containing polyolefin and aramid. The fiber content was set to 454g per ton of mixture. Low temperature creep tests were conducted on asphalt mixture small specimens, together with dynamic modulus tests at different temperatures and frequencies. The experimental results indicate that FPMAC mixtures present better relaxation properties and higher dynamic modulus at higher temperatures compared to the control mixture. This behavior was associated with the contribution of the “melted and plastically deformed polyolefin fibers” and the “reinforcement effect of the aramid fibers”, respectively. The field sections placed in northern Arizona provided solid support to the laboratory study, showing a formation of cracks of one order magnitude smaller in the FPMAC mixture compared to the control material. In addition, within a two-year monitoring plan, no rutting was developed in the pavement.

A research on the use of cellulosic fibers was recently proposed for porous asphalt by Afonso et al. (2017). The study concluded that mixtures including fibers had higher resistance to permanent deformation tensile strengths and resistance to cracking, whereas resistance to moisture was not affected. The results demonstrated that PA with higher percentages of bitumen improved the performance to permanent deformation. This fact was only possible due to the bitumen retention by the cellulosic fibers.

The combination of recycled fiber of tetra pak material (composed of 63% cellulose, 30% low-density polyethylene and 7% aluminum) and cellulose fiber was investigated in a recent research work by Andrés-Valeri et al. (2018) to produce fiber-reinforced porous asphalt (PA) mixtures. Experimental tests were observed the both of fibers with PA mixture have same effects on the permeability average total air voids and. Also, the experimental results indicate that fibers and PA mixtures present better properties for indirect tensile strength and higher resistance and moisture susceptibility. Moreover, water stability and demand of bitumen content were improved with tetra pak material fiber compared to cellulose fiber. Voskuilen et al., (2016) and Woldekidan et al., (2013) concluded that fiber reinforced porous asphalt with plain bitumen outperforms porous asphalt with polymer modified bitumen in terms of life expectancy.

A research on the use of a different fibers group was recently proposed by Giustozzi et al. (2015). In this study, the use of synthetic polyester and cellulose fibers together with styrene–butadiene–styrene (SBS), paraffin polymer (wax), rejuvenator, adhesion promoters, and surfactants was investigated for producing Warm Mix Asphalt (WMA) mixtures with high Reclaimed Asphalt Pavement (RAP) content. The volumetric analysis, conducted according to the national Italian specifications showed that SBS polymer and fibers, together with paraffin polymer, result in good compaction properties. Stiffness, fatigue, and rutting were evaluated based on conventional standardized tests. It was observed that a higher amount of fibers in combination with SBS and lower paraffin content lead to a stiffening effect at higher temperature, without significantly affecting the low temperature cracking susceptibility. Fibers were also beneficial in terms of fatigue and rutting resistance, leading to the conclusion that a balanced combination of additives, polymer, and fibers provides WMA-RAP mixture with performance similar to polymer modified mixtures. In addition, it was observed that thermal susceptibility of WMA with high percentages of RAP could be reduced when SBS polymer and cellulose–synthetic fibers were included in the mix design.

In literature, different percentages of fibers are reported for modification of asphalt materials. Table 1 summarizes some chemical and physical properties of fibers used in asphalt binders.

Table 1. Physical and chemical characteristics properties of fibers

Fibers	Type of filament	Specific gravity	Tensile strength (MPa)	Length (mm)	Acid/alkali resistance	Decomposition Temp. (°C)	Contents (%)	Color	Diameter (μm)	References
Polyolefin	multi	0.91	>483	19	Inert	130	0.05	tan		(Takaikaew et al., 2018)
Jute	multi	1.45	1450	18		210	0.35	brown	16-21	(Shanbara et al., 2018)
Aramid	single	1.45	>2750	19	Good	>450	0.05	yellow	12	(Takaikaew et al., 2018)
Glass	multi	1.38	1600			850	0.36		15-19	(Shanbara et al., 2018)
Hemp	single	1.5	1500		Good	380	0.33	brown	17-23	(Shanbara et al., 2018)
Polyacrylonitrile	multi	1.15	>910	4		>240	0.35	light yellow	13	(Xu et al., 2010)
Coir Fiber	multi	1.25	1250	50			0.35	yellow	18-23	(Shanbara et al., 2018)
Polyethylene	multi	0.97	400	20	Good	115	0.05	white	38	(Tanzadeh et al., 2017)
Polyester	multi	1.36	531	6	Good	>249	0.35	white	20	(Xu et al., 2010)
Polypropylene	multi	0.9	450	20	Inert	157		white	22	(Kaloush et al., 2010)
Lignin	multi			1.1		>200	0.35		45	(Xu et al., 2010)
Asbestos	singe	2.25	30	5.5	Limited	1400	0.35	gray	0.2	(Xu et al., 2010)

2 Modification of Asphalt Materials

2.1 Need for Modification

Modification of asphalt binder has been performed for over fifty years; however, this practice has received special attention only in the last two decades (Polacco, et al., 2015). In order to meet specifications, some asphalt binders require modification. The following factors represent some of the main driving aspects behind the significant effort devoted to modification of asphalt materials over the years (Roberts, et al., 1996; Kanabar, 2010):

a) Specifications of Superpave® asphalt binder: according to the current Superpave® specifications developed in the 1990s (Kanabar, 2010), asphalt binder requires considerable stiffness at high temperature and flexibility at low temperature. Such a rheological behavior over a wide spectrum of conditions cannot be not conventionally obtained without specific modifications, especially in regions with extreme climatic conditions.

b) Increased traffic demand: in recent years, traffic volume together with load and truck tire pressure have seen a substantial increase, leading to more severe rutting and cracking phenomena. For this purpose, many modifiers were used to improve rutting resistance while enhancing the relaxation properties of the binder component at low temperatures to mitigate thermal cracking (Roberts, et al., 1996).

c) Environmental and economic benefit/drawbacks: recycling waste and industrial by-and co-products (such as tire rubber, roofing shingles, glass and fly ash among others) may provide both economic and environmental benefits to the pavement industry and eventually to the construction process (Yee, et al., 2006). Nevertheless, in order to incorporate this type of materials into the mix design, without significantly compromising the pavement performance, different additives, such as rejuvenators, and reinforcements (Kanabar, 2010), are commonly added to the final mixture.

2.2 Type of Fibers

Many types and forms of fibers have been used in asphalt mixtures, either at the research level as well as on a routine basis in real pavement application. Cellulose, mineral, and polymer fibers are the most common (McDaniel, 2015). A comparison of different commercial fibers is presented in Figure 3 with respect modulus of elasticity, tensile strength, and density of fibers. It can be clearly shown that fibers vary in their physical and mechanical properties (McDaniel, 2015). Also, the most commonly used types of fibers and their behavior are summarized in Table 2.

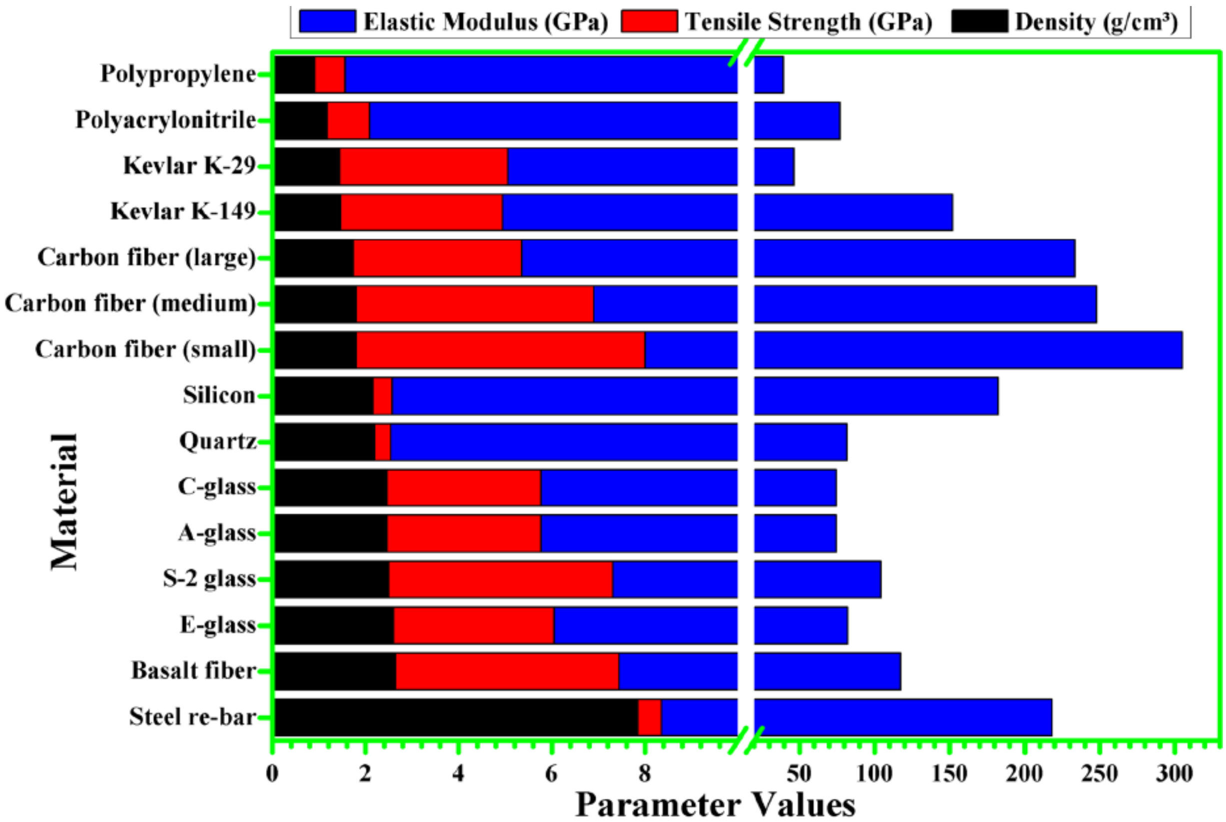

Figure 3. Stacked bar chart depicting the comparative mechanical properties of different known materials. (Dhand, 2015).

Table 2. Reported types of fibers and their behavior

Fibers	Observed effect	References
Polyolefin	Improved the indirect stiffness modulus, fatigue life, tensile strength, resilient modulus, permanent deformation, and pavement rutting resistance.	(Takaikaew et al., 2018)
Jute	Improved tensile strength, pavement rutting resistance, permanent deformation, and resilient modulus. Also, mixtures can carry heavier traffic loads in hot climatic conditions.	(Shanbara et al., 2018)
Aramid	Improved the fatigue life, tensile strength, pavement rutting resistance, permanent deformation, and resilient modulus.	(Takaikaew et al., 2018)
Glass	Improved tensile strength, pavement rutting resistance, permanent deformation, and resilient modulus. Also, mixtures can carry heavier traffic loads in hot climatic conditions.	(Shanbara et al., 2018)
Hemp	Improved the tensile strength, pavement rutting resistance, and permanent deformation.	(Shanbara et al., 2018)
Polyacrylonitrile	Improved the fatigue life, rutting resistance, toughness of AC mixtures, low-temperature flexural strength, split indirect tensile strength, and ultimate flexural strain.	(Xu et al., 2010)
Coir Fiber	Improved the tensile strength, pavement rutting resistance, and permanent deformation.	(Shanbara et al., 2018)

Polyethylene	Improved fatigue performance, tensile strength, resilient modulus, resistance against permanent deformations and thermal cracks.	(Tanzadeh et al., 2017)
Polyester	Improved the fatigue life, rutting resistance, toughness of AC mixtures, low-temperature flexural strength, and split indirect tensile strength.	(Xu et al., 2010)
Polypropylene	Improved resistance to shear deformation, resistance against thermal cracks, and tensile strength.	(Kaloush et al., 2010)
Lignin	Improved the toughness of AC mixtures, low-temperature flexural strength, and ultimate flexural strain.	(Xu et al., 2010)
Asbestos	Improved the toughness of AC mixtures, low-temperature flexural strength, and ultimate flexural strain.	(Xu et al., 2010)

2.2.1 Polymer Modified Mixtures

Polymer additives are generally thought of as "plastic" fibers (Frketic, et al., 2017). Polymers are large molecules created by joining together many small molecules. There are two actions needed in order for the polymerization processes to occur, namely the "addition" and "condensation" processes (Kaloush, et al., 2012). "Addition" polymers are produced by covalently joining the individual molecules, producing very long chains. When two or more types of molecules are joined by a chemical reaction, a byproduct (such as water) is released, called "condensation" polymers. A lattice within the asphalt binder is created by combining small molecules into larger ones. The larger molecule lattice is more stable under high and low temperatures, thus it may help in resisting to thermally induced cracking in the winter and permanent deformation or rutting in the summer (Kalsoush, et al., 2010).

The addition of polymers to asphalt binders has been shown to improve the overall performance. Researchers observed benefits such as better resistance to rutting and thermal cracking, decreased fatigue damage, improved stripping and reduced temperature susceptibility (King, et al., 1999; Yildirim, 2007). Polymer modified binders have been used with success in pavement sections experiencing high-stress fields, such as heavy-traffic intersections, airports, vehicle weigh stations and race tracks. Various types of polymers are used to modify the asphalt binder. Examples are styrene–butadiene–styrene (SBS), styrene butadiene rubber (SBR), Elvaloy, rubber, ethylene vinyl acetate (EVA), polyethylene, and others. Desirable characteristics of the polymer modified binders include greater elastic recovery, a higher softening point, viscosity, cohesive strength and ductility (King, et al., 1999; Yildirim, 2007). At the same time, low-temperature cracking can be controlled through the use of low-viscosity based asphalt binder (Novophalt, 1989). An anti-stripping group is used to reduce moisture damage and increase adhesion in asphalt binder and aggregate, e.g. polyamines and fatty amino-amines. Acid modification represents an alternative modification approach and dates back to 1930 (Brule, 1997). The main function of this modification is to increase the softening point of a binder. Polyphosphoric acid (PPA) is typically used as an acid modifier. It was observed that the use of such modifier helps to increase the grading range at high temperature but there are some negative effects observed according to the source of asphalt (Burk & Whitcare, 1939). In modified asphalt, it is thought that the final product has to become a microheterogeneous blend to obtain the most beneficial performance. In this, asphalt forms the continuous phase and the polymers are dispersed throughout the matrix (Kodrat, et al., 2007).

In a 2003 US Army Corps of Engineers study (Yildirim, 2007), it is pointed out that polymer modified binders provided resistance to multiple distresses, such as rutting, fatigue, thermal cracking and water damage (Partl & Newman, 2012). Novophalt is a specific type of polymer modified asphalt that was developed in Europe in 1976, and later (ten years) introduced in the United States. It is known for increased resiliency and durability while substantially minimizing rutting and shoving at elevated temperatures. It is also known for its ability to increase the cohesion and adhesion of the binder to the aggregate, thereby reducing stripping and raveling (Novophalt America Inc, 1989). Research studies indicated that a mixture with Novophalt was approximately seven times more resistant to rutting than the control at 60 °C/140°F. About 4% to 6% (by weight of binder) of polyethylene is added to asphalt binder in a high shear mixer to obtain the Novophalt modified mixture. In 1990, about 92% of the resin used by Novophalt came from recycled material. Polyolefin, the original source of polyethylene, is one of the resins used by Novophalt that is found in many commonly used plastic materials such as, milk jugs, trash bags, and sandwich bags. (McDaniel & Shah, 2003).

Polypropylene Fiber

Polypropylene fibers are widely used as a reinforcing agent for asphalt composites. A major benefit of using polypropylene fibers consists in providing three-dimensional reinforcement of the mixture (Tapkın, 2008). However, wire mesh reinforcement cannot be replaced by these fibers (Hensher, 2016). Using polypropylene fibers as a secondary reinforcement can decrease costs by partially replacing steel fibers. Based on a study conducted at the Ohio Department of Transportation (ODOT), a standard was proposed on the use of polypropylene fibers in high-performance asphalt mixture (Murali & Rajagopal, 2003). According to this ODOT's standard, high-performance hot asphalt mixture (HMA) is composed of three materials: aggregates, asphalt binder, and polypropylene fibers. The polypropylene fibers should be added to the asphalt mixture in a ratio of about 2.7 kg/ton. However, this ratio can be changed in order to satisfy the desired mechanical properties of asphalt pavement. The fibers are added to the heated aggregate prior to mixing with asphalt binder. The aggregate and fibers are mixed dry for an additional 10 seconds after the introduction of the fibers (Tapkın, 2008).

In a 1993 study, Jiang et al. utilized polypropylene fibers in an attempt to reduce reflection cracking in asphalt overlays. A reduction or delay in reflection cracking was not observed, although the frequency of cracking was less on the fiber modified overlay sections. Sections in which the mixture was cracked before the overlay were found to have less reflection cracking when fibers were used in either the base or binder layers (Jiang & McDaniel, 1993). In different research effort from Huang & White (1996), a study of asphalt overlays modified with polypropylene fiber was conducted. Control and fiber-modified mixtures were prepared to show that fibers had a stiffening effect associated with enhanced fatigue life. On the other hand, polypropylene fibers exhibited an inherent incompatibility issue with hot asphalt binder due to the low melting point of the fiber. Huang also pointed out that the viscoelastic properties of fiber-modified asphalt mixtures needed further research in order to fully understand their properties and functionalities as demonstrated in a later research (Cleven, 2000).

Polypropylene fibers can also find application in combination with other types of fibers, such as polyester fibers (Jenq & Chwen-Jang Liaw, 1993; Simpson & Mahboub, 1994; Cleven, 2000) and with aramid fibers (Alrajhi, 2012) as later reported in the present review.

Polyester Fiber

Polyester is the polymerized product of components from crude oil of which asphalt binder is also a component (Abtahi, et al., 2010). Polyester fibers, and by this we refer to largely polyethylene terephthalate (PET) fibers, dominate the world of synthetic fibers industry (Zhou, et al., 2017). They constitute, by a considerable margin, the largest volume (≈ 18 million tonnes/yr in 2000) of synthetics and far outweigh nylons, rayon and acrylic fibers (Singh, 2018). They are inexpensive, easily produced from petrochemical sources, and have a desirable range of physical properties. Polyester fibers are strong, lightweight, easily dyeable and wrinkle-resistant, and have very good wash–wear properties (Izgi, et al., 2018). Polyester fibers are produced by the melt spinning process (Bansal & Raichurkar, 2016). Raw materials are heated to a spinning mass, which is then pressed through spinnerets (McIntyre, 2009). The morphology of polyester fiber is shown in Figure 4. Polyester fibers can be used when strong and durable reinforcement of asphalt mastics is needed at higher temperatures. When tested for rheological characteristics and fatigue properties, the use of polyester fibers indicates that the viscosity of asphalt binder increases with the increase in polyester fiber contents, especially at lower temperatures and lower stress levels (Shiuh & Kuei-Yi, 2005).

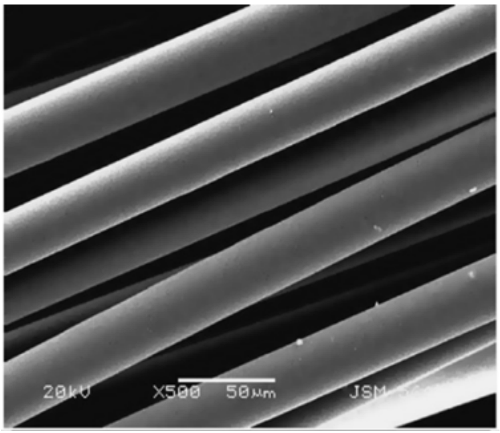

Figure 4. SEM morphological image of polyester fiber. (Wu, et al., 2008)

In a previous study, the effect of fibers in overlay mixtures was investigated by Maurer et al. (1989). Due to its higher melting point, polyester fibers were selected over polypropylene fibers. The performance of the polyester fiber modified mixture was compared with several types of fiber reinforced interlays and a control section. Each tested section was rated for ease of construction, cost, and resistance to reflective cracking. It was observed that sections using loose modified fiber performed best overall (Maurer & Malasheskie, 1989).

In a different research, a fracture mechanics approach was used to evaluate the effects of fiber reinforcement on crack resistance (Jenq & Chwen-Jang Liaw, 1993). Polyester and polypropylene fibers were combined to produce modified mixtures that were then tested for modulus of elasticity and tensile strength. The study showed that toughness was increased together with an increase between 50 to 100 percent in the fracture energy, while a limited effect on elasticity and tensile strength were observed (Cleven, 2000). In 1994, Simpson & Mahboub conducted a study on modified asphalt mixtures in Somerset, Kentucky that utilized polypropylene and polyester fibers and polymers to modify the asphalt binder. The study evaluated two blends of modified binders. Tests included Marshall Stability, Indirect Tensile Strength (IDT), moisture damage susceptibility, freeze/thaw susceptibility, resilient modulus, and repeated load deformation. The study concluded that mixtures including polypropylene fibers had higher tensile strengths and resistance to cracking, whereas resistance to moisture and freeze/thaw damage was not affected. IDT results predicted that the control and polypropylene mixtures are not affected by thermal phenomena, whereas mixtures made with polyester fibers and polymers may experience this phenomenon. High temperature resilient modulus testing showed that the polypropylene fiber modified mixtures were the stiffest. Decreasing of rutting measured by repeated load deformation testing was only found for the polypropylene modified samples (Cleven, 2000; Simpson & Mahboub, 1994).

2.2.2 Cellulose Fiber

Natural fibers themselves are cellulose fiber reinforced materials as they consist of microfibrils that run all along the length of the fiber in an amorphous matrix of lignin and hemicellulose. The hydrogen bonds and other linkages provide the necessary strength and stiffness to the fibers. (Saheb & Jog, 1999)

Decoene et al. (1990) investigated the effects of cellulose fibers on bleeding, air voids content reduction, abrasion, and drainage in porous asphalt. While significantly decreasing in binder bleeding was observed, cellulose fibers required a higher amount of asphalt binder for HMA mix design. No remarkable changes in erosion and air voids contents could be detected when cellulose fibers were incorporated. Tests sections were also prepared and drainage monitored for six months. Sections containing fibers retained the same drainage quality, while the drainage time doubled in sections without fibers (Decoene, 1990).

In a more recent effort, Shanbara et al. (2018) presented a detailed investigation of the properties of asphalt binders with different types of natural fiber reinforcement; hemp, jute, and coir. Their goal was to evaluate the applicability of these fibers to asphalt mixtures at lower service temperatures and compared with traditional cold and hot mix asphalt mixtures. Figure 5 presents the Scanning Electron Microscope (SEM) micrographs for cellulose fiber (coir fibers) distributed in the asphalt matrix with uniform fiber formation.

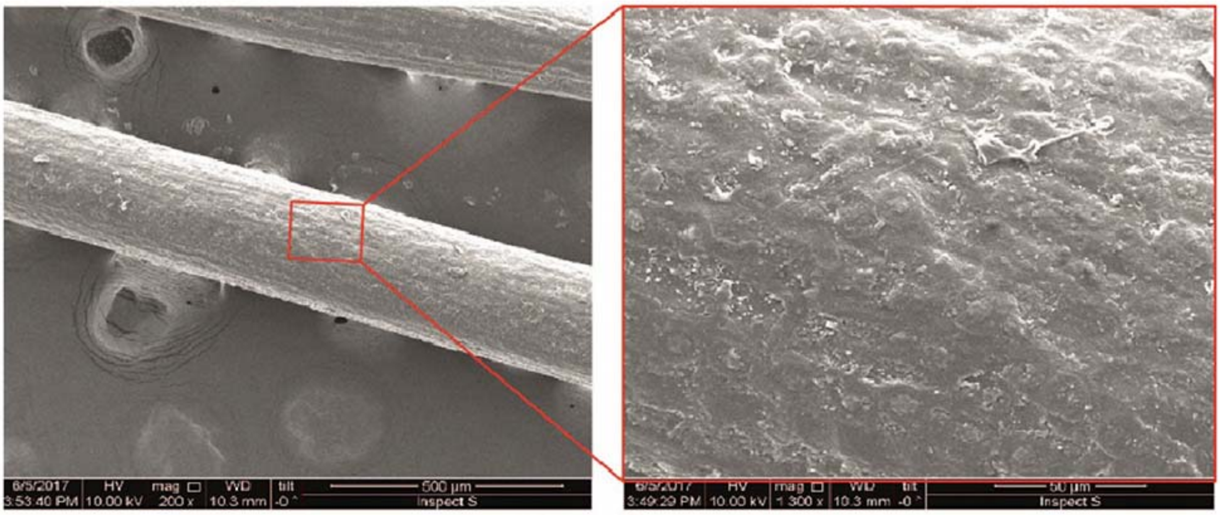

Figure 5. Cellulose fibers. (Shanbara, et al., 2018)

In a different study by Stuart et al. (1994), loose cellulose fibers, pelletized cellulose fiber, and two polymer fibers were used to investigate binder drain-down, resistance to rutting, low temperature cracking, aging and moisture damage. Drain-down test results indicated that mixtures with polymers and the control material drained remarkably more than those with fibers. (Stuart & Malmquist, 1994).

The impact of various contents of cellulose fibers on the properties of Stone Matrix Asphalt (SMA) was studied by Partl et al. (1994). Thermal stress restrained specimen test (TSRST) and indirect tensile test (IDT) were performed for this purpose. Experimental results were initially affected by the formation of fiber clumping that occurred during the mixing process. This effect was partially mitigated by increasing mixing temperate and duration. No significant improvements were observed by blending cellulose fiber in SMA, most likely due to the poor distribution of fibers. In another study on SMA, the effects of cellulose fibers were investigated by Selim et al. (1994). Binder drain-down, moisture susceptibility (reported as tensile strength ratio), static creep modulus, and recovery efficiency were evaluated. Fibers were added to mixtures including standard and polymer modified binders. From results, a remarkable improvement in all mixtures containing the cellulose fibers was exhibited during the drain-down test. Mixtures with plain asphalt binder and fibers showed the highest indirect tensile strength and tensile strength ratio after conditioning compared to polymer modified mixtures containing fibers that showed the lowest tensile strength and resistance to moisture induced damage of all the mixtures tested. (Selim, 1994; Alrajhi, 2012).

In one research effort Shaopeng (2007), the dynamic characteristics of fiber-modified asphalt mixture were investigated using cellulose, polyester, and mineral fibers. Each fiber type was tested with the following dosages: 0.3%, 0.3%, and 0.4%, respectively. A gyratory compactor was used to prepare samples for the dynamic modulus test. The testing focused on the characteristics of the dynamic modulus (E^*) and the phase angle (δ) at various temperatures and frequencies. The results showed that all fiber modified asphalt mixtures had a higher dynamic modulus compared with the control mixture. In a previous research, Serfass & Samanos (1996) reported that two million load applications were imposed to fiber modified asphalt mixture for pavements overlay to evaluate fatigue cracking. As a result, the macrostructure of the pavement surface did not show any significant sign of cracking proving the effectiveness of the fiber modified asphalt as an overlay mixture. In view of macrostructure integrity, preserved skid resistance and lack of fatigue cracks, they showed that the fatigue life of the fiber modified overlay was better than the fatigued, unmodified pavement which was underneath the overlay layer.

2.2.3 Geogrid and Glass fiber

Geogrid is a type of geosynthetic fiber commonly used as a reinforcing agent in soil; however, this can be also used for asphalt pavements. Geogrids are made of different fiber reinforced materials, such as glass fibers and/or polymeric fibers and are usually stiff materials formed into a grid-like structure with large mesh matrix (Harvey & Monismith, 1993). The fibers are formed into a matrix in order to transfer loads to the fibers and to shield the fibers against degrading conditions such as chemical substances. Not only they increase the tensile strength, but also provide good lateral confinement for the reinforcement mechanism (Kutuk, 1998; Ling, 2001). Figure 6 presents the SEM micrographs for glass fiber distributed in the asphalt matrix.

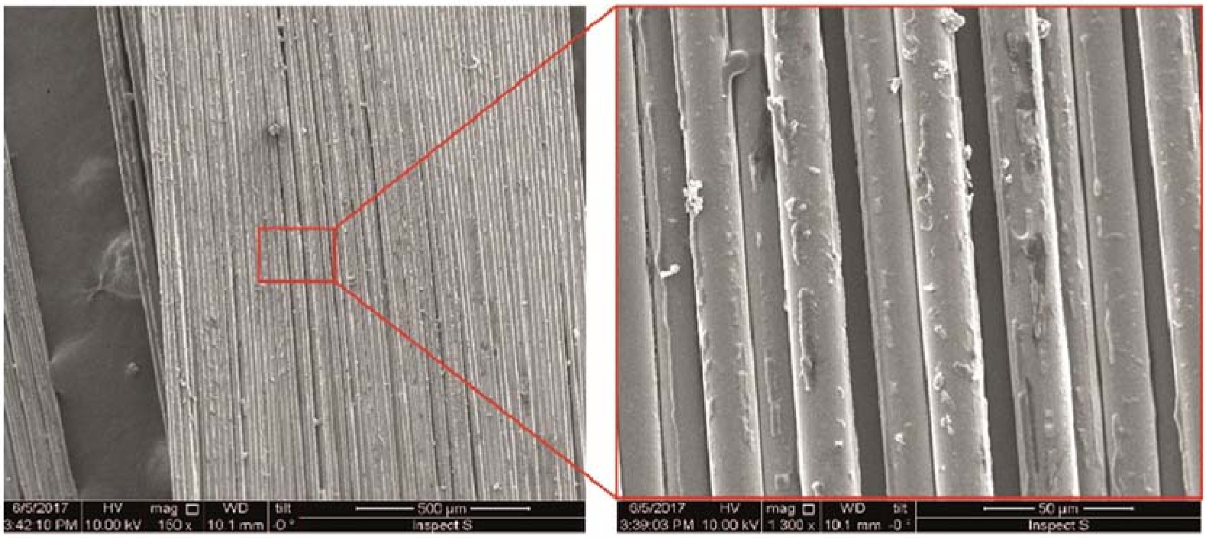

Figure 6. Glass fiber. (Shanbara, et al., 2018)

In Lee's study (2003), several geogrids were selected to investigate the formation and development of fatigue cracks in asphalt concrete beams. The test results of a beam reinforced with geogrids indicated the fatigue life of the pavement overlay improved five to nine times more than an unreinforced beam (Lee, 2003).

In a series of studies, Chen et al. (2009) concluded that adding glass fiber increases the optimum asphalt content, which can be attributed to the full coverage of fiber surfaces by the asphalt. They also observed that fiber-reinforced specimens were more resistant. The reason for the high resistance of fiber reinforced specimens is the interlock between the fiber, aggregates, and binder, which causes no crack growth when fibers are present near a stone-stone interface; the fibers, binder, and aggregates become interlocked under loading (Khanghahi & Tortum, 2018).

In another study, polyoxymethylene fibers were used as geogrids to reinforce asphalt. The durability, such as plastic flow resistance and crack resistance of the geogrid-reinforced asphalt mixture, was investigated at the laboratory scale using the wheel tracking test.

Results indicated a remarkable increase in the durability by using the geogrid reinforced asphalt mixture in comparison with the control without geogrids. The crack resistance was directly connected to the plastic flow resistance. Decreasing geogrid-mesh size and a strong adhesion to the asphalt material were strong signs of improved durability. This was because the stress concentration applied by a wheel load was greatly reduced by the high stiffness and small meshes of the thin geogrid inserted in the asphalt mixture (Komatsua et al., 1998; Alrajhi, 2012).

2.2.4 Fabric and Carpet Fiber

In the past, the use of fabric and carpet fiber for pavement application was also investigated. In one study, focusing on nylon fibers (Lee, 2003) it was shown that asphalt mixture reinforced by nylon fibers present better resistance against fatigue cracking with increased fracture energy. Maurer & Malasheskie (1989) and Alrajhi (2012) investigated the impact of using fabrics, polypropylene, and polyester fibers to hinder reflective cracking in a hot mix asphalt overlay. Paving fabrics, fiberized-asphalt membrane, and fiber-reinforced asphalt better performed over non-reinforced samples in terms of construction, maintenance costs, ease of placement, and the ability to prevent or hinder reflective cracking. The dosage was set at 0.3% by volume of the total asphalt mixture. Their analysis indicated that beams reinforced with woven grid and nonwoven fabric composites performed significantly better than beams containing nonwoven paving fabric alone

2.2.5 Carbon Fiber

Carbon fibers, which are a breed of high-strength materials, are mainly used as reinforcements in composite materials such as carbon fiber reinforced plastics, carbon-carbon composite, carbon fiber reinforced materials, and carbon fiber reinforced cement. Carbon fibers offer the highest specific modulus and highest specific strength of all reinforcing fibers (Chand, 2000).

There are many resources to extract carbon fiber such as polyacrylonitrile (PAN), or rayon, but only fibers derived from mesophase pitch were considered. Pitch is generally cheaper, making it the lowest cost carbon fiber in production. Furthermore, it uses less energy compared to other fiber types, and there is a low percentage of N2, H2, and other non-carbons to drive off carbonization (Buckley, et al., 1993). From 1968 to 1972, the Federal Highway Administration (FHWA) sponsored the use of carbon black fibers as reinforcement in hot mix asphalt (Fitzgerald, 2000). The results of this research conducted at the laboratories of Materials Research and development in Oakland, California, showed that carbon black in asphalt mixture gave significant improvements in durability, wear resistance, low-temperature cracking, high-temperature deformation, and temperature – viscosity properties of the asphalt mixture. These improvements are due to the carbon black stiffening and increasing the toughness of the asphalt binder. Carbon black is easily dispersed in the asphalt binder by first being pelletized and then being subjected to the shearing action between aggregate particles during mixing. Careful selection of asphalt binder allows for the basic characteristics of the asphalt mixture to remain unchanged after the addition of carbon black (Tomlinson, 1995; Fitzgerald, 2000).

Aren Cleven investigated two aspects of carbon fiber-modified asphalt mixtures (Cleven, 2000): 1) the feasibility of achieving improvements in mechanical behavior with the addition of carbon fibers; 2) the parameters that contribute to the new behavior. Carbon fibers were found to provide improvements both in high and low temperature behavior. HMA samples containing 0.5% to 0.8% weight carbon fiber in the asphalt binder showed an improvement in resistance to deformation associated with repeated loading in the range between 38% to 182%. Potential problems identified in this study were the final fiber length, even distribution of fibers, and the initial asphalt binder quality (Cleven, 2000). The final optimal fiber length was determined to be 6 mm in order to improve mechanical properties such as, controlling micro cracking and reducing creep phenomena (Fitzgerald, 2000).

In a study by Cleven (2000), the characteristics and properties of carbon fiber reinforced asphalt mixtures were investigated. Samples with and without fibers were tested to assess the effect of fiber contents on asphalt mixtures. Marshall, indirect tensile test, creep and repeated load indirect tensile test were performed. Results showed that the addition of fiber does affect the properties of asphalt mixtures. On the other hand, two more recent research efforts observed that the addition of carbon fiber improved some of the mechanical properties including fatigue and deformation (Jahromi, 2008; Alrajhi, 2012).

2.2.6 Aramid Fiber

Aramid fibers belong to a family of synthetic products characterized by strength (about five times tougher than steel on an equal weight basis) and heat-resistance (more than 500 degrees Celcius). This type of fibers finds various applications such as composites, ballistics, aerospace, advanced composites, protective clothing against heat/radiation/chemicals, asbestos substitute, telecommunications (optical fiber cables) and many other. (Fibermax, 2018; Reglero Ruiz, et al., 2017).

Kaloush et al. (2010) investigated the performance of asphalt binder blended with aramid and polypropylene fibers. The results indicated that the reinforced aramid and polypropylene fibers had better performance in terms of permanent deformation and thermal cracking. In a different study from Arizona State University (ASU) (Alrajhi, 2012), polypropylene and aramid fibers were used in the asphalt paving mixtures to evaluate the performance characteristics of a modified asphalt mixture. A designated road section in Tempe, Arizona was used as the test site to perform the project. Triaxial shear strength, dynamic modulus, repeated load permanent deformation, beam fatigue, crack propagation, and indirect diametral tensile tests were conducted in the laboratory to compare the performance of the fiber modified mixture to the control. From the experimental results, it was observed that the fibers enhanced the mixture's performance against the anticipated major pavement distresses: permanent deformation, fatigue cracking, and thermal cracking (Kaloush, 2010; Alrajhi, 2012).

In a more recent research effort, the results indicated that the addition of aramid fiber in Grave Bitume (GB20) (an asphalt mix with a nominal maximum aggregate size of 20 mm used in Canada) decreased the fracture temperature and fracture strength (Badeli, et al., 2018). Klinsky et al. (2018) showed that the hot mix asphalt with aramid fibers have better fatigue cracking resistance than the control hot mix asphalt at moderate to low strain levels.

An analogous study was proposed by Ho & Shan (2016). In the specific case, the potentially higher performance of asphalt mixture prepared with a mix of polyolefin and aramid fibers was compared to the behavior of rubber modified asphalt (RMA) mixtures. Low temperature response of both mixture types was evaluated in the laboratory through freeze-thaw cycles and Bending Beam Rheometer (BBR) tests, while the field performance was investigated through an overlay project section in Arizona. From a simple volumetric analysis, it was observed that the initial air voids content decreases when aramid fibers are used in place of rubber. However, the fiber reinforced mixture appears to retain higher stiffness than the rubber modified asphalt (RMA), ultimately showing poorer relaxation properties. This is confirmed by the larger number of thermal cracks present in the field section prepared with aramid fiber reinforced mixture in comparison to the undamaged RMA pavement surface.

2.3 Summary on the Use of Fibers in Asphalt Materials

For over six decades, fibers have been widely used in several civil engineering applications (Panzera, et al., 2013; Jahromi & Khodaii, 2008). Fiber reinforcement refers to incorporating materials with desired properties within a matrix of a different material lacking in the specific target properties to obtain a composite which benefits of both material characteristics. The use of fiber-reinforced binders is not new in the pavement industry as it finds its first application in the 1950s. Since then, a number of fibers and fiber reinforced materials have been introduced in the market (Jahromi & Khodaii, 2008).

Fibers are primarily used as reinforcement in order to provide additional tensile strength in the resulting composite, which can increase the amount of strain energy that can be absorbed/dissipated during fatigue and fracture processes (Mahrez, 2003). Since fibers have higher tensile strengths compared to bituminous mixtures, they have the possibility to enhance the cohesive and tensile strength of the mixture in which they are incorporated. Fibers have the ability to impart physical changes to bituminous mixtures, such as reinforcement and toughening (Brown, 1990). Figure 7 shows the images of fiber spatial distribution in asphalt binder obtained with a scanning electronic microscope (SEM).

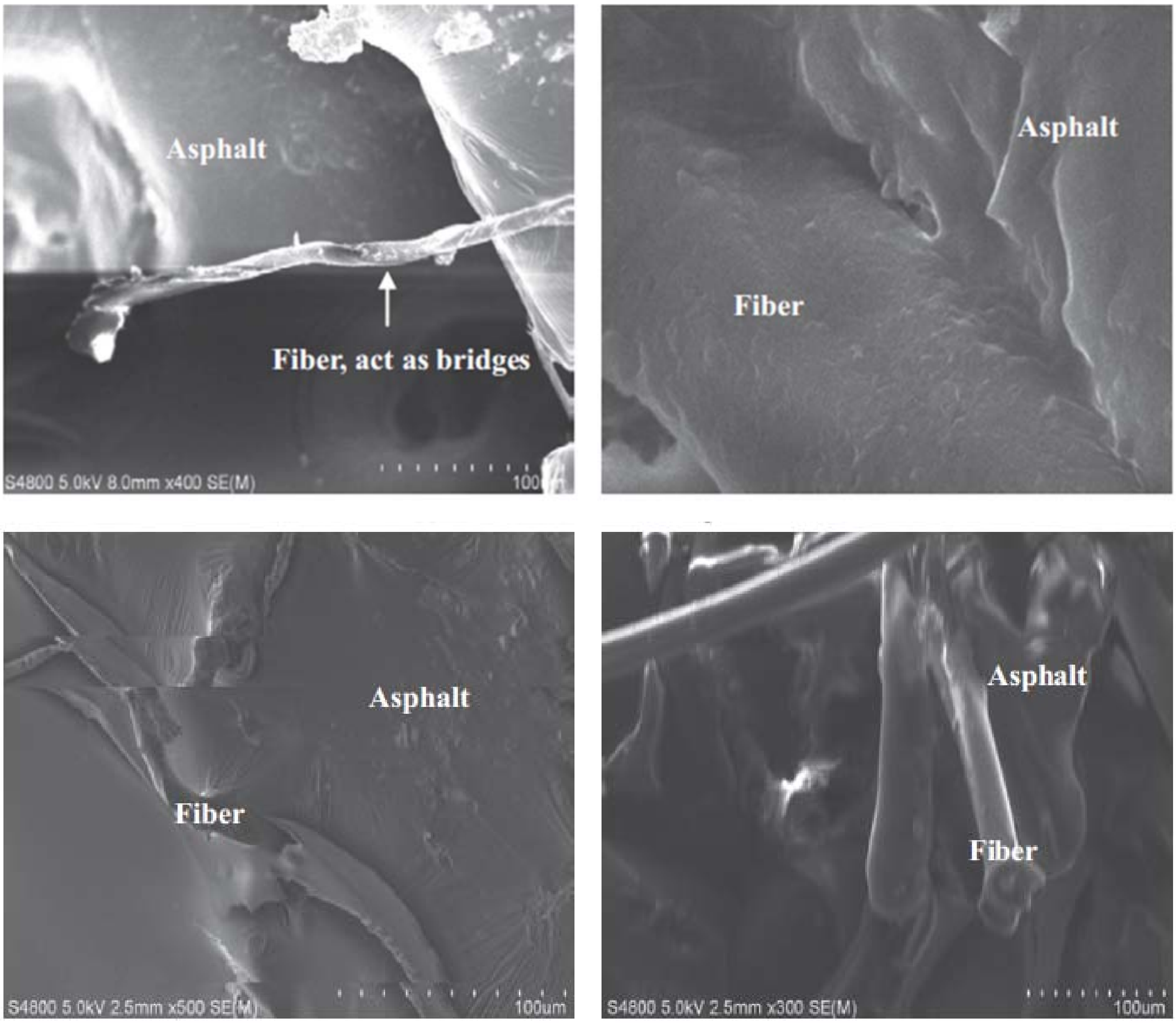

Figure 7. SEM microstructure of fiber modified asphalt. (Xiong, et al., 2015)

As previously mentioned, both natural and synthetic fibers have been used with asphalt materials. Natural fibers include asbestos, cellulose, and rock wool. While synthetic fibers include polypropylene, polyester, and aramid. Fibers do not react chemically with the asphalt binder but rather reinforce and stiffen the asphalt mastic. The possible advantages of using fibers to reinforce asphalt binder and eventually the actual paving mixtures include reduced fatigue, thermal and reflective cracking; increased service life; and economic benefits (Terrel, 1989; Button & Epps, 1981; Mahrez & Karim 2007). Rapid advances in technology have led to the development of construction materials allowing the combination of fibers to increase the serviceability and safety of structures (Lee, 2003). The most commonly used types of fibers and their benefits and drawbacks are summarized in Table 3 (McDaniel, 2015).

Table 3. Reported benefits and drawbacks of common fiber types (McDaniel, 2015)

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	• Lower melting point than some other fiber materials requires control of production temperatures. • Begins to shorten at 300°F. • Cost-effectiveness not proven/varies.

	added.	
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.

2.4 Mixing process

According to the research of Liu et al. (2012), the mixing process of fiber into asphalt mixture is of great importance; however, no specification for this mixing procedure is available for fiber modified mixtures. There are two potential methods for the introduction of the fibers: the wet process and the dry process. In the wet process, the fibers are blended with asphalt binder prior to incorporating the binder into the mixture. The dry process mixes the fibers with the aggregates before adding the binder. Generally, the dry method is more commonly used due to several advantages. Experimentally, the dry process is the easiest to perform and allows for the best fiber distribution in the mixture. Meanwhile, since the fibers used do not melt in the binder there are no apparent special benefits to the wet process. In addition, in the field work and experimentation conducted on fiber reinforced asphalt mixtures, the dry process is generally adopted (Echols, 1989; Munn, 1989; Hejazi, 2007). The selection of this approach may be also related to production problems potentially arising when introducing the fibers directly into the asphalt binder. Another reason for using the dry process is that it minimizes the major problem of clumping or balling of fibers in the mixture (Labib & Maher, 1999). Figure 8 illustrates fibers addition to the aggregate during the preparation of asphalt mixture in the laboratory according to the dry process.

The drum and the batch plant are two types of asphalt mixing process plants commonly in use for fiber. The choice of a drum or batch plant depends on technical and economic factors as production requirements, purchase price and operating costs (Anon. 2018).

Figure 8: Addition of fibers to the hot aggregates, before asphalt binder addition. (Klinsky et al., 2018)

Effect of content and size of fibers on the asphalt mixtures

In the recent past, Gao (2012) demonstrated that 0.07% and 0.15% were optimal fiber contents for application in asphalt mixture when a length of 9mm and 6mm was used, respectively. A different recommendation was proposed in the work of Morva (2013) in which an optimal fiber content of 0.5% was associated with a length of 3.94mm. In am ore recent study, Garcia et al. (2014) observed a relationship between characteristics of mixtures such as particle loss and air void with diameter and length of fibers. In different research efforts, Fu, et al. (2007) and Park, et al. (2015) found that long fibers provide a more effective bridging action. Qin et al. (2018) investigated fiber length and content of basalt fiber to enhance the properties of asphalt materials; the resutls indicated that 6 mm was the optimal length for strength and asphalt binder adsorption.

Additional research efforts were proposed to investigate the potential effects of contents and length of fibers on the asphalt mixture showing an overall beneficial impact on the material properties (Wang et al., 2018). Gao et al. (2017) Revalauted the use of the different contents and lengths of glass fibers in the asphalt mixture. In this investigation, the maximum equivalent stress (MES) of the fiber reinforced asphalt concrete was found to be sensitive to the length of fibers, showing that long fibers (12 mm) better contribute in decreasing stress concentration. A comparison of different contents and length of fibers is presented in Figure 9 with respect the MES of asphalt mixture.

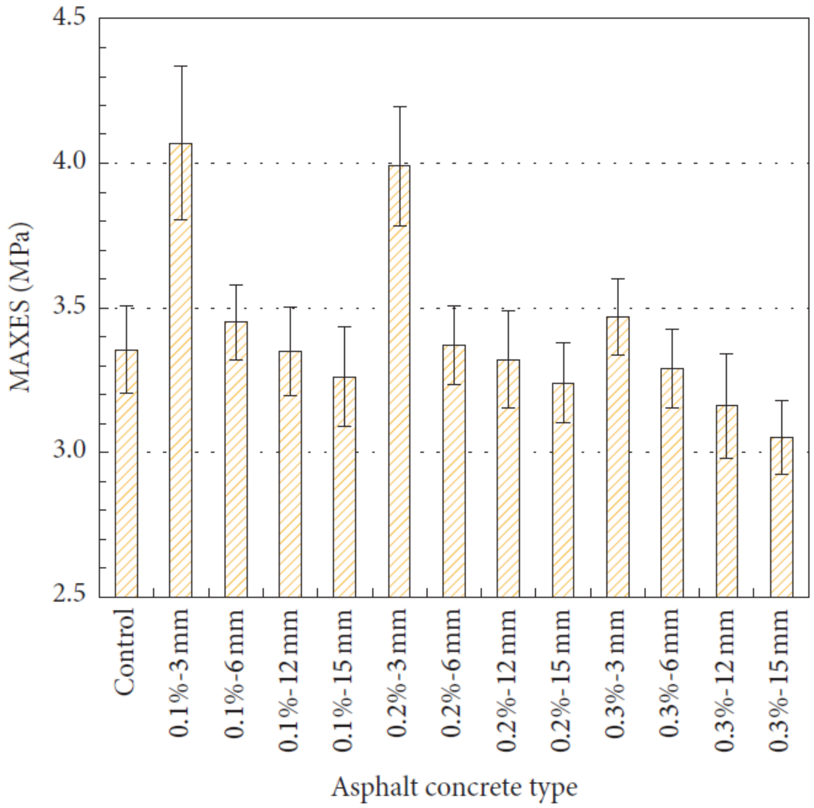

Figure 9. Maximum equivalent stress of asphalt (Gao et al., 2017).

In the same study, Gao et al. (2017) also observed (Figure 10) that higher amount and longer fibers decrease the creep deformation of fiber-modified asphalt concrete. One of the reason for this reduction in creep is due to the fact that the viscoelastic deformation is strictly related to the stress level (Katman et al. 2016); in addition, fibers tend to stabilize the viscoelastic deformation (Hassan and Al-Jabri, 2005). Therefore, content and length of fiber play an important role in the viscoelastic performance of fiber reinforced asphalt concrete (Gao et al., 2017).

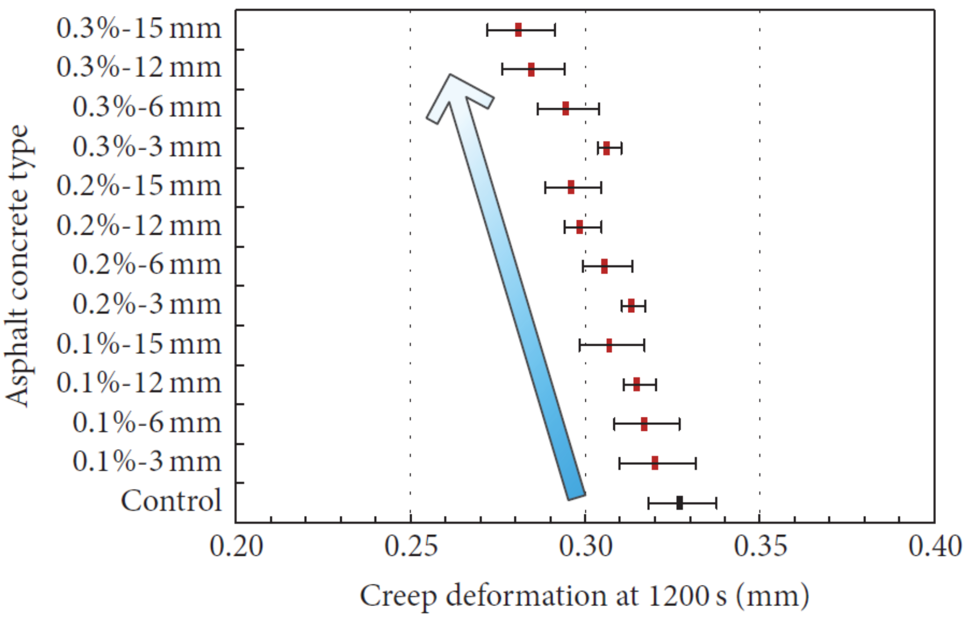

Figure 10. Creep deformations of different asphalt concrete (Gao et al., 2017).

3 Mechanical Properties and Durability of Fiber Modified Asphalt Materials

The typical failure mechanisms of asphalt pavement, such as rutting, cracking, and long-term fatigue durability, have been practically addressed by improvements in mix design and with the use of specific additives to produce polymer or fiber modified materials (Lancaster, 2016). In the U.S., the Strategic Highway Research Program (SHRP) led to the implementation of the Superpave (SUperior PERforming Asphalt PAVEments) system (Kennedy, et al., 1994) for binder specification and asphalt mixture design which prompted the increase in the use of polymer additives to improve the Performance Grade range of binders. The use of polymer fiber modified binders in asphalt mixture to resist deformation, is relatively well established (Valkering, et al., 1990), but their use to improve fatigue life is less well defined even though in practice they have often been used with this purpose in mind (Delorme, de la Roche & Wendling, 2007). However, there remains a need to develop laboratory tests which can determine the fundamental properties of the modified asphalt, and hence provide a sound engineering basis for the specification of fiber-modified binders (Lancaster, 2016).

Fiber reinforcement is usually used as a crack barrier whose function is to carry the tensile loads as well as to prevent the formation and propagation of cracks (Maurer & Gerald, 1989). Park et al. (2015) investigated the use of three fibers types in combination with asphalt material. Figure 11 shows indirect tensile stress-strain curves from the fiber reinforced asphalt with steel fibers (SR3), carbon fibers (CB), and Polyvinyl alcohol (PVA) fibers. The influence of fiber content is clear and shows similar trends in all test series. Overall, the addition of fibers led to improvements in the material response.

Over the years, it was observed that fibers can change the viscoelastic behavior of the modified asphalt (Huang & White, 1996), increase the dynamic modulus (Wu, et al., 2007), moisture resistance (Putman & Amirkhanian, 2004), creep compliance, rutting resistance (Chen, et al., 2004) and freeze-thaw resistance (Echols 1989), while reducing the reflective cracking of asphalt mixtures and pavements (Echols, 1989; Tapkın, 2008; Maurer & Malasheskie, 1989). Research also shows that fiber-reinforced asphalt materials (FRAM) develop good resistance to aging, fatigue cracking, moisture damage, bleeding, and reflection cracking (Goel & Das, 2004).

Fibers are also used to prevent drain down of asphalt mixtures (Hassan & Al-Oraimi, 2004; Peltonen, 1991; Hansen, 2000). Finely dispersed fibers provide a high surface area per unit weight and behave much like filler materials. Fibers also tend to increase the viscosity of the mastic. In terms of efficiency, mixtures with fibers show a slight increase in the optimum binder content compared to the control mix. In this sense, adding fibers to asphalt is very similar to the addition of very fine aggregates to it. Thus, fiber can stabilize asphalt binder to prevent its drainage (Peltonen, 1991). For this reason, fibers find application in stone matrix asphalt (SMA) and open graded friction-course (OGFC) (Park, et al., 2015).

Fibers can be also used as conductive additives to improve the electrical conductivity of asphalt mixtures as reported in several research efforts by Wu (Wu, et al., 2002, 2005 and 2006). In this series of studies, asphalt mixture was designed with conductive fibers (Wu, et al., 2002 and 2005) and combined with thermo-electrical techniques to remove snow and ice on in winter. Wu et al also developed conductive asphalt mixtures for self-monitoring purposes, exploiting the change in resistance which may be potentially linked to changes in the internal structure (Wu, et al., 2006). Alternative applications of conductive asphalt pavements include energy and solar radiations harvesting for powering simple road signals or heating and cooling of adjacent buildings (Wu, et al., 2008). Table 4 summarizes the maximum improvements of the fiber reinforced asphalt as reported in previously published papers. The most significant improvement in mechanical response is reported by Kaloush et al. (2010); by adding 0.10% of commercial fibers by volume, they observed a 25–50% increase in indirect tensile strength (ITS) and a 50–75% increase in fracture energy (FE) at low temperature. In the case of steel fibers, Serin et al. (2012) noted approximately a 20%

improvement in Marshall Stability by using 60 mm long hooked fibers (Park, et al., 2015).

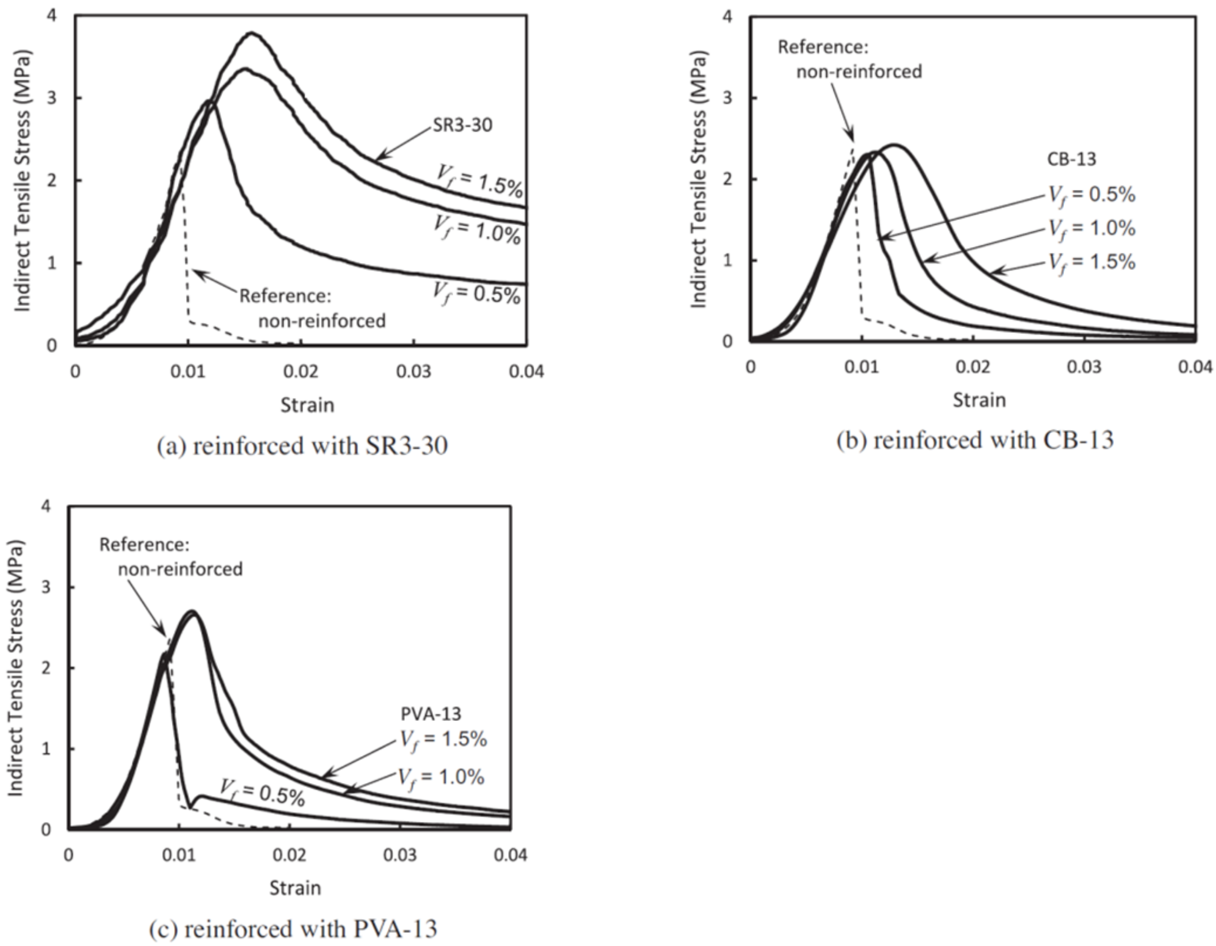

Figure 11. Three typical patterns of indirect tensile stress-strain curves (averaged) of fiber reinforced asphalt. (Park et al., 2015)

Table 4. Comparison of the documented strength improvements attributed to fiber addition (Park et al., 2015)

Citation	Maximum improvement*				Fibers (L = length, W_f = fiber content by weight, V_f = fiber content by volume)	V_f*****	Note
	ITS**	FE***	Toughness	MS****			
Freeman et al. 1989	15%				Polyester fibers, L = 6 mm, W_f = 0.35%	0.60%	Wet ITS and wet toughness, adjusted optimum binder content
			117%		Polyester fibers, L = 13 mm, W_f = 0.50%	0.85%	
Kim et al. 1999	5%			10%	Polyester fibers, L = 6 mm	–	Dry ITS
Bueno et al. 2003				−57%	Polypropylene fibers, L = 20 mm, W_f = 0.5%	1.3%	Maximum strength reduction
Lee et al. 2005	−18%	85%			Recycled carpet (nylon) fibers, L = 12 mm, V_f = 1.0%	1.0%	Test at +20 °C
Tapkin 2008				58%	Polypropylene fibers, L = 10 mm, W_f = 1.0%	2.5%	
Li et al. 2008	28%				Carbon fibers, L = 5 mm, W_f = 0.3%, mixed with 18% graphite filler	0.38%	ITS with loading rate of 1 mm/min
Anurag et al. 2009	31%		80%		Waste polyester fibers, L = 13 mm, W_f = 0.5%	0.85%	Wet ITS and wet toughness
Chen et al. 2009				8%	Polyacrylonitrile, W_f = 0.3%	0.60%	Adjusted optimum binder content
Xu et al. 2010	8%		71%		Polyacrylonitrile, L = 5 mm, W_f = 0.3%	0.60%	Adjusted optimum binder content
Kaloush et al. 2010	49%	75%			Blend of polypropylene and aramid fibers, L = 19 mm, W_f = 0.045%	0.10%	Test at −10 °C
Serin et al. 2012				20%	Hooked steel fibers, L = 60 mm, W_f = 0.75%	0.23%	Adjusted optimum binder content
Park et al. 2015	**63%**	286%	727%		Hooked steel fibers, L = 30 mm, W_f = 5.0%	1.5%	Test at −20 °C
	56%	**370%**	**896%**		Twisted steel fibers, L = 30 mm, W_f = 5.0%	1.5%	Test at −20 °C

* Improvement = [(strength of Fiber reinforced asphalt mixture /non- reinforced strength) – 1] ×100 (%).
** ITS = indirect tensile strength.
*** FE = fracture energy.
**** MS = Marshall stability.
***** Some papers describe the fiber contents in percent weight, which is converted into volume content in this table.

Many different types of fibers were tested. According to the Natural Sciences and Engineering Research Council of Canada (NCHRP) Synthesis entitled Fiber Additives in Asphalt Mixtures (McDaniel, 2015), the fibers can be separated into different types: cellulose, mineral, polyester, polypropylene, aramid, aramid and polyolefin, and fiberglass that. The use of high tensile strength fibers, (when properly homogenized in the asphalt mixture), would result in a longer lasting material. (Saliani, et al., 2018).

In a recent study, it was found that the addition of aramid fibers –Aramid Pulp Fiber (APF)- could increase the ductility and tensile strength even at temperatures below zero (Saliani, et al., 2017). The effects of fiber on the strength for different binder types are summarized in Table 5. From this table, fiber generally increases the strength of asphalt binders.

Table 5. TSRST test results (Badeli et al., 2018)

Mix type	Average fracture temperature		Average Fracture strength		Average Transition temperature		Average Transition strength	
	Value (°C)	CV (%)	Value (MPa)	CV (%)	Value (°C)	CV (%)	Value (MPa)	CV (%)
Reference	−28	6	3.601	5	−13.5	6	2.260	7
APF	−36	7	2.651	6	−22	7	1.755	7

CV: Coefficient of variation which is calculated by dividing the standard deviation from the mean value.

Tanazadeh et al. (2017) demonstrated that when using aramid fiber in asphalt mixtures, improved rutting resistant and delay in cracking propagation can be achieved. Based on the results of their analysis, the behavior and the fatigue life of fiber reinforced mixtures have been significantly improved in comparison with the control mixtures. These tests highlighted that the fatigue life of the asphalt reinforced with 0.50 kg fibers per each ton of asphalt, is 2.2 times that of the control ordinary asphalt. Figure 12 shows that the tensile strength of Aramid fibers is equal to 3000 MPa, which is several times higher than that of on conventional asphalt mixture. Therefore, reinforcement through aramid fibers results into increased tensile strength of the mixture and higher resistance against the fatigue cracking.

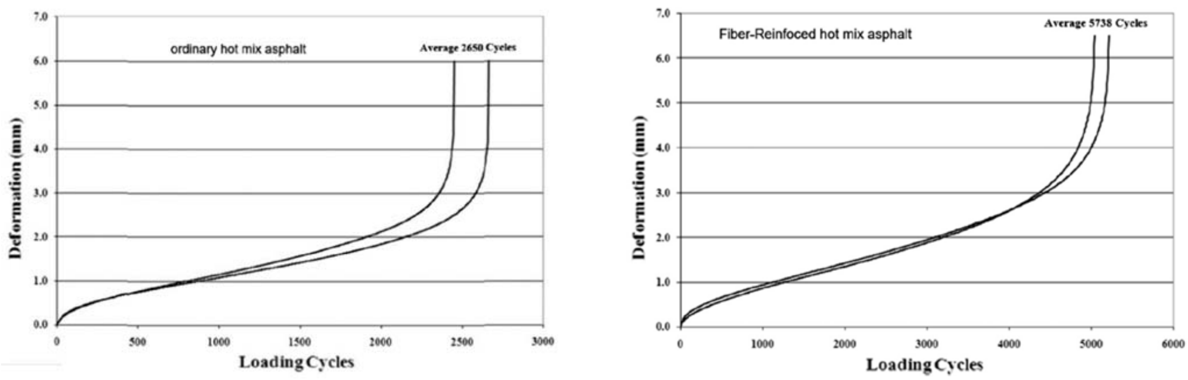

Figure 12. Comparison of fatigue life in conventional and reinforced hot mix asphalt. (Tanazadeh et al., 2017)

In a study by Gibson et al. (2012, 2015), characteristics and properties of polyester fiber-reinforced asphalt mixtures were investigated. The results indicated that the fatigue cracking of the fiber reinforced section was considerably less than it was in the polymer modified and unmodified sections. Chen et al. (2009) investigated the effect of different types of fibers on the volumetric and mechanical properties of asphalt mixtures (Chen, et al., 2009). Four fibers were used: polyester, polyacrylonitrile, lignin, and asbestos fibers. Test results showed that the addition of fibers to the mixtures decreased the bulk specific gravity, whereas the addition of fibers increased the optimum asphalt content, air void, voids in mineral aggregate (%), and Marshall stability. Optimum asphalt content, Marshall stability, and dynamic stability increased initially and then decreased with an increase in fiber content.

Kaloush et al. (2010) undertook a study evaluating the material properties of conventional and fiber-reinforced asphalt mixtures using advanced material characterization tests, which included triaxial shear strength, dynamic modulus, repeated load permanent deformation, fatigue, crack propagation, and indirect tensile strength tests. Synthetic fibers (polypropylene and aramid fibers) were reported to improve performance in several ways against anticipated major pavement distresses, including permanent deformation, fatigue cracking, and thermal cracking, compared with a conventional mixture. Kaloush et al. (2009) reported that the fiber-reinforced asphalt showed slower crack propagation according to the indirect tensile test (IDT) and C* line integral test. Also, the results of the dynamic modulus test indicated that the polymer modification had more of an effect than fiber modification. Cyclic fatigue test results showed that fiber-modified mixes and styrene–butadiene–styrene (SBS) performed better than the control mix in both sets of materials, with fiber mixes performing better at higher fatigue stains. However, the SBS-modified mixtures showed better response under small fatigue strains. In a different study by Park et al. (2015) in which steel fibers were included in asphalt mixture, substantially better performance at low temperature was observed. Figure 13 illustrates the evolution of an IDT test on steel fiber reinforced asphalt mixture.

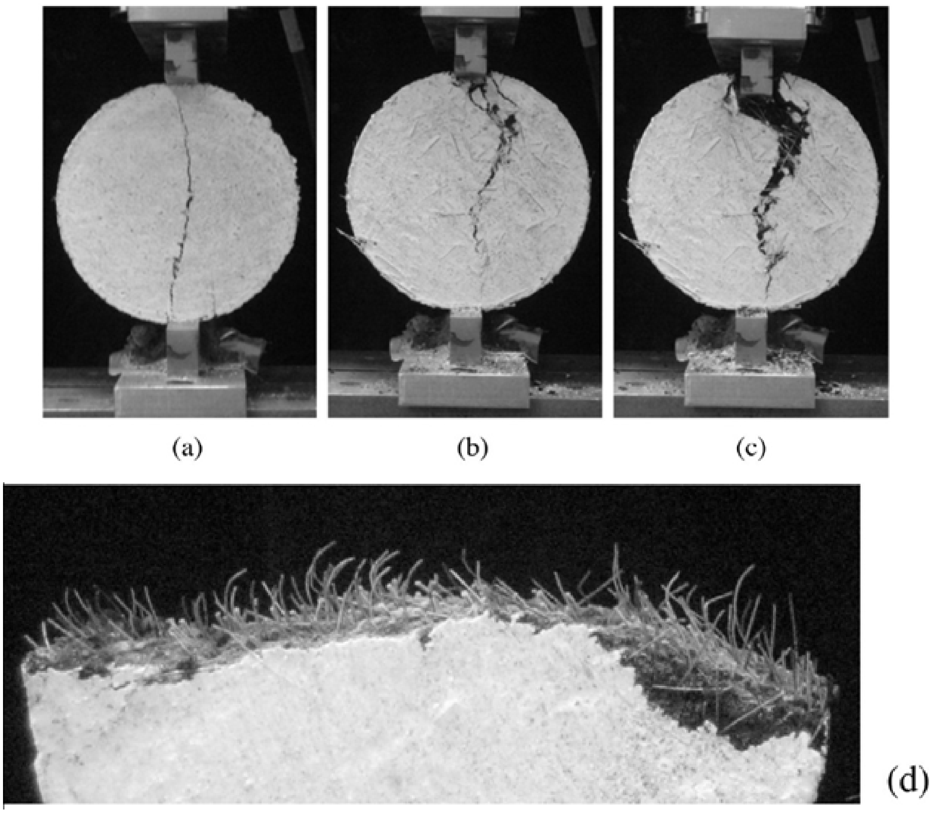

Figure 13. Fracture mode of non-reinforced specimen and highly-reinforced specimen: (a) non-reinforced specimen right after the peak stress, a crack initiated and propagated through the specimen instantaneously; (b) 1.5% fiber, right after the peak stress, a crack developed but does not propagate to the other end yet; (c) 1.5% fiber, after the test, the top of the specimen crushed but the specimen does not completely split down into two pieces; (d) 1.5% fiber, fractured surface showing the fibers pulled-out cleanly. (Park et al., 2015)

Fiber-reinforced mixtures had higher recoverable deformation than the control mix. This indicates that fiber-reinforced mixtures have better potential to resist permanent deformation than the control mix. In other words, the addition of fibers had a greater influence on deformation values and improved resistance to fatigue cracking (Takaikaew, et al., 2018). In another research Tanzadeh et al. (2017) investigated asphalt mixtures reinforced with hybrid fibers consisting of Polypropylene and Polyethylene with aramid fibers. Increased resilient modulus and rutting resistance together with reduced permanent deformation and cracking at low temperatures were observed (Tanzadeh, et al., 2017).

Muftah et al. (2017) evaluated the use of aramid and polyolefin fibers and wax-treated aramid fiber for Fiber-Reinforced Asphalt, observing their positive effect on the performance of the asphalt mixtures. Fibers behaved like any other fillers inside the mix, which was an observation made in all of the laboratory testings that did not result in higher deformations. However, when a crack started to propagate, the fibers began to absorb part of the strain energy and helped reduce crack propagation.

4 Economic and environmental benefits

Based on the above-summarized literature, it can be noticed that fiber-reinforced mixtures had better fatigue and rutting resistance performance over unmodified asphalt mixtures. However, in order to extend pavement life (and rehabilitation intervals), maintenance action and proper pavement treatment applications have to be conducted (Sousa & Way, 2009). In most cases, significant differences in maintenance costs are visible after about five to six years; after about eight years double differences in maintenance costs can be recognized (Carlson & Zhu, 1999; McNally, 2011). Some of the cited studies demonstrate the benefits of using fibers, including, but not limited to:

- Reduced draindown in open- and gap-graded mixtures;
- Increased resistance to rutting and cracking;
- Improved durability; and
- Increased toughness and stability.

Life cycle cost analysis has been used to assess the costs of rehabilitation activities using hot mix asphalt with and without polypropylene and aramid fibers. The addition of fibers at 0.45 kg/ton can result in a saving in the net present worth dollar value ranges from $14,000 to $50,000 per mile/lane or a reduction in the equivalent annual cost ranges from 750 to 2000 mile/lane/ year (Klinsky, et al., 2018). However, documented benefit–cost ratios or cost-effectiveness studies are lacking in the literature.

Together with material and pavement performance and economic feasibility, environmental aspects need to be evaluated when using synthetic materials in the construction industry. Accordingly, environmental and economic benefits are the most important impact factors in the pavement industry when using recycled asphalt pavement materials in construction (Copeland, 2011).

Over the past two decades, many transportation agencies, asphalt producers and pavement construction companies have taken major initiatives to implement green paving technologies (NAPA, 2011). Saving energy during asphalt production and increased use of reclaimed materials are important elements of these initiatives. Many studies have been conducted and are being conducted in the United States and abroad to find innovative ways to design and construct environmentally friendly and durable pavements. (Ghabchi, 2014)

In 2009 and 2010, the Federal Highway Administration (FHWA) contracted with NAPA and conducted a survey on the implementation of recycling and energy efficiency techniques in asphalt pavements. The survey introduced reclaimed asphalt pavement, reclaimed asphalt shingles, and warm mix asphalt as three key areas of implementation by the asphalt paving industry (NAPA, 2011).

Effect of the fibers in reclaimed asphalt pavement (RAP)

Using RAP material has well-recognized financial and environmental benefits (Al-Qadi, and Elseifi, 2007). The combination of RAP modified binders and Lignin fiber was investigated in a recent research work by Xu et al. (2014) to produce fiber-reinforced RAP-modified asphalt. Based on experimental tests it was observed similar cracking resistance at low temperatures with respect to conventional mixtures, when incorporating lignin fiber into warm recycled asphalt mixture, same cracking. Moreover, water stability and ductility of the RAP was improved with fiber.

In a different project (González et al., 2018), it was found that the addition of steel fiber to recycled asphalt mixtures increased the indirect tensile stiffness modulus. Improved crack-healing was obtained with microwave heating and temperature characteristics for steel fiber-modified asphalt by 30% of RAP and metal fibers. Figure 14 illustrates the evolution of healing through CT-Scan images on fiber reinforced asphalt mixture. Fracture of fibers was not observed, indicating that the strength of the fibers can withstand three point strength test loads.

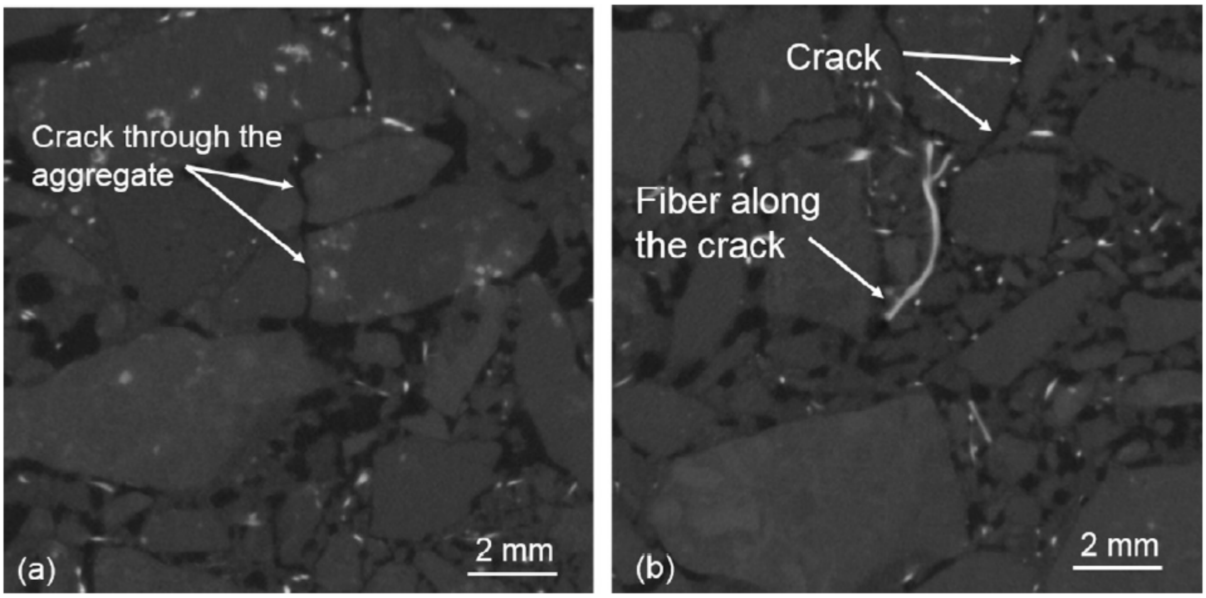

Figure 14. Top cross-section of the samples after seven healing cycles (a) cracking through the aggregate and (b) fiber orientation throughout the crack.

Chomicz-Kowalska et al. (2017) used of polymer-basalt fibers and RAP for fiber-reinforced asphalt. Their results illustrated that the polymer-basalt fibers have positive effect on the performance of the asphalt mixtures and also resistance binder to rutting.

The combination of RAP and glass fiber was investigated in a recent research work by Fakhri & Hosseini (2017) to produce warm mix asphalt. Experimental tests were conducted on matrix asphalt prepared with and without fibers in the dry and wet conditions. The experimental results indicate that fibers and RAP mixtures present better properties and higher resistance and moisture susceptibility at short aged and unaged conditions.

Other research on the use of the fibers for designing recycled mixtures was proposed in the recent past by Hoyos et al. (2011). In this study, the glass fibers with different dosages of Portland cement type I/II was used to assessing their suitability in combination with RAP as a structurally sound and environmentally safe material. The results confirmed the potential of cement-fiber-treated RAP material as an environmentally alternative to materials for base and subbase applications in pavements.

5 Fiber selection

Six fibers were selected for the further evaluation of their technical, environmental and economic performance. From this evaluation, two fibers were selected to carry on with laboratory testing on the next work package of the FIBRA project (WP3). Fibers selected were: polyacrylonitrile (PAN), aramid/polyolefin blend (Aram/Pol), polypropylene (PP), polyester (PET), nylon and steel fibers.

5.1 Multicriteria decision methodology

Introduction

Multicriteria decision making (MCDM) methods have been applied to solve several types of problems including energy source selection (Kumar et al. 2017), construcción problems (Jato-Espino et al. 2014), plastic recycling (Vinodh et al. 2014), computing services (Alam et al. 2018), among others. All these situations involve multiple alternatives and often conflicting criteria. In this chapter, a multicriteria decision making methodology is proposed to rank the most promising type of fibers that can be used in Hot Asphalt Mixtures (HMA).

5.1.1 Criteria selection

As it has been reflected in the literature review, fibers can resist cracking, increase mix strength and stability and strengthen the bonds with asphalt, therefore improving the mechanical and rheological performance of the asphalt mixture. However, this improvement is linked to the type and properties of the fiber. The selection of the evaluation criteria will be done considering the most analysed parameters according to the literature review presented in this document. Thus, the first step of the MCDM methodology proposed here consists in gathering all the quantitative data available in the literature review (Table 6). The main parameters that have been considered in the different research studies are rutting, fatigue life, toughness and indirect tensile strength. Rutting refers to the accumulation of the permanent deformation in the surface of the asphalt pavement typically shown by a wheel path printed on the surface. Fatigue life is considered one of the most relevant pavement failure mode and it is investigated by many researchers. It refers to the allowable number of repetitions that can be supported by the asphalt mixture given a level of strain or stress. Toughness is used to monitor the cracking development in the mixture. Additionally, toughness, also termed fracture energy, is a mechanical property that represents the ability of the mixture to resist the material fast fracture. Finally, the indirect tensile strength (ITS) defines the crack initiation and tensile strength of the mixture. It is worth mentioning that this parameter is one of the most common in the literature, probably because its simplicity.

Table 6. Specifications and improvements of different fiber types in HMA

Fiber's characteristics									Maximum improvement										
citation	Fibers	Length (mm)	Diameter (mm)	Density (g/cm^3)	Fiber content by weight of mixture	Tensile Strength (Mpa)	Elastic modulus (Mpa)	Softening point (°C)	Rutting	MS[b]	MF[c]	Toughness	Moisture susceptibility	Fatigue life	ITS[d]	FE[e]	Dynamic stability	Complex modulus E*	Resilient modulus
[113]	Macro glass	36	0.54	2.68	0.40%	1700	72000	860	47%	1%	23%	24%							
	Micro glass	25	0.21	2.68	0.40%			860	25%										
[85]	Aramid	19		1.45	0.05%	3000	83000	> 450				32%	20%	20%	21%			30%	15%
[148]	Polyester	6	0.02		0.30%	531			19.57%			43.52%		57.66%		46.15%			
	Polyacrilonitrile	4.00 - 6.00	N/A[a]		0.30%	> 910			32.56%			61.11%		66.78%		26.92%			
	lignin	1.1	0.045		0.30%	N/A[a]			8.43%			12.03%		40.88%		0%			
	Asbestos	5.5	N/A[a]		0.30%	30 - 40			11.40%			28.71%		22.52%		34.61%			
[149]	Hooked steel	30	0.4		5%	1345	210000					727%			63%	286%			
	Twisted steel	30	0.3		5%	1345	210000					896%			56%	370%			
[74]	Coconut			1.18	0.30%	118	2800												8.79%
[134]	Polypropylene	6	0.04	0.91	1.0%f	500	3500	160	27.50%	11.50% - 0%	11.43%				2.35%				
	Polyester	6	0.041	1.4	1.0%f	1147	11600	256		15.30%	14.28%						62.70%		
	Nylon	12	0.023	1.14	1.0%f	800	3500 - 7000	220		8.10%	2.53%	158%					51.00%		
	Carbon	12	0.007	1.37	1.0%f	4900	230000	over 1000		0.88%		12.10%							
[99]	Polyester	6		1.4	0.35%										15%				
	Polyester	13		1.4	0.50%							117%							
[28]	Waste nylon wire	20	0.2	1.11	1%	357		220		23%			9.02%		14.89%				
[127]	Basalt		0.01 - 0.019	2.67	0.30%		84000	1350	33.30%										
[48]	Carbon	5	0.01		2%[f]	1680	752000		2.56%	5.47%	14.65%								2.86%
[101]	Polyacrylonitrile	6	0.0013	1.18	2%		> 910	240	45.96%										
[150]	waste polyester	13			0.50%	680		265			80%			31%					
[12]	Waste cellulose	0.5 - 2.00		0.52 - 0.56	0.50%										22%				
[80]	Nylon		12		1.00%							85%							
[151]	Polyolefin +	19		0.91	0.05%	483		130		17%					11%				31%
	aramid	19		1.45		2750		450											
[139]	Aramid	19	0.012		0.07%	2700		426	139%										
[121]	Polypropylene +	19		0.91	-	483		157							25 - 50%	50 -75%		20 -50%[g]	
	Aramid	19		1.45	-	3000		>450											

[a] Not available
[b] Marshall Stability
[c] Marshall flow
[d] Indirect Tensile Strength
[e] Fracture Energy
[f] Dosage made by volume
[g] Depending on the temperature of the test

5.1.2 Criteria evaluation – Analytics Hierarchy Process

Multicriteria decision making methods can be divided into two categories, multi-attribute decision making (MADM) and multi-objective decision making (MODM). MADM techniques, unlike MODM, heavily involves human participation and judgements. In this study, and Analytics Hierarchy Process (AHP), the most widely MADM techniques applied nowadays, was selected. The advantage to incorporate this technique is that reduces personal biases and sllows for comparing dissimilar alternatives (kubler et al. 2016). AHP method is used to solve the complex decision problem of determining the relative importance of a set of parameters previously stablished. In addition, the AHP technique was combined with fuzzy sets to take into account the uncertainty associated with the process and deal with the unbalnce scale of judgement. Details of this methodology can be found in Liao et al. (2011), Lima Junior et al. (2014), Li (2010), and Aryafar et al. (2013).

To give weights to the different criteria, the judgement of different experts was requested. Thus, a series of questionnaires were elaborated and sent to worldwide experts in the topic. These questionnaires were completed by 25 experts from different sectors and perspectives: academic, industry and public authorities. In the preparaed surveys, a numerical from 1 to 9 was created in which each odd number indicates linguistic terms such as equal, moderate, strong, very strong and extreme, and the even numbers indicate intermediate scales between two adjacent judgements. The experts had to indciate the importance of each parameter against the other and select the most appropriate according to their professional experience. An example of this survey is shown in Figure 15.

Analytic Hierarchy Process expert survey

In order to prioritize the criteria weightage related to **mechanical performance** of fiber reinforced asphalt mixtures this survey is designed to collect and analyze judgements from experts in asphalt mixtures.

Example

Indicate the importance of each parameter against the other

Select the most appropriate for you

1 = Equal 3 = moderate 5 = strong 7 = very strong 9 = Extreme

2,4,6,8 Intermediate values between the two adjacent judgements

Parameter																		Parameter
A	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	B

means that parameter A is very strong over parameter B

Survey

Indicate the importance of each parameter against the other

Select the most appropiate for you

1 = Equal 3 = moderate 5 = strong 7 = very strong 9 = Extreme

2,4,6,8 Intermediate values between the two adjacent judgements

Parameter																		Parameter
Rutting resistance	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Fatigue Life
Rutting resistance	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Toughness
Rutting resistance	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Indirect tensile Strength
Fatigue Life	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Toughness
Fatigue Life	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Indirect tensile Strength
Toughness	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	Indirect tensile Strength

Figure 15. Example of the Questionnaire.

According to the results obtained from the questionnaire, the most voted criteria were toughness and fatigue life with weights of 30.6 and 25.8% respectively (Figure 16) and rutting and indirect tensile strength had the lowest scores with 22.9 and 17.4 respectively. On the other hand, the highest improvements achieved by fibers in HMA were related with the toughness of fracture energy. In this sense, Park et al. (2015) reported improvements up to 370% using steel fibers in asphalt concrete.

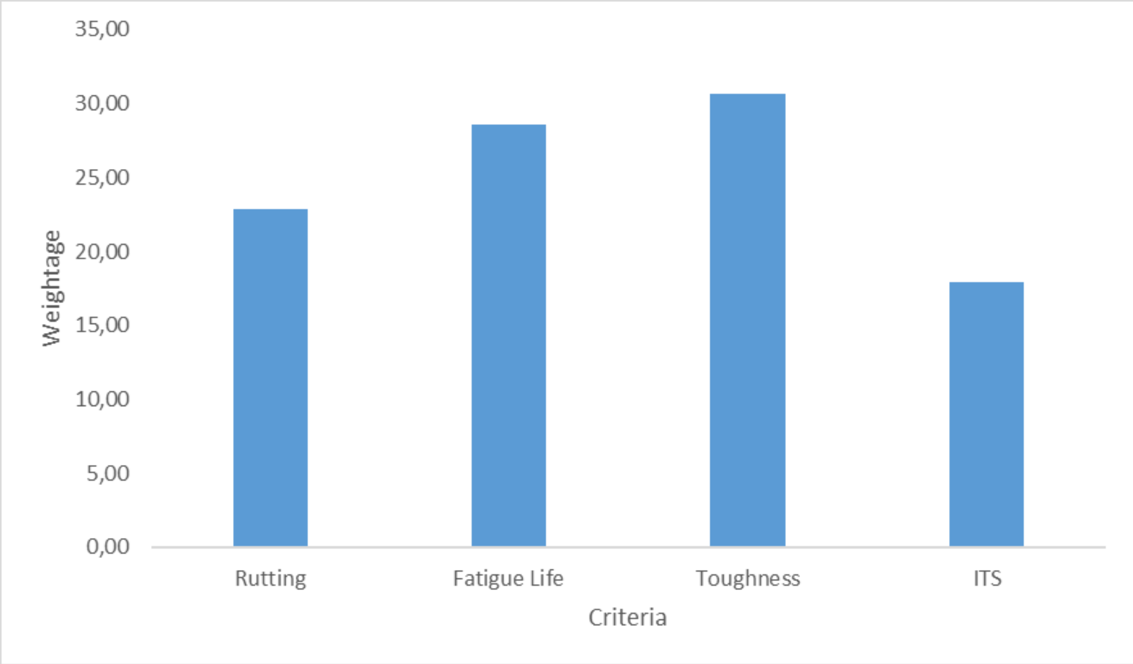

Figure 16. Priority weights for criteria.

5.1.3 Weighted Aggregated Sum – Product Assessment (WASPAS)

Once the weights were defined according to the priority of experts, the multicriteria decision methodology was applied. Nylon was not included in the study due to lack of enough data to carry out the analysis.

Several multicriteria methodologies have been developed in the last decades. In this study, the FAHP method was integrated with the Weighted Aggregated Sum Product Model (WASPAS). This method that belongs to the newer generation of MCDM methods comprises two methodologies, the Weighted Sum Model (WSM) and the Weighted Product Model (WPM). In addition, this model is based on the additive utility assumption which states the total value of an alternative (Alam et al., 2018). The final selection of this methodology was based on its low computational effort and the high accuracy of its results. Details of the computational algorithm can be found in Mardani et al. (2017) and Deveci et al. (2018).

The resulted ranking of fiber alternatives obtained from the WASPAS evaluation is shown in Figure 17. In this list, polyacrylonitrile and aramid/polyolefin fibers (a blend of polyolefin and aramid fibers) are at the top with a final score of 0.36 and 0.33 respectively and steel fiber at the botton with a score of 0.2. It is important to mention that this analysis considers only the improvement of fibers when incorporated into asphalt dense mixture due to the lack of information related to the use of fiber reinforcement in open grade asphalt mixes. Similarly, it should be noted that other factors such as moisture sensitivity, ravelling, freezing-thaw cycles, among other, were not considered within the selection criteria, due to the lack of quantitative data.

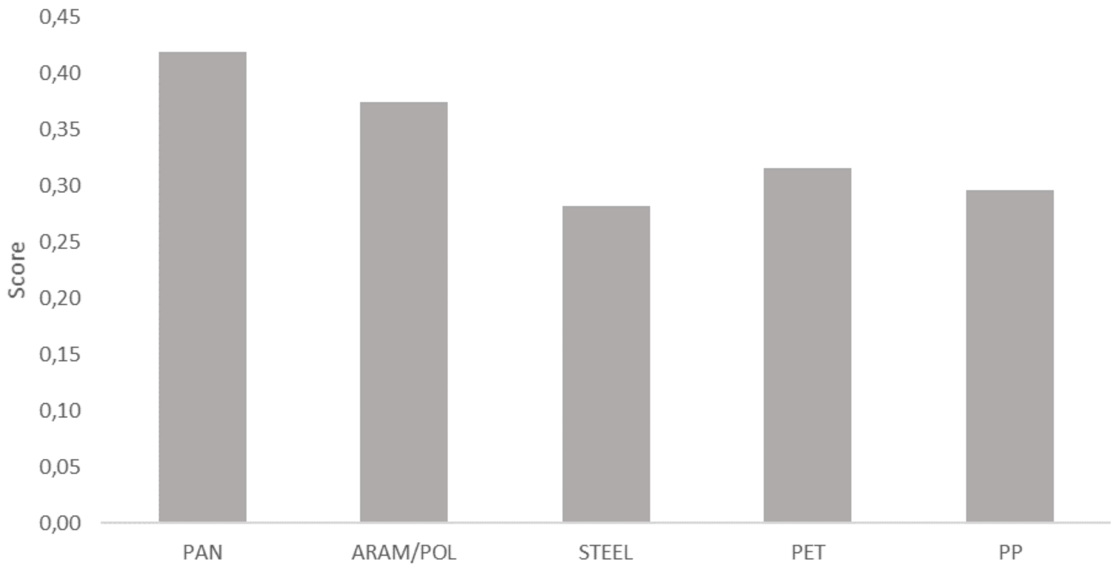

Figure 17. WAPAS service ranking.

5.2 Environmental impact

As the effect of the different fibers in the durability of the asphalt mixes is still not quantitatively stablished in the literature, the evaluation of the fiber alternatives in terms of environmental impact will be carried out by comparing the environmental impact of the production process of each fiber and the mass of fiber that should be added to the HMA.

In order to do so, the life cycle inventory (LCI) of the fibers has been searched through different databases and literature research. Fortunately, the LCI of all the fibers with the exception of the aramid/polyolefin fiber was found. In the case of the aramid/polyolefin, the only data available was the carbon footprint of the production of aramid fibers.

It should be noted that the transportation distances of the fibers to the asphalt plant were not included in the study because the lack of data. In Table 7, the data sources used for each fiber is presented.

Table 7. Life cycle inventory data sources.

FIBER	SOURCE
PAN	Gabi 2017 database
PP	Gabi 2017 database
STEEL	Gabi 2017 database
PET	Gabi 2017 database
ARAMID	Only GWP from Teijin Aramid (provider)
NYLON	Gabi 2017 database
HMA	Gabi 2017 database

In Table 8, the percentage of each fiber according to the literature that should be added to the HMA for reinforcement purposes is shown. For the calculations, when a range was found in the literature, the average was used. With the information presented in this table, the mass content of each fiber in 1 ton of HMA was calculated.

Table 8. Percentage of different type of fibers in HMA.

	(%w/w in HMA)min	(%w/w in HMA)max	(% w/w in HMA)Average
PAN	0.05	0.15	0.1
ARAM/POL	0.05	-	0.05
PET	0.3	-	0.3
NYLON	0.25	0.5	0.375
STEEL	0.75	-	0.75
PP	0.3	1	0.65

A cradle to gate Life Cycle Assessment (LCA) of 1 ton of HMA with and without the incorporation of reinforcement fibers was carried out. This assessment was performed for three different assessment methods: ReCiPe 1.08, ReCiPe 2016 (end point) and CML 2016. The aim of selecting two different methodologies was the evaluation of the sensitivity to the selected model.

The normalized results of the LCA using the ReCiPe 1.08, ReCiPe 2016 and CML 2016 are shown in table 9, 10 and 11, respectively.

Table 9. Cradle to gate Life Cycle Assessment of different FRAM. ReCiPe 1.08 (H) Mid-point assessment method. Normalization (H, Europe, excl. Biogenic carbon – person equivalents)

	HMA (1 ton)	FRAM (PAN) (1 ton)	FRAM (NYLON) (1 ton)	FRAM (PP) (1 ton)	FRAM (STEEL) (1 ton)	FRAM (PET) (1 ton)
Agricultural land occupation	0,000327	3,50E-04	4,95E-04	4,05E-04	3,62E-04	4,68E-04
Climate change	0,00566	6,13E-03	9,22E-03	7,00E-03	7,15E-03	6,91E-03
Fossil depletion	0,0512	5,29E-02	6,10E-02	5,88E-02	5,40E-02	5,55E-02
Freshwater ecotoxicity	0,00261	2,77E-03	3,69E-03	3,14E-03	2,65E-03	2,90E-03
Freshwater eutrophication	0,000198	2,25E-04	3,87E-04	2,57E-04	2,24E-04	3,17E-04
Human toxicity	0,0066	6,86E-03	8,52E-03	7,60E-03	7,45E-03	1,23E-02
Ionising radiation	0,000475	5,45E-04	9,92E-04	7,11E-04	4,89E-04	5,69E-04
Marine ecotoxicity	0,00661	6,76E-03	7,62E-03	7,50E-03	6,89E-03	7,76E-03
Marine eutrophication	0,000812	9,30E-04	1,31E-03	9,49E-04	9,41E-04	9,20E-04
Metal depletion	0,00024	2,56E-04	3,64E-04	2,97E-04	1,65E-02	3,20E-04
Natural land transformation	0,00095	1,10E-03	2,07E-03	1,43E-03	-4,78E-03	1,89E-03
Ozone depletion	1,47E-08	1,66E-08	2,95E-08	2,16E-08	-3,27E-06	1,59E-08
Particulate matter formation	0,00369	3,96E-03	5,16E-03	4,35E-03	4,84E-03	4,05E-03
Photochemical oxidant formation	0,0031	3,40E-03	4,74E-03	3,77E-03	3,80E-03	3,60E-03
Terrestrial acidification	0,00462	4,97E-03	6,52E-03	5,46E-03	5,95E-03	5,08E-03
Terrestrial ecotoxicity	4,65E-05	5,11E-05	8,08E-05	6,14E-05	7,00E-05	1,74E-04
Urban land occupation	0,000206	2,06E-04	2,07E-04	2,07E-04	2,15E-04	2,07E-04
TOTAL ENVIRON. IMPACT (SUM)		**9,14E-02**	**1,12E-01**	**1,02E-01**	**1,07E-01**	**1,03E-01**

Table 10. Cradle to gate Life Cycle Assessment of different FRAM. ReCiPe 2016 (H) End-point assessment method.

	HMA (1 ton)	FRAM (PAN) (1 ton)	FRAM (NYLON) (1 ton)	FRAM (PP) (1 ton)	FRAM (STEEL) (1 ton)	FRAM (PET) (1 ton)
Human health [DALY]	1,0E-04	1,1E-04	1,6E-04	1,3E-04	1,3E-04	1,2E-04
Ecosystems [species.yr]	3,9E-06	4,4E-06	7,6E-06	5,8E-06	4,5E-06	5,7E-06
Resources [$]	3,7E+01	3,8E+01	4,2E+01	4,1E+01	3,7E+01	3,9E+01

Table 11. Cradle to gate Life Cycle Assessment of different FRAM. CML2001 (2016) assessment method. Normalization (EU 25 region equivalents.

	HMA (1 ton)	FRAM (PAN) (1 ton)	FRAM (NYLON) (1 ton)	FRAM (PP) (1 ton)	FRAM (STEEL) (1 ton)	FRAM (PET) (1 ton)
Abiotic Depletion (ADP el.)	6,1E-14	7,0E-14	1,3E-13	9,6E-14	1,1E-13	9,1E-14
Abiotic Depletion (ADP fossil)	9,6E-11	9,9E-11	1,1E-10	1,1E-10	1,0E-10	1,0E-10
Acidification Potential	1,2E-11	1,3E-11	1,6E-11	1,4E-11	1,5E-11	1,3E-11
Eutrophication Potential	1,3E-12	1,4E-12	2,0E-12	1,5E-12	1,5E-12	1,5E-12
Freshwater Aquatic Ecotoxicity Pot.	5,3E-12	5,4E-12	6,1E-12	6,1E-12	6,0E-12	5,6E-12
Global Warming Potential	1,2E-11	1,3E-11	2,0E-11	1,5E-11	1,6E-11	1,5E-11
Human Toxicity Potential	1,3E-11	1,3E-11	1,5E-11	1,4E-11	3,0E-10	1,4E-11
Marine Aquatic Ecotoxicity Pot.	8,2E-11	8,6E-11	1,1E-10	9,9E-11	1,1E-10	9,9E-11
Ozone Layer Depletion Potential	3,2E-17	3,6E-17	6,4E-17	4,7E-17	-7,0E-15	3,4E-17
Photochem. Ozone Creation Potential	5,9E-12	6,7E-12	1,1E-11	8,9E-12	9,5E-12	8,0E-12
Terrestric Ecotoxicity Potential	4,4E-13	4,5E-13	5,4E-13	5,2E-13	6,2E-13	3,0E-12
TOTAL ENVIRON. IMPACT (SUM)	**2,3E-10**	**2,4E-10**	**2,9E-10**	**2,7E-10**	**5,6E-10**	**2,6E-10**

To reduce the number of category impacts provided by the ReCiPe 1.08 and CML2016 methods, those impacts that contribute to the total sum with less than 2% where discarded and not considered for the rest of the study (highlighted in green in table 9 And 11).

From the results in table 9, 10 and 11, and assuming 10 years of service life for a conventional HMA (wearing course), the estimation of the minimum service life that each FRAM layer should have in order to equal the impact of the HMA is carried out (table 12 to 14). At the bottom of each table and later in Figure 18 the minimum service life for each FRAM is shown by selecting the highest service life considering all the category impacts.

Table 12. Minimum service life of different FRAM to equal the environmental impact of a conventional HMA. ReCiPe 1.08 (H) Mid-point assessment method. Normalization (H, Europe, excl. Biogenic carbon – person equivalents)

	HMA (1 ton)	FRAM (PAN) (1 ton)	FRAM (NYLON) (1 ton)	FRAM (PP) (1 ton)	FRAM (STEEL) (1 ton)	FRAM (PET) (1 ton)
Climate change	10	10.8	16.3	12.4	12.6	12.2
Fossil depletion	10	10.3	11.9	11.5	10.6	10.8
Freshwater ecotoxicity	10	10.6	14.1	12.0	10.2	11.1
Human toxicity	10	10.4	12.9	11.5	11.3	18.6
Marine ecotoxicity	10	10.2	11.5	11.3	10.4	11.7
Metal depletion	10	10.7	15.2	12.4	689.2	13.3
Particulate matter formation	10	10.7	14.0	11.8	13.1	11.0
Photochemical oxidant formation	10	11.0	15.3	12.2	12.2	11.6
Terrestrial acidification	10	10.8	14.1	11.8	12.9	11.0
Min service life	**10.0**	**11.0**	**16.3**	**12.4**	**689.2**	**18.6**

Table 13. Minimum service life of different FRAM to equal the environmental impact of a conventional HMA. ReCiPe 2016 assessment method.

	HMA (1 ton)	FRAM (PAN) (1 ton)	FRAM (NYLON) (1 ton)	FRAM (PP) (1 ton)	FRAM (STEEL) (1 ton)	FRAM (PET) (1 ton)
Human health	10	10,8	16,0	12,7	12,6	12,3
Ecosystems	10	11,3	19,6	14,9	11,6	14,6
Resources	10	10,2	11,5	11,2	10,1	10,6
Min service life	10	10.8	19.6	14.9	12.6	14.6

Table 14. Minimum service life of different FRAM to equal the environmental impact of a conventional HMA. CML2001 (2016) assessment method. Normalization (EU 25 region equivalents.

	HMA (1 ton)	FRAM (PAN) (1 ton)	FRAM (NYLON) (1 ton)	FRAM (PP) (1 ton)	FRAM (STEEL) (1 ton)	FRAM (PET) (1 ton)
Abiotic Depletion (ADP fossil)	10	10.3	11.9	11.5	10.6	10.8
Acidification Potential	10	10.6	13.5	11.6	12.6	10.9
Freshwater Aquatic Ecotoxicity Pot.	10	10.2	11.4	11.4	11.3	10.6
Global Warming Potential	10	10.8	16.2	12.4	12.6	12.2
Human Toxicity Potential (HTP inf.)	10	10.2	11.8	11.1	231.9	10.8
Marine Aquatic Ecotoxicity Pot.	10	10.5	13.4	12.0	13.5	12.0
Photochem. Ozone Creation Potential	10	11.4	18.8	15.1	16.1	13.5
Min service life	**10**	**11.4**	**18.8**	**15.1**	**231.9**	**13.5**

As the only available data for aramid fibers is the carbon footprint of aramid fibers, the same comparative study was carried out but only considering the emissions of CO_{2eq} during the production of the fibers and the HMA.In figure Figure 18, the results obtained by each fiber with each method is presented.

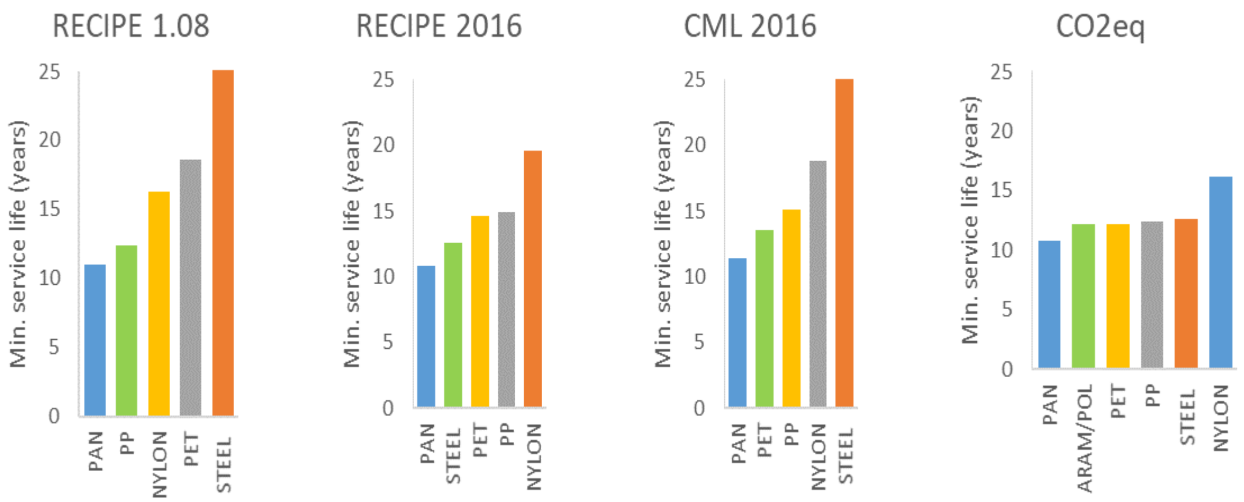

Figure 18. Minimum service life extension for each FRAM to equal the impact of a conventional HMA.

According to the results, the assessment method affects significantly the ranking of fibers in terms of environmental impact. However, some trends are observed. PAN fibers are the fibers with the lowest environmental impact in all the methods used in this study. On the other hand, Nylon and steel fibers are in most of the cases at the bottom of the ranking. Finally, PP and PET have similar results and their position are swapped depending on the selected method.

5.3 Cost-benefit analysis

The cost benefit analysis has been carried out by comparing the cost per kilometer of each FRAM layer (Table 15). In order to calculate the cost increase due to the fiber addition, the cost of producing and laying a conventional HMA has been assumed in 65 €/ton. Fiber costs are estimates found on the internet or on literature with the exception of PAN that was given by the provider. Finally, the service life extension or the thickness reduction that is needed to equal the cost per kilometer of a HMA layer was calculated (Table 15).

Table 15. Economic impact of adding different type of fibers in 1 kilometer HMA layer.

	FIBER COST (€/Kg)	FIBER CONTEN (kg / ton HMA)	COST (€/ton FRAM)	COST (€/km layer)	Life extension NO savings	Thickness reduction NO savings
HMA	-	0	65	54600	-	-
FRAM (PAN)	8	1	73	61320	1.2	0.5
FRAM (Aramid/Polyolefin)	23.3	0.5	76.7	64386	1.8	0.8
FRAM (PET)	2	3	71	59640	0.9	0.4
FRAM (NYLON)	4	3.75	80	67200	2.3	0.9
FRAM (STEEL)	1.5	7.5	76	64050	1.7	0.7
FRAM (PP)	2	6.5	78	65520	2.0	0.8

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Finally, the estimated minimum percentage of service life extension that should be achieved by the FRAM layer to obtain cost benefits of 10, 20 or 30% is shown in Table 16.

Table 16. Minimum service life extension to achieve 10, 20 or 30% cost savings.

	% Service life extension 10% savings	% Service life extension 20% savings	% Service life extension 30% savings
FRAM (PAN)	25	40	60
FRAM (Aramid/Polyolefin)	31	47	68
FRAM (PET)	21	37	56
FRAM (NYLON)	37	54	76
FRAM (STEEL)	30	47	68
FRAM (PP)	33	50	71

This preliminar cost benefit analysis gives an idea of the minimum effectivity that should be provided by each fiber. However, these results should be only considered when the effect of the fibers on the durability of the asphalt mixtures is known.

5.4 State of development of the technology

To analyse the state of development of the technology, three categories have been considered, laboratory testing, implementation of pilot sections and commercially available for asphalt mixes reinforcement applications. Therefore, the pre-selected fibers have been evaluated according to these three categories (Table 17).

Table 17. State of development of the technology

	State of development of the technology		
	Laboratory	Pilot sections	Commercial for road application
FRAM (PAN)	Yes	Yes	Yes
FRAM (Aramid/Polyolefin)	Yes	Yes	Yes
FRAM (PET)	Yes	No*	Yes
FRAM (NYLON)	Yes	No*	No*
FRAM (STEEL)	Yes	No*	No*
FRAM (PP)	Yes	No*	No*

*No information has been found

5.5 Fiber selection

With the results and conclusions obtained in this document, the members of the FIBRA consortium decided the selection of the fiber by votation. Finally, two fibers were selected for its further analysis in WP3: Polyacrylonitrile and the blend of aramid/polyolefin.

6 Conclusions

In the present literature review the state of the art in the use of fibers in asphalt materials was reported. Fiber types, their properties, how they are tested, used in the mix design and mixing process, the types of applications in which fibers have been used in asphalt materials, and the laboratory and field performance of fiber mixes were addressed. The following conclusions can be drawn:

- Overall, fibers can improve the mechanical and rheological response of asphalt mixture in terms of rutting resistance, freeze thaw resistance, moisture susceptibility, strength, dynamic modulus, fatigue, thermal and reflective cracking;
- The improvement in mechanical and rheological properties appears to be related to fiber type, lenght and content.
- A few studies of the laboratory and field performance of fiber-reinforced mixtures, however, have yielded mixed results showing that in some cases the fibers have not resulted in significant performance improvements.
- Economic, environmental and ecological evaluations of fibers modified asphalt need to be also considered before a large-scale application.

On the other hand, a multicriteria decision making methodology was applied with the preselected list of fibers in order to rank them in terms of their mechanical performance. In addition, a preliminary environmental and economic study has been carried out to make it easier the selection of the most promising fibers for the reinforcement of asphalt mixtures. Finally, the current state of the technology was evaluated according to the level of development of the fiber. The following conclusions can be drawn:

- Based on the multicriteria decision making method, the experts opinions and the mechanical performance of the FRAM found in the literature, polyacrylonitrile, aramid/polyolefin blends and polyester seem to be the fibers with the highes impact on the mechanical performance of the asphalt mixtures.
- The life cycle assessment methodology impacts significantly in the life cyle results obtained for each fiber. However, polyacrylonitrile fibers turn out to be the fibers with the less environmental impact in all the studied methods. Also, the production of nylon and steel fibers caused the higher environmental impacts according to most of the methods. Polypropylene and polyester fibers had similar and variable results depending on the selected method.
- According to the cost-benefit assessment, in order to get at least 20% savings, a minimum increase in the service life between 37% and 54% is needed depending on the type of fiber.
- Based on the results obtained in the multicriteria decision method, the life cycle assessment and the cost-benefit, polyacrylonitrile and a blend of aramid/polyolefin are considered the most promising fibers for future works.

References

A. García, J. Norambuena-Contreras, M. Bueno, and M. N. Partl, “Influence of steel wool fibers on the mechanical, termal, and healing properties of dense asphalt concrete,” Journal of Testing and Evaluation, vol. 42, no. 5, 2014.

AASHTO T 240. (2013). Standard method of test for effect of heat and air on a moving film of asphalt binder (rolling thin-film oven test). American Association of State Highway and Transportation Officials, Washington, DC.

AASHTO T 315. (2013). Standard method of test for determining the rheological properties of asphalt binder using a dynamic shear rheometer (DSR). American Association of State Highway and Transportation Officials, Washington, DC.

Abtahi, S. M., Sheikhzadeh, M., & Hejazi, S. M. (2010). Fiber-reinforced asphalt-concrete–a review. Construction and Building Materials, 24(6), 871-877. doi: 10.1016/j.conbuildmat.2009.11.009

Afonso, M. L., Dinis-Almeida, M., & Fael, C. S. (2017). Study of the porous asphalt performance with cellulosic fibers. Construction and Building Materials, 135, 104-111.

Airey, G. D. (2004). Fundamental binder and practical mixture evaluation of polymer modified bituminous materials. International Journal of Pavement Engineering, 5(3), 137-151. doi: 10.1080/10298430412331314146

Alam, K.A., Ahmed, R., Butt, F.S., Kim, S.G., Ko, K.M. (2018). An Uncertainty-aware Integrated Fuzzy AHP-WASPAS Model to Evaluate Public Cloud Computing Services, Procedia Comput. Sci. 130, 504–509. doi:10.1016/j.procs.2018.04.068.

Al-Qadi, I. L., Elseifi, M., & Carpenter, S. H. (2007). Reclaimed asphalt pavement—a literature review.

Alrajhi, A. (2012). Fiber Dosage Effects in Asphalt Binders and Hot Mix Asphalt Mixtures. Master thesis, Arizona State University, USA.

Andrés-Valeri, V. C., Rodriguez-Torres, J., Calzada-Perez, M. A., & Rodriguez-Hernandez, J. (2018). Exploratory study of porous asphalt mixtures with additions of reclaimed tetra pak material. Construction and Building Materials, 160, 233-239.

Anon, (2018). Available at: https://www.lafarge.ca/en/asphalt.

Anurag, K., Xiao, F., & Amirkhanian, S. N. (2009). Laboratory investigation of indirect tensile strength using roofing polyester waste fibers in hot mix asphalt. Construction and building materials, 23(5), 2035-2040. doi: 10.1016/j.conbuildmat.2008.08.018

Aryafar, A., Yousefi, S., Doulati Ardejani, F. (2013). The weight of interaction of mining activities: Groundwater in environmental impact assessment using fuzzy analytical hierarchy process (FAHP), Environ. Earth Sci. 68, 2313–2324. doi:10.1007/s12665-012-1910-x.

Asphalt Industry Alliance. (2015). Annual local authority road maintenance (ALARM) survey, HMPR Limited.

Asphalt Material Garers Top Honors in PN Contest. (1990). Plastic News, Sept. 17, 1990, 1.

ASTM D4694-09. (2009). Standard Test Method for Deflections with a Falling-Weight-Type Impulse Load Device. American Association of State Highway and Transportation Officials.

ASTM D4695-03. (2003). Standard Guide for General Pavement Deflection Measurements. American Association of State Highway and Transportation Officials.

ASTM D6931-07. (2007). Standard test method for indirect tensile (IDT) strength of bituminous mixtures. West Conshohocken, PA.

Badeli, S., Carter, A., Doré, G., & Saliani, S. (2018). Evaluation of the durability and the performance of an asphalt mix involving Aramid Pulp Fiber (APF): Complex modulus before and after freeze-thaw cycles, fatigue, and TSRST tests. Construction and Building Materials, 174, 60-71. doi: 10.1016/j.conbuildmat.2018.04.103

Badeli, S., Saliani, S. & Carter, A. (2017). Effect of Short Aramid Fibers on Asphalt Performance. Substance ÉTS.

Bansal, S., & Raichurkar, P. (2016). Review on the Manufacturing Processes of Polyester-PET and Nylon-6 Filament Yarn. International Journal on Textile Engineering and Processes, 2(3), 23-28.

Bonica, C., Toraldo, E., Andena, L., Marano, C. & Mariani, E. (2016). The effects of fibers on the performance of bituminous mastics for road pavements. Composites Part B: Engineering, 95, 76-81. doi: 10.1016/j.compositesb.2016.03.069

Brown, B. C., & Zearley, L. J. (1977). Investigation of Synthetic Fiber as a Replacement for Asbestos in Asphalt Curb Mixes. Iowa Department of Transportation, Ames, Iowa, December 1977.

Brown, S. F., Rowlett, R. D., & Boucher, J. L. (1990). Asphalt modification. In: Proceedings of the conference on the United States strategic highway research program: sharing the benefits. London: Thomas Telford (Pub.), 181-203.

Brule, B. (1997). Polymer-Modified Asphalt Cement Used in the Road Construction Industry: Basic Principles in Asphalt Science and Technology. Usmani, AM., Ed.

Buckley, John, D., & Edie, D. D. (Eds.) (1993). Carbon-Carbon Materials and Composites (Vol. 1254). William Andrew.

Burk, R. E., Whitcare, C. H. (1939). Asphalt from Petroleum Residue. US Patent 2179208, 1939.

Busching, H. W., Elliott, E. H., & Reyneveld, N. G. (1970). A State-of-the-Art Survey of Reinforced Asphalt Paving. Proceedings of the Association of Asphalt Paving Technologists, 39, 766-798.

Button, J. W. & Hunter, T. G. (1984). Synthetic Fibers in Asphalt Paving Mixtures. Texas Transportation Institute, Texas A&M University System College Station, Texas, November 1984.

Button, J. W., & Epps J. A. (1981). Mechanical Characterization of Fiber-Reinforced Bituminous Concrete. Texas Transportation Institute, College Station, Texas, Report 4061-1, 99, February 1981.

C. M. Gao, Microcosmic analysis and performance research of basalt fiber asphalt concrete [Ph.D. disseration], Jilin University, 2012 (Chinese).

Carlson, D. C. & Zhu, H. (1999). Asphalt–rubber, an anchor to crumb rubber markets. Third Joint UNCTAD/IRSG Workshop on Rubber and the Environment, International Rubber Forum, Veracruz, Mexico.

Cellulose Fiber - definition of cellulose fiber in the Free Online Enciclopedy. (2014). The Free Online Dictionary. Retrieved December 7, 2014.

Champion, L., Gerard, J. F., Planche, J. P., Martin, D. & Anderson, D. (2001). Low Temperature Fracture Properties of Polymer-Modified Asphalts Relationships with the Morphology. Journal of Material Science, 36(2), 451–460. doi: 10.1023/A:1004836814699

Chand, S. (2000). Review carbon fibers for composites. Journal of materials science, 35(6), 1303-1313. doi: 10.1023/A:1004780301489

Chen, B., Wu, K., & Yao, W. (2004). Conductivity of carbon fiber reinforced cement-based composites. Cement and Concrete Composites, 26(4), 291-297. doi: 10.1016/S0958-9465(02)00138-5

Chen, H., Li, N., Hu, C., & Zhang, Z. (2004). Mechanical performance of fibers-reinforced asphalt mixture. Journal of Chang'an University (Nature Science Edition). 24(2): 1–5.

Chen, H., Xu, Q., Chen, S. & Zhang, Z. (2009). Evaluation and design of fiber-reinforced asphalt mixtures. Materials & Design, 30(7), 2595-2603. doi: 10.1016/j.matdes.2008.09.030

Chen, J. S., & Lin, K. Y. (2005). Mechanism and behavior of bitumen strength reinforcement using fibers. Journal of materials science, 40(1), 87-95. doi: 10.1007/s10853-005-5691-4.

Chomicz-Kowalska, A., Iwański, M. M., & Mrugała, J. (2017). Basic Performance of Fiber Reinforced Asphalt Concrete with Reclaimed Asphalt Pavement Produced In Low Temperatures with Foamed Bitumen. In IOP Conference Series: Materials Science and Engineering (Vol. 245, No. 3, p. 032092). IOP Publishing.

Cleven, M. A. (2000). Investigation of the Properties of Carbon Fiber Modified Asphalt Mixtures. Master's thesis. Michigan Technological University, USA.

Copeland, A. (2011). Reclaimed asphalt pavement in asphalt mixtures: State of the practice (No. FHWA-HRT-11-021).

de S. Bueno, B., Da Silva, W. R., de Lima, D. C., & Minete, E. (2003). Engineering properties of fiber reinforced cold asphalt mixes. Journal of Environmental Engineering, 129(10), 952-955. doi: 10.1061/(ASCE)0733-9372(2003)129:10(952)

Decoene, Y. (1990). Contribution of cellulose fibers to the performance of porous asphalts. Transportation Research Record, 1265, 82-86.

Delorme, J. L., Roche, C. de la, & Wendling, L. (2007). LCPC Bituminous Mixtures Design Guide. Laboratoire central des ponts et chaussées, Paris, France.

Deveci, M., Canıtez, F., Gökaşar, I. (2018). WASPAS and TOPSIS based interval type-2 fuzzy MCDM method for a selection of a car sharing station, Sustain. Cities Soc. 41, 777–791. doi:10.1016/j.scs.2018.05.034.

Dhand, V., Mittal, G., Rhee, K. Y., Park, S. J., & Hui, D. (2015). A short review on basalt fiber reinforced polymer composites. Composites Part B: Engineering, 73, 166-180. doi: 10.1016/j.compositesb.2014.12.011

Echols, J. B. (1989). New mix method for fiber-reinforced asphalt. Public Works, 119(8): 72-3.

Fakhri, M., & Hosseini, S. A. (2017). Laboratory evaluation of rutting and moisture damage resistance of glass fiber modified warm mix asphalt incorporating high RAP proportion. Construction and Building Materials, 134, 626-640. doi: 10.1016/j.conbuildmat.2016.12.168

Fibermax. (2018). Introduction to Aramid fiber. [online] Available at: http://www.aramid.eu/ [Accessed 4 Sep. 2018].

Finemore. G. L. (1979). Synthetic Fiber Applications. Tri-Regional Quality Assurance Workshop, Federal Highway Administration. Harrisburg. Pennsylvania. 1979.

Fitzgerald, R. L. (2000). Novel applications of carbon fiber for hot mix asphalt reinforcement and carbon–carbon pre-forms. Master thesis, Department of Chemical Engineering, Michigan Technological University, USA.

Freeman, R. D., Burati, J. L., Amirkhanian, S. N., & Bridges, W. C. (1989). Polyester fibers in asphalt paving mixtures. In Association of Asphalt Paving Technologists Proc (Vol. 58).

Frketic, J., Dickens, T., & Ramakrishnan, S. (2017). Automated manufacturing and processing of fiber-reinforced polymer (FRP) composites: An additive review of contemporary and modern techniques for advanced materials manufacturing. Additive Manufacturing, 14, 69-86. doi: 10.1016/j.addma.2017.01.003

Fu, J., Liu, H. and Cheng, Y. (2007). Mechanical parameter measuring and contrastive analysis on pavement performance of glass fiber reinforced bituminous mixtures. Proceedings of the International Conference on Transportation Engineering, pp. 425–430, Chengdu, China.

Gao, Y., Guo, Q., Guo, Y., Wu, P., Meng, W., & Jia, T. (2017). Investigation on Reinforced Mechanism of Fiber Reinforced Asphalt Concrete Based on Micromechanical Modeling. Advances in Materials Science and Engineering, 2017.

Gibson, N., & Li, X. (2015). Characterizing cracking of asphalt mixtures with fiber reinforcement: use of cyclic fatigue and direct tension strength tests. Transportation Research Record: Journal of the Transportation Research Board, (2507), 57-66. doi: 10.3141/2507-07

Gibson, N., Qi, X., Shenoy, A., Al-Khateeb, G., Kutay, M.E., Andriescu, A., Stuart, K., Youtcheff, J., & Harman, T. (2012). Performance testing for Superpave and structural validation (No. FHWA-HRT-11--45).

Giustozzi, F., Crispino, M., Toraldo, E., & Mariani, E. (2015). Mix design of polymer-modified and fiber-reinforced warm-mix asphalts with high amount of reclaimed asphalt pavement: Achieving sustainable and high-performing pavements. Transportation Research Record: Journal of the Transportation Research Board, (2523), 3-10. doi: 10.3141/2523-01

Goel, A., Das, A. (2004). Emerging road materials and innovative. In: National conference on materials and their application in civil engineering, Hamipur, India.

González, A., Norambuena-Contreras, J., Storey, L., & Schlangen, E. (2018). Effect of RAP and fibers addition on asphalt mixtures with self-healing properties gained by microwave radiation heating. Construction and Building Materials, 159, 164-174.

H. F. Hassan and K. S. Al-Jabri, “Effect of organic fibers on open-graded friction course mixture properties,” International Journal of Pavement Engineering, vol. 6, no. 1, pp. 67–75, 2005.

H. Y. Katman,M. R. Ibrahim, M. R. Karim, S. Koting, and N. S. Mashaan, “Effect of rubberized bitumen blending methods on permanent deformation of SMA rubberized asphalt mixtures,” Advances inMaterials Science and Engineering, vol. 2016,Article ID 4395063, 14 pages, 2016.

Hansen, R., et.al. (1959). Effects of Asbestos Fibers in Asphaltic Concrete Paving Mixtures, Waterways Experiment Station. Miscellaneous Papers 4-344. Vicksburg, Mississippi, April 1959.

Hansen, R., McGennis, B., Prowell, B., & Stonex, A. (2000). Current and future uses of nonbituminous components of bituminous paving mixtures. Transportation Research Board, Washington, DC.

Hanson, I., Foo, K. Y., Brown, E. R., & Denson, R. (1994). Evaluation and Characterization of a Rubber-Modified Hot Mix Asphalt Pavement. Transportation Research Record 1436, Transportation Research Board, 1994, Washington, D. C., 98-107.

Harvey, J. & Monismith, C. L. (1993). Effects of Laboratory Asphalt Concrete Specimen Preparation Variables on Fatigue and Permanent Deformation Test Results Using Strategic Highway Research Program a-003 a Proposed Testing Equipment. Transportation Research Record 1417, 38-48.

Hassan, H., Al-Oraimi, S., Taha, R. (2005). Evaluation of open-graded fiction come mixtures with cellulose fibers and styrene butadiene rubber polymer. Jounral of Materials in Civil Engineering, 17(4): 415-22. doi: 10.1061/(ASCE)0899-1561(2005)17:4(416)

Heitzman, M. (1992). Design and Construction of Asphalt Paving Materials with Crumb Rubber Modifier. Transportation Research Record 1339, Transportation Research Board, Washington, D.C., 1-8.

Hejazi, S. M. (2007). Mechanical reinforcement of hot mix asphalt using textile materials. Master thesis, Isfahan University of Technology, Iran.

Hensher, D. A. (2016). Fiber-reinforced-plastic (FRP) reinforcement for concrete structures:

properties and applications (Vol. 42). Elsevier.

Ho, C. H. & Shan, J. (2016). Performance Comparison between Fiber-Reinforced and Rubber-Modified Asphalt. In Geotechnical and Structural Engineering Congress 2016, 1166–1175.

Ho, C. H., Shan, J., Wang, F., Chen, Y. & Almonnieay, A. (2016). Performance of Fiber-Reinforced Polymer-Modified Asphalt Two-Year Review in Northern Arizona. Transportation Research Record: Journal of the Transportation Research Board, (2575), 138-149. doi: 10.3141/2575-15

Hoyos, L. R., Puppala, A. J., & Ordonez, C. A. (2011). Characterization of cement-fiber-treated reclaimed asphalt pavement aggregates: preliminary investigation. Journal of Materials in Civil Engineering, 23(7), 977-989. doi: 10.1061/(ASCE)MT.1943-5533.0000267

Huang, H, & White, T. (1996). Dynamic properties of fiber-modified overlay mixture. Transportation Research Record: Journal of the Transportation Research Board, (1545), 98-104. doi: 10.3141/1545-13

Isacsson, U., & Lu, X. (1995). Testing and appraisal of polymer modified road bitumens—state of the art. Materials and Structures, 28(3), 139-159. doi: 10.1007/BF02473221

Izgi, A. A., Kocak, E. D., Şahinbaskan, B. Y., Merdan, N., & Ardic, B. (2018). Studies on mechanical performance of cynara scollymus/polyethylene therephthalate nanwoven composites. Selçuk-Teknik Dergisi, 107-116.

Jahromi, S., & Khodaii, A. (2008). Carbon Fiber Reinforced Asphalt Concrete. Arabian Journal for Science and Engineering, 33(2B), 355-364.

Jato-Espino D., Castillo-Lopez, E., Rodriguez-Hernandez, J., Canteras-Jordana, J.C. (2014). A review of application of multi-criteria decision making methods in construction, Autom. Constr. 45 (2014) 151–162. doi:10.1016/j.autcon.2014.05.013.

Jenq, Y. S., Liaw, C. J., & Lieu, P. (1993). Analysis of Crack Resistance of Asphalt Concrete Overlays--a Fracture Mechanics Approach. Transportation Research Record, 1388, 160-166.

Jiang, Y., & McDaniel, R. S. (1993). Application of cracking and seating and use of fibers to control reflective cracking. Transportation Research Record, 150-159.

Kaloush, K. E., Biligiri, K. P., Rodezno, M. C., Zeiada, W. A., Souliman, M. I., & Reed, J. X. (2009). Performance evaluation of asphalt rubber mixtures in Arizona—Lake Havasu project. Arizona Dept. of Transportation, Materials Group, Phoenix.

Kaloush, K. E., Biligiri, K. P., Zeiada, W. A., Rodezno, M. C., & Reed, J. X. (2010). Evaluation of fiber-reinforced asphalt mixtures using advanced material characterization tests. Journal of Testing and Evaluation, 38(4), 400-411. doi: 10.1520/JTE102442

Kaloush, K., Biligiri, K., Nordgen, T., Zeiada, W., Rodezno, M., Souliman, M., & Stempihar, J. (2012). Laboratory evaluation of asphalt-rubber gap graded mixtures constructed on Stockholm highway in Sweden. In Asphalt Rubber Conference, Munich, Germany. October, 2012.

Kanabar, N. (2010). Comparison of ethylene terpolymer, styrene butadiene, and polyphosphoric acid type modifiers for asphalt cement. Ph.D. dissertation. Queen's University, Canada.

Kennedy T. W., Huber, G. A., Harrigan, E. T., Corninsky, R. J., Hughes, C. S., Von Quintus, H., & Moulthrop, J. S. (1994). Superior Performing Asphalt Pavements (Superpave): The product of the SHRP asphalt research program. Publication SHRP-A-410, Strategic Highway Research Program, National Research Council, Washington DC.

Khanghahi, S. H., & Tortum, A. (2018). Determination of the Optimum Conditions for Gilsonite and Glass Fiber in HMA under Mixed Mode I/III Loading in Fracture Tests. Journal of Materials in Civil Engineering, 30(7), 04018130. doi: 10.1061/(ASCE)MT.1943-5533.0002278

Kim, K. W., Doh, Y. S., & Lim, S. (1999). Mode I reflection cracking resistance of strengthened asphalt concretes. Construction and Building Materials, 13(5), 243-251. doi: 10.1016/S0950-0618(99)00032-X

Kim, Y. R. (2008). Modeling of asphalt concrete. Reston, VA: ASCE.

King, G., King, H., Pavlovich, R. D., Epps, A. L., & Kandhal, P. (1999). Additives in asphalt. Journal of the Association of Asphalt Paving Technologists, 68, 32-69.

Klinsky, L. M. G., Kaloush, K. E., Faria, V. C. & Bardini, V. S. S. (2018). Performance characteristics of fiber modified hot mix asphalt. Construction and Building Materials, 176, 747-752. doi: 10.1016/j.conbuildmat.2018.04.221

Koch, C., & Brilakis, I. (2011). Pothole detection in asphalt pavement images. Advanced Engineering Informatics, 25(3), 507-515. doi: 10.1016/j.aei.2011.01.002

Kodrat, I., Sohn, D., & Hesp, S. (2007). Comparison of polyphosphoric acid-modified asphalt binders with straight and polymer-modified materials. Transportation Research Record: Journal of the Transportation Research Board, 1998, 47-55. doi: 10.3141/1998-06

Komatsu, T., Kikuta, H., Tuji, Y., & Muramatsu, E. (1998). Durability assessment of geogrid-reinforced asphalt concrete. Geotextiles and Geomembranes, 16(5), 257-271. doi: 10.1016/S0266-1144(97)10011-5

Kubler, S., Robert, J., Derigent, W., Voisin, A., Le Traon, Y. (2016). A state-of the-art survey & testbed of fuzzy AHP (FAHP) applications, Expert Syst. Appl. 65, 398–422. doi:10.1016/j.eswa.2016.08.064.

Kumar, A., Sah, B., Singh, A.R., Deng, X., Kumar, P., Bansal, R.C. (2017). A review of multi criteria decision making (MCDM) towards sustainable renewable energy development, Renew. Sustain. Energy Rev. 69, 596–609. doi:10.1016/j.rser.2016.11.191.

Kutuk, B. (1998). Performance of Flexible Pavements Reinforced with Geogrids. Ph.D. Dissertation, West Virginia University, Morgantown.

Labib, M., & Maher, A. (1999). Recycled plastic fibers for asphalt mixtures. Report No: FHWA 2000-04.

Lancaster, I. M. (2016). Influence of polymer modification on cracking and fatigue of asphalt mixtures. Ph.D. dissertation, University of Liverpool.

Lee, S. (2004). Long-term performance assessment of asphalt concrete pavements using the third scale model mobile loading simulator and fiber reinforced asphalt concrete. Ph.D. Dissertation, North Carolina State University, USA.

Lee, S. J., Rust, J. P., Hamouda, H., Kim, Y. R., & Borden, R. H. (2005). Fatigue cracking resistance of fiber-reinforced asphalt concrete. Textile Research Journal, 75(2), 123-128. doi: 10.1177/004051750507500206

Li, N., Wu, S. P., & Liu, C. H. (2008). Investigation of static and dynamic response of graphite and carbon fiber modified conductive asphalt-based composite. In Key Engineering Materials (385, 469-472). Transportation Technology Publications.

Li, T. (2010). Applying TRIZ and AHP to develop innovative design for automated assembly systems, Int. J. Adv. Manuf. Technol. 46, 301–313. doi:10.1007/s00170-009-2061-4.

Liao, C.N. (2011). Fuzzy analytical hierarchy process and multi-segment goal programming applied to new product segmented under price strategy, Comput. Ind. Eng. 61, 831–841. doi:10.1016/j.cie.2011.05.016.

Lima Junior, F.R., Osiro, L., Carpinetti, L.C.R. (2014). A comparison between Fuzzy AHP and Fuzzy TOPSIS methods to supplier selection, Appl. Soft Comput. J. 21, 194–209. doi:10.1016/j.asoc.2014.03.014.

Ling, H. I., & Liu, Z. (2001). Performance of geosynthetic-reinforced asphalt pavements.

Journal of Geotechnical and Geoenvironmental Engineering, 127(2), 177-184. doi: 10.1061/(ASCE)1090-0241(2001)127:2(177)

Liu, Q., Schlangen, E., & van de Ven, M. (2012). Induction healing of porous asphalt concrete beams on an elastic foundation. Journal of Materials in Civil Engineering, 25(7), 880-885. doi: 10.1061/(ASCE)MT.1943-5533.0000677

Mahrez, A., & Karim, M. R. (2007). Rutting characteristics of bituminous mixes reinforced with glass fiber. In Proceedings of the Eastern Asia Society for Transportation Studies The 7th International Conference of Eastern Asia Society for Transportation Studies, 2007 (282-282). Eastern Asia Society for Transportation Studies.

Mahrez, A., Karim, M., & Katman, H. (2003). Prospect of using glass fiber reinforced bituminous mixes. Journal of the Eastern Asia Society for Transportation Studies, 5, 794-807.

Marasteanu, M. O., & Cannone Falchetto, A. (2018). Review of experimental characterisation and modelling of asphalt binders at low temperature. International Journal of Pavement Engineering, 19(3), 279-291. doi: 10.1080/10298436.2017.1347436

Mardani, A., Nilashi, M., Zakuan, N., Loganathan, N., Soheilirad, S., Saman, M.Z.M, Ibrahim, O. (2017). A systematic review and meta-Analysis of SWARA and WASPAS methods: Theory and applications with recent fuzzy developments, Appl. Soft Comput. J. 57, 265–292. doi:10.1016/j.asoc.2017.03.045.

Martins, L., Ribeiro, A., e Sousa, J.A., Freire, A., Fontul, S., Batista, F., & Maia, A. (2018). Uncertainty evaluation for the dynamic measurement of deflections with a falling-weight-type impulse load device. In Journal of Physics: Conference Series (1044, 1, 012072). IOP Publishing.

Maurer, D.A., & Malasheskie, G.J. (1989). Field performance of fabrics and fibers to retard reflective cracking. Geotextiles and Geomembranes, 8(3), 239-267. doi: 10.1016/0266-1144(89)90005-8

McDaniel, R. S. (2015). Fiber additives in asphalt mixtures (No. Project 20-05 (Topic 45-15)).

McDaniel, R., & Shah, A. (2003). Asphalt Additives to Control Rutting and Cracking. Report from Joint Transportation Research Program, Purdue University.

McIntyre, J. E. (2005). Synthetic fibers: nylon, polyester, acrylic, polyolefin. Taylor & Francis US.

McNally, T. (Ed.). (2011). Polymer modified bitumen: properties and characterisation. Elsevier.

Muftah, A., Bahadori, A., Bayomy, F., & Kassem, E. (2017). Fiber-Reinforced Hot-Mix Asphalt: Idaho Case Study. Transportation Research Record: Journal of the Transportation Research Board, (2633), 98-107.

Munn D (1989). Fiber reinforced hot mix promises improved stability. High Health Constr 132 (10):54-56. doi: 10.3141/2633-12

Murali, K. J, & Rajagopal, K. R. (2003). Review of the Uses and Modeling of Bitumen from Ancient to Modern Times. Application Mech Review, 56 (2): 672-5. doi: 10.1115/1.1529658

N.Morova, "Investigation of usability of basalt fibers in hot mix asphalt concrete," Construction and Building Materials, vol. 47, pp. 175–180, 2013.

NAPA. (2011). Mix Production Survey Reclaimed Asphalt Pavement, Reclaimed Asphalt Shingles, Warm-mix Asphalt Usage: 2009-2010. Technical Report, National Asphalt Pavement Association, Washington, DC.

NAPA. (2011). Recycling. National Asphalt Pavement Association, Online access: https://www.asphaltpavement.org/index.php?option=com_content&task=view&id=25&Itemid=45 (Last accessed: February 2014).

Novophalt Permanent Deformation Laboratory Rutting Tester. (1989). Bulletin #CT-004, Novophalt America, Inc., Sterling, Virginia, February 1989, 10 pages.

Novophalt Product Information Bulletin. (1989). Bulletin #PIB-02, Novophalt America, Inc., Sterling, Virginia, February 1989, 11 pages.

Novophalt User Guidelines. (1989). Bulletin #PIB-01, Novophalt America, Inc., Sterling, Virginia, February 1989, 3 pages.

P. Park, S. El-Tawil, S.-Y. Park, and A. E. Naaman, "Cracking resistance of fiber reinforced asphalt concrete at −20 ∘C," Construction and Building Materials, vol. 81, pp. 47–57, 2015.

Page, G. C. (1992). Florida's Initial Experience Utilizing Ground Tire Rubber in Asphalt Concrete Mixes. Journal of the Association of Asphalt Paving Technologists, 61, 446-472.

Palit, S. K., Reddy, K. S., & Pandey, B. B. (2002). Permanent deformation of crumb rubber modified bituminous mixes. In ACE 2002: International Conference on Advances in Civil Engineering (2002).

Palit, S. K., Reddy, K. S., & Pandey, B. B. (2004). Laboratory evaluation of crumb rubber modified asphalt mixes. Journal of materials in civil engineering, 16(1), 45-53. doi: 10.1061/(ASCE)0899-1561(2004)16:1(45)

Panzera, T. H., Christoforo, A. L., & Borges, P. R. (2013). High performance fiber-reinforced concrete (FRC) for civil engineering applications. In Advanced Fiber-Reinforced Polymer (FRP) Composites for Structural Applications, 552-581.

Park, P., El-Tawil, S., Park, S. Y. & Naaman, A. E. (2015). Cracking resistance of fiber reinforced asphalt concrete at −20 C. Construction and Building Materials, 81, 47-57. doi: 10.1016/j.conbuildmat.2015.02.005

Partl, M. N., Newman, J. K. (2003). Flexural Beam Fatigue Properties of Airfield Asphalt Mixtures Containing Styrene–Butadiene Based Polymer Modifiers. In Proceedings of the Sixth International Rilem Symposium, Zurich, Switzerland, 357–63.

Partl, M. N., Vinson, T. S., & Hicks, R. G. (1994). Mechanical Properties of Stone Mastic Asphalt. In Proceedings of the Third Materials Engineering Conference, Oct 1994, ASCE 849-858.

Peltonen, P. (1991). Wear and deformation characteristics of fiber reinforced asphalt pavements. Construction and building materials, 5(1), 18-22. doi: 10.1016/0950-0618(91)90027-I

Polacco, G., Filippi, S., Merusi, F., & Stastna, G. (2015). A review of the fundamentals of polymer-modified asphalts: Asphalt/polymer interactions and principles of compatibility. Advances in Colloid and Interface Science, 224, 72-112. doi: 10.1016/j.cis.2015.07.010

Putman, B. J., & Amirkhanian, S. N. (2004). Utilization of waste fibers in stone matrix asphalt mixtures. Resources, conservation and recycling, 42(3), 265-274. doi: 10.1016/j.resconrec.2004.04.005

Qin, X.; Shen, A.Q.; Guo, Y.C.; Li, Z.N.; Lv, Z.H. Characterization of asphalt mastics reinforced with basalt fibers. Constr. Build. Mater. 2018, 159, 508–516.

Rahnama, E. (2009). A comparison on the performance of styrene–butadiene–styrene (SBS) polymer and textile fibers modifying asphalt concrete (AC). Master of Science thesis, Department of civil engineering, University of Science and Technology, Iran.

Reglero Ruiz, J. A., Trigo-López, M., García, F. C., & García, J. M. (2017). Functional aromatic polyamides. Polymers, 9(9), 414. doi: 10.3390/polym9090414

Roberts, C. J., Panagiotopoulos, A. Z., & Debenedetti, P. G. (1996). Liquid-liquid immiscibility in pure fluids: polyamorphism in simulations of a network-forming fluid. Physical review letters, 77(21), 4386. doi: 10.1103/PhysRevLett.77.4386

Rouzbeh, G. (2014). Laboratory Characterization of Recycled and Warm Mix Asphalt for Enhanced Pavement Applications. Ph.D. thesis, University of Oklahoma, USA.

Saeedzadeh, R., Romanoschi, S. A., Akbariyeh, N., Khajeh-Hosseini, M., & Abdullah, A. Q. (2018). Sustainability Assessment of Recycled Asphalt Mixtures Based on Performance in Full-Scale Testing. Journal of Transportation Engineering, Part B: Pavements, 144(2), 04018024. doi: 10.1061/JPEODX.0000048

Saheb, D. N., & Jog, J. P. (1999). Natural fiber polymer composites: a review. Advances in Polymer Technology: Journal of the Polymer Processing Institute, 18(4), 351-363. doi: 10.1002/(SICI)1098-2329(199924)18:4<351::AID-ADV6>3.0.CO;2-X

Saliani, S. S., Carter, A., Baaj, H., & Badeli, S. (2017). Investigation of the tensile strength of hot mix asphalt incorporating pulp aramid fiber. In Proceedings of the Sixth-Second Annual Conference of the Canadian Technical Asphalt Association (CTAA): Halifax, Nova Scotia.

Selim, A.A., Taha, R., & Bayomy, F. (1994). Laboratory performance of quartzite based Stone Matrix Asphalt Mixtures (SMAM). In Proceedings of the Third Materials Engineering Conference, 635-642, ASCE.

Serfass, J.P., & Samanos, J. (1996). Fiber-modified asphalt concrete characteristics, applications and behavior. Journal of the Association of Asphalt Paving Technology, 65, 193-230.

Serin, S., Morova, N., Saltan, M., & Terzi, S. (2012). Investigation of usability of steel fibers in asphalt concrete mixtures. Construction and Building Materials, 36, 238-244. doi: 10.1016/j.conbuildmat.2012.04.113

Shanbara, H. K., Ruddock, F., & Atherton, W. (2018). A laboratory study of high-performance cold mix asphalt mixtures reinforced with natural and synthetic fibers. Construction and Building Materials, 172, 166-175. doi: 10.1016/j.conbuildmat.2018.03.252

Simpson, A. L., & Mahboub, K. C. (1994). Case study of modified bituminous mixtures: Somerset, Kentucky. In Infrastructure: New Materials and Methods of Repair, 88-96. ASCE.

Singh, R. (2018). An Overview of Polyester Fiber. [online] Textilelearner.blogspot.com. Available at: http://textilelearner.blogspot.com/2013/08/an-overview-of-polyester-fiber.html.

Smith, R. D., & Forsyth, R. A. (1983). Experimental AC Overlays of PCC Pavement. WORK, 57324, 633352.

Sousa, J. B. & Way, G. B. (2009). Optimum timing for pavement treatment application. Proceeding of Asphalt Rubber 2009 Conference, Nanjing, China, 73–96.

Stempihar, J., Pourshams-Manzouri, T., Kaloush, K., & Rodezno, M. (2012). Porous asphalt pavement temperature effects for urban heat island analysis. Transportation Research Record: Journal of the Transportation Research Board, (2293), 123-130. doi: 10.3141/2293-15

Stempihar, J., Souliman, M., & Kaloush, K. (2012). Fiber-reinforced asphalt concrete as sustainable paving material for airfields. Transportation Research Record: Journal of the Transportation Research Board, (2266), 60-68. doi: 10.3141/2266-07

Stuart, K. D., & Malmquist, P. (1994). Evaluation of Using Different Stabilizers in the U.S. Route 15 (Maryland) stone matrix asphalt. Transportation Research Record 1454, 48-57.

Sui, C., Farrar, M., Harnsberger, P., Tuminello, W., & Turner, T. (2011). New low-temperature performance-grading method: Using 4-mm parallel plates on a dynamic shear rheometer. Transportation Research Record: Journal of the Transportation Research Board, (2207), 43-48. doi: 10.3141/2207-06

Takaikaew, T., Tepsriha, P., Horpibulsuk, S., Hoy, M., Kaloush, K. E., & Arulrajah, A. (2018). Performance of Fiber-Reinforced Asphalt Concretes with Various Asphalt Binders in Thailand. Journal of Materials in Civil Engineering, 30(8), 04018193. doi:

10.1061/(ASCE)MT.1943-5533.0002433

Tanzadeh, J., Vafaeian, M., & Yusefzadeh-Fard, M. (2017). Laboratory study on the performance of hybrid macro soil fiber reinforced mixture. Construction and Building Materials, 134, 50-55. doi: 10.1016/j.conbuildmat.2016.12.053

Tapkın, S. (2008). The effect of polypropylene fibers on asphalt performance. Building and Environment, 43(6), 1065-1071. doi: 10.1016/j.buildenv.2007.02.011

Tasdemir, Y., & Agar, E. (2007). Investigation of the low temperature performances of polymer and fiber modified asphalt mixtures. Indian Journal of Engineering & Materials Sciences, 14, 151–157.

Terrel, R. L., & Epps, J. A. (1989). Using Additives and Modifiers in Hot Mix Asphalt (Part A). National Asphalt Pavement Association, Lanham, MD, Report No. QIP 114A.

Tian, Y., Lee, J., Nantung, T., & Haddock, J. E. (2017). Development of a mid-depth profile monitoring system for accelerated pavement testing. Construction and Building Materials, 140, 1-9. doi: 10.1016/j.conbuildmat.2017.02.106

Tomlinson, A. (1995). Heated Runways Using Electrically Conductive Asphalt. Superior Graphite Co.

Tripathi, A. (2018). Mechanistic Analysis and Economic Benefits of Fiber-Reinforced Asphalt Mixtures. Civil Engineering Theses. Paper 6.

Valkering, C. P., Lancon, D. J. L., Dehilster, E., & Stoker, D. A. (1990). Rutting resistance of asphalt mixes containing non-conventional and polymer-modified binders (with discussion and closure). Journal of the Association of Asphalt Paving Technologists, 59.

Vinodh, S., Prasanna, M., Hari Prakash, N. (2014). Integrated Fuzzy AHP-TOPSIS for selecting the best plastic recycling method: A case study, Appl. Math. Model. 38, 4662–4672. doi:10.1016/j.apm.2014.03.007.

Voskuilen, J., van den Top, H., Evaluatie proefvakken, wat kunnen we daarvan leren?. CROW Infradagen 2016. (in Dutch)

Wang, W., Cheng, Y., & Tan, G. (2018). Design Optimization of SBS-Modified Asphalt Mixture Reinforced with Eco-Friendly Basalt Fiber Based on Response Surface Methodology. Materials, 11(8), 1311.

Woldekidan M.F., Voskuilen J., Vliet D., Leegwater G.A. (2013) Research into Applications of Acrylic Fibers in Porous Asphalt: Laboratory, Numerical and Field Study. In: Kringos N., Birgisson B., Frost D., Wang L. (eds) Multi-Scale Modeling and Characterization of Infrastructure Materials. RILEM Bookseries, vol 8. Springer, Dordrecht.

Wu, S. P., Li, B., Wang, H., & Qiu, J. (2008). Numerical simulation of temperature distribution in conductive asphalt solar collector due to pavement material parameters. In Materials Science Forum (575, 1314-1319). Trans Tech Publications. doi: 10.4028/www.scientific.net/MSF.575-578.1314

Wu, S. P., Liu, X. M., Ye, Q. S., & Ning, L. I. (2006). Self-monitoring electrically conductive asphalt-based composite containing carbon fillers. Transactions of Nonferrous Metals Society of China, 16, 512-516. doi: 10.1016/S1003-6326(06)60246-X

Wu, S. P., Mo, L. T., & Shui, Z. H. (2002). An Improvement on electrical properties of asphalt. Journal of Wuhan University of Technology. Materials Science Edition. 17(4): 63-65.

Wu, S., Mo, L., Shui, Z., & Chen, Z. (2005). Investigation of the conductivity of asphalt concrete containing conductive fillers. Carbon, 43(7), 1358-1363. doi: 10.1016/j.carbon.2004.12.033

Wu, S., Ye, Q. & Li, N. (2008). Investigation of rheological and fatigue properties of asphalt mixtures containing polyester fibers. Construction and Building Materials, 22(10), 2111-2115.

doi: 10.1016/j.conbuildmat.2007.07.018

Wu, S., Ye, Q., Li, N., & Yue, H. (2007). Effects of fibers on the dynamic properties of asphalt mixtures. Journal of Wuhan University of Technology-Materials Science Edition, 22(4), 733-736. doi: 10.1007/s11595-006-4733-3

Xiong, R., Fang, J., Xu, A., Guan, B., & Liu, Z. (2015). Laboratory investigation on the brucite fiber reinforced asphalt binder and asphalt concrete. Construction and Building Materials, 83, 44-52. doi: 10.1016/j.conbuildmat.2015.02.089.

Xu, Q., Chen, H., & Prozzi, J. A. (2010). Performance of fiber reinforced asphalt concrete under environmental temperature and water effects. Construction and Building materials, 24(10), 2003-2010. doi: 10.1016/j.conbuildmat.2010.03.012

Xu, S., Wu, Z., Xu, Y., & Chen, S. (2014). Performance Evaluation of High RAP Asphalt Mixture with Fiber and Warm Mixing Agent. In Challenges and Advances in Sustainable Transportation Systems (pp. 343-351).

Yee, P., Aida, B., Hesp, S. A. M., Marks, P., Tam, K. K. (2006). Analysis of three premature low temperature pavement failures. Transportation Research Record: Journal of the Transportation Research Board, 1962, 44.

Yildirim, Y. (2007). Polymer Modified Asphalt Binders. Construction and Building Materials, 21(1), 66–72. doi: 10.1016/j.conbuildmat.2005.07.007.

Zhou, J., Li, M., Zhong, L., Zhang, F., & Zhang, G. (2017). Aminolysis of polyethylene terephthalate fabric by a method involving the gradual concentration of dilute ethylenediamine. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 513, 146-152. doi: 10.1016/j.colsurfa.2016.11.016.