Laboratory Investigation of the Performance of Fiber-Modified Asphalt Mixes in Cold Regions

by

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Abstract

An efficient and safe road network is of great importance for a country, not only to ensure its competitiveness and productivity in the global trade market, but also to connect its territory internally. Thus, increasing the lifespan of asphalt concrete roads and the enhancement of the mechanical properties of asphalt mixes are desired targets among transportation ministries. There are traditional ways to achieve this aim, for instance, modification of asphalt with polymers is a common way to enhance the mechanical properties of the binder. Meanwhile, fibers with high-mechanical performance represent an important case to evaluate in terms of their effectiveness to improve asphalt concrete properties.

Improvement of the mechanical properties of asphalt mixtures allows them to be more resilient to rapid deterioration, in particular, distresses such as thermal cracking. Thermal cracking is caused by contraction of asphalt layers at low temperatures: under these conditions, tensile stresses build up to a critical point, where crack formation starts. The cracks then propagate under traffic loading conditions. In cold regions, freeze-thaw cycles accelerate crack propagation within the asphalt. Later, this deterioration in the asphalt layer may lead to the formation of more severe distresses such as potholes. Furthermore, other distresses may appear simultaneously within the asphalt layer, including rutting failure at warm temperatures and fatigue failure at intermediate temperatures.

Fibers have attracted increasing attention within the asphalt industry due to their potential use as asphalt concrete modifiers. The addition of fibers within of Hot Mix Asphalt (HMA) could result in a composite material that has higher tensile strength, along with the ability to absorb greater energy during the fracture process. The fiber–aggregate–asphalt cement interlock acts as a crack barrier, preventing the formation and especially the propagation of cracks in the asphalt mix.

Besides these effects, fibers may also increase the fatigue life of hot mix asphalt (HMA) and provide resistance to permanent deformation.

This research focuses on the evaluation of the effectiveness of the addition of polymeric fibers to HMA to increase resistance to cracking at intermediate and low temperatures, and rutting resistance and moisture susceptibility at high temperatures, and evaluation of the effect of the addition of polymer fibers on fatigue failure of HMA. For this purpose, three different types of polymeric fibers, including uncoated aramid (Aromatic polyamide), polyethylene terephthalate (PET), and polyacrylonitrile (PAN), were added to conventional hot asphalt mixes. The resulting samples were compacted, and the mechanical properties of the fiber-modified HMA were compared to conventional HMA samples in the laboratory. Based on the results obtained, the addition of fiber showed, in most cases, a consistent trend compared to conventional HMA samples. This included improvements in rutting control, cracking resistance, and fatigue life. Finally, a material cost comparison was conducted for use as a reliable source of information when selecting materials to employ as a cost-effective solution, while fulfilling minimum industry specifications.

Preface

This thesis is an original work by Luis Alberto Perca Callomamani under the supervision of Dr. Leila Hashemian. The research project, of which this thesis is based on, has been submitted for publication as conference papers and journal papers.

Parts of this thesis' chapters have been submitted for publication. The third chapter, *"Laboratory Evaluation of Cracking Potential of Fiber Modified Asphalt Mixes",* has been submitted and accepted for publication and presentation to the Transportation Association of Canada (TAC) conference held in Halifax in September 2019. The fourth chapter *"Laboratory investigation of the performance evaluation of fiber modified asphalt mixes in cold regions"* has been submitted and it is under final review to be published in the Transportation Research Record (TRR) journal. Besides, it has been accepted for presentation in the next Transportation Research Board (TRB) conference to be held in Washington DC in January 2020. Finally, the fifth chapter *"Investigation of Cracking Potential of Modified Asphalt Mixes Composed of Synthetic Fibers by performing 4-point bending test"* has been submitted and it is under final review to be published in the International Symposium on Bituminous Material (ISBM) conference to be held in Lyon, France in June 2020.

I was responsible for the major parts of the data collection composition, for the edition of the manuscript, and improvement of the analysis and the composition of the manuscript. Leila Hashemian, Katrina Sha, Jintao Liu, and Jay Kwon were involved with concept formation, editing of the manuscript, and improvement of the analysis.

Dedicated to

God, for guiding me in the correct direction.

My sweet and loving wife, for all the invaluable support over these two years, for her strength and good humor, even in difficult times. I couldn't have done this without her.

My parents, for always inspiring me to be a better human being.

The memory of my grandparents and my aunt Yaneth.

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1 Introduction

Canada is the world's second-largest country by total area, and it demands an extensive pavement infrastructure to connect its sparsely urban cities and rural areas. Canada has an extensive network of paved roads, in which asphalt concrete roads represent almost 95% of the total infrastructure. This road network is not only subjected to vehicle loads but also to thermal stresses due to seasonal changes. For instance, during the first week of January 2019, in the winter season, the heaviest-ever load (820 tons) was transported on Alberta roads. The move of a splitter, from the Dacro Industries Inc. facility in Edmonton to the Inter Pipeline Petrochemical Complex north of Scotford, Alberta, represented the demand placed by super-heavy loads on pavement structure [1]. Thus, the effect of traffic overload and climatic factors, both result in the appearance of premature pavement distresses, which, without a proper program of maintenance measures, can cause a reduction in the service life of the asphalt pavement.

Maintenance and prevention plans play an important role in extending the service life of road networks, especially in cold regions. For instance, Canada spends billions of dollars annually on rehabilitation and new construction of asphalt pavements [2]. Because of economic constraints, as well as weather and traffic conditions, ongoing research has been performed to find alternative and innovative materials to enhance pavement performance. Scientists have commonly approached this problem by modifying either the asphalt cement or the asphalt mixture; among all possible alternatives investigated, the inclusion of fibers in asphalt mixes represents a promising opportunity due to their high mechanical properties.

The inclusion of fibers to enhance the behavior of pavement materials is not a recent suggestion. Abtahi et al. [3] mentioned that as early as 2000 years ago, builders considered the use of fibers in the construction of the Great Wall in China. However, the same author described how in the asphalt industry, fibers were widely used from the early 1960s. Especially during the last five decades, with the introduction of different high-performance in the market, the development of fibers as a pavement reinforcement is of interest. The fibers, which are normally classified, based on their origin, include but are not limited to natural fibers, synthetic fibers, waste fibers, carbon fibers, steel fibers, and glass fibers.

Although some investigations have shown successful applications of different synthetic fibers [4],[5],[6] to date there has not been a broad investigation about the incorporation of fibers in asphalt mixes to improve resistance to thermal cracking, an application that would be extremely beneficial for road construction in cold regions, where temperatures can drop below -30°C. Furthermore, even though synthetic fibers could provide considerable improvements in asphalt concrete, it is the economic factor that is decisive in justifying their use in different projects. The initial increase in project cost could be justified by an extension in years of service life [7], [8].

In the short term, global climate change represents a major challenge for asphalt pavement design. Resilient transportation infrastructure must be able to maintain the highest quality standards over the long term and must be able to adapt and withstand changing climatic conditions and their consequences on pavement structures. The inclusion of synthetic fibers in asphalt pavement represents a feasible technique to face these challenges.

1.1 Objective

The objective of this research is to evaluate and compare the effectiveness of incorporation of three different fibers in asphalt mixes, polyethylene terephthalate (PET), polyacrylonitrile (PAN) and uncoated aramid (Aromatic polyamide), and their effect on performance parameters such as permanent deformation, moisture susceptibility, fatigue cracking and cracking resistance of asphalt mixes at high, intermediate and low temperatures. For this purpose, the hot mix asphalt (HMA) design was prepared and the optimum content for each fiber was determined, taking into consideration the no alteration of the original mix design. Then, conducted a detailed evaluation of both, the control mix and fiber-modified mixes, was conducted to show the performance improvement under different testing conditions. Finally, a brief cost analysis of the additives was carried out to determine the cost-effectiveness of using different fibers in asphalt mixes.

1.2 Methodology

This research was conducted in three individual phases, which relate in one way or another to each paper prepared during the investigation: low temperature cracking, rutting failure and moisture susceptibility, and fatigue cracking. Furthermore, the research also included a section related to the cost analysis of adding fibers to hot mix asphalt.

The first phase of the research focused on the evaluation of the cracking resistance of asphalt mixes at intermediate temperatures. Samples modified with PET, PAN and aramid fibers were evaluated by conducting an indirect tensile strength (ITS) test under dry conditions and then, compared with the control mixture. The stress-strain curves from ITS tests were used to calculate the cracking tolerance (CT) index, which was used as a parameter to indicate low-temperature cracking resistance. To investigate the cracking resistance of the fiber-modified mixes and the control mixture at low temperatures, indirect tensile strength and creep compliance (IDT) tests were performed at 0°C, -10°C, and -20°C. Finally, moisture susceptibility was evaluated for all unmodified and fiber-reinforced mixes by conditioning samples with freeze and thaw cycles.

The second phase consisted of the evaluation of the rutting resistance and moisture susceptibility at high temperatures. Fiber-modified samples and control mixtures were tested using a Hamburg wheel tracking device (HWTD) test at 45°C. In a conditioned chamber, a wheel moved forth and back over the control mixtures and fiber-modified samples. The stripping inflection point (SIP) was evaluated to determine the susceptibility of the samples to moisture. Furthermore, the rutting resistance was evaluated by calculating the total number of passes and the rut depth.

The third phase consisted of the evaluation of the fatigue life of mixtures incorporated with fibers and control mix by using a four-point bending apparatus to determine the improvement on the fatigue resistance of all studied samples. The assessment of fatigue properties was made at two different microstrains, at constant strain mode of loading of 600 microstrains and at 900 microstrains, at room temperature between 20 °C to 25°C, and at haversine-shaped wave loading at a frequency of 10 Hz.

A cost comparison of adding fibers to HMA was conducted for each type of fiber studied by considering the output of the aforementioned performance-based tests and the cost per ton of asphalt control mix and with the incorporation of polymer fibers. The estimated cost of fibers relied on the provider's price and the literature review.

Finally, the evaluation of fiber dispersion on asphalt mixes was conducted by using the Zeiss Stemi 508 Stereo microscope at the NanoFab Facility at University of Alberta. The half splitting compacted specimens from the test samples were examined to identify the distribution of fibers on the rough surface.

1.3 Thesis Structure

The paper-based thesis is organized into six chapters and has the following structure:

Chapter 1 – Introduction: A brief background of the research topic, motivations of the research, objective, methodology, and thesis structure are provided.

Chapter 2 – Literature Review: Fiber-modified asphalt concrete and its challenges are discussed in depth. The most common distresses on asphalt pavement, mixing procedures, advantages of fiber inclusion on traditional asphalt mixes, and available literature of fiber incorporation as pavement reinforcement are cited, as well as relevant case studies.

Chapter 3 – Performance Evaluation of Fiber Modified Asphalt Mixes in Cold Regions: In this chapter, results of tests of the cracking resistance of asphalt mixes at intermediate and low temperatures from indirect tensile strength tests are presented. The cracking tolerance (CT) index was determined, as well as the Indirect Tensile Strength (IDT) and Fracture Energy tests at -20°C are discussed.

Chapter 4 – Laboratory investigation of the performance evaluation of fiber modified asphalt mixes in cold regions: The performance of rutting resistance and moisture susceptibility at high temperatures was evaluated by comparing all the different samples, as well as performing a cost comparison between the different specimens. Finally, the results of the evaluation of cracking resistance of the fiber-modified mixes at low temperature (IDT test) are presented for 0°C, - 10 °C and - 20°C. A short analysis of the cost-effectiveness of the use of different fibers in asphalt mixes is also included.

Chapter 5 – Investigation of Cracking Potential of Modified Asphalt Mixes Composed of Synthetic Fibers by performing 4-point bending test: Assessment of the fatigue life performance, of mixtures reinforced with fibers and control mixes, was completed at two different microstrains (600 and 900 $\mu\varepsilon$). Analysis and evaluation of the test results on the beams were based on loading cycles, representing the fatigue life of the sample. A brief evaluation of fiber dispersion on asphalt mixes was also conducted.

Chapter 6 – Summary and conclusions: In this chapter, differences in the performance of fiber-reinforced specimens are summarized and explained. Laboratory observations are summarized.

Possible future steps and recommendations for further study to get a better prediction of the real improvement of synthetic fibers on HMA.

2 Literature Review

2.1 State-of-the-art of asphalt pavement

Hot Mix Asphalt (HMA) is a viscoelastic and flexible pavement, which experience different performance under extreme temperature oscillations [9]. In cold regions, flexible pavements are subjected to different distresses due to thermal variations, moisture and mechanical loadings, which might affect the service life of the asphalt pavement, accelerating a premature failure. In effect, low-temperature cracking and frost heave occur due to thermal variations. Furthermore, stripping and raveling distresses occur due to the presence of moisture. Finally, rutting failure and fatigue cracking are the main structural distresses modes in asphalt pavement due to mechanical loadings [10]. Different distresses may exist and occur simultaneously, reducing the asphalt pavement serviceability. However, there are three main distresses that affect drastically the life of roadways and accelerate the premature failure of asphalt pavements. The major pavement distresses are permanent deformation, fatigue cracking and low temperature cracking.

Permanent deformation or rutting is the most common structural distress at high temperatures. The asphalt concrete is affected by traffic loading and consolidation of underneath layers. Rutting is characterized by longitudinal surface depressions under the vehicle wheel paths [8], which eventually leads to a loss of serviceability. The rapid deterioration of pavement by rutting is due to the low speed of the vehicles and the heavy load of the trucks. For instance, a usual rutting pattern is observed in the pavement sections surrounding the bus stops and traffic lights [11]. At high temperature, the asphalt pavement softens and the desired behavior is to get a stiffer mixture. From the literature review, the rutting evaluation of asphalt mixes is performed by identifying the Flow Number (FN) in the Marshall Test, or by conducting the static and dynamic creep tests, or by conducting the Wheel tracking test [12]. However, the Wheel Tracking test is widely accepted and performed due to a close field simulation.

Fatigue cracking takes place when the pavement asphalt is subjected to excessive traffic loading repetitions. The cyclic loadings result in tensile and shear stresses, and when those stresses reach the asphalt concrete strength, it starts an eventual reduction in the structural integrity of the road. The development of failures is associated with the flexural stresses developed at the bottom of the asphalt pavement. Eventually, the fatigue cracking propagates from the bottom to the surface, simulating an alligator pattern, called bottom-up failure [8]. Nevertheless, recent investigations have determined that fatigue cracks could originate in the surface and then propagate downwards, which refers to the top-down cracking. The fatigue resistance of asphalt mixes can be characterized by different test methods such as Four-point Beam fatigue, Indirect Tension (IDT) and Semi-circular Bend (SCB), which have as common parameters to the tensile strain and mix stiffness [13].

Considering that asphalt concrete withstands forces very well in compression but not in tension [14], the most concerning pavement distress in freezing regions such as Canada is thermal cracking [2]. According to Strategic Highway Research Program (SHRP) report 400 [15], at low temperature, asphalt pavement’s tensile stresses reach the tensile strength of the asphalt mixture, and the appearance of transversal microcracks is the most common pattern of this distress. The water is conducted and storage through those cracks, reducing severely its service life. Currently, there are different laboratory methods to evaluate the resistance to low temperature cracking; for instance, Indirect Tensile test and Creep Compliance, and based on fracture mechanics theory [16].

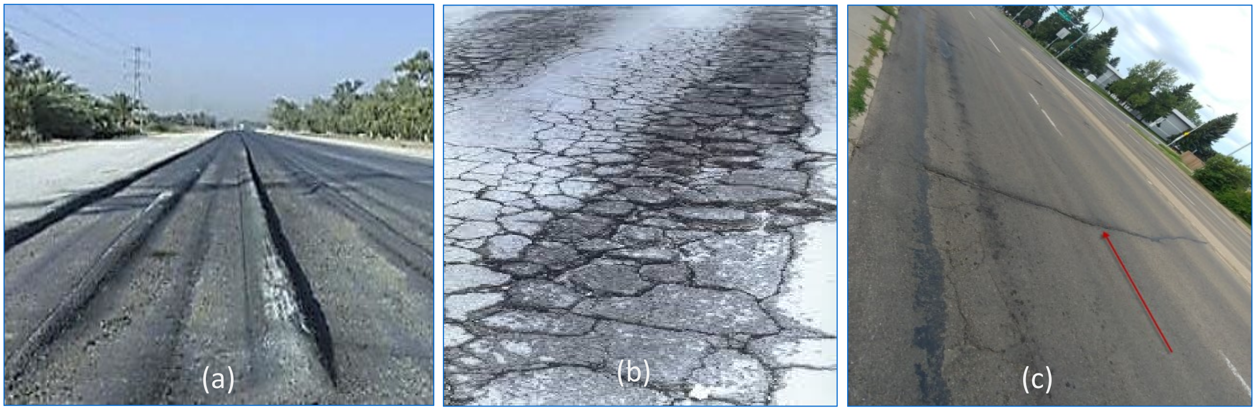

Figure 2-1: Common distresses (a) Rutting- permanent deformation (b) Fatigue cracking (c) Low temperature cracking

2.2 Fiber use in asphalt pavement

According to the National Cooperative Highway Research Program (NCHRP) report 475 [14], the addition of fibers as a reinforcement in asphalt pavement is not a new procedure. This technique has been used for several decades; however, its usage has been traditionally to control the drain down of the asphalt cement [3]. After the 1960’s, the development of technology has promoted the appearance of different types in the market.

There is a broad discussion in the literature about the use of different fibers in asphalt mixes [3], [14], [17], [18]. Fibers are normally classified based on their origin [18] and include but are not limited to natural fibers, polymer fibers, inorganic fibers, carbon fibers, steel fibers, and glass fibers. The main drawback of natural fibers is that they are affected by water, which reduces their limited tensile strength and stiffness. Natural fibers are also subject to attack by fungi and have a high absorption of binder, which is not cost-effective. For synthetic polymers such as polyester and polypropylene, the melting point needs to be considered because it may result in a serious loss of desirable physical properties such as strength. Inorganic materials, such as asbestos, were widely used for many years but the use is now limited due to the associated health hazards. Carbon fibers can be very strong (60 GPa), have no melting point limitations and good electrical conductivity, but their cost limits their usage. Steel fibers have electrical conductivity potential as well, but they might get corroded upon exposure to water. Finally, glass fibers have a high tensile modulus, but are very brittle and easily broken during the construction stage.

2.3 Dispersion and bonding of fibers

Fiber inclusion in asphalt mixes is normally random [3], but an adequate dispersion must be achieved to get the necessary bond among fibers, binder, and aggregates [4]. Jaskula et al. [16] explained that once the optimum fiber content is achieved, a larger dosage might produce fiber agglomeration and with meaningless results. The author also analyzed the effect of a blend of polyolefin and aramids as an asphalt reinforcement, in which the mixing process was executed both in an industrial plant and in a laboratory. An important observation was that a better uniform fiber distribution was achieved in the plant, rather than in the laboratory. The reason behind this observation may be the large-scale production in an asphalt plan rather than in a laboratory. Another reason could be that the optimum asphalt content may be altered by the absorption rate and the surface area of the different types of fibers.

The reinforcing effect of fibers in asphalt concrete may depend on the inner mechanical properties of fibers such as tensile strength, geometrical dimensions in length and diameter, the easy fiber inclusion, and the correct dispersion in asphalt mixes. For instance, the length of fiber may affect the performance; while shorter fibers may be mix easily in HMA than longer fiber [9], it might have a negligible effect on mixes [3], longer fibers give a better interlock effect between asphalt concrete (AC) components [17], [19], but at the same time, really long fibers leads to balling problems, affecting the blending process and the interlock between the aggregates [20].

Abtahi et al. [3] elaborated an approach to evaluate the bond of the fiber within the asphalt concrete (AC) specimen taking into consideration the inherent properties of each fiber. It is called "The Slippage Theory", which tries to predict the performance of fibers, through the finding of a fiber slippage ratio, defined as the index "λ". From formula 1, d_f, E_f, ϵ_f, τ, and L_f are diameter, Young's Modulus, induced strain of fiber, shear stress between fiber and matrix, and length respectively. When increasing the index, there is a reduction of the interlock between fiber and AC components, whereas a fiber with a larger value "λ", has worse fiber-matrix cooperation to withstand induced tensile stresses into the matrix [21].

$$\lambda = (d_f * E_f * \epsilon_f)/(2 * \tau * L_f) \ldots\ldots\ldots\ldots \text{(1)}$$

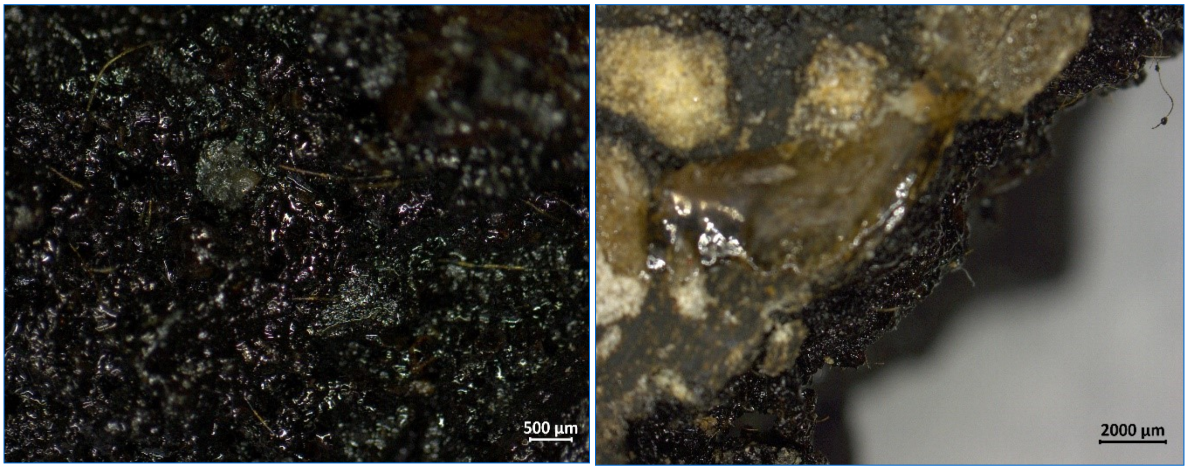

Figure 2-2: Fiber - Aggregates – Asphalt Cement interlock of a PAN-fiber reinforced asphalt mix

Wang et al. [21] evaluated four types of synthetic fibers: glass, nylon, polypropylene, and polyester, following the " Slippage Theory". Among the properties of the fibers used in the study, the fiber length was similar in all the four types, but the Young's modulus, diameter, and strain at failure were different for all the samples. In the end, the performance of glass fibers showed a more coherer composite, allowing a better interaction between fibers and matrix.

2.4 Advantages

According to NCHRP report 475 [14], the inclusion of fibers in asphalt mixes makes possible a feasible control of main distresses, by improving mechanical properties such as tensile strength, stiffness, crack appearance control, crack propagation and toughness [3], [16], [19], [22], [23]. Consequently, the addition of fibers increases pavement service life [24].

From the literature review, laboratory and trial results have shown that the addition of polymer fibers to asphalt mixes has resulted in the enhancement of fatigue properties [4], [13], [25], [26], tensile strength [19], [27], [28] and freeze-thaw resistance [5], [18], as well as delayed cracking growth by providing ductility due to its "bridge effect" [16], [17], [19] and rutting susceptibility [8], [24]. However, there has not been a broad investigation about the incorporation of fibers in asphalt mixes to improve resistance to thermal cracking, an application that would be extremely beneficial for road construction in cold regions, where temperatures can drop below -30°C.

2.5 Polymer fibers

2.5.1 Aramid fibers

Aramid fiber is an "aromatic polyamide" synthetic polymer fiber, an advanced composite with over five times the tensile strength of steel, 400 000 psi, and high modulus material. It also has a remarkable stress/strain ratio and a higher melting point than the average asphalt mixing temperatures, 500°C. Aramid fibers are widely applied in different industries such as automotive, military, sporting goods, among others. The most common fiber brands are Kevlar™ and Nomex™ [29], [30].

Aramid fibers are reported in different case studies, such as Muftah's work, which showed that a blend of polyolefin and aramid fibers acted effectively to reduce or control crack propagation [4]. Fibers acted as a bridge, connecting all mix components; larger amounts of fiber gave significant improvements [4], [17]. In 2018, Kaloush et al. reported that a blend of fibers, aramids, and polypropylene, gave a considerable improvement of 25%-50% in tensile strength at different temperatures (T°) and concluded that the strength followed a pattern: when the T° dropped, the tensile strength increased. Similarly, the work also reported that the fracture energy of fiber-modified mixes was larger than the control mixes in 50%-75% of all tested temperatures and that the fracture energy maintained a direct relationship with T°: once the temperature went up, fracture energy followed an incremental tendency [23]. Comparable results are found in [24], [31]. Ho evaluated a blend of polyolefin and aramid fibers through laboratory experiments and 2-year field observation. The results showed fewer cracks in the fiber modified mixes compared with the control mix, with a cumulative crack length difference of 33.5 m [5].

A laboratory-work performed in the Pavement Research Center of the University of California [32] aims to answer the question, how much does fiber improve the performance of mixes? As a reference, fiber-modified samples used 0.013% of aramid fibers, a Superpave mix was used, with 15% reclaimed asphalt pavement (RAP) and a maximum aggregate size (MAS) of 19mm. After testing in the laboratory, it was seen that the fibers had little effect on the stiffness of the samples but did improve the fatigue life at high strain values, beyond 600 microstrains. The report also mentioned an improvement in the rutting resistance.

2.5.2 Polyacrylonitrile (PAN) fiber

Polyacrylonitrile (PAN) fiber is the result of the acrylonitrile polymerization process in the presence of a catalyst peroxide and, is a precursor material of the carbon fibers. PAN fiber is widely applied in different industries such as military and commercial aircraft [17], [30].

PAN fiber used in asphalt concrete (AC) mixes, is reported by Slebi et al. [17], who observed improvements in rutting resistance, a slightly positive impact on the moisture susceptibility of the asphalt mixtures after the freeze-thaw effect, and superior fiber-binder-aggregate interlock. Another study is the reported by Wang et al. [26], who developed an alternative fatigue performance model including the fiber content, tensile strain, mixture initial flexural stiffness, and voids filled with asphalt (VFA), concluding that PAN fiber-modified mixes had higher fatigue life than the control mix. In addition, Xu et al. [18] studied four different types of fibers, evaluating their performance properties such as fatigue life, rutting, and freeze-thaw cycling test, concluding that PAN fibers had one of the best performances among all tested samples. Although, a drawback is the fiber's high absorption rate, which alters and increments the binder content [18], [33].

2.5.3 Polyethylene Terephthalate (PET) fibers

Polyethylene Terephthalate (PET) fibers are semi-crystalline, thermoplastic, and non-biodegradable polymer. PET fibers come from the group of polyesters and are originated from a polymerization reaction between an acid and alcohol. There is no alteration on PET properties when is subjected to different conditions, which makes a recyclable product. PET is widely applied in the film industry, the textile industry, as electrical insulation, and most plastic bottles are made from this material [34], [35]. PET fiber usage as reinforcement on HMA is a relatively new concept, and there is not extensive information about it. Each year, plastic waste material is accumulated in an accelerated way and consequently, safe disposal of it has a considerable economic cost. Thus, the recycling of plastic waste to produce PET represents an affordable and environmental way to reduce the impact of waste plastic material in the environment [36]

Usman et al. [34] investigated the reinforcement of PET fiber addition, at different dosages, on control HMA. The authors' findings concluded the improvement in rutting resistance and resilient modulus as an indicator of fatigue resistance. Also, Moghaddam et al. [37] also found the enhancement of fatigue life by the evaluation of Indirect tensile stiffness modulus test and indirect tensile fatigue test at different stress levels, and at room temperature. Another important author's conclusion was the change from brittle fracture to plastic fracture after the addition of fibers. In addition, Dehghan et al. [25] evaluated the fatigue life of fiber-reinforced HMA, considering different lengths and different amounts of PET fibers. After the evaluation of the fatigue response at the strain range of 300, 500 and 700 microstrains under the four-point bending test, the fatigue lives were improved in more than 100% at the different three microstrains. Similarly, Ahmadinia et al. [12] made experimental research to evaluate the moisture susceptibility, the rutting tolerance, the resilient modulus and the drain down tolerance on PET fiber modified Stone Mix Asphalt (SMA). The authors concluded that at a specific fiber content, the modified mixes showed positive trends in the improvement and control of the detailed performance tests. Finally, Modarres et al. [6] compared a PET fiber modified mix against Styrene-Butadiene-Styrene (SBS) modified mix, evaluating the stiffness and the fatigue resistance at 20°C and 5°C. The author concluded that at 20°C, fiber-modified mixes achieved better performance than SBS-modified mixes, whereas, at 5°C, major improvements were achieved with the SBS polymer additive.

2.6 Cost-effectiveness

As cost-effectiveness is essential to justify fiber usage in all projects, the fiber dosage should be controlled [14], [38], to get a feasible and economical product. Even when fiber inclusion means an initial increase in project cost, it should be considered, because the cost of fibers could be justified with an extension in years of service life and a decrease in CO_2 emissions in the long term [7], [8].

Stempihar et al. [7] analyzed the inclusion of a blend of polypropylene and aramid fibers to improve the performance of two asphalt-concrete runways. He also performed a cost analysis of these two similar runway projects in Wyoming (United States). Although for both projects the cost production increase ($/ton) of adding fibers to the HMA was about 11% of the original cost, the authors relied on "the equivalent uniform annual cost (EUAC)" to conclude that the over cost can be justified if the fiber-reinforced roadway is able to extend in 1-year the service life, considering the service life range of 5-15 years.

Tripathi et al. [8] considered pavement sections of 1 mile (1.6km) each one to study the cost-effectiveness of fiber-reinforced trials compared with control unmodified sections. For the study, the inclusion of aramid fibers was evaluated under fatigue and rutting tests. Finally, the performance results were compared with the total pavement life cost. Although the estimated cost of production/mile was higher than the control trials, the cost of fatigue and rutting life was significantly less than the control sections. For instance, the fatigue and rutting analyses showed an improvement of 4.25 and 4.52 times, respectively on cost-savings of the fiber-reinforced mixes versus the control unmodified trials.

3 Laboratory Evaluation of Cracking Potential of Fiber Modified Asphalt Mixes

3.1 Abstract

In cold regions such as Canada, pavement structures are subject to extremely low air temperatures and seasonal freeze-thaw cycles over the life cycle of the roadway, resulting in pavement distress, deterioration, and decreased service life. Each year, billions of dollars are spent in Canada on rehabilitation and new construction of asphalt pavements. Hence, the prevention of premature failure has become of prime strategic importance for road owners.

Fibers have already been used to reinforce paving materials for many decades in various parts of the world. Polymer fibers have high tensile strength relative to asphalt mixtures, and thus, have the potential to improve the cohesive and tensile strength of bituminous mixes and prevent crack propagation in the resulting composite. The most commonly used polymer fibers are polyester, polypropylene, aramid, and various combinations of these. There has, however, been less attention to the incorporation of fibers in asphalt mixes to improve resistance to thermal cracking, an application that would prove extremely beneficial for road construction in cold climates.

The objective of this research is to evaluate the effectiveness of adding polymer fibers to hot mix asphalt to increase its resistance to thermal cracking. For this purpose, three different types of polymer fibers including aramids, polyethylene terephthalate (PET) and polyacrylonitrile (PAN), in different sizes, were added to conventional hot asphalt mixes. The resulting samples were compacted in the laboratory and their mechanical properties were compared to conventional hot mix asphalt.

3.2 Introduction and Background

Asphalt concrete withstands forces very well in compression but not in tension [14]. Therefore, there is ongoing research to improve the tensile strength performance and thus, the service life of asphalt pavement. The addition of specific fibers to asphalt mixes is one possible solution for increasing asphalt tensile strength and consequently, improving its resistance to cracking [4], [19]. Thermal cracking is a critical concern in asphalt pavements in cold regions, including Canada, because the pavement is not only subjected to vehicle loading but also to thermal stresses during cold seasons [15], [39].

Fibers have already been used to reinforce paving materials for many decades in various parts of the world [3], [24] and their main application in asphalt mixes has been to prevent drain-down of the binder from the aggregate particles [8]. Polymer fibers have high tensile strength relative to asphalt mixtures and thus have the potential to improve the cohesive and tensile strength of bituminous mixes and prevent crack propagation in the resulting composite [2], [19], [40]. The most commonly used polymer fibers are polyester, Polyethylene Terephthalate (PET), polypropylene, aramid, and combinations of these [4], [22], [36], [41]. However, there has not been an adequate literature review on the incorporation of fibers in asphalt mixes to improve resistance to thermal cracking, an application that would be extremely beneficial for road construction in cold climates. The appropriate specifications and material characteristics to ensure the best performance of asphalt mixes containing fibers in cold climates and under different traffic loading conditions have also not been widely investigated [2].

There is a broad discussion about the use of different fibers in asphalt mixes in the literature [3], [14], [17], [18]. The main drawbacks of natural fibers for this application are not only that they are affected by water, which reduces their limited tensile strength and stiffness, but also they are subject to attack by fungi and have a high absorption of binder, which is not cost-effective. For synthetic polymers, the melting point needs to be considered because this might result in a serious loss of desirable physical properties, such as a reduction in strength. Inorganic materials, such as asbestos, have been widely used for many years but are limited due to the associated health hazards. Glass fibers have a high tensile modulus, but are very brittle and easily broken during the construction stage. Finally, carbon fibers can be very strong (60 GPa) but their cost and low modulus (70 GPa) limit their usage.

The addition of polyester fibers to asphalt mixes has resulted in enhancement of the fatigue properties [13], [25], tensile strength [19], [27], [38], and freeze-thaw resistance [18], while decreasing cracking potential [19], [38], [42] and rutting distress [8], [40]. The use of a blend of polypropylene and aramid fibers in an asphalt mixture in an airport pavement in a cold climate was estimated to result in an increase in the service life of 8 years, which could yield a 33% decrease in CO2 emissions [7]. Finally, PET fibers, which are part of a group of polyesters, are affordable fibers that show similar or better improvements in asphalt mixes [35]. Beyond the consideration of its mechanical properties, PET use may help to reduce the impact of waste plastic material by re-using waste materials [34].

3.3 Objectives and Scopes

The objective of this paper is to analyze the impact of fibers on the cracking resistance of asphalt mixes at intermediate and low temperatures. For this purpose, a mix design was prepared for hot mix asphalt and the optimum fiber content was determined. To investigate the cracking resistance of asphalt mixes at intermediate temperatures, samples modified with fibers were evaluated conducting the Indirect Tensile Strength test (ITS) by conditioning the samples using freeze and thaw cycles. To investigate the cracking resistance of the fiber-modified mixes at low temperature, the Indirect tensile creep compliance and strength (IDT) test was performed at -20°C.

3.4 Materials and mix design

A control asphalt mix was first designed using asphalt cement with a performance grade (PG) of 58-31. The aggregate grain size distribution of the control mix is shown in Table 3.1. The properties of the control mix are summarized in Table 3.2.

TABLE 3-1: Combined Aggregates Gradation of Control Mix

	Sieve size(mm)										
Aggregate	12.5	10	8	6.3	5	2.5	1.25	0.63	0.315	0.16	0.08
% passing	1	0.983	0.885	0.754	0.648	0.49	0.395	0.327	0.202	0.103	0.051

TABLE 3-2: Mix Design and Volumetric Properties

Mix Design Properties	Actual	Specifications
Number of gyrations	100.0	100.0
Asphalt Cement (A.C.)%	5.5	-
Gmm (kg/m3)	2431	
Gmb (kg/m3)	2337	
Air Voids (%)	3.9	3.6 - 4.4
VMA (%)	14.9	13
VFA(%)	73.8	70 - 80
%Gmm @ Nmax	96.8	98.0 max.
Dust /AC	1.0	-

The HMA was modified with three types of fibers. These are PET fibers, uncoated aramid fibers, and polyacrylonitrile (PAN) fibers, which are shown in Figure 3.1. The basic properties of the fibers are given in Table 3.3.

TABLE 3-3: Fiber properties

Fiber(s)	Aramid Fiber	PET fiber	PAN fiber
Length (mm)	38±1.3	6±1.5	6±1
Diameter (µm)	15	20	11
Density (g/cm^3)	1.44-1.45	1.41	1.18
Tensile Strength (MPa)	> 2758	≥500	600
Melting point (°C)	> 425	≥256	≥220

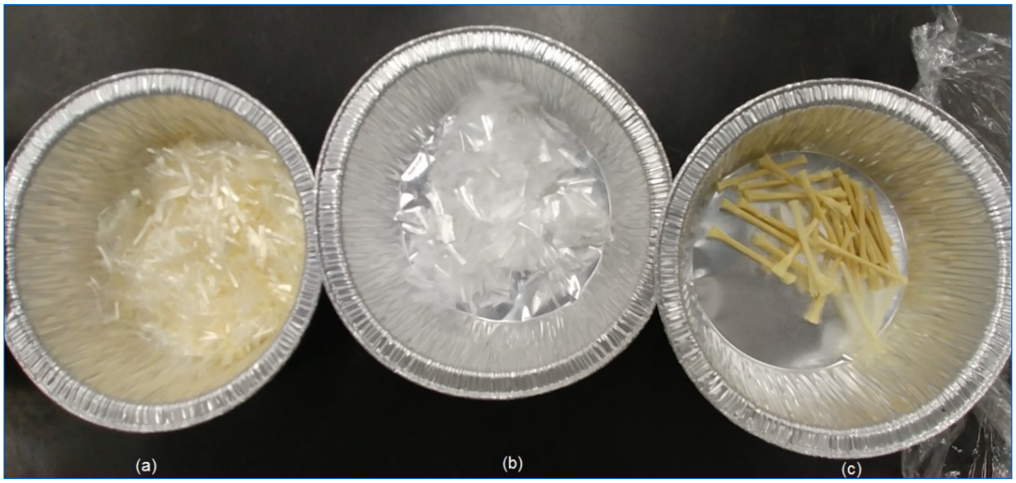

Figure 3-1: Photo of fibers selected for the study: (a) polyacrylonitrile (PAN) fibers (b) polyethylene terephthalate (PET) fibers (c) uncoated aramid fibers

According to Abtahi et al. [3], the most common methods for the introduction of fibers in HMA samples are the wet process and the dry process. In the first case, fibers are blended with the binder before the addition of it into the traditional asphalt mixing process; but in the other case, fibers are mixed with aggregates prior to the addition of binder. In both cases, there is a random inclusion of fibers into the bucket mixer.

For the present work, the dry process was followed, with a minor change. Instead of mixing the dry aggregate with the fibers prior to the addition of binder, the standard mixing process between the aggregate and the asphalt binder was followed. Once the aggregates were perfectly coated after 1-minute on average, fibers were gradually introduced into the mixing bucket until they were coated completely. In total, the mixing time was 2-2.5 min. This approach allowed better control of some drawbacks such as binder absorption of fibers.

3.5 Optimum fiber content

The appropriate amounts of each type of fiber were selected based on the maximum allowable air void content of the modified mix. The binder content was kept constant, to allow for comparison between the properties of the modified mix and control mix. Table 3.4 shows the effect of the addition of different amounts of PET fiber to the asphalt mix. From the table, it can be concluded the maximum value for PET fiber should be 0.1% by weight of mix to maintain the target void content of three to five percent. To increase the PET content to 0.2%, the mix design should be modified by adding 0.5% of asphalt cement.

Table 3.5 shows the impact of adding PAN fiber to the volumetric properties of the asphalt mix. From Table 3.5, the trend shows that the air voids content increased as the percent of PAN content increased. The maximum amount of PAN fiber to maintain the allowable air void content was calculated as 0.065% by the total weight of the mix.

TABLE 3-4: PET fiber content (percentage by weight), air void content and its increment in (%) binder

Type of Fiber	Fiber content (%)	Binder Content (%)	Gmb	Air Void (%)
PET fiber	0.5	5.5	2.24	7.82
	0.4	5.5	2.25	7.45
	0.3	5.5	2.30	5.59
	0.2	5.5	2.29	5.62
	0.1	5.5	2.34	3.82
	0.065	5.5	2.35	3.48
PET fiber	0.4	6.0	2.27	6.81
	0.3	6.0	2.31	4.79
	0.2	6.0	2.34	3.62

TABLE 3-5: PAN fiber content (percentage by weight), air void content and its increment in (%) binder

Type of Fiber	Fiber content (%)	Binder Content (%)	Gmb	Air Void (%)
PAN fiber	0.4	5.5	2.22	8.58
	0.3	5.5	2.27	6.43
	0.2	5.5	2.29	5.79
	0.1	5.5	2.30	5.44
	0.065	5.5	2.33	3.97
PAN fiber	0.3	6.0	2.13	5.25
	0.2	6.0	2.32	4.62

Aramid fibers are the most expensive of the three types of fibers used. Taking this into account, the addition of aramid fibers was restraint by the optimal PAN fiber content (0.065 %wt). After running some tests with 0.065%wt of Aramid fibers, the output was an improvement in mechanical properties of asphalt concrete (AC) mixes, without any affection on the air void content of the mix. From this outcome, the dosage of aramid fibers used was reduced 10 times, testing Asphalt Concrete mixes with a comparative dosage of 0.00065% by weight.

3.6 Indirect tensile test (ITS)

Sets of three different samples for each type and amount of fiber were prepared and tested following the standard AASHTO T-283 [43]. One set of three samples was tested in dry conditions, and another set of three was tested after conditioning. For conditioning, the samples were saturated in water and subjected to a single freeze-thaw cycle [43]. The saturated samples were sealed in a plastic package and stored in a freezer for 16 hours at -18°C. After that, the samples were placed in a warm water bath at 60°C for 24 hours. Then, they were placed in a water bath at 25°C for two hours. Finally, an ITS test was conducted at room temperature (25°C) by applying a constant rate of vertical deformation (50.8 mm/min) until the sample failed. Figure 3.2 shows wrapped samples in the freezer, as well as a sample undergoing the testing procedure.

The moisture susceptibility of AC mixes indicates the potential damaged by water, which affects the bond between the aggregates and asphalt binder, precipitating the occurrence of distresses such as raveling and cracking [12].

The results of the ITS test are shown in Table 3.6. As can be seen in the table, the changes in the tensile strength of the fiber-modified samples are not significant compared with the control mix. Additionally, the tensile strength ratio (TSR) for each sample is above 75%, indicating that all mixes may have adequate resistance against damage induced by moisture. From literature review, minimum TSR values are above 70-75% [12], [24], [44].

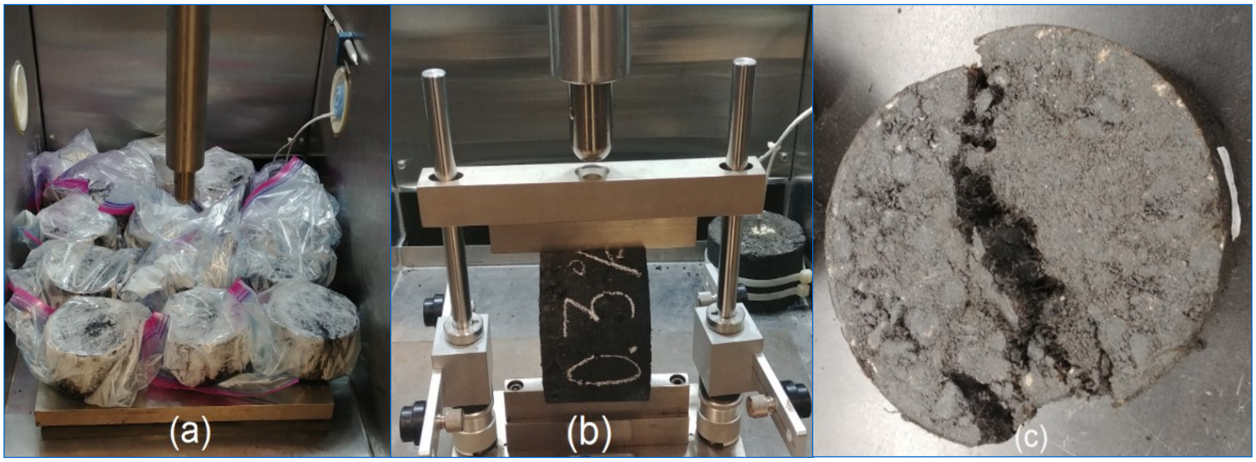

Figure 3-2: ITS test process: (a) frozen samples, (b) application of force to the sample, and (c) a broken sample

TABLE 3-6: ITS test result for fiber modified and unmodified samples

Mixture	Dry		Saturated		
	Maximum Load (N)	Tensile Strength (kPa)	Maximum Load (N)	Tensile Strength (kPa)	Tensile Strength Ratio
NO FIBER, 5.5% binder	9575.3	943.1	12728.7	1272.5	1.3
0.0065% ARAMID, 5.5% binder	9522.7	945.2	12624.0	1140.8	1.2
0.065% ARAMID, 5.5% binder	12170.3	1202.7	12624.0	1252.6	1.0
0.1% PET, 5.5% binder	12194.3	1188.5	11607.3	1150.0	1.0
0.065% PAN, 5.5% binder	10300.0	1026.7	11358.7	1121.3	1.1
0.2% PAN, 6.0% binder	10786.3	1059.0	9971.7	979.9	0.9
0.3% PET, 6.0% binder	12506.3	1219.2	8158.7	793.3	0.7

3.7 Determination of cracking tolerance index of asphalt mixtures (IDEAL CT Test)

The standard ASTM D8225-19 [45] was used to calculate the cracking resistance of the asphalt mixtures, based on fracture mechanics theory. The cracking index or CT_{Index} is obtained from the fracture energy (G_f), which has a proportional relationship to the cracking resistance and is defined as:

$$CT_{Index} = \frac{t}{62} * \frac{l_{75}}{D} * \frac{G_f}{|m_{75}|} * 10^6 \ldots\ldots\ldots\ldots\ldots (2)$$

Where CT_{Index} is the cracking tolerance index, t is the specimen thickness (mm), l_{75} is the displacement at 75% of the peak load after the peak (mm), D is the specimen diameter (mm), G_f is the fracture energy (J/m^2), and m_{75} is the post-peak slope around the 75% peak load point after the peak (N/m). Further reference to parameters is shown in Figure 3.3.

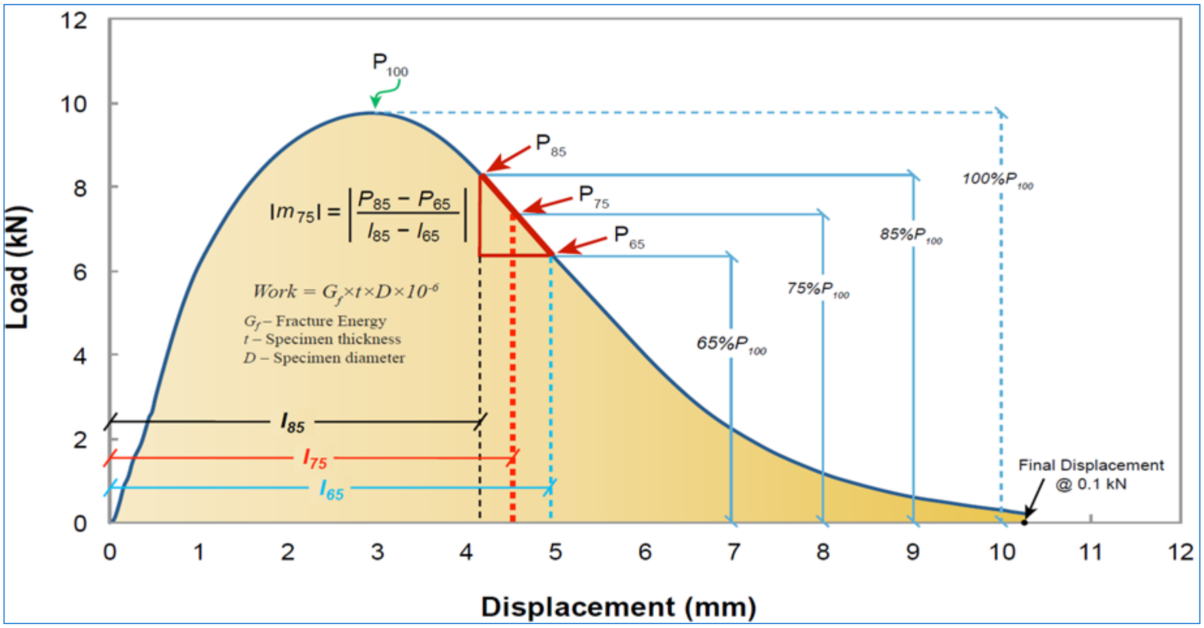

Figure 3-3: Parameters within the force-displacement curve, ASTM D8225 reference

The work of fracture (W_f) is estimated as the area under the force-displacement curve (see Figure 3.3). The fracture energy (G_f) is calculated by dividing the work of fracture (W_f) by the cross area of the specimen (the product of the diameter and thickness of the sample).

For calculation of the cracking tolerance index (CT_{Index}), Force versus Vertical displacement graphs from the dry ITS test were used (Figure 3.4). The results of the calculation are shown in Table 3.7.

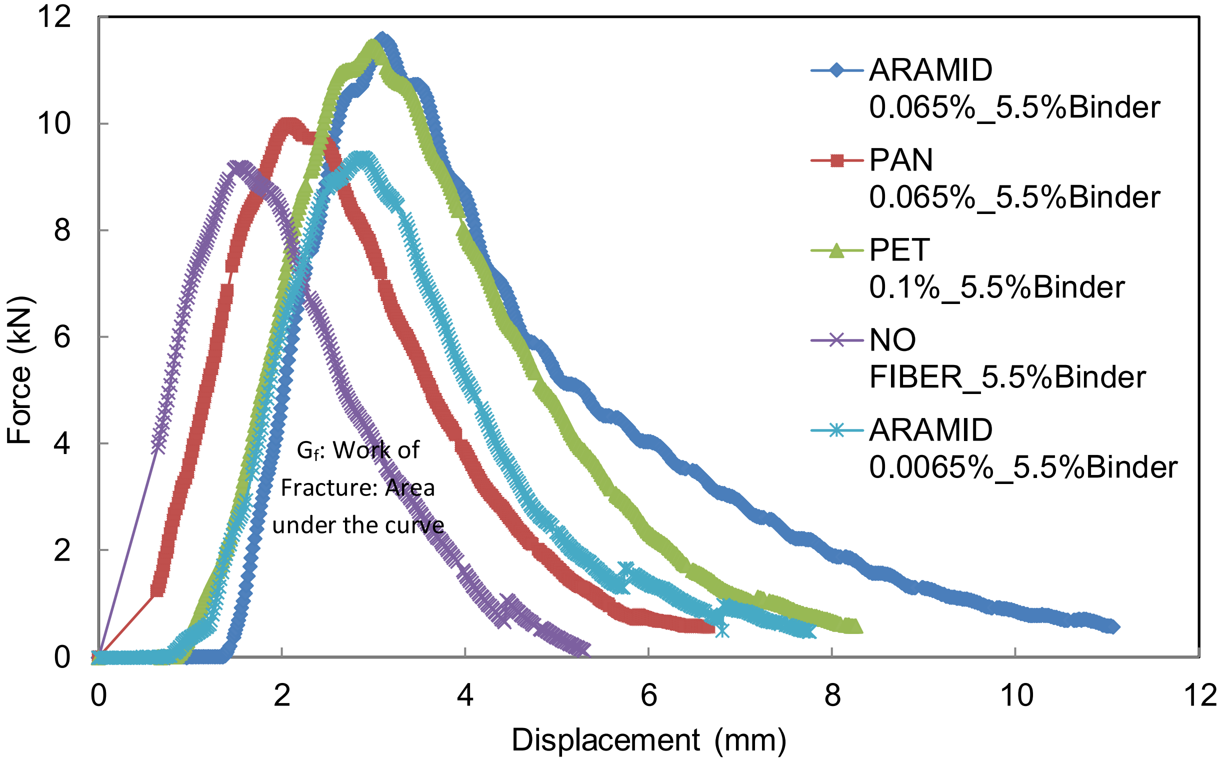

Figure 3-4: Force-Displacement curve: work of failure (W_f) - area under the curve

Using Figure 3.4, three parameters were determined through the CT_{Index} calculation, the energy dissipated up to the point of maximum load (pre-cracking energy), the energy dissipated after the point of maximum load (post-cracking energy) and the total energy: that is, the sum of the previous two values. In general, the pre-cracking energy is an indicator of the cracking resistance, the post-cracking energy is an indicator of cracking propagation and total energy is a good indicator of the cracking potential of asphalt concrete (AC) mixes [19], [27].

The results of the calculation are given in Table 3.7, it can be seen that there was a significant difference between the fracture energy of the fiber-reinforced asphalt mixes compared to the control mix. Aramid fiber (0.065%wt) and PET fiber (0.1%wt) showed a significant increase in fracture energy (between 70% to 100% for the same binder content). This indicates that the addition of these fibers retarded crack propagation in the tested samples. Comparing the CT indices for the mixtures, the CT index of aramid- and PET-modified mixes are 3.2 and 1.9 times greater than the CT index of the control mix. The PAN fiber (0.065%wt) and Aramids (0.0065%wt) modified mixes, minimum differences were observed in the CT indices that were still 160% and 230% higher compared to the control mix. The table shows that using higher amounts of PAN fibers, will improve the cracking resistance, but increasing the binder content (see Table 5). Finally, post-crack toughness for Fiber Reinforced Asphalt Concrete (FRAC) mixes increased from 20% to 120% compared to the control mixe; however, there was no significant change in the pre-crack toughness.

TABLE 3-7: CT Index Results for Different Fiber Mixes

MIXTURE	Pre-crack Toughness	Post-crack Toughness	Work of Failure (kN.mm)	Fracture Energy (J/m^2)	CT Index
NO FIBER, 5.5% binder	7.9	14.0	21.8	3374.9	17.3
0.0065% ARAMID, 5.5% binder	9.4	16.7	26.1	4058.6	39.5
0.065% ARAMID, 5.5% binder	11.2	32.2	43.4	6731.4	73.1
0.1% PET, 5.5% binder	12.7	24.7	37.5	5736.1	51.0
0.065% PAN, 5.5% binder	10.3	18.4	28.8	4502.9	27.9
0.2% PAN, 6.0% binder	11.9	27.3	39.2	6039.6	108.9
0.3% PET, 6.0% binder	15.6	39.0	54.6	8360.0	188.1

3.8 Determination of Indirect tensile creep compliance and strength (IDT) test

Indirect tensile strength and creep compliance of HMA mixes are the two main outputs of the IDT test based on AASHTO T322-07 [46]. For this test, different sets of fiber-modified mixes and the control mix were prepared using a gyratory compactor. Each set of specimens was conditioned for three hours at -20°C and then tested using an IPC Global Universal Testing Machine (UTM-100). The cylindrical specimens were loaded vertically to a target creep load of 1 kN for 100 seconds, after which the IDT test was conducted at a loading rate of 12.5 mm/min. Specimen displacement was measured using horizontal and vertical linear variable differential transducers (LVDTs) mounted on brass gauge points with a gauge length of 75 mm on each face of the specimen (see Figure 3-5).

Figure 3-5: (a) IDT samples, (b) test configuration

Figure 3.6 shows a qualitative comparison between a cracked fiber modified sample and the control mix after an IDT test. As can be seen in the figure, unlike the control mix, the fiber-reinforced mixes were not completely separated after cracking. The samples modified with PET (0.1 % by weight) and aramid (0.065 % by weight) showed the best fracture performance in terms of slowing down crack propagation.

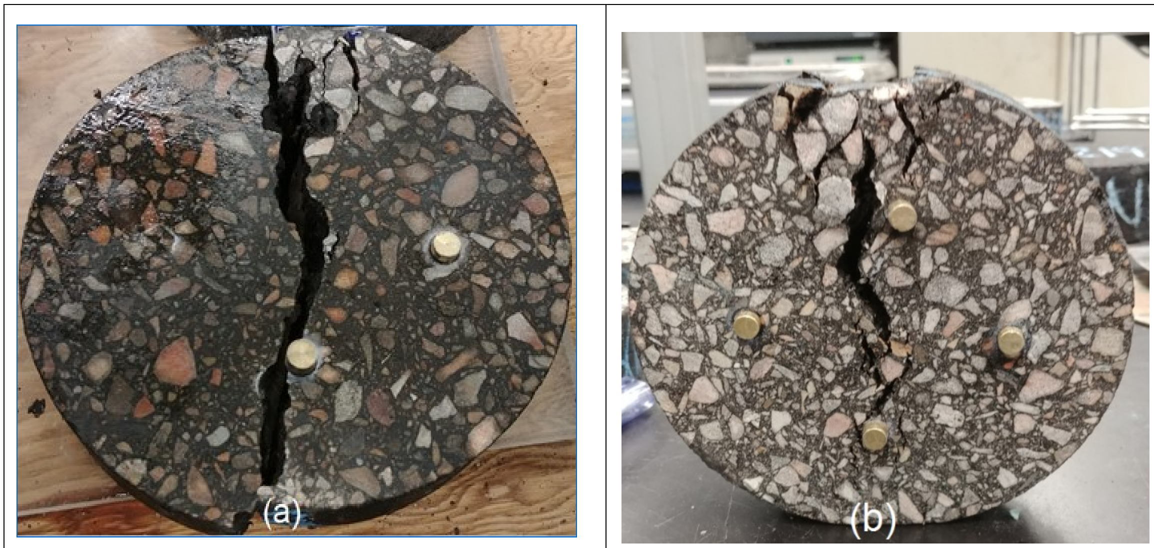

Figure 3-6: IDT test results at -20°C: (a) control mix, (b) PET (0.1 %wt) and aramid (0.065 % wt) fiber modified mix

The summary of the IDT test results is given in Table 3.8. From this table, the tensile strength for fiber modified mixes does not show a significant difference compared to the control mix. However, all fiber-modified samples have higher fracture energy compared to the control mix at -20°C, with the exception of the samples modified with PAN. This shows that, in some cases, the fiber modified samples are more resistant to cracking at low temperatures compared to the control mix.

TABLE 3-8: Work and fracture energy of mixes containing different types and amounts of fiber

MIXTURE	Tensile strength (MPa)	Pre-crack Toughness	Post-crack Toughness	Work (kN.mm)	Fracture Energy (J/m^2)
NO FIBER, 5.5% binder	3.689	38.5	11.4	49.9	8630.6
0.0065% ARAMID, 5.5% binder	4.022	37.1	29.4	66.5	9319.3
0.065% ARAMID, 5.5% binder	3.029	30.9	53.8	84.8	13083.6
0.1% PET, 5.5% binder	3.571	36.3	40.3	76.7	11756.9
0.065% PAN, 5.5% binder	3.472	34.6	26.7	61.3	8824.5

3.9 Conclusions and Future Steps

The conclusions of this study are summarized as follows:

1. As previous After increasing the amounts of PET and PAN fibers into the mix, from 0.065% to 0.6% by the total weight, the results show fiber-modified mixes required a higher binder content because most of them present larger air voids content than the targeted content. The maximum amounts for mixes modified with PET and PAN fibers to maintain the same binder content as the control mix were 0.1% and 0.065% by the total weight of the mix, respectively. The addition of aramid fibers until the tested amount of 0.065%wt did not affect the volume of the mix. The results conclude that at the different fiber dosage used, there was no change in the mix design.
2. ITS test results showed that the addition of fibers did not significantly increase the tensile strength of the asphalt mixes. PET (0.1% by total weight), PAN (0.065% by total weight),

Aramid (0.065% and 0.0065% by total weight) fiber-modified mixes were resistant to moisture after freeze/thaw conditioning.

3. The comparison among the fracture energy and CT indices of fiber-modified mixes with the control mix showed that the addition of fibers has significantly improved the cracking resistance of the asphalt mixes. Aramid (0.065%wt) and PET (0.1%wt) fiber-modified mixes had the most significant improvement in both parameters.
4. Findings from the IDT test at -20°C showed that at low temperatures, the crack propagation of modified samples is slowed down by the fibers, especially for PET (0.1%wt) and Aramid (0.065%wt). In addition, the fracture energy of fiber-modified mixes was significantly higher compared to the control mix, which demonstrates the higher cracking resistance of the modified mixes.
5. Testing at room temperature (25°C) and at low temperature (-20°C) concludes that fibers work actively, especially after the cracking starts. The post-crack toughness values collected after running all tests improved up to 80%, limiting the crack propagation once the crack starts.

Based on the above conclusions, it is advisable as the next steps for the research, future performance tests are needed to better understand the effects of fiber added to the asphalt concrete mixes. These tests could include dispersion analysis, fatigue cracking, rutting tests and IDT tests at other temperatures, which may give a better understanding of the fiber-reinforced mixes at high and low temperatures.

4 Laboratory investigation of the performance evaluation of fiber modified asphalt mixes in cold regions

4.1 Abstract

Thermal cracking is caused by contraction of the asphalt layer at low temperatures; tensile stresses build up to a critical point at which a crack is formed. The cracks formed propagate under traffic loading conditions. Freeze-thaw cycles accelerate crack propagation and asphalt layer deterioration and can also lead to the formation of more severe distresses such as potholes. Fibers have attracted increasing attention in the asphalt industry for use as asphalt concrete modifiers. The addition of fibers to hot mix asphalt results in a composite material that has higher tensile strength, along with the ability to absorb greater energy during the fracture process. The fibers within the material also act as a crack barrier, preventing the formation and propagation of cracks in the asphalt mix.

This research focuses on the evaluation of the effectiveness of adding polymer fibers to hot mix asphalt to increase both its resistance to cracking at intermediate and low temperatures, and its rutting resistance and moisture susceptibility at high temperatures. For this purpose, three different types of polymer fibers, including aramids, polyethylene terephthalate (PET) and polyacrylonitrile (PAN), were added to conventional hot asphalt mixes. The resulting samples were compacted in the laboratory and their mechanical properties were compared to conventional hot mix asphalt in the laboratory. At the end of this report, a material cost comparison is provided as a reliable source of information when selecting materials to fulfill minimum industry specifications.

4.2 Introduction and Background

Canada has an extensive network of paved roads, in which asphalt concrete roads represent almost 95% of the total infrastructure [47]. Maintenance and preventive plans play an important role in extending service life, especially in cold regions like Canada. The reason is the pavement is not only subjected to vehicle loads but also to thermal stresses during cold seasons [2], [15], [39]. Thermal cracking is the most concerning pavement distress in freezing conditions [2]. Considering that asphalt concrete withstands forces very well in compression but not in tension [14], there has long been discussion about improving asphalt pavement performance not only against thermal cracking but also against rutting and fatigue cracking. The inclusion of fibers in asphalt mixes controls mentioned distresses with improving mechanical properties such as tensile strength, stiffness, crack appearance control, crack propagation and toughness [3], [16], [19], [22], [40]. Consequently, the addition of fibers increases pavement service life [24].

There is a broad discussion in the literature about the use of different fibers in asphalt mixes [3], [14], [17], [18]. Fibers are normally classified based on their origin [17] and include but are not limited to natural fibers, polymer fibers, inorganic fibers, carbon fibers, steel fibers, and glass fibers. The main drawback of natural fibers is that they are affected by water, which reduces their limited tensile strength and stiffness. Natural fibers are also subject to attack by fungi and have a high absorption of binder, which is not cost-effective. For synthetic polymers such as polyester and polypropylene, the melting point needs to be considered because it may result in a serious loss of desirable physical properties such as strength. Inorganic materials, such as asbestos, were widely used for many years but use is now limited due to the associated health hazards. Carbon fibers can be very strong (60 GPa), have no melting point limitations and good electrical conductivity, but their cost and low modulus (70 GPa) limit their usage. Steel fibers have electrical conductivity potential as well, but they might get corroded upon exposure to water. Finally, glass fibers have a high tensile modulus, but are very brittle and easily broken during the construction stage.

In the literature, laboratory and trial results have shown that the addition of polymer fibers to asphalt mixes has resulted in the enhancement of fatigue properties [4], [13], [25], [26], tensile strength [19], [27], [28] and freeze-thaw resistance [5], [18], as well as decreased cracking potential [16], [19] and rutting susceptibility [8], [24]. However, there has not been a broad investigation about the incorporation of fibers in asphalt mixes to improve resistance to thermal cracking, an application that would be extremely beneficial for road construction in cold regions, where temperatures can drop below -30°C.

Fiber inclusion in asphalt mixes is normally random [3], but an adequate dispersion must be achieved to get the necessary bond among fibers, asphalt cement, and aggregates [4]. The length of fiber may affect the performance. While shorter fibers might have a negligible effect on mixes, longer fibers give a better interlock effect between asphalt concrete (AC) components [17], [19]. Once the optimum fiber content is achieved, fiber agglomeration might provide meaningless results [16].

Aramid fibers are reported in different case studies, such as Muftah's work, which showed that a blend of polyolefin and aramid fibers acted effectively to reduce or control crack propagation [4]. Fibers acted as a bridge, connecting all mix components; larger amounts of fiber gave significant improvements [4], [17]. In 2018, Kaloush et al. reported that a blend of aramids and polypropylene gave a slight improvement of 25%-50% in tensile strength at different temperatures (T°), and concluded that the strength followed a pattern: when the T° dropped, the tensile strength increased. Similarly, his work reported that the fracture energy of fiber-modified mixes was larger than the control mixes in 50%-75% of all tested temperatures and that the fracture energy maintained a direct relationship with T°: once the temperature went up, fracture energy followed an incremental tendency [40]. Comparable results are found in [24], [31]. Ho evaluated a blend of polyolefin and aramid fibers through laboratory experiments and 2-year field observations. The results showed fewer cracks in the fiber modified mixes compared with the control mix, with a cumulative crack length difference of 33.5 m [5].

Polyacrylonitrile (PAN) fiber used in asphalt concrete (AC) mixes is reported by Slebi et al., who observed improvements in rutting resistance, a slightly positive impact on the moisture susceptibility of the asphalt mixtures after the freeze-thaw effect, and superior fiber-binder-aggregate interlock [17]. Wang et al. concluded that PAN fiber-modified mixes had higher fatigue life than the control mix [26]. A drawback is the fiber's high absorption rate, which alters and increments the binder content [17], [18].

Polyethylene Terephthalate (PET) fibers, part of a group of polyesters, are affordable fibers that improve the fatigue and rutting resistance of asphalt mixes [34], [35]. Beyond the consideration of its mechanical properties, PET use may help to reduce the impact of waste plastic material by re-using plastic waste materials [34].

As cost-effectiveness is essential to justify fiber usage in all projects, the amount of fibers used should be controlled [38] to get a feasible and economical product, and it should be considered that an initial increase in project cost could be justified with an extension in years of service life and a decrease in CO2 emissions in the long term [7], [8].

4.3 Objectives and Scope

The objective of this paper is to analyze and compare the impact of different fibers (PET, PAN, and aramid) on performance parameters such as permanent deformation, moisture susceptibility and cracking resistance of asphalt mixes at high, intermediate and low temperatures. For this purpose, a mix design was prepared for hot mix asphalt (HMA) and the optimum content for each fiber was determined. To investigate the rutting resistance and moisture susceptibility at high temperatures, fiber-modified samples were tested by a Hamburg Wheel Tracking Device (HWTD) test. For the cracking resistance of asphalt mixes at intermediate temperatures, samples modified with fibers were evaluated by conducting an Indirect Tensile Strength (ITS) test at the dry condition and after freeze and thaw cycle. To investigate the cracking resistance of the fiber-modified mixes at low temperature, the Indirect Tensile Creep Compliance and Strength (IDT) test was performed at 0°C, -10°C, and -20°C. The stress-strain curves from the ITS and IDT tests were used to calculate the cracking tolerance (CT) index as a cracking resistance parameter. Finally, a short analysis of the cost-effectiveness of using different fibers in asphalt mixes was carried out.

4.4 Materials and mix design

4.4.1 Mix Design and Volumetric Properties

A control asphalt mix was first designed using asphalt cement with a performance grade (PG) of 58-31. The volumetric properties of the control mix are summarized in Table 4.1. The aggregate grain size distribution of the control mix is shown in Figure 4.1.

TABLE 4-1: Mix Design and Volumetric Properties

a) Mix Design Properties	Actual	Specifications
Number of gyrations	100.0	100.0
Asphalt Cement (AC)% of Total Mix	5.5	-
Gmm (kg/m3)	2431	
Gmb (kg/m3)	2337	
Air Voids (%)	3.9	3.6 - 4.4
VMA (%)	14.9	13
VFA (%)	73.8	70 - 80
%Gmm @ Nmax	96.8	98.0 max.
Dust /AC	1.0	-

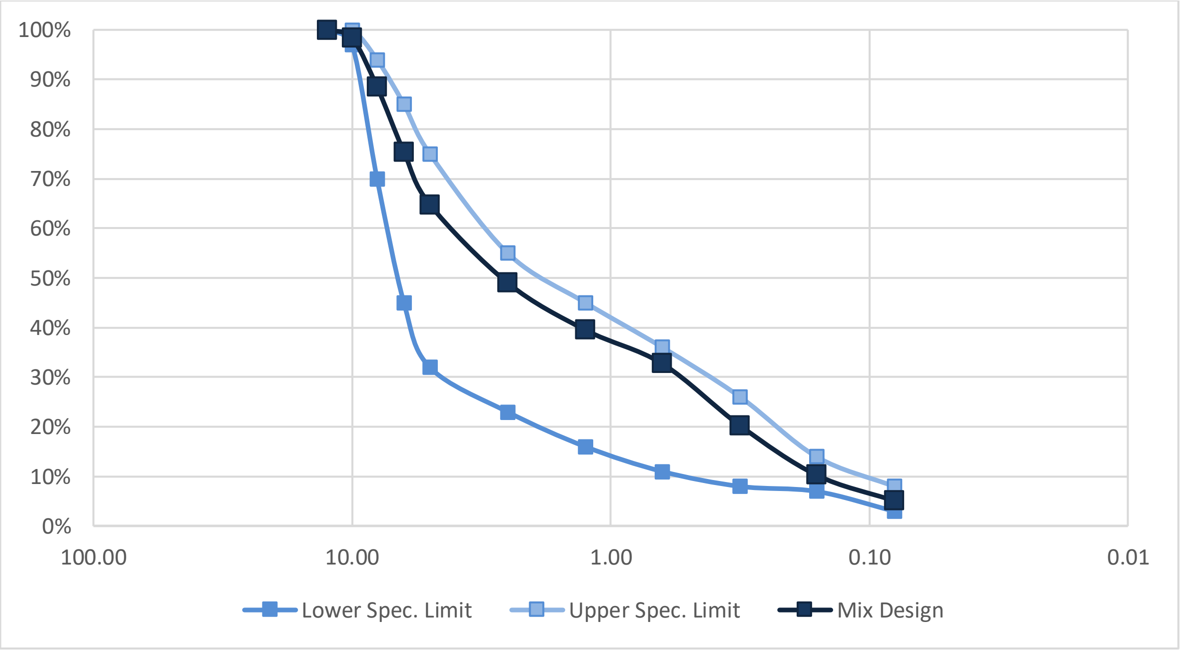

Figure 4-1: Combined aggregates gradation of control mix

4.4.2 Fiber Properties

The HMA sample was modified with three types of fibers. These are uncoated aramid (no wax coating) fibers, PET fibers, and PAN fibers, which are shown in Figure 4.2. The basic properties of the fibers are given in Table 4.2. The same mix design used for the control mix was used for fiber-modified mixes as well.

TABLE 4-2: Fiber Properties

Fiber(s)	Aramid Fiber	PET Fiber	PAN Fiber
Length (mm)	38 ± 1.3	6 ± 1.5	6 ± 1
Diameter (µm)	15	20	11
Density (g/cm^3)	1.44 - 1.45	1.41	1.18
Tensile Strength (MPa)	> 2758	≥ 500	600
Melting point (°C)	> 425	≥ 256	≥ 220

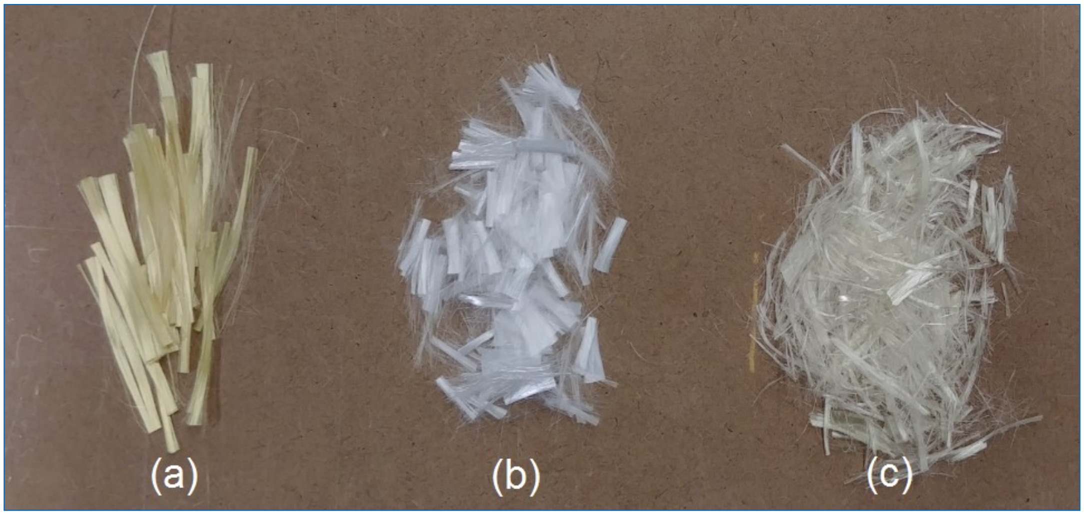

Figure 4-2: Photo of fibers selected for the study: (a) uncoated aramid fibers, (b) PET fibers, and (c) PAN fibers

4.4.3 Mixing process

As suggested in the literature review, an adequate dispersion of fibers is essential to get reliable mechanical improvements. To ensure an optimal result, each strand of uncoated aramid fiber was separated as much as possible using fingers prior to proceeding with the mixing operation (Figure 4.3). For PET fibers and PAN fibers, it was determined that no separation was needed prior to mixing.

According to [3], the most common methods for introducing fibers into HMA samples are the wet process and the dry process. In the wet process, fibers are blended with the binder and then, the modified binder is blended with aggregates. In the dry process, fibers are mixed with aggregates first, then placed into the mixing bucket prior to pouring the specified amount of asphalt binder into it. In both cases, there is a random inclusion of fibers in the bucket mixer.

For the present work, the dry process was followed, with a minor change. Instead of mixing the dry aggregate with the fibers prior to the addition of binder, the standard mixing process between the aggregate and the asphalt binder was followed. Once the aggregates were coated (after 1.5 minutes, on average), loose fibers were gradually introduced into the mixing bucket until they were coated completely (Figure 4.3). In total, the mixing time was 2.5-3.5 min. This approach allowed better control of some drawbacks such as binder absorption of fibers and agglomeration of fibers.

Figure 4-3: (a) Manual separation process of uncoated aramid fibers; (b) Uncoated Aramid fibers being poured into the mixing bucket; (c) aggregate-binder-fiber interlock result

4.5 Optimum Fiber Content

Fiber usage in asphalt mixtures increases the binder content mainly due to the binder absorption of fibers. The fiber addition may alter the original asphalt mix design by raising the optimum asphalt content [17]; however, an adjusted binder content might show results that confuse whether the mechanical improvement is because of the fibers or the increased binder content [19].

For the work presented in this paper, the appropriate amounts of each type of fiber were selected based on the maximum allowable air void content of the modified mix. The binder content was kept constant to allow for a comparison between the properties of the modified mixes and the control mix.

The following table summarizes the effect of the addition of different amounts of PAN and PET fibers to the asphalt mix (Table 4.3). As the table describes, the trend shows that the air void content increased as the amount of PAN content increased. The maximum amount of PAN fiber that would maintain the allowable air void content was calculated as 0.065% by the total weight of the mix.

On the other hand, the table shows that the maximum value for PET fibers needed to be 0.1% by weight of mix to maintain the target void content of 3%-5%. It was also concluded that to increase the PET content to 0.2%, the mix design should be modified by adding 0.5% asphalt cement.

TABLE 4-3: PAN and PET Fiber Content (Amount by Total Weight), Air Void Content and the Increment in (%) Binder

Type of Fiber	Fiber Content (%)	Binder Content (%)	Gmb	Air Void (%)
PAN Fiber	0.4	5.5	2.22	8.58
	0.3	5.5	2.27	6.43
	0.2	5.5	2.29	5.79
	0.1	5.5	2.30	5.44
	0.065	5.5	2.33	3.97
PAN Fiber	0.3	6.0	2.13	5.25
	0.2	6.0	2.32	4.62
PET Fiber	0.5	5.5	2.24	7.82
	0.4	5.5	2.25	7.45
	0.3	5.5	2.30	5.59
	0.2	5.5	2.29	5.62
	0.1	5.5	2.34	3.82
	0.065	5.5	2.35	3.48
PET Fiber	0.4	6.0	2.27	6.81
	0.3	6.0	2.31	4.79
	0.2	6.0	2.34	3.62

Aramid fibers are the most expensive of the three types of fibers used. Taking this into account, the addition of aramid fibers was restrained by the optimal PAN fiber content (0.065 wt%). Based on the supplier's recommendation, the amount of aramid fibers should be reduced 10 times, and the asphalt concrete mixes were tested with a comparative dosage of 0.0065% aramid fibers by weight.

4.6 Test results and discussion

4.6.1 Rutting Test

Sets of two cylindrical specimens with the same aggregate and same binder source for each type of fiber were prepared according to the standard AASHTO T 324-16 [48]. They were compacted in the laboratory with a Superpave Gyratory Compactor, in accordance with AASHTO T 312 [49], at a target height of 60 ± 1 mm, a diameter of 150 mm and 7.0% ± 0.5% air voids. Once the samples cooled enough, they were sawed along a secant line to allow joining, controlling to not exceed a gap of 7.5 mm once they were placed in the high-density polyethylene molds.

Before placing the specimens into the Hamburg Wheel Tracking Device (HWTD), the device was conditioned at the required temperature of 45°C [50]. Then, the samples were conditioned for a timeframe of 30 minutes prior to starting the test. In accordance with AASHTO T 324-16, the HWTD device evaluates not only the rutting potential of the asphalt concrete mix but also the moisture susceptibility of AC mixes. The machine applied a cyclic load of 705 ± 4.5 N via 47-mm steel wheels over the specimen, at a frequency of 52 ± 2 passes per minute and a maximum speed of 0.305 m/s at the midpoint. The HWTD is set up to stop either when 20,000 passes or a 12-mm rut depth is achieved at a predefined temperature of 45°C.

A summary of the five types of samples prepared and tested is presented in Table 4.4. The base point was the control mix (PG 58-31 without fibers), which failed at 12,428 passes and a rut depth of 12 mm. On the other hand, the fiber-modified replicates performed better, with an increased number of passes until failure. For instance, the aramid fiber (0.0065 wt%) and PAN fibers (0.065 wt%) showed a gain of 1,544 passes and 5,546 passes, respectively. Results also showed that aramid (0.065 wt%) and PET fiber (0.1 wt%) achieved much greater effects on reducing the maximum rut depth to 7.5 mm and 9.0 mm respectively (a 25% to 37.5% rut reduction).

TABLE 4-4: Rutting Test Results for All Fiber-Modified Mixes

Mixture type	Test Temperature (45°C)	Air Void Content (%)	Stripping Inflection Point (# of passes / mm)	Failure (# of passes)	Rut Depth (mm)
No Fiber, 5.5% Binder	45.0	5.97	10350 / 7.5	12428.0	12.0
0.0065% Aramid, 5.5% Binder	45.0	6.50	9619 / 8.7	13972.0	12.0

0.065% Aramid, 5.5% Binder	45.0	6.24	13445 / 5.8	20000.0	7.5
0.1% PET, 5.5% Binder	45.0	6.43	14253 / 6.5	20000.0	9.0
0.065% PAN, 5.5% Binder	45.0	5.74	14908 / 6.8	17974.0	12.0

Figure 4.4 shows the different stages of the wheel tracking test for different asphalt samples. As it can be seen in the figure, aramid fibers (0.065 wt%), PAN fibers (0.065 wt%) and PET fibers (0.1 wt%) all show smooth slopes, indicating better material stability. The overall improvement might be because of the fiber dosage, the length of fibers and the binder-aggregate-fiber interlock [18].

Another comparative result is the increment in the number of passes at the Stripping Inflection Point (SIP), which is a reference point to evaluate how susceptible an AC mix is to moisture. With the exception of the aramid fiber sample (0.0065 wt%), all other fiber composites showed significant improvements (30%-45%).

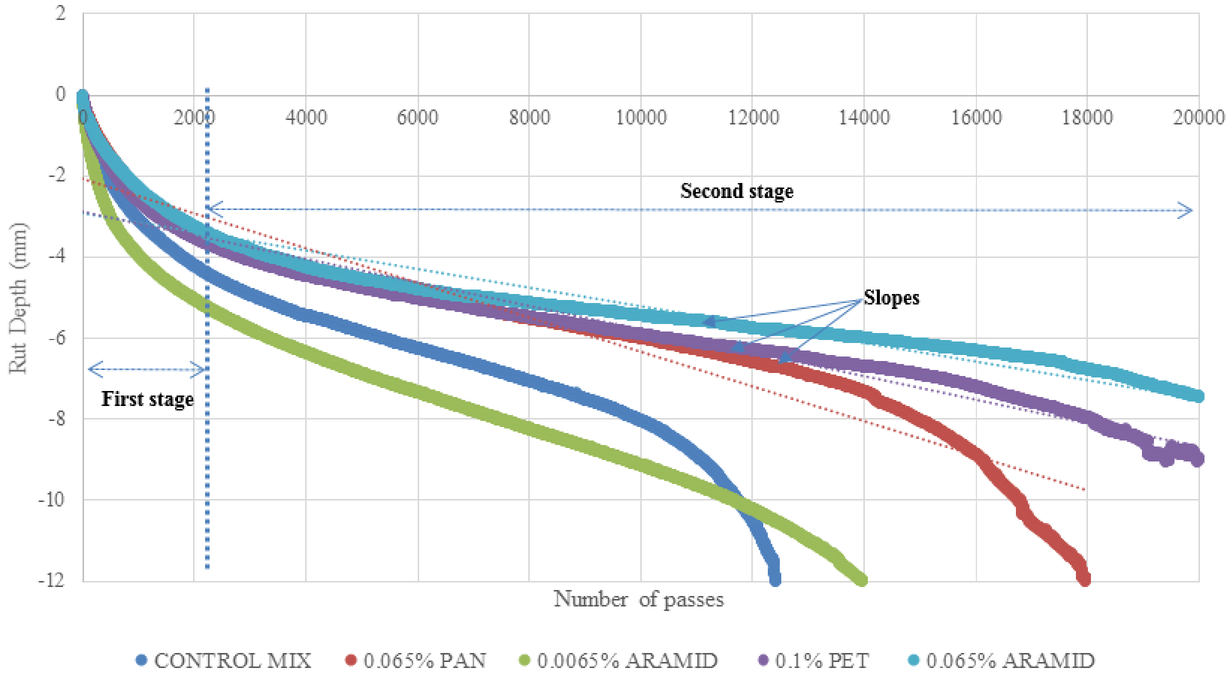

Figure 4-4: Rutting developments of fiber-modified asphalt mixes

Finally, visual inspection showed (Fig 4-5) what was observed in the analysis presented above

Figure 4-5: Rutting developments of: (1) PAN 0.065%; (2) CONTROL mix; (3) PET 0.1%; (4) ARAMID 0.0065%; (5) ARAMID 0.065%

4.6.2 Indirect Tensile Strength Test

Two sets of three different samples for each type and amount of fiber were prepared and tested following the standard AASHTO T 283 [43]. One set of three samples was tested in dry conditions, and another set of three was tested after conditioning. For conditioning, the samples were saturated in water and subjected to a single freeze-thaw cycle [43]. The saturated samples were sealed in a plastic package and stored in a freezer for 16 hours at -18°C. After that, the samples were placed in a warm water bath at 60°C for 24 hours. Then, they were placed in a water bath at 25°C for two hours. Finally, an Indirect Tensile Strength (ITS) test was conducted at room temperature (25°C) by applying a constant rate of vertical deformation (50.8 mm/min) until the sample failed.

The moisture susceptibility of AC mixes indicates the potential of damage from water, which affects the bond between the aggregates and asphalt binder and precipitates the occurrence of distresses such as raveling and cracking [12].

The results of the ITS test are shown in Table 4.5. As can be seen in the table, the changes in the tensile strength of the fiber-modified samples are not significant compared with the control mix. Additionally, the tensile strength ratio (TSR) for each sample is above 70%, indicating that all mixes may have adequate resistance against damage induced by moisture. As indicated in the literature review, minimum TSR values are above 70%-75% [12], [24], [44].

TABLE 4-5: Indirect Tensile Strength Test Results for Fiber-Modified and Unmodified Samples

Mixture	Dry		Saturated		
	Maximum Load (N)	Tensile Strength (kPa)	Maximum Load (N)	Tensile Strength (kPa)	Tensile Strength Ratio
No Fiber, 5.5% Binder	9575.3	943.1	12728.7	1272.5	1.3
0.0065% Aramid, 5.5% Binder	9522.7	945.2	12624.0	1140.8	1.2
0.065% Aramid, 5.5% Binder	12170.3	1202.7	12624.0	1252.6	1.0
0.1% PET, 5.5% Binder	12194.3	1188.5	11607.3	1150.0	1.0
0.065% PAN, 5.5% Binder	10300.0	1026.7	11358.7	1121.3	1.1
0.2% PAN, 6.0% Binder	10786.3	1059.0	9971.7	979.9	0.9
0.3% PET, 6.0% Binder	12506.3	1219.2	8158.7	793.3	0.7

4.6.3 Determination of Cracking Tolerance Index of Asphalt Mixtures

The standard ASTM D8225-19 [45] was used to calculate the cracking resistance of the asphalt mixtures, based on fracture mechanics theory. The cracking tolerance (CT) index is obtained from the fracture energy (G_f), which has a proportional relationship to the cracking resistance and is defined in Equation 1:

$$CT_{Index} = \frac{t}{62} * \frac{l_{75}}{D} * \frac{G_f}{|m_{75}|} * 10^6 \quad \text{...........} (3)$$

Where CT_{Index} is the cracking tolerance index, t is the specimen thickness (mm), l_{75} is the displacement at 75% of the peak load after the peak (mm), D is the specimen diameter (mm), G_f is the fracture energy (J/m^2), and m_{75} is the post-peak slope around the 75% peak load point after the peak (N/m). All defined parameters are shown in the graph below, including the Work of fracture (W_f) as the area under the force-displacement curve (Figure 4.6.a), which was extracted from ASTM D8225 [45]. G_f is calculated by dividing W_f by the cross area of the specimen (the product of the diameter and thickness of the sample).

For calculation of the CT index, Force versus Vertical displacement graphs from the dry ITS test were used (Figure 4.6.b).

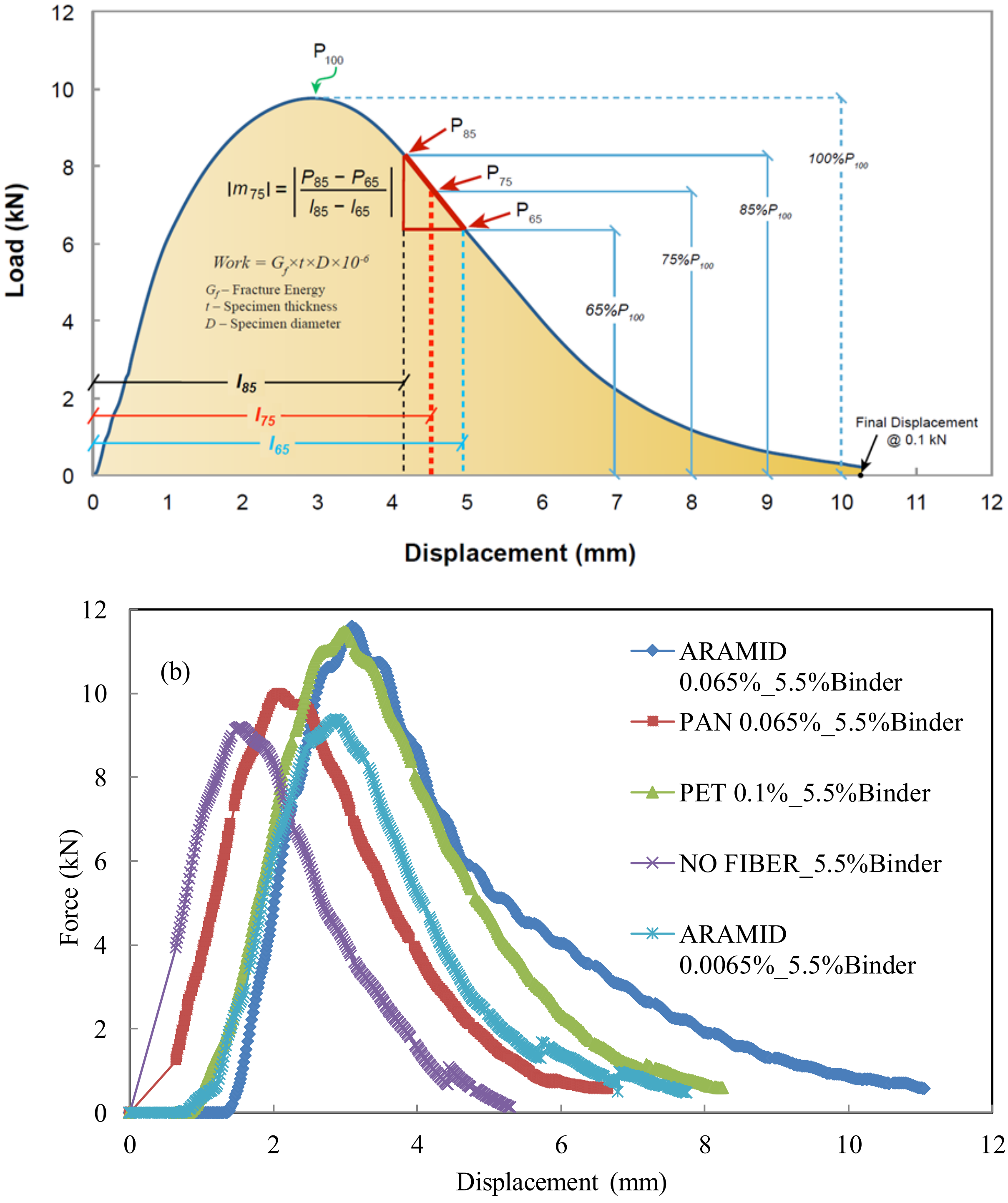

Figure 4-6: (a) Parameters within the force-displacement curve, ASTM D8225; (b) Force-displacement curve: work of failure (Wf) – area under the curve

As shown in Figure 5.b, three parameters were determined through the CT index calculation: the energy dissipated up to the point of maximum load (pre-cracking energy); the energy dissipated after the point of maximum load (post-cracking energy); and the total energy, which is the sum of the previous two values. In general, the pre-cracking energy is an indicator of the cracking resistance, the post-cracking energy is an indicator of crack propagation, and total energy is a good indicator of the cracking potential of asphalt concrete (AC) mixes [19], [27].

The results of the calculation are given below (Table 6), which shows a significant difference between the fracture energy of the fiber-reinforced asphalt mixes compared to the control mix. Aramid fiber (0.065 wt%) and PET fiber (0.1 wt%) showed a significant increase in fracture energy (between 70% to 100% for the same binder content). This indicates that the addition of these fibers retarded crack propagation in the tested samples. Comparing the CT indices for the mixtures, the CT indices of aramid- and PET-modified mixes are 3.2 and 1.9 times greater than the CT index of the control mix. For the PAN fiber (0.065 wt% content) and aramid–modified (0.0065 wt%) mixes, minimum differences were observed in the CT indices, which were still 160% and 230% higher compared to the control mix. The table shows for higher amounts of PET and PAN fiber, CT indices improve significantly, which could be in part because of the addition of 0.5% more binder. Finally, post-crack toughness for fiber-reinforced asphalt concrete mixes increased from 20% to 120% compared to the control mix; however, there was no significant change in the pre-crack toughness.

The CT index of each mix is presented in Table 4.6, which gives more details of how those fiber-modified mixes would act against cracking distress, given that the CT index provides better field correlation than a pure tensile strength property evaluation [51].

TABLE 4-6: CT Index Results for Different Fiber Mixes

Mixture	Pre-Crack Toughness	Post-Crack Toughness	Work of Failure (kN.mm)	Fracture Energy (J/m^2)	CT Index
No Fiber, 5.5% Binder	7.9	14.0	21.8	3374.9	17.3
0.0065% Aramid, 5.5% Binder	9.4	16.7	26.1	4058.6	39.5
0.065% Aramid, 5.5% Binder	11.2	32.2	43.4	6731.4	73.1
0.1% PET, 5.5% Binder	12.7	24.7	37.5	5736.1	51.0
0.065% PAN, 5.5% Binder	10.3	18.4	28.8	4502.9	27.9
0.2% PAN, 6.0% Binder	11.9	27.3	39.2	6039.6	108.9
0.3% PET, 6.0% Binder	15.6	39.0	54.6	8360.0	188.1

4.6.4 Determination of Indirect Tensile Strength at Low Temperature

Indirect tensile strength and creep compliance (IDT) of HMA mixes are the two main outputs of the IDT test based on AASHTO T 322-07 [46]. For this test, different sets of fiber-modified mixes and the control mix were prepared using a gyratory compactor. Each set of specimens was conditioned for three hours at the specified temperature (-20°C, -10°C and 0°C) and then tested using a Universal Testing Machine (UTM-100). The cylindrical specimens were loaded vertically to a target creep load of 1 kN for 100 seconds, after which the IDT test was conducted at a loading rate of 12.5 mm/min. Specimen displacement was measured using horizontal and vertical linear variable differential transducers (LVDTs) mounted on brass gauge points with a gauge length of 75 mm on each face of the specimen (Figure 4.7.a, 4.7.b).

The results also show a qualitative comparison between a cracked fiber-modified sample and the control mix after an IDT test (Figure 4.7.c, 4.7.d). As can be seen in the figure, unlike the control mix, the fiber-reinforced mixes were not completely separated after cracking. The samples modified with PET (0.1% by weight) and aramid (0.065% by weight) showed the best fracture performance in terms of slowing down crack propagation.

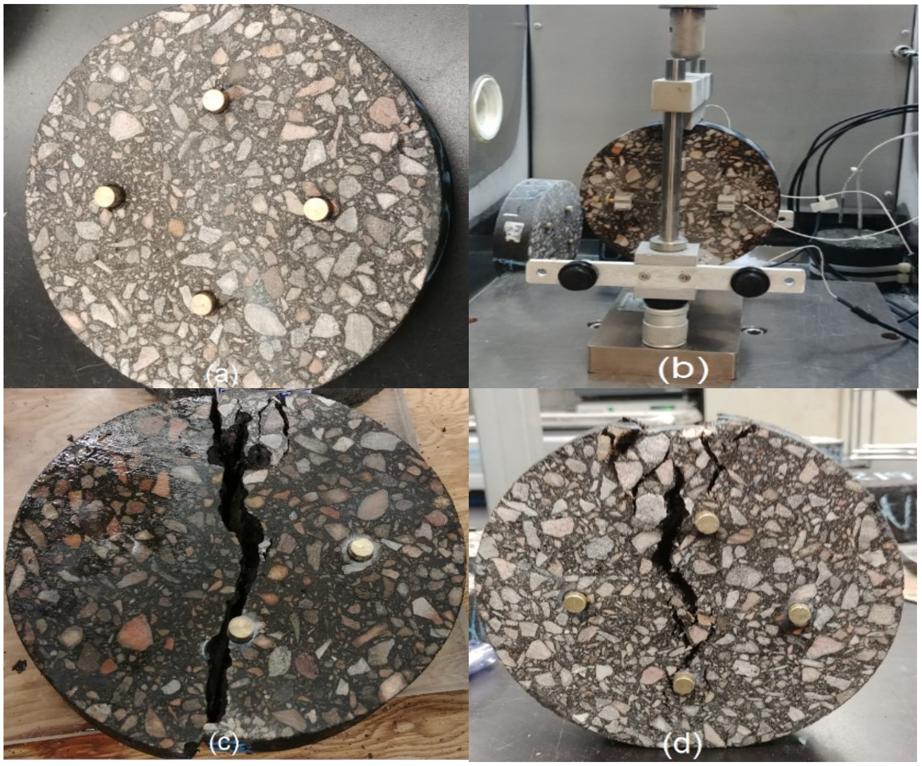

Figure 4-7: (a) IDT samples; (b) The IDT test configuration; (c) The fracture path of the control mix; and (d) The fracture path of a fiber modified mix

Table 4.7 shows the summary of IDT test results is given for -20°C, -10°C, and 0°C (. From these values, the tensile strength for fiber-modified mixes does not show a significant difference compared to the control mix at the same temperature; but they all followed an inverse relationship with the temperature (T°): when the T° decreased, the tensile strength increased. On the other hand, all fiber-modified samples had higher fracture energy compared to the control mix at all temperatures (-20°C, -10°C and 0°C), with two specific exceptions of the samples modified with aramid fiber. This shows that in most of the presented cases, the fiber-modified samples are more resistant to cracking at low temperatures compared to the control mix. Moreover, the fracture energy followed a direct relationship with the temperature (T°): when the T° increased, the fracture energy increased.

At all three of the temperatures tested, aramid fiber (0.065 wt%) and PET fiber (0.1 wt%) presented higher total fracture energy than the control mixture. The increase in fracture energy ranged from 22% to 45%. Moreover, the energy after the fracture (post-crack toughness) increased up to three times at -20°C, up to two times at -10°C, and up to 70% at 0°C. This demonstrates that the fibers worked effectively while the temperature dropped. This could be related to the fibers' contribution to the cracking pattern of these mixes at low temperatures because, although the specimens cracked, they required more energy to fail due to the fibers holding the specimen together.

TABLE 4-7: Work and Fracture Energy of Mixes Containing Different Types and Amounts of Fiber at a) -20°C, b) -10°C, and c) 0°C

a) Asphalt Mixes at -20°C	Tensile Strength (MPa)	Pre-Crack Toughness	Post-Crack Toughness	Work (kN.mm)	Fracture Energy (J/m^2)
No Fiber,_5.5% Binder	3.7	38.5	11.4	49.9	8630.6
0.0065% Aramid, 5.5% Binder	4.0	37.1	29.4	66.5	9319.3
0.065% Aramid, 5.5% Binder	2.9	30.9	53.8	84.8	12450.5
0.1% PET, 5.5% Binder	3.6	36.3	40.3	76.7	11756.9
0.065% PAN, 5.5% Binder	3.5	34.6	26.7	61.3	8824.5

b) Asphalt Mixes at -10°C					
No Fiber,_5.5% Binder	3.9	51.1	14.3	65.4	9824.3
0.0065% Aramid, 5.5% Binder	3.9	57.5	9.0	66.5	9706.4
0.065% Aramid, 5.5% Binder	2.8	38.9	51.6	90.6	13822.2
0.1% PET, 5.5% Binder	3.4	46.3	34.1	80.4	12015.3
0.065% PAN, 5.5% Binder	3.5	26.3	30.7	57.1	9949.2

c) Asphalt Mixes at 0°C					
No Fiber,_5.5% Binder	2.7	41.5	31.4	72.9	10594.1
0.0065% Aramid, 5.5% Binder	3.5	52.4	15.6	68.0	9842.0
0.065% Aramid, 5.5% Binder	2.5	50.0	56.7	106.7	14521.5
0.1% PET, 5.5% Binder	2.5	35.0	55.4	90.4	13891.2
0.065% PAN, 5.5% Binder	2.6	33.5	52.4	85.9	13286.5

4.7 Cost performance analysis of fiber-modified asphalt mixes

Although the inclusion of fibers can improve the mechanical properties of asphalt mixes, it also increases the regular cost of the traditional HMA mixes. To evaluate the feasibility of fiber-modified mixes, costs were compared between the control mixture (without fibers) and the mixtures containing the test fibers.

The following cost analysis evaluated one ton of each asphalt concrete mix. All estimated prices are in US dollars (USD), and the different fiber dosages are in kilograms (kg). For the cost analysis, it was mainly considered the original binder content, at 5.5% according to the mix design. However, to increase the fiber dosage, a 6.0% binder was included in the PET fiber (0.3 wt%) and PAN fiber (0.2 wt%) mixes.

In the table below, the unit prices of aramid fibers were determined based on Muftah et al.'s work [4], which indicated that the cost per kilogram for wax-coated aramid fibers was $74.96/ kg. Price quotations were received for PET and PAN fibers; the costs per kilogram were $1.95 and $2.00 respectively. For all tests presented in the paper, uncoated aramid (pure aramid) was used, but for the cost comparison analysis (Table 4.8), wax-coated aramid fibers were used. After the wax is melted, the coated aramid fiber weight is equivalent to the weight of the pure aramid fibers evaluated in the cost comparison.

TABLE 4-8: Cost Comparison of Control Mix and Fiber-Modified Mixes

a) No Fiber, 5.5% Binder (USD per ton)			
	Unit	$/Unit	Total Cost (USD/ton)
High Traffic (HT) -10 mm (ton)	0.945	40.00	$37.80
PG 58-31 Binder (ton)	0.055	765.00	$42.08
Cost per Ton of HMA Mixture ($/ton)			**$79.88**

b) 0.0065% Aramid, 5.5% Binder (USD per ton)			
High Traffic (HT) -10 mm (ton)	0.945	40.00	$37.80
PG 58-31 Binder (ton)	0.055	765.00	$42.08
Fiber Reinforcement (kg/ton of mix)	0.130	74.96	$9.74
Cost per Ton of HMA Mixture ($/ton)			**$89.62**

c) 0.065% Aramid, 5.5% Binder (USD per ton)			
High Traffic (HT) -10 mm (ton)	0.945	40.00	$37.80
PG 58-31 Binder (ton)	0.055	765.00	$42.08
Fiber Reinforcement (kg/ton of mix)	1.300	74.96	$97.45
Cost per Ton of HMA Mixture ($/ton)			**$177.32**

d) 0.1% PET, 5.5% Binder (USD per ton)

High Traffic (HT) -10 mm (ton)	0.945	40.00	$37.80
PG 58-31 Binder (ton)	0.055	765.00	$42.08
Fiber Reinforcement (kg/ton of mix)	1.000	1.95	$1.95
Cost per Ton of HMA Mixture ($/ton)			**$81.83**

e) 0.065% PAN, 5.5% Binder (USD per ton)

High Traffic (HT) -10 mm (ton)	0.945	40.00	$37.80
PG 58-31 Binder (ton)	0.055	765.00	$42.08
Fiber Reinforcement (kg)	0.650	2.00	$1.30
Cost per Ton of HMA Mixture ($/ton)			**$81.18**

f) 0.2% PAN, 6.0% Binder (USD per ton)

High Traffic (HT) -10 mm (ton)	0.940	40.00	$37.60
PG 58-31 Binder (ton)	0.060	765.00	$45.90
Fiber Reinforcement (kg)	2.000	2.00	$4.00
Cost per Ton of HMA Mixture ($/ton)			**$87.50**

g) 0.3% PET, 6.0% Binder (USD per ton)

High Traffic (HT) -10 mm (ton)	0.940	40.00	$37.60
PG 58-31 Binder (ton)	0.060	765.00	$45.90
Fiber Reinforcement (kg/ton of mix)	3.000	1.95	$5.85
Cost per Ton of HMA Mixture ($/ton)			**$89.35**

A summary (Table 4.9) showed that aramid fiber (0.0065 wt%) and PAN (0.0065 wt%) improved the mix's mechanical properties, especially the CT index, at a low cost increase. As shown below, aramid fiber (0.065 wt%) and PET (0.1 wt%) had significant improvements in rutting control, cracking tolerance, etc. However, these fibers came with cost increases of 122% and 2.44%, respectively. Finally, it is important to point out that the 0.5% increase in binder enabled the increase in PET and PAN fibers, with outstanding results in fracture resistance for both specimens (IDEAL-CT Index) and minimal increases in cost. For instance, PAN fibers with 6% binder (0.2 wt%) and PET fibers with 6% binder (0.3 wt%) had an additional cost of 9.6% and 11.9%, but an increase of 500% and 1,000% in the cracking resistance index, respectively.

TABLE 4-9: Cost-Benefit Analysis of Control Mix and Fiber-Modified Mixes: Cost per Ton of HMA Mixture vs Improvement of Mechanical Properties

Type of Fiber	Cost/Ton of HMA Mixture	Cost Overrun (%)	Fracture Energy Increase (J/m2) at -20°C (%)	CT Index Improvement at Room T°	Rutting Resistance Increase
No Fiber, 5.5% Binder	$79.88	0	0	0	0
0.0065% Aramid, 5.5% Binder	$89.62	12.20%	7.98%	128.32%	12.42%
0.065% Aramid, 5.5% Binder	$177.32	122.00 %	44.26%	322.54%	97.48%
0.1% PET, 5.5% Binder	$81.83	2.44%	36.22%	194.80%	81.24%
0.065% PAN, 5.5% Binder	$81.18	1.63%	2.25%	61.27%	44.63%
0.2% PAN, 6.0% Binder	$87.50	9.55%	No applied	529.48%	No applied
0.3% PET, 6.0% Binder	$89.35	11.86%	No applied	987.28%	No applied

4.8 Conclusions

Given the results presented in this work, the conclusions of this study can be summarized as follows:

1. After increasing the amounts of PET and PAN fibers in the mix from 0.065% up to 0.5% by total weight, test results showed fiber-modified mixes required a higher binder content because most contain larger air void content than the target. The maximum amounts of fibers for mixes modified with PET and PAN fibers, to maintain the same binder content as the control mix, were 0.1% and 0.065% by total weight of the mix, respectively. The addition of aramid fibers up to 0.065 wt% did not affect the volume of the mix.
2. The addition of aramid fiber (0.065 wt%) and PET fiber (0.1 wt%) to the asphalt mixes provided significant improvements in rutting resistance and moisture sensitivity, whereas PAN fiber and the lower amount of aramid fiber (0.0065%) showed only a slight enhancement.

3. ITS test results showed that the addition of fibers did not significantly increase the tensile strength of the asphalt mixes. All fiber-modified mixes were resistant to moisture after freeze-thaw conditioning.
4. The comparison of the fracture energy and CT indices of fiber-modified mixes with the control mix showed that the addition of fibers significantly improved the cracking resistance of the asphalt mixes. Aramid (0.065 wt%) and PET (0.1 wt%) fiber-modified mixes had the most significant improvements in both parameters.
5. Findings from IDT testing at -20°C, -10°C, and 0°C showed that, at low temperatures, the crack propagation of modified samples was slowed by the fibers, especially for PET (0.1 wt%) and aramid (0.065 wt%). In addition, the fracture energy of fiber-modified mixes was significantly higher compared to the control mix, which demonstrated the higher cracking resistance of the modified mixes.
6. Testing at room temperature (25°C) and at low temperature (-20°C) indicated that the fibers were effective on increasing fracture energy, especially after the crack appeared. The post-crack toughness values collected after running all tests showed the same tendency of improvement in the control/limit of crack propagation once the crack started.
7. Cost-benefit analysis showed that fibers could be a valuable alternative for transportation agencies to consider to boost the performance of traditional asphalt mixes at a reasonable extra cost.

Future performance tests are needed to better understand the effects of adding fiber to the asphalt concrete mixes. Microscopic investigation to observe fiber dispersion in the asphalt mix, impact of fiber length on mixture properties and determination of fatigue life of fiber modified asphalt mixes are the next steps of this research.

4.9 Acknowledgements

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5 Investigation of Cracking Potential of Modified Asphalt Mixes Composed of Synthetic Fibers by performing 4-point bending test

5.1 Abstract

Fatigue cracking is a structural distress often observed on HMA and may be accelerated in cold regions such as Canada. A review of the literature shows that during the last decades, fibers have been used in various parts of the world to reinforce asphalt concrete. Past studies have shown that synthetic fibers have the potential to enhance the fatigue properties of asphalt concrete.

However, information related to the assessment of fiber performance at low temperatures is limited. Furthermore, there has been less attention paid to the incorporation of fibers in asphalt mixes to improve resistance to thermal cracking, an application that would prove extremely beneficial for road construction in cold climates. Meanwhile, the benefits of fiber addition on roadways also have economic implications. The incorporation of waste fibers in asphalt mixes may represent a cost-effective option due to their reduced cost; in addition, recycling of waste fibers has remarkable environmental advantages, making eco-friendly road construction possible.

The objective of this research is to evaluate the effectiveness of adding polymer fibers to hot mix asphalt to increase the resistance of HMA to fatigue cracking at intermediate temperatures. For this purpose, three different types of polymer fibers, including aramids, polyethylene terephthalate (PET) and polyacrylonitrile (PAN), in different sizes and at different concentrations, were added to conventional hot asphalt mixes. Samples were compacted in the laboratory and their mechanical properties were compared to conventional hot mix asphalt.

5.2 Introduction and Background

Fatigue cracking is a serious structural pavement distress, mainly induced by repetitive traffic loading, but also due to insufficient thickness of the asphalt course, and asphalt pavement designs that are prone to fatigue failure [13]. This problem, which is commonly observed on HMA roadways, results when tensile stresses build to the strength limit of the material at the bottom of the pavement layer. As the strains become critical, cracks start propagating from the bottom of the pavement course to the top of the road surface. This phenomenon is known as bottom-up fatigue cracking, which is the most common fatigue cracking. [26], [52]. Moreover, the results of current investigations have suggested that fatigue cracks might first appear on the surface and then start propagating downwards, a phenomenon which is known as top-down fatigue cracking. Eventually, the pavement life is affected and the serviceability and quality on roads turn detrimental for road users due to the appearance of longitudinal cracks (top-down cracking) and alligator crack formation (bottom-up cracking) [23].

Badeli et al. [9] evaluated the addition of aramid pulp fiber (APF) on an asphalt control mix and studied the improvement in fatigue life. The authors found an improvement in fatigue life at high strain modes (heavy truckloads) for the fiber-reinforced mix. Also, Wang et al. [26] evaluated the fatigue life of asphalt mixes reinforced by PAN fibers at constant strains using the central-point bending fatigue test. After modeling the fatigue performance, the authors found an enhancement in fatigue life for the PAN-reinforced asphalt mix compared to the original control mix. In addition, Xu et al [18] conducted a comparative performance analysis among four different types of fibers: polyester, PAN, lignin, and asbestos. By running a three-point bending fatigue test at room temperature, the study showed that polymer fibers (polyester and PAN) extended the fatigue performance of HMA significantly. Additionally, Moghaddam et al. [37], found an enhancement of fatigue life after the addition of PET fiber for stone mix asphalt (SMA) mixes using the indirect tensile stiffness modulus test and indirect tensile fatigue test at different stress levels at room temperature. Similarly, Dehghan et al. [25] evaluated the fatigue life of fiber-reinforced HMA, considering different lengths and different amounts of PET fibers. After the evaluation of the fatigue response over the strain range of 300, 500 and 700 microstrains under the four-point bending test, it was found that the fatigue life was improved by more than 100% at the different three microstrains. Finally, Stempihar et al.[7] and Mateos et al. [32] evaluated the performance of multiple SMA and dense-graded HMA mixes by running the four-point beam fatigue test. The mixes included aramid fibers, and the fiber content impacted the fatigue performance of the original mix considerably, especially at high strain levels.

The indirect tensile asphalt cracking (IDEAL-CT) test is an alternative to evaluate the fatigue life of asphalt mixes. The aforementioned test relies on using a cracking test (CT) index as an indicator of cracking observed in the field. Zhou et al. [53] have collected a vast amount of information from the comparison of field test sections versus laboratory evaluations using the IDEAL-CT test, concluding that fatigue cracking resistance improved whenever the CT index increased.

5.3 Objectives and Scope

The aim of this paper was to investigate and compare the effect of three different fibers (PET, PAN, and aramid) on the fatigue cracking response of asphalt mixes at intermediate temperatures. To achieve this purpose, a mix design was prepared for hot mix asphalt (HMA) and the optimum content for each fiber was determined. To investigate the fatigue resistance of reinforced and unreinforced mixes, the impact of different parameters such as strain level and fiber content were evaluated by the four-point beam fatigue test. Moreover, the output of the bending fatigue test was compared with the results of the IDEAL CT test to evaluate the correlation between these tests.

5.4 Materials and Mix Design

5.4.1 Mix Design and Volumetric Properties

Asphalt cement with a performance grade (PG) of 58-31 was used to prepare the asphalt mixes. The basic volumetric properties of the control mix are summarized in Table 5.1. The aggregate grain size distribution of the control mix is shown in Table 5.2 and had a maximum aggregate size (MAS) 12.5mm.

TABLE 5-1: Mix Design and Volumetric Properties

Mix Design Properties	Actual	Specifications
Number of gyrations	75	75
Asphalt Cement (AC)%	5.5	-
G_{mm} (kg/m^3)	2431	
G_{mb} (kg/m^3)	2337	
Air Voids (%)	3.9	3.6 - 4.4
VMA (%)	14.9	13
VFA (%)	73.8	70 - 80
%G_{mm} @ N_{max}	96.8	98 max.
Dust /AC	1.0	-

TABLE 5-2: Aggregate grain size distirbution

	Sieve size(mm)										
Aggregate	12.5	10	8	6.3	5	2.5	1.25	0.63	0.315	0.16	0.08
% passing	1	0.983	0.885	0.754	0.648	0.49	0.395	0.327	0.202	0.103	0.051

5.4.2 Fiber Properties

The fibers used in this work are synthetic fibers, including uncoated (i.e. no wax coating) aramid fibers, PET fibers, and PAN fibers. Aramid fibers are an aromatic polyamide synthetic polymer fiber, with a high tensile strength of 400 000 psi, comparable to that of steel, and is a high modulus material. Aramid is widely applied in different industries [29]. Polyethylene Terephthalate (PET) is a non-biodegradable polymer, a thermoplastic, and its fibers are semi-crystalline. There is no alteration of the properties of PET when it is subjected to different conditions, and it is known for being a recyclable product [34]. Polyacrylonitrile (PAN) fibers are the result of the acrylonitrile polymerization process in the presence of a catalyst peroxide and are a precursor material for carbon fibers [17]. The three different types of fibers are shown in Figure 5.1, and the mechanical properties of the fibers are given in Table 5.3. The same mix design was used for the control mix as well as the fiber-modified mixes.

TABLE 5-3: Properties of the different fibers used for asphalt modification

Fiber(s)	Aramid Fiber	PET Fiber	PAN Fiber
Length (mm)	38 ± 1.3	6 ± 1.5	6 ± 1
Diameter (μm)	15	20	11
Density (g/cm^3)	1.44 - 1.45	1.41	1.18
Tensile Strength (MPa)	> 2758	≥ 500	600
Melting point (°C)	> 425	≥ 256	≥ 220

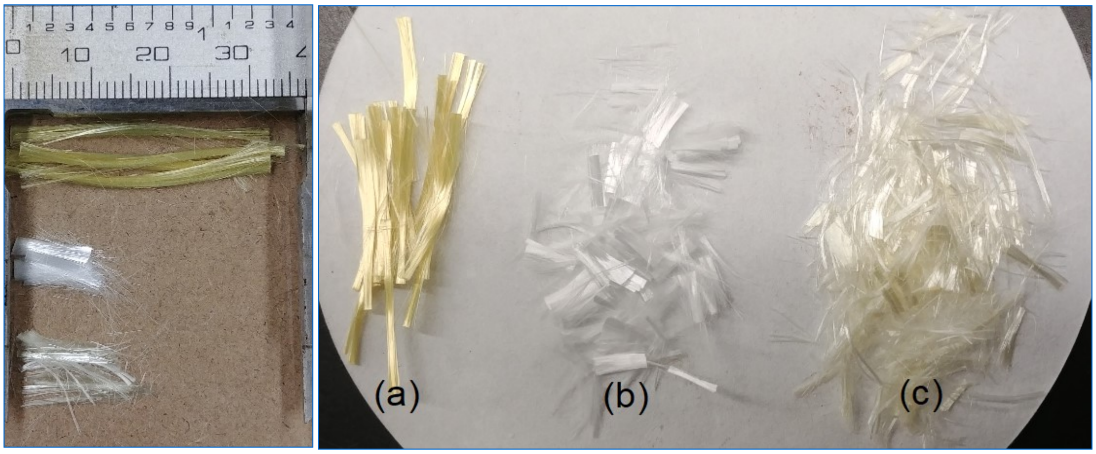

Figure 5-1: Fibers selected for the study: Left to right / Top to bottom (a) uncoated aramid fibers, (b) PET fibers, and (c) PAN fibers

5.4.3 Mixing process

Adequate dispersion of fibers is essential to get reliable mechanical improvements. To ensure optimal results, each strand of uncoated aramid fiber was separated manually as much as possible prior to the mixing operation (Figure 5.2). For PET fibers and PAN fibers, no separation was needed prior to mixing.

The most common methods for random inclusion of fibers into HMA samples are the wet process and the dry process [54]. For the present work, the dry process was followed, with a minor change. Instead of mixing the dry aggregate with the fibers prior to the addition of binder, the standard mixing process between the aggregate and the asphalt binder was followed. Once the aggregate was coated (after 1.5 minutes, on average), loose fibers were gradually introduced into the mixing bucket until they were completely coated (Figure 3). In total, the mixing time was 2.5-3.5 min. This approach allowed better control of certain drawbacks, such as binder absorption by fibers and agglomeration of fibers.

Figure 5-2: (a) Manual separation process for uncoated aramid fibers; (b) uncoated Aramid fibers being poured into the mixing bucket; (c) aggregate-binder-fiber interlock result

5.5 Optimum Fiber Content

A review of the literature indicates that the binder absorption capability of fibers increases the required binder content. As the fiber geometry and fiber content determine the performance improvement of HMA, for the work presented in this paper, the appropriate amount of each type of fiber was selected based on the maximum allowable air void content of the modified mix. The binder content was kept constant to allow for a comparison between the properties of the modified mixes and the control mix.

A trial and error process determined that to maintain the target void content of 3%-5%, the amount of PAN and PET fibers to be added to the asphalt mix was 0.065% by total weight of the mix and 0.1% by weight of mix, respectively. The trend shows that air void content increased as the amount of PAN and PET content increased [54]. The aramid fiber content used was 0.0065% by total weight, the content recommended by the provider. Since aramid fibers did not affect the air void content, it was also tested at the comparative fiber content of 0.065 % by weight.

5.6 Dispersion evaluation by microscope

From the literature review, it is evident that the uniform distribution of fibers is required to ensure a considerable improvement with the addition of fibers to HMA. A loose and scattered distribution of fibers does not create a network, limiting the reinforcing effect. The optimum fiber content creates a strong network, but an excessive amount of fiber will weaken the interlock between the asphalt cement and aggregates. For this reason, the Marshall mixtures used in the IDEAL CT test were selected, prepared and analyzed using the Zeiss Stemi 508 Stereo microscope at the NanoFab Facility at the University of Alberta [55]. The half splitting specimens from the test samples were examined to identify the distribution of fibers on the rough surface by the microscope. As can be seen from Figures 5.3 a and b, the sample with a low aramid content (0.0065% by weight) did not show a strong network of aramids, which could have contributed that the reinforcing effect was not homogeneous in all zones. Certainly, in a sample containing ten times the original content, the fibers were observed to be better connected and provided a dense network, but there were also agglomerated zones with clustered fibers, as shown in Figure 5.4 a and b. Similarly, the HMA sample containing PAN at a concentration of 0.065% by weight constituted a more compacted network with sparsely agglomerated zones, as shown in Figure 5.5 a and b. Finally, the PET sample (0.1% by weight) constituted a strong network. In this case, the fibers were close to each other but without agglomeration detected, as it can be seen in images 5-6-a and 5-6-b.

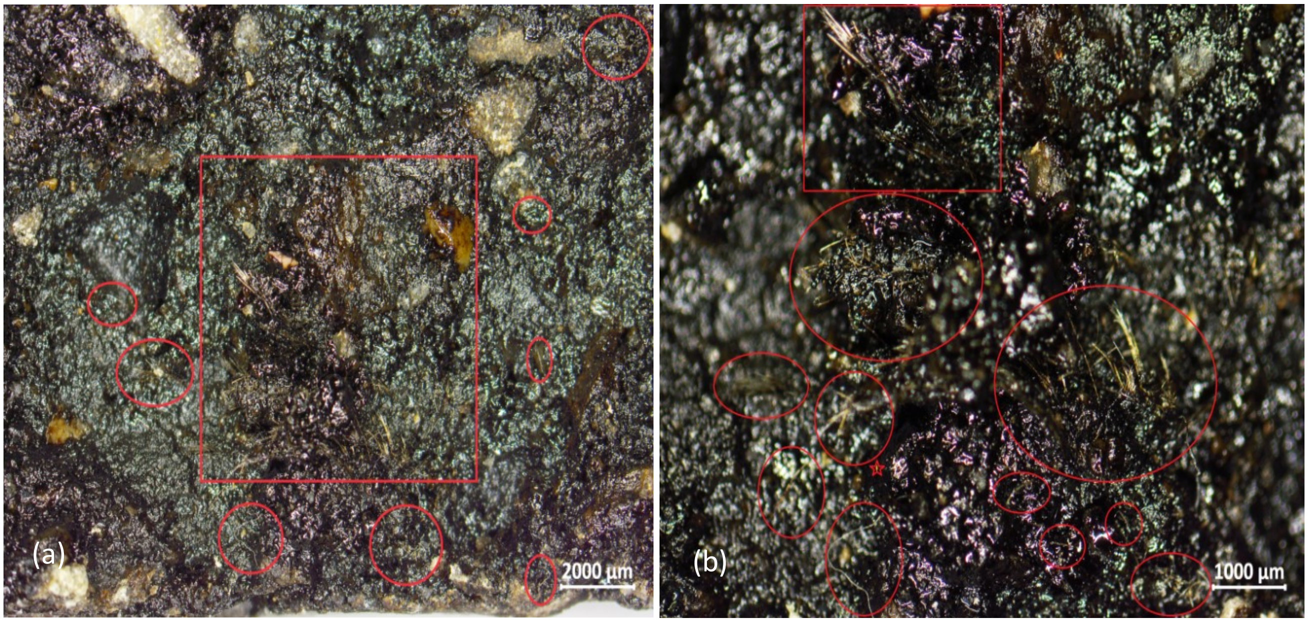

Figure 5-3: Surface fracture of uncoated aramid 0.0065%wt reinforced sample (a) surface evaluation; (b) enlarged photo of the central section.

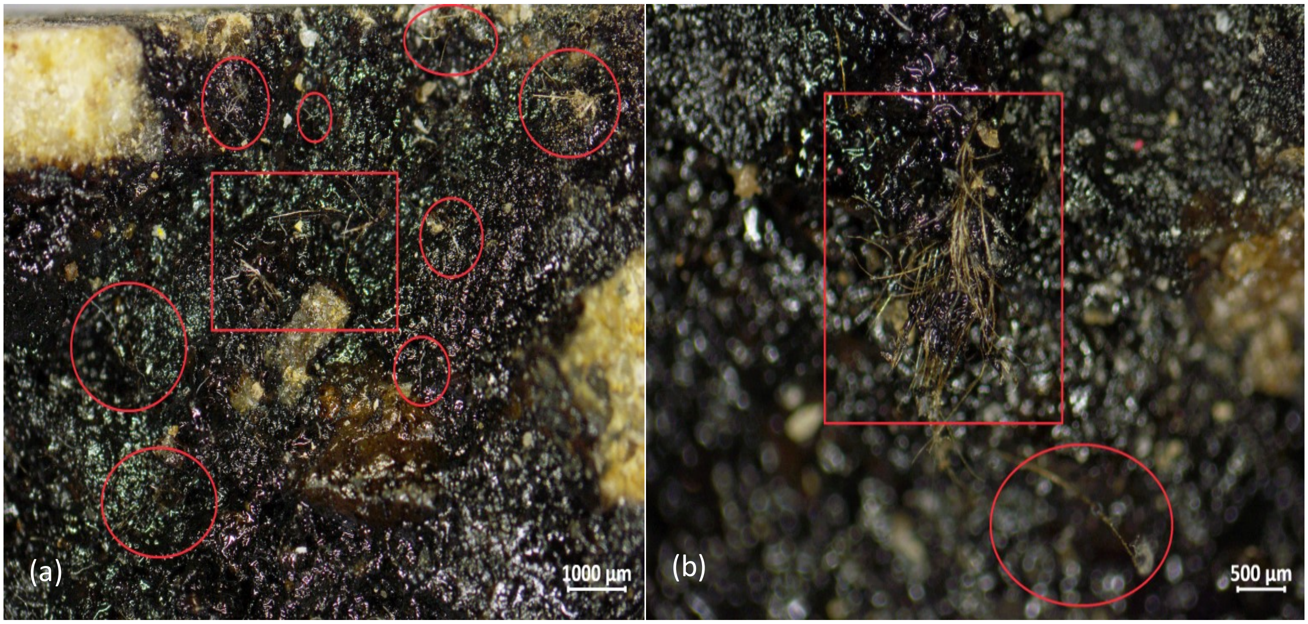

Figure 5-4: Surface fracture of uncoated aramid 0.065%wt reinforced sample (a) surface evaluation; (b) enlarged photo of the central section.

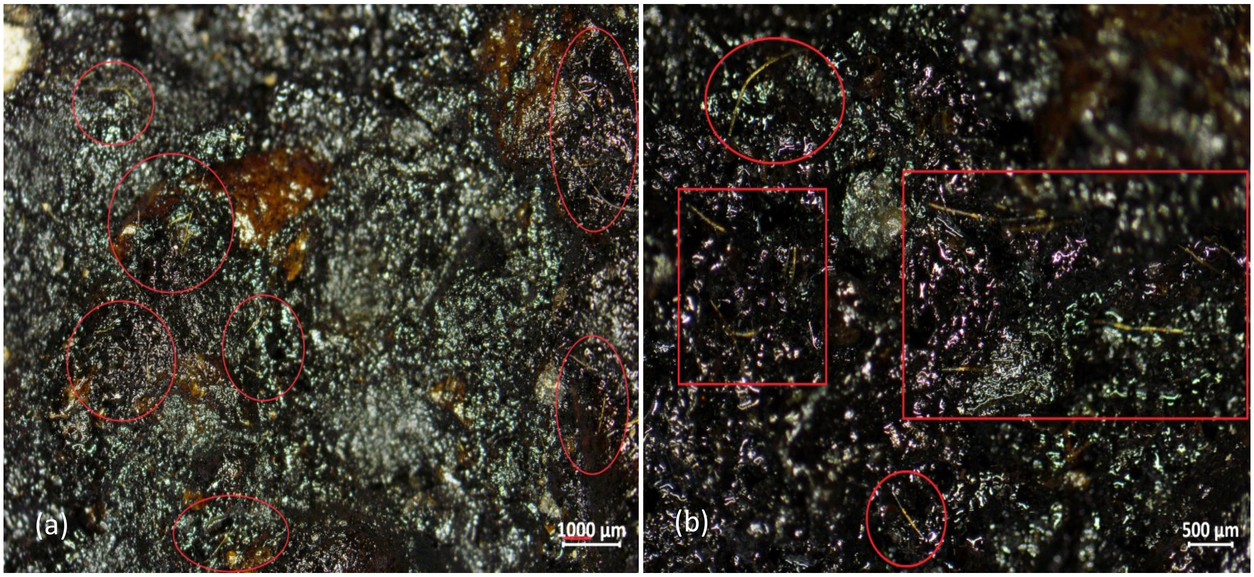

Figure 5-5: Surface fracture of PAN 0.0065%wt reinforced sample (a) surface evaluation; (b) enlarged photo of the central section.

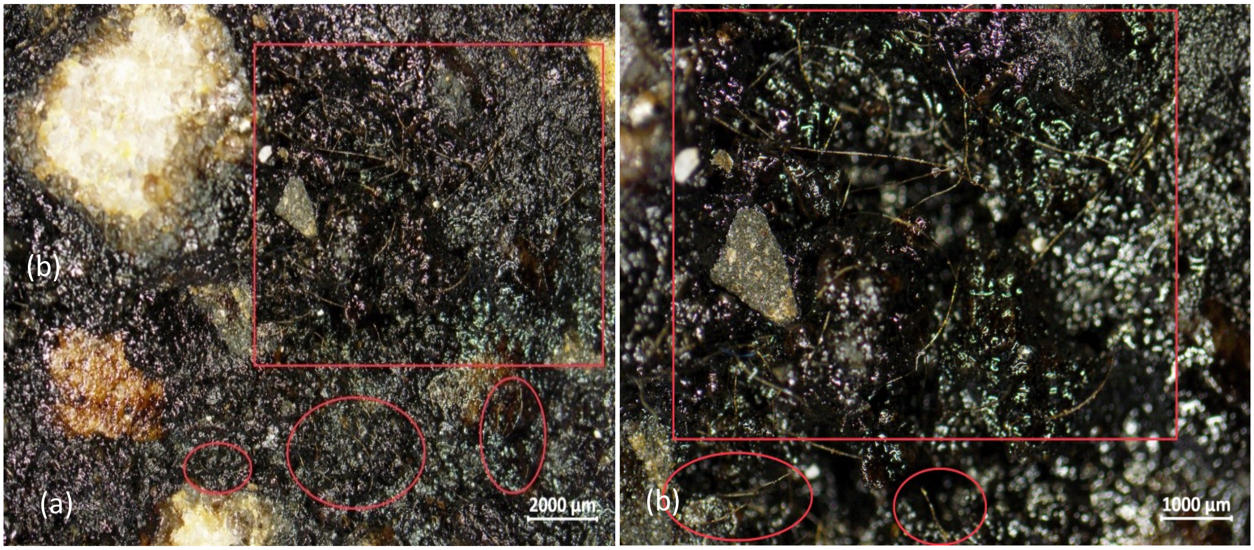

Figure 5-6: Surface fracture of PET 0.1%wt reinforced sample (a) surface evaluation; (b) enlarged photo of the central section.

5.7 Performance Tests at intermediate temperature

5.7.1 Fatigue Test by four-point bending test

After defining the optimum fiber content for each type of fiber [54], five slabs of 400 x 300 x 50 mm were prepared by following the dry mix procedure. When the mixing process was complete, samples were compacted using a heated asphalt roller compactor (InstroTek Co). In total, five slabs were prepared, one slab for each fiber type and content, and another slab as the control sample (unmodified HMA). During compaction, a fixed load of 500 kg was applied for the number of times necessary, with the compactor going back and forth until a slab thickness of 50 mm was attained for each sample. After compaction, the targeted air voids were in the range of 4% to 5%. Once the compaction process was complete and the slabs cooled (at least overnight), the slabs were demolded and cut into beam-shaped specimens with a height of 50 mm, length of 400 mm and width of 60 mm, as shown in Figure 5.7.

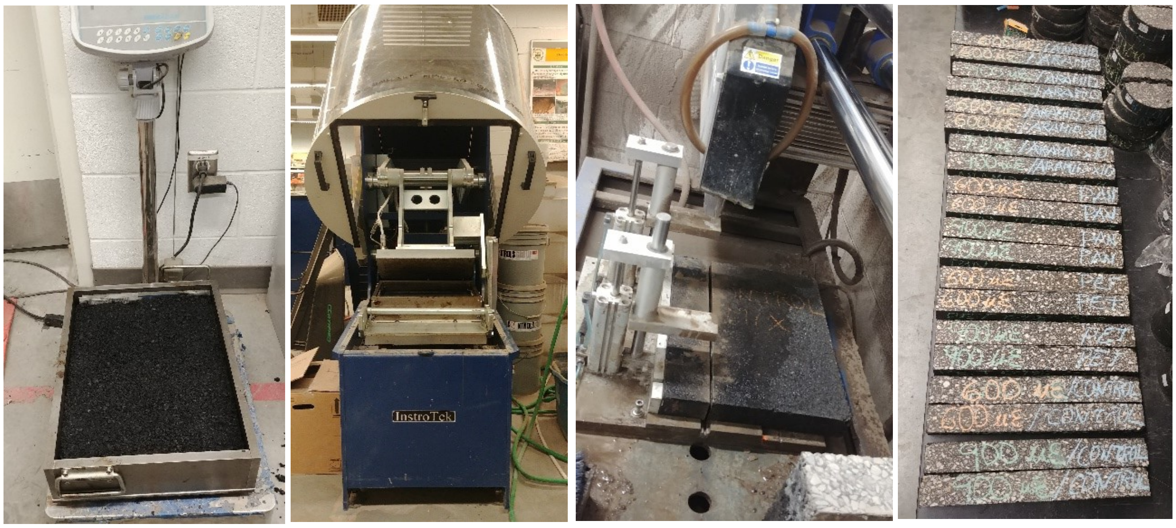

Figure 5-7: (a) Pouring asphalt mix into steel rectangular mold; (b) compaction of samples using roller compactor; (c) slabs cut to prepare beam specimens; (d) beam-shaped specimens prepared for the fatigue test

As the work performed by [32] concluded that the fatigue properties of fiber-modified asphalt mixes did not achieve considerable improvement at intermediate strain levels, but the fatigue life was more susceptible to high strains. Therefore, each slab was subjected to two high strain-controlled modes (600 and 900 microstrains). For this reason, in the present research, the strain levels of 600 microstrains and 900 microstrains were chosen (high strain levels). For each fiber content and strain level, two beams were made; hence, 20 beam-shaped specimens were prepared by cutting five compacted slabs. In the end, at least two fiber-reinforced or control beams were prepared for testing at each strain level.

The fatigue test was performed in compliance with standard AASHTO T321-17 [56] using the four-bending fatigue apparatus (see Figure 5-8). All specimens were tested at room temperature (20-25°C), in the constant strain mode, and applying a haversine-shaped wave at a frequency of 10 Hz.

According to standard T321-17 [56], "fatigue life is defined as the number of cycles when the flexural stiffness of the beam is equal to 50% of the initial flexural stiffness value, which is considered at the 50th cycle". In the present work, the four-bending fatigue apparatus was set up to consider the ending point to be 40% of the initial flexural stiffness value. Then, the number of cycles was calculated by interpolation at the point corresponding to 50% of the initial stiffness in the fatigue life curve generated, as shown in Figure 5.9b. According to Modarres et al. [25], fatigue cracking begins at 50% of the flexural stiffness (S). Consequently, after this point – i.e. 40% of the initial flexural stiffness – cracks may be visible and the beam may fail.

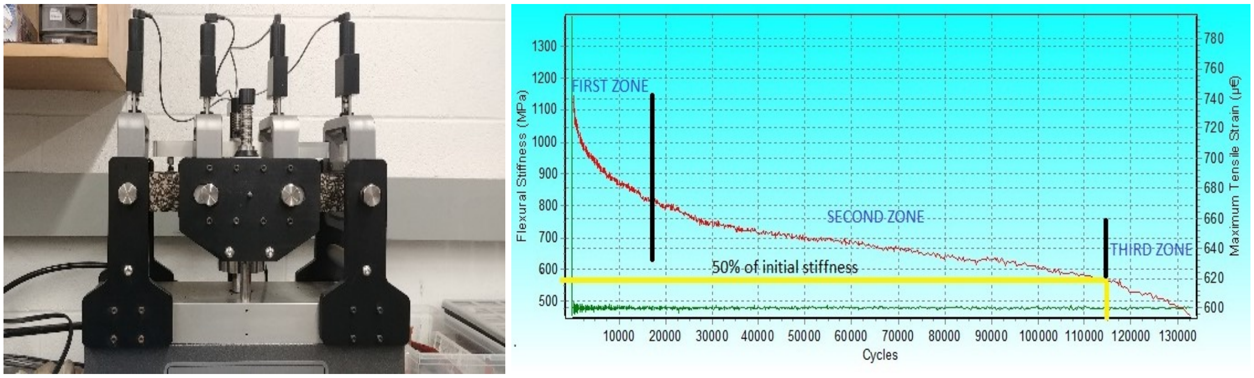

Figure 5-8: (a) Flexural Fatigue Apparatus; (b) Interpolating 50% of initial stiffness

The effect of fiber content on fatigue life was evaluated for the different beams of fiber-modified HMA. All of the curves for stiffness vs. loading cycle followed a similar trend, specified in [25], and there were three different zones (Figure 5.8b), in which the stiffness decreased as the number of cycles progressed. The first zone represented a quick drop in stiffness; the second zone was a smooth line in the reduction of stiffness, and the third zone was characterized by the approximated fatigue life of the HMA. This third zone meant the appearance of failure by fatigue and is normally equal to 50% of the initial flexural stiffness value. After this point, some micro-cracks turn into considerable cracks. It is also important to point out that in the third zone the stress was almost constant; in other words, it is in this zone, where the stopping point is established.

On the other hand, the initial flexural stiffness, calculated at the 50th cycle, showed a contrary relationship with the fiber content, it decreased with increasing fiber content. In particular, the samples containing 0.065% by weight and 0.1% by weight showed a significant decrease in the initial stiffness compared to the control mixture as shown in Figure 5.9. From previous studies such as [6], [25], the decrease is due to the addition of a flexible material, fibers, into a stiffer conglomate of aggregates, however a controlled reduction of stiffness can lead to more flexible mixtures with higher cracking resistance when subjected to repetitive loadings.

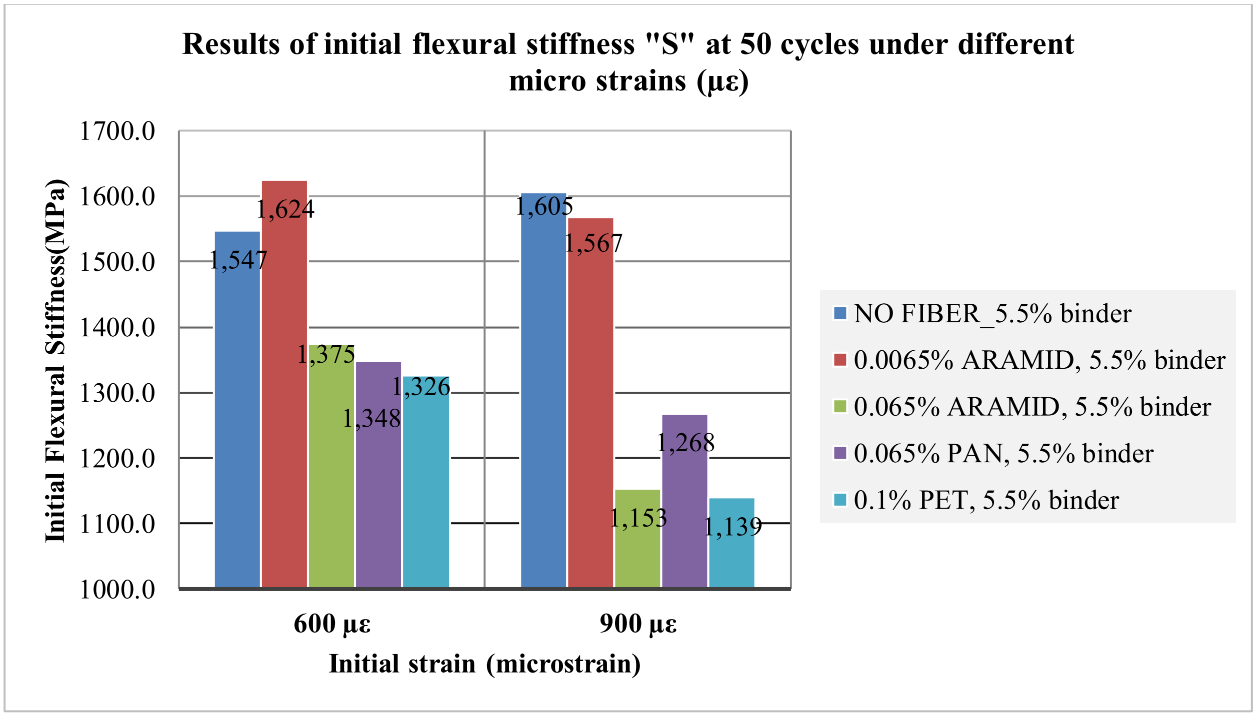

Figure 5-9: Initial flexural stiffness of HMA control mix and fiber modified under 600 and 900 με

Finally, Table 5.4 shows that the addition of adequate fiber content to HMA has a positive impact on fatigue life at high strains, either 600 microstrains or 900 microstrains. Table 5.4 also shows that in general, fatigue life decreased as the strain level increased – note that a high strain level mimics heavy traffic loading.

To begin with the fatigue life at 50% “S” at 600 με, there was an improvement in fatigue resistance by 25% to 63% for the modified HMA compared to the control mixture. At 900 με, the fatigue life for fiber-modified HMA was observed to increase by 30% to 95% compared to the control mixture. Similarly, the fatigue life of the samples containing fiber (40% S) at 600 microstrains showed an improvement of 55% to 115% compared to the control mixture. At 900 microstrains, the fatigue life of the modified samples increased by 29% to 117% compared to the control mixture. From the results of these fatigue tests, it can be seen that PET 0.1% by weight and aramid fibers 0.065% by weight showed the best fatigue performance at both strain levels.

TABLE 5-4: Comparison of loading cycles to failure by testing of the flexural stiffness of the control mixture and fiber-reinforced specimens at 600 and 900 microstrains

Type of Fiber	50 % of Initial Flexural Stiffness (S)		40 % of Initial Flexural Stiffness (S)	
	600 micro strains (με)	900 micro strains (με)	600 micro strains (με)	900 micro strains (με)
NO FIBER_5.5% binder	**82387**	**23321**	**111097**	**44907**
0.0065% ARAMID, 5.5% binder	117320	37692	172368	85920
0.065% ARAMID, 5.5% binder	133895	43651	232914	93066
0.1% PET, 5.5% binder	131534	45582	239226	97542
0.065% PAN, 5.5% binder	103514	30549	180729	58163

5.7.2 Fatigue Test – IDEAL CT Test

The indirect tensile asphalt cracking (IDEAL-CT) test is another indicator of the fatigue life of asphalt mixes. The correlation between the IDEAL CT index and the fatigue cracking is presented in work performed by Zhou et al. [53] involving the comparison of the performance of field test sections versus laboratory evaluation of samples using the IDEAL-CT test.

The standard ASTM D8225-19 [45] was used to calculate the cracking tolerance (CT) index, which is obtained from the fracture energy (Gf), and is defined in Equation 1:

$$CT_{Index} = \frac{t}{62} * \frac{l_{75}}{D} * \frac{G_f}{|m_{75}|} * 10^6 \quad \ldots\ldots\ldots\ldots (5)$$

where CT_{Index} is the cracking tolerance index, t is the specimen thickness (mm), l_{75} is the displacement at 75% of the peak load after the peak (mm), D is the specimen diameter (mm), G_f

is the fracture energy (J/m^2), and m_{75} is the post-peak slope around the 75% peak load point after the peak (N/m). G_f is calculated by dividing W_f (work -area under the curve) by the cross area of the specimen (the product of the diameter and thickness of the sample).

The results of this calculation are given below in Table 5.5 and show a significant difference between the fracture energy of the fiber-reinforced asphalt mixes compared to the control mix. Aramid fiber 0.065% by weight and PET fiber 0.1 % by weight showed a significant increase in fracture energy (between 70% to 100% for the same binder content). This indicates that the addition of these fibers retarded crack propagation in the tested samples. Comparing the CT indices for the different mixtures, the CT indices of aramid- and PET-modified mixes are 3.2 and 1.9 times greater than the CT index of the control mix. For PAN fiber 0.065 % by weight and aramid–modified mixes 0.0065 % by weight, the minimum difference in CT indices was observed, however, these were still 160% and 230% higher than the control mix. Finally, post-crack toughness (area under the curve after the crack starts) for fiber-reinforced asphalt concrete mixes was observed to increase by 20% to 120% compared to the control mix; however, there was no significant change in the pre-crack toughness.

The CT index of each mix is presented in Table 5.5, which gives a better indication of how the fiber-modified mixes would act with regards to cracking, given that the CT index has a better correlation to what happens in the field than the evaluation of pure tensile strength.

TABLE 5-5: CT Index Results for Different Fiber Mixes

Mixture	Pre-Crack Toughness	Post-Crack Toughness	Work of Failure (kN.mm)	Fracture Energy (J/m^2)	CT Index
No Fiber, 5.5% Binder	7.9	14.0	21.8	3374.9	17.3
0.0065% Aramid, 5.5% Binder	9.4	16.7	26.1	4058.6	39.5
0.065% Aramid, 5.5% Binder	11.2	32.2	43.4	6731.4	73.1
0.1% PET, 5.5% Binder	12.7	24.7	37.5	5736.1	51.0
0.065% PAN, 5.5% Binder	10.3	18.4	28.8	4502.9	27.9

5.8 Comparative Analysis between 4-Point Bending Test and IDEAL CT Index

The analysis presented in this paper is based on Tables 5.4 and Table 5.5, which details the findings for fatigue life enhancement under different strain levels and CT Index results, respectively. Overall, whenever the CT Index had a higher value, it correlated to an increase in the fatigue life assessed at different micro strains, using the four-point bending test. The Figure 5-10 describes the correlation between the Fatigue Life enhancement, at 40% of the Initial Stiffness at 600 and 900 με, and the CT Index improvement.

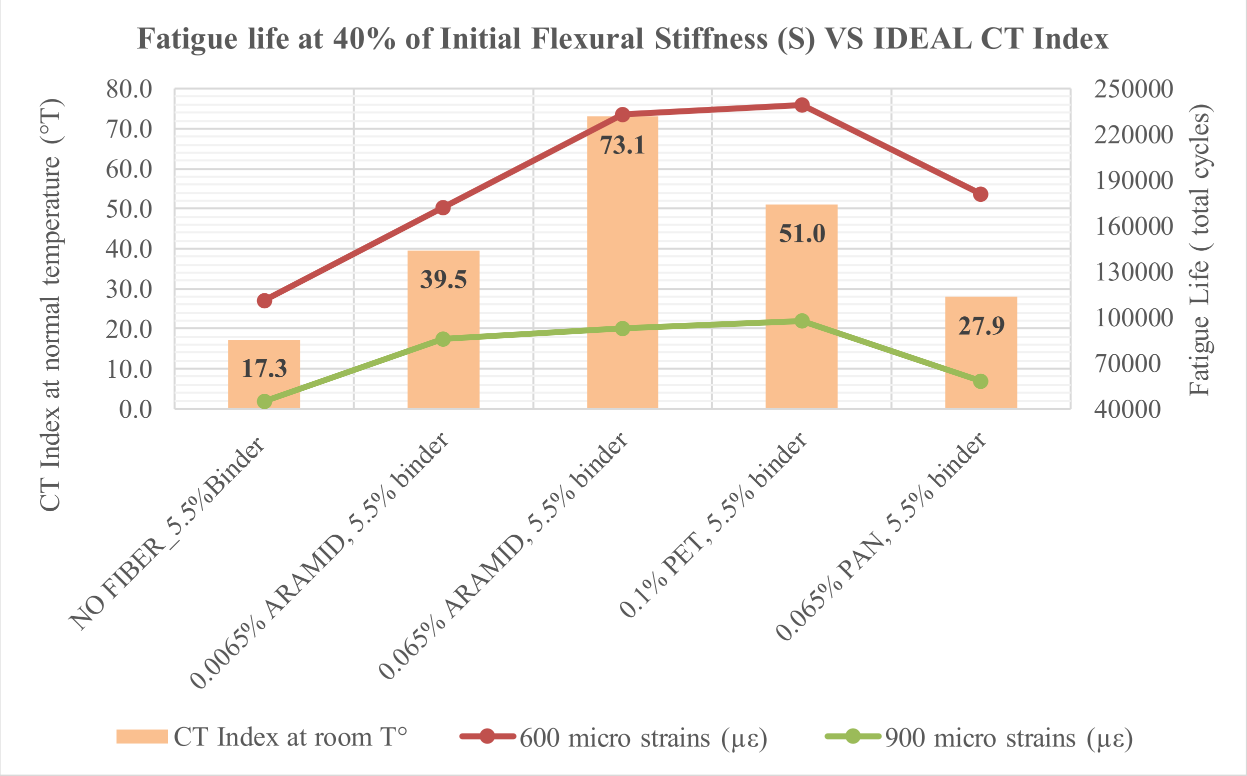

Figure 5-10: Fatigue life determined at 40% of Initial Flexural Stiffness (S) vs. IDEAL CT Index

5.9 Conclusions

The conclusions reached from this study can be summarized as follows:

1. The maximum amounts of fiber determined for mixes modified with PET and PAN fibers, such that the same binder content as the control mix was maintained, was 0.1% and 0.065% by total weight of the mix, respectively. The addition of aramid fibers up to 0.065 % by weight did not affect the volume of the mix. Microscopic analysis showed that all fibers

were generally dispersed into the mixture. The PET 0.1% by weight reinforced mixture showed a strong network without agglomeration zones.

2. The addition of fiber to asphalt mixes affected the initial flexural stiffness of HMA. When the fiber content was increased, the stiffness decreased, which indicates an improvement in the flexibility of the material. This phenomenon was observed for 0.1% by weight PET, 0.065 % by weight PAN and 0.065% by weight aramid at both strains tested, 600 and 900 με.
3. The evaluation of the fatigue characteristics of all HMA's was determined based on when the initial flexural stiffness reached 50% and 40% of its initial value. Overall, all of the fiber-modified mixes tested were more resilient and showed improved resistance to fatigue cracking compared to the reference sample at 600 and 900 microstrains.
4. A comparison of CT indices of fiber-modified mixes with the reference mix showed that the addition of fiber significantly improved the cracking resistance of the asphalt mixes. Fiber-modified mixes containing aramid (0.065% by weight) and PET (0.1% by weight) showed the most significant improvements in both parameters.
5. An analysis done to compare the CT indices and fatigue life of fiber-modified mixtures showed a direct correlation between them, in most of the analyzed fiber-modified mixes.

5.10 Future study and recommendations

Based on the above findings, the following next steps are recommended. First, further imaging tests (i.e. microtomography microscopes) are needed to better understand the distribution and dispersion of fibers on HMA. It is also advisable the evaluation of the effects of fiber content on HMA, as well as an investigation of the impact of fiber length on the improvement of asphalt properties and performance. Finally, it is strongly recommended to perform additional testing at low temperatures to gather larger information about the fatigue performance of fiber-modified HMA under cold climatic conditions.

6 Summary and Conclusions

6.1 Summary

Developing a tougher, more resilient transportation infrastructure is vital to boost the economy and integrate a country. Even though knowledge related to the use of fibers in asphalt mixes goes back several decades, the development of high-performance fibers and the necessity of extending the life span of roads results in an opportunity to explore the advantages of different fibers for use as reinforcement in asphalt mixes. Although there is a wide range of fiber options, the present research focused on three types of synthetic fibers, with the aim of offering an analysis of the capabilities of fibers in increasing the performance of traditional asphalt concrete.

The focus of this study is to investigate the performance improvements observed in asphalt mixes containing aramid, polyacrylonitrile, or polyethylene terephthalate (PET) fibers relative to a control mix. For this purpose, fiber-modified mixes were evaluated at high temperature (45 °C) with the aim of identifying the rutting and moisture improvement by performing Hamburg wheel tracking tests. Then, fiber-modified mixes were evaluated at low temperatures to determine their tensile strength and fracture energy by performing an indirect tensile strength test, calculating the cracking tolerance index, and performing creep compliance and tensile strength tests at -20°C, -10°C, and 0°C. Finally, fiber-modified samples were evaluated at room temperature to determine fatigue resistance of asphalt mixes with the addition of different fibers by performing the four-point bending test. In all cases, results were compared with a control sample. A cost comparison was made based on each individual component of the mixes. Recommendations were then presented for future considerations.

6.2 Conclusions

Laboratory tests of fiber-modified asphalt mixes were compared to the control mixes, in order to get a broader understanding of their mechanical performance improvements on asphalt pavement. The performance outputs were compared with a brief cost analysis of each mixture of HMA. The conclusions obtained are summarized as follows:

1. There is an optimum fiber content that maintains the air void target without altering the original mix design. After increasing the amounts of PET and PAN fibers in the mix from 0.065% to 0.5% by total weight, test results showed that fiber-modified mixes demanded

higher asphalt cement content due to their absorption properties and due to the increase in the air void content relative to the target. To maintain the same binder content as the control mix, the maximum amounts of fibers for mixes modified with PET and PAN were 0.1% and 0.065% by total weight of the mix, respectively. The addition of aramid fibers up to 0.065 % by total weight did not affect the volume of the mix.

2. After performing indirect tensile strength tests, the first conclusion is that the tensile strength of all fiber-modified mixes was not significantly different from the control mix. Secondly, the tensile strength ratio (TSR) determined from ITS test results showed that all fiber-modified mixes were resistant to moisture after freeze-thaw conditioning. Furthermore, the Hamburg Wheel Tracking Device (HWTD) test allowed the Stripping Inflection Point (SIP) of the different fiber composites to be compared. The results showed a significant increment in the number of passes at the SIP, approximately 30-45% relative to the reference point (control mix), except for the aramid fiber samples (0.0065 wt%). From both tests, it is possible to conclude that the inclusion of fibers did not affect the moisture susceptibility of the HMA itself. Indeed, the fiber addition on asphalt mixes helps to reduce the moisture susceptibility on HMA, acting as an anti-stripping agent.
3. From the evaluation of rutting resistance by Hamburg wheel tracking device (HWTD) testing, it was noted that the addition of aramid fiber (0.065 % by weight) and PET fiber (0.1 % by weight) to the asphalt mixes provided significant improvements, reducing the maximum rut depth to 7.5 mm and 9.0 mm, respectively (a reduction of 25% to 37.5%) with respect to the maximum total depth of 12 mm. However, other fiber-modified composites showed only a slight enhancement, with an increased number of passes until failure. For instance, aramid fiber (0.0065 % by weight) and PAN fibers (0.065 % by weight) showed gains of 1,544 passes and 5,546 passes, respectively. It could be concluded that there is a direct relationship between the rutting resistance and the fiber content. The rutting depth is observed to decrease with an increase in fiber content, regardless of the fiber used.
4. From the evaluation of low temperature cracking resistance by the IDEAL CT test, the fracture energy and CT indices of fiber-modified mixes showed that the addition of fibers significantly improved the cracking resistance of the asphalt mixes, in contrast with the control mix. Aramid (0.065 % by weight) and PET (0.1 % by weight) fiber-modified mixes

showed the most significant improvements in both parameters, with an improvement in fracture energy of 70-100% compared to the control mix. It can be concluded that the addition of PET or aramid fibers retarded crack propagation in samples tested, having into consideration the total fracture energy as an indicator of crack propagation control of asphalt concrete. Comparing the CT indices for the mixtures, it was found that the CT indices of aramid- and PET-modified mixes are 3.2 and 1.9 times greater than the CT index of the control mix.

5. Findings from IDT testing at -20°C, -10°C, and 0°C showed that, at low temperatures, although cracks occurred, crack propagation of modified samples was slowed down by the bridge action of fibers, especially for PET (0.1 % by weight) and aramid (0.065 % by weight). For instance, the mentioned samples did not split completely after experiencing excessive stresses and the time for the total fracture propagation was larger than the other mixes, including PAN and control mixtures. In addition, the fracture energy of fiber-modified mixes increased from 22 to 45% relative to the control mix, which indicates the higher cracking resistance of the modified mixes. Testing at room temperature (25°C) and at a low temperature (-20°C) indicated that the fibers were effective at slowing crack propagation, especially after cracks first appeared. The post-crack toughness values collected after running the test showed the same tendency of improvement in controlling or limiting crack propagation once the crack started.
6. Findings from the four-point bending test showed that the initial flexural stiffness of the control mix was larger than that of the mixes with fibers, and the same trend was observed in both strain levels (600 micro strains and 900 micro strains). As the fatigue resistance was determined at 50% and 40% of the initial value of the flexural stiffness, it could be concluded that all fiber-modified samples had better results compared to the control mix samples. For instance, the effect of PET at 0.1% by weight and aramid at 0.065% by weight resulted in the best fatigue performance at both levels, 600 micro strains and 900 micro strains.
7. The observed performance improvement of fiber-modified mixes was contrasted with the additional cost of inclusion of fibers in traditional asphalt mixes. The cost-benefit analysis showed that fibers could be a potential alternative to be considered for transportation agencies in Canada, due to the capability of boosting the performance of traditional asphalt

mixes at a reasonable extra cost. In general, aramid fiber (0.065 % by weight) and PET (0.1 % by weight) had significant improvements in rutting control, cracking tolerance, and fatigue cracking. However, these improvements came with cost increases of 122% and 2.44%, on aramid and PET, respectively. This remarkable difference in cost/benefit ratio leads to the conclusion that incremental improvement in the performance of asphalt cement using PET and PAN fibers is achievable, due to the low cost of the raw material, however, the cost/benefit analysis is not promising for aramid fibers. The positive cost/benefit ratio enabled to increase the binder content in PET and PAN modified asphalt mixes. For instance, a 0.5% increase in asphalt cement enabled the increase in PET and PAN fibers content, up to 0.3 % by weight and 0.2 % by weight, respectively, with outstanding results in fracture resistance for both specimens (IDEAL-CT Index) and minimal increases in cost. For instance, PAN fibers with 6% binder (0.2 % by weight) and PET fibers with 6% binder (0.3 % by weight) resulted in an additional cost of 9.6% and 11.9% and an increase of 500% and 1,000% in the cracking resistance index, respectively. Overall, Aramid showed significant improvements but after varying the fiber content, making it to not be cost-effective. However, PET performed better than PAN based on analysis of the test data and presented similar low costs.

6.3 Future Research

Future performance tests are needed to address the few gaps to better understand the effects of adding fibers to asphalt concrete mixes.

To begin with, a deeply 3D investigation (using a microtomography microscope) of fiber distribution and fiber dispersion in the asphalt mixes should be performed. This would show the internal network, either weak or strong, of fiber-reinforced HMA, and would be another aspect to take into consideration for defining optimum fiber content. Similarly, further analysis is also required to evaluate the effect of fiber length on the performance of fiber-reinforced HMA.

It is recommended to run different tests of a series of mixes containing different fiber contents, until optimizing the fiber content, taking into consideration the mix design, aggregate size, the inclusion of Reclaimed Asphalt Pavement (RAP) in the mix gradation and different lengths on fibers.

It is also recommended a test section could also be constructed using a fiber modified asphalt mix to enable field observations to be made for a specific length of time. Pavement conditions would be reported after periodic assessments, particularly after freeze-thaw cycles and under cold climate conditions. The pilot project would make in situ evaluation of distresses such as cracks on lanes, permanent deformation and fatigue cracking possible, and thus the advantages of using fiber modification to extend the life of pavement roadways could be determined in real conditions. It would also make it possible to collect not only plant mix samples, but also cores for further evaluation in the lab. Future monitoring of the performance of test sections constructed using fiber-modified asphalt would be useful to confirm or challenge the laboratory results demonstrated in the present work.

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Appendix

Appendix A

In an effort to evaluate the dispersion and bonding of fibers, the microscopic evaluation and "The Slippage Theory" were followed, respectively, as it is defined in the Chapter 2 and Chapter 5.

The results obtained, by using Zeiss Stemi 508 Stereo microscope, showed an increment of agglomerated zones when the fiber dosage increased. For instance, higher fiber content of PAN and PET fibers could lead to the development of weaken zones due to the poor dispersion of fibers. Test results are presented as follows:

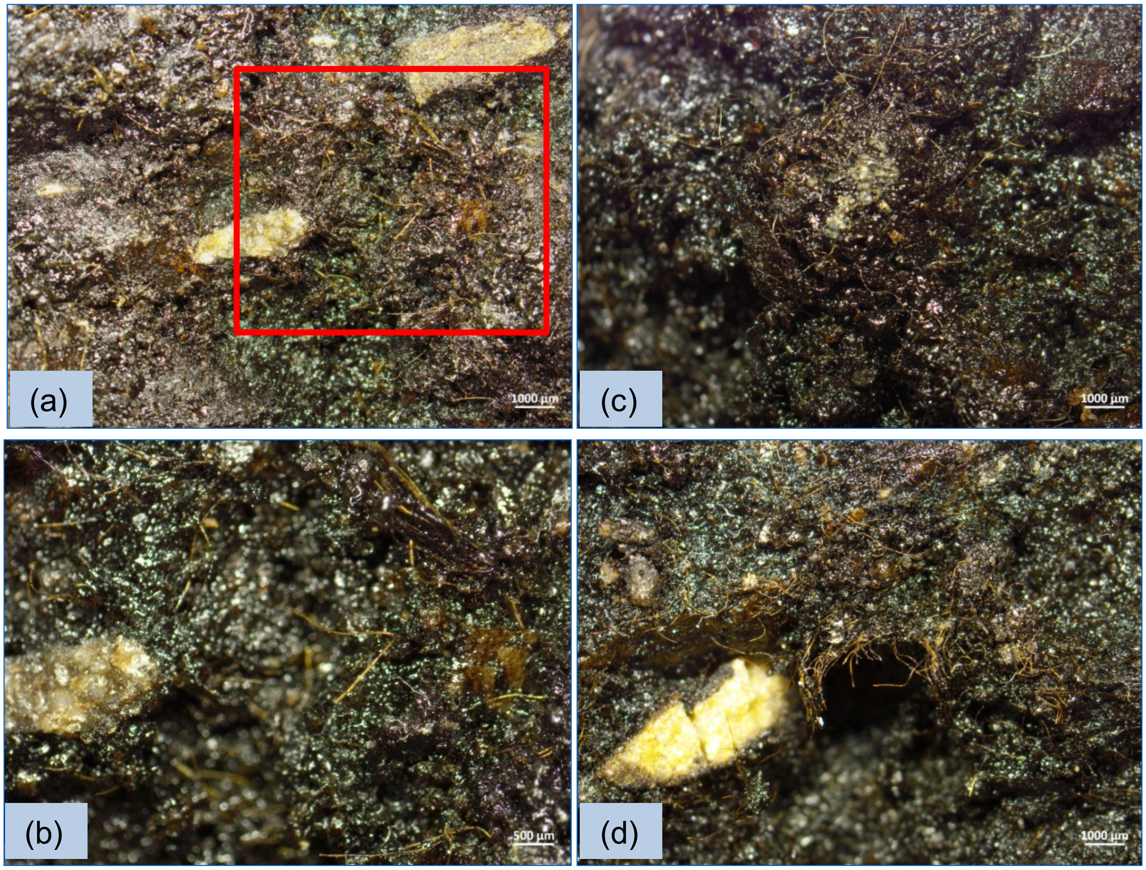

Figure: (a) PAN 0.1%wt; (b) Zoom of section (a); (c) PAN 0.2%wt; (d) PAN 0.3%wt

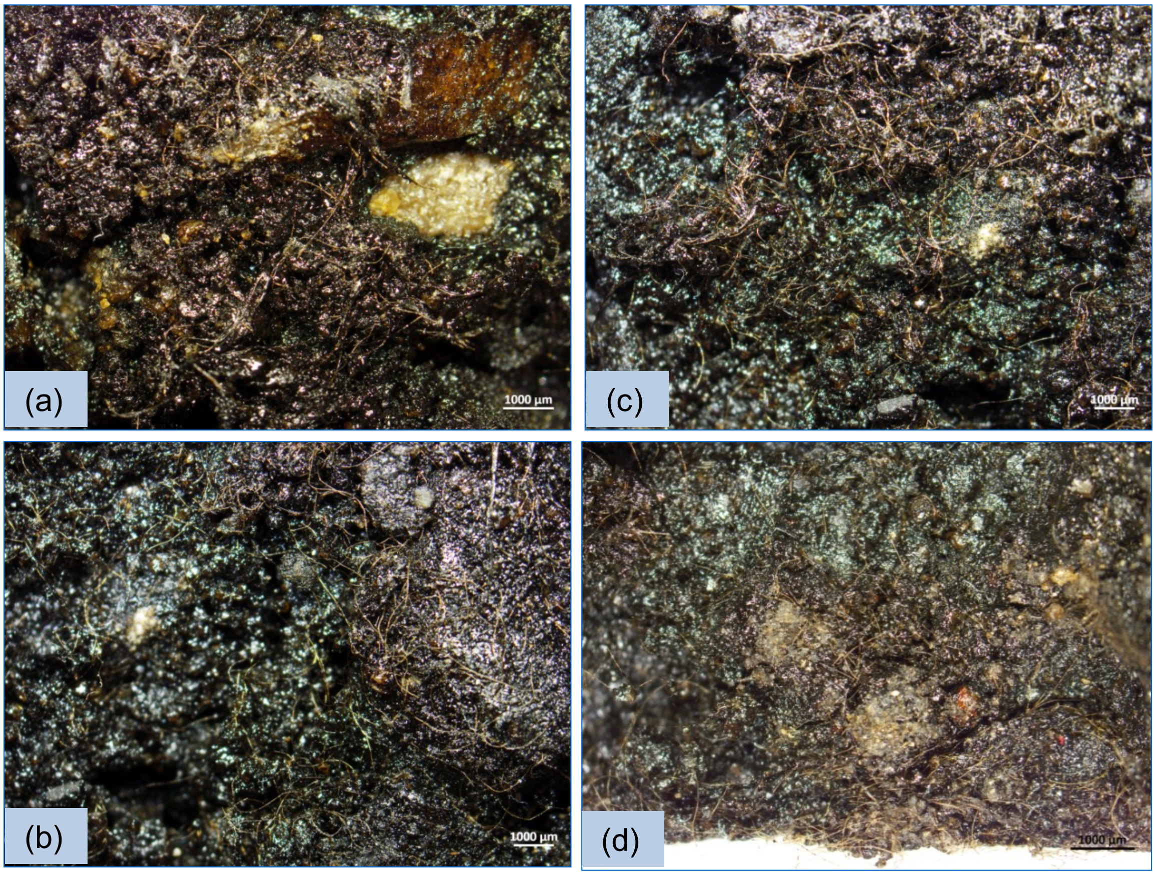

Figure: (a) PET 0.2%wt; (b) PET 0.3%wt; (c) PET 0.3%wt; (d) PET 0.4%wt

The application and results of “The Slippage theory” for the different samples tested on the present work, indicated that the Uncoated Aramid should have the best bonding performance, with the smallest fiber slippage ratio (λ) of 82.5. However, the reduction of length from 38mm to 6mm, in order to perform a better evaluation, gave λ of 522.5

TABLE: Fiber slippage ratio (λ) of Aramid, PET and PAN modified HMA

Properties of fibers	Uncoated ARAMID	PET	PAN
Fiber slippage ratio (λ)	**82.5**	**375.0**	**131.8**
Diameter, $\mathbf{d}_{\mathbf{f}}$ (mm)	0.015	0.020	0.011
Young's modulus, $\mathbf{E}_{\mathbf{f}}$ (10^{8} Pa)	9,500,000	1,500,000	700,000
Strain at failure, $\boldsymbol{\epsilon}_{\mathbf{f}}$ (adimensional)	0.044	0.150	0.200

Interfacial shear stress, **(Ʈ)**	1	1	1
Fiber length, $\mathbf{L_f}$ (mm)	38	6	6

Appendix B

Methodology: Laboratory work