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

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Abstract

Thermal cracking of pavement is caused by contraction of the asphalt layer at low temperatures, when tensile stresses build up to a critical point at which a crack is formed. The cracks formed then propagate under traffic loading conditions. Freeze-thaw cycles accelerate crack propagation and deterioration of the asphalt layer, 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 (HMA) results in a composite material that has a higher tensile strength, along with the ability to absorb greater energy during the fracture process. The fibers within the material also act as a barrier preventing the formation and propagation of cracks in the asphalt mix. This research evaluates the effectiveness of adding polymer fibers to HMA 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: aramids, polyethylene terephthalate (PET), and polyacrylonitrile (PAN), were added to conventional HMA mixes. The resulting samples were compacted, and their mechanical properties were compared with conventional HMA in the laboratory. At the end of the paper, a material cost comparison is provided as a reliable source of information when selecting materials to fulfill minimum industry specifications.

Canada has an extensive network of paved roads, in which asphalt concrete roads represent almost 95% of the total infrastructure (*1*). Maintenance and preventive plans play an important role in extending service life, especially in cold regions like Canada, where the pavement is subjected not only to vehicle loads but also to thermal stresses during cold seasons (*2–4*). The most concerning pavement distress in freezing conditions is thermal cracking (*4*). Considering that asphalt concrete withstands forces very well in compression but not in tension (*5*), 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 such distresses by improving mechanical properties such as tensile strength, stiffness, crack appearance control, crack propagation, and toughness (*6–10*). Consequently, the addition of fibers increases pavement service life (*11*).

There is broad discussion in the literature about the use of different fibers in asphalt mixes (*5, 6, 12, 13*). Fibers are normally classified based on their origin (*12*) 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 their use is now limited because of 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

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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 (*14–17*), tensile strength (*9, 18*), (*19*), and freeze-thaw resistance (*13, 20*), as well as decreased cracking potential (*8, 9*) and rutting susceptibility (*11, 21*). However, there has not been 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 (*6*), but an adequate dispersion is needed to achieve the necessary bond among fibers, binder, and aggregates (*16*). The length of fibers may also affect the performance. While shorter fibers might have a negligible effect on mixes (*6*), longer fibers give a better interlock effect between the components of asphalt concrete (*9, 12*). Once the optimum fiber content is achieved, fiber agglomeration might provide meaningless results (*8*).

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 (*16*). Fibers acted as a bridge, connecting all mix components; larger amounts of fiber gave significant improvements (*12, 16*). Kaloush et al. reported that a blend of aramids and polypropylene gave a slight improvement of 25–50% in tensile strength at different temperatures and concluded that the strength followed a pattern: when the temperature dropped, the tensile strength increased. They also reported that the fracture energy of fiber-modified mixes was greater than the control mixes in 50–75% of all tested temperatures, and that the fracture energy maintained a direct relationship with temperature: once the temperature increased, fracture energy followed an incremental tendency (*10*). Comparable results are found in Klinsky et al. (*11*) and Marasteanu et al. (*22*). Ho evaluated a blend of polyolefin and aramid fibers through laboratory experiments and field observations over 2 years. 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 (*20*).

Polyacrilonitrile (PAN) fiber used in asphalt concrete 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 (*12*). Wang et al. concluded that PAN fiber-modified mixes had longer fatigue life than the control mix (*17*). One drawback, however, is the high absorption rate of PAN fiber, which alters and increments the binder content (*12, 13*).

Polyethylene terephthalate (PET) fibers, part of a group of polyesters, are relatively inexpensive fibers that improve the fatigue and rutting resistance of asphalt mixes (*23, 24*). Beyond the consideration of its mechanical properties, use of PET may also help to reduce the environmental impact of waste plastic material by re-using plastic waste materials (*23*).

As cost effectiveness is essential to justify fiber usage in all projects, the amount of fibers used should be controlled (*25*) to obtain a feasible and economical product. It should be taken into consideration that an initial increase in project cost could be justified with an extension in years of service life and a decrease in CO_2 emissions in the long term (*21, 26*).

Objectives and Scope

The objective of this paper is to analyze and compare the effects of different fibers (PET, PAN, and aramid) on the 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 fiber content for each type of fiber was determined. To investigate 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 HMA at intermediate temperatures, samples modified with fibers were evaluated by conducting an indirect tensile strength test in dry conditions and after a freeze and thaw cycle. To investigate the cracking resistance of the fiber-modified mixes at low temperature, an indirect tensile creep compliance and strength (IDT) test was performed at 0°C, –10°C, and –20°C. The stress-strain curves from 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.

Materials and Mix Design

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 1. The granular aggregates were virgin crushed aggregates collected from an asphalt plant. To prepare each mix, aggregates were sieved in the laboratory and were mixed using the grain size distribution shown in Figure 1.

The HMA sample was modified with three types of fibers: uncoated aramid (no wax coating) fibers, PET fibers, and PAN fibers, which are shown in Figure 2. The basic properties of the fibers are given in

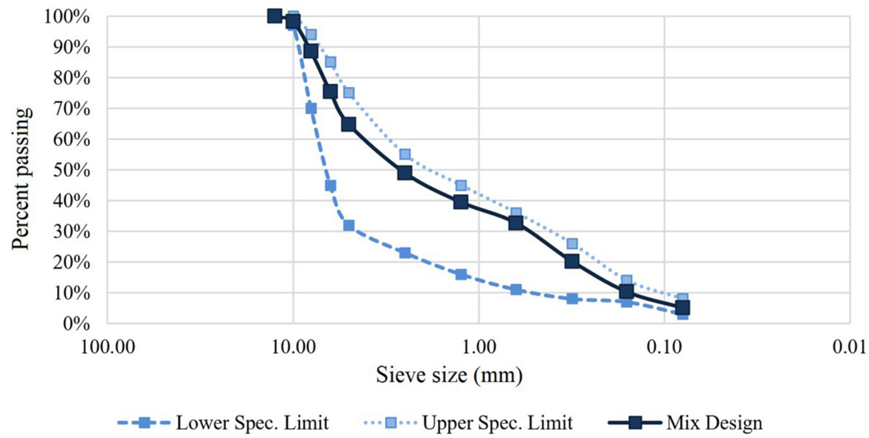

Figure 1. Combined aggregates gradation of control mix.

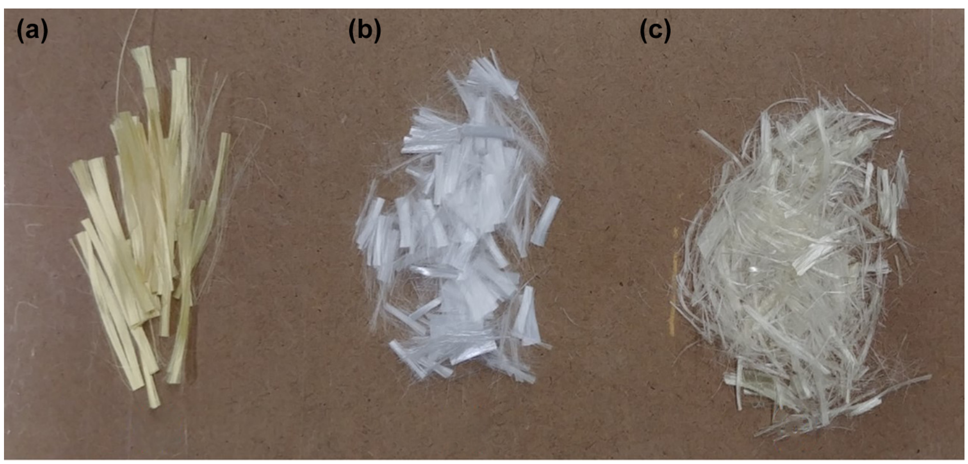

Figure 2. Photographs of fibers selected for the study: (*a*) uncoated aramid fibers, (*b*) PET fibers, and (*c*) PAN fibers.
Note: PAN = polyacrylonitrile fibers; PET = polyethylene terephthalate fibers.

Table 1. Mix Design and Volumetric Properties

Mix design properties	Actual	Specifications
Number of gyrations	100.0	100.0
Asphalt cement % of total mix	5.5	NA
Gmm (kg/m^3)	2431.0	NA
Gmb (kg/m^3)	2337.0	NA
Air voids (%)	4.0	3.6–4.4
VMA (%)	14.9	13
VFA (%)	73.8	70–80
%Gmm @ Nmax	96.8	98.0 max.
Dust/AC	1.0	NA

Note: AC = asphalt content; NA = not applicable; VFA = voids filled in asphalt; VMA =voids in mineral aggregate.

Table 2. Fiber Properties

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

Note: PAN = polyacrylonitrile fibers; PET = polyethylene terephthalate fibers.

Table 2. The same mix design used for the control mix was used for fiber-modified mixes as well. According to Abtahi et al. (*6*), a low melting point of the fiber leads to an ineffective HMA modification. For instance, this is the case with polypropylene fibers. However as Table 2 shows, the fibers used in this research had melting points higher than 200°C, which was much higher than mixing temperature (146°C) of the HMA used.

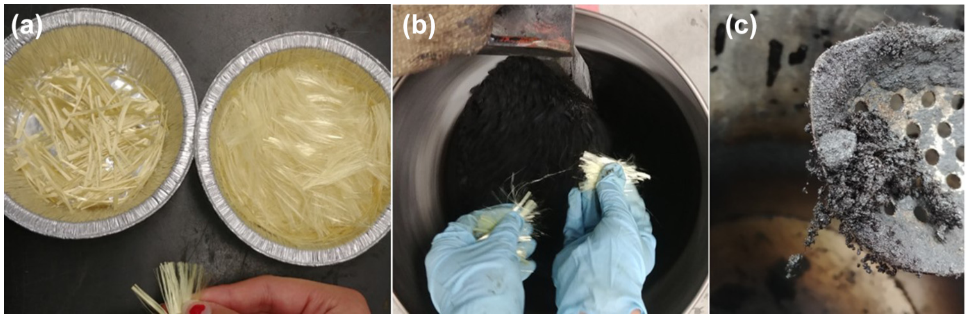

Figure 3. (*a*) Manual separation process of uncoated aramid fibers, (*b*) uncoated aramid fibers being added into the mix bucket, and (*c*) aggregate-binder-fiber interlock result.

Mixing Process

As suggested in the literature review, an adequate dispersion of fibers is essential to obtain reliable mechanical improvements. To ensure an optimal result, each strand of uncoated aramid fiber was separated as much as possible manually, using fingers, before proceeding with the mixing operation (Figure 3). For PET fibers and PAN fibers, it was determined that no separation was needed before mixing.

According to Abtahi et al. (*6*), the two 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 the modified binder is then blended with aggregates. In the dry process, fibers are mixed with aggregates first, then placed into the mixing bucket before 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 before the addition of binder, the standard mixing process between the aggregate and the asphalt binder was followed. Initially, aggregates and asphalt cement were placed in an oven at 165°C and 146°C, respectively. The aggregates were placed overnight and the binder PG 58-31 for 2 h. Once the aggregates, coarse, fines, and filler, were coated (after 1.5 min, on average), at a mixing temperature of 146°C, loose fibers were gradually introduced into the mixing bucket until they were coated completely (Figure 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.

Optimum Fiber Content

Fiber usage in asphalt mixtures increases the binder content mainly because of the binder absorption of fibers. The addition of fiber may alter the original asphalt mix design by raising the optimum asphalt content (*12*); however, an adjusted binder content might show results that confuse whether the mechanical improvement is because of the fibers or the increased binder content (*9*).

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 comparison between the properties of the modified mixes and the control mix. Table 3 summarizes the effect of the addition of different amounts of PAN and PET fibers to the asphalt mix. As the table shows, the trend is 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 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.

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.

Mix Performance Tests

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 (*27*). They were compacted in the laboratory with a Superpave gyratory compactor, in accordance with AASHTO T 312

Table 3. PAN and PET Fiber Content (Amount by Total Weight), Air Void Content and 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

Note: Gmb = bulk specific gravity; PAN = polyacrylonitrile fibers; PET = polyethylene terephthalate fibers.

Table 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	10,350/7.5	12,428.0	12.0
0.0065% aramid, 5.5% binder	45.0	6.50	96,19/8.7	13,972.0	12.0
0.065% aramid, 5.5% binder	45.0	6.24	13,445/5.8	20,000.0	7.5
0.1% PET, 5.5% binder	45.0	6.43	14,253/6.5	20,000.0	9.0
0.065% PAN, 5.5% binder	45.0	5.74	14,908/6.8	17,974.0	12.0

Note: PAN = polyacrylonitrile fibers; PET = polyethylene terephthalate fibers.

(*28*), 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 not to exceed a gap of 7.5 mm once they were placed in the high-density polyethylene molds. Although the target air void content for the complete research was 4%, it was redefined to 7% for this test to comply with the HWTD test specifications.

Before placing the specimens into the HWTD, the device was conditioned at the required temperature of 45°C (*29*). The samples were then conditioned for a time frame of 30 min before 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 its moisture susceptibility. 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 midpoint. The HWTD is set up to stop when either 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. 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).

Figure 4 shows different stages of the wheel tracking test for different asphalt samples. As 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 (*13*).

Another comparative result is the increment in number of passes at the stripping inflection point, which is a reference point to evaluate how susceptible an asphalt concrete mix is to moisture. With the exception of the

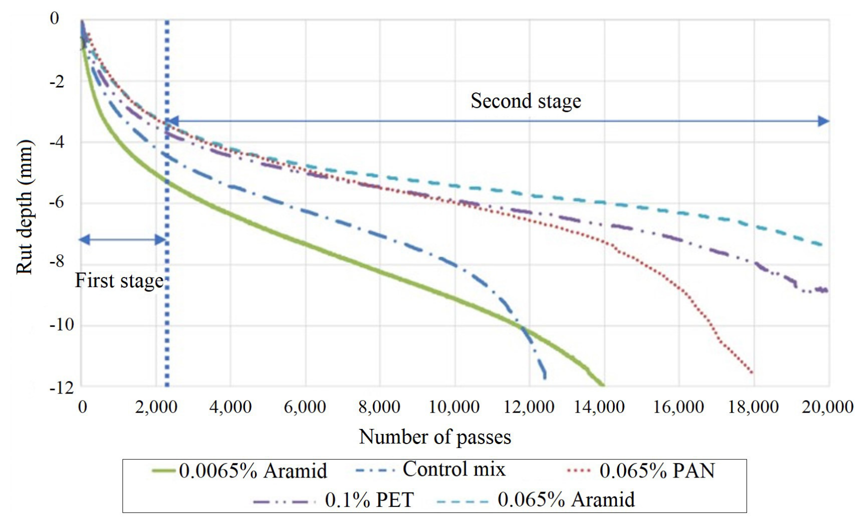

Figure 4. Rutting development in fiber-modified asphalt mixes.
Note: PAN = polyacrylonitrile; PET = polyethylene terephthalate.

Table 5. Indirect Tensile Strength Test Results for Fiber-Modified and Unmodified Samples

	Dry		Saturated		
Mixture	Maximum load (N)	Tensile strength (kPa)	Maximum load (N)	Tensile strength (kPa)	Tensile strength ratio
No fiber, 5.5% binder	9,575.3	943.1	12,728.7	1,272.5	1.3
0.0065% aramid, 5.5% binder	9,522.7	945.2	12,624.0	1,140.8	1.2
0.065% aramid, 5.5% binder	12,170.3	1,202.7	12,624.0	1,252.6	1.0
0.1% PET, 5.5% binder	12,194.3	1,188.5	11,607.3	1,150.0	1.0
0.065% PAN, 5.5% binder	10,300.0	1,026.7	11,358.7	1,121.3	1.1
0.2% PAN, 6.0% binder	10,786.3	1,059.0	9,971.7	979.9	0.9
0.3% PET, 6.0% binder	12,506.3	1219.2	8,158.7	793.3	0.7

Note: PAN = polyacrylonitrile fibers; PET = polyethylene terephthalate fibers.

aramid fiber sample (0.0065 wt%), all other fiber composites showed significant improvements (30–45%).

Indirect Tensile Strength Test

Two sets of three different Marshall samples for each type and amount of fiber were prepared and tested following the standard AASHTO T 283 (*30*). 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 (*30*). The saturated samples were sealed in a plastic package and stored in a freezer for 16 h at –18°C. After that, the samples were placed in a warm water bath at 60°C for 24 h. They were then placed in a water bath at 25°C for 2 h. 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 asphalt concrete 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 (*31*).

The results of the ITS test are shown in Table 5. As can be seen in the table, the changes in 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% (*11, 31*, *32*). It should be mentioned that the void contents of the samples were similar to Table 3. This could be a reason for having higher TSR values for the control sample and low fiber content samples compared with high fiber content samples with greater air void content.

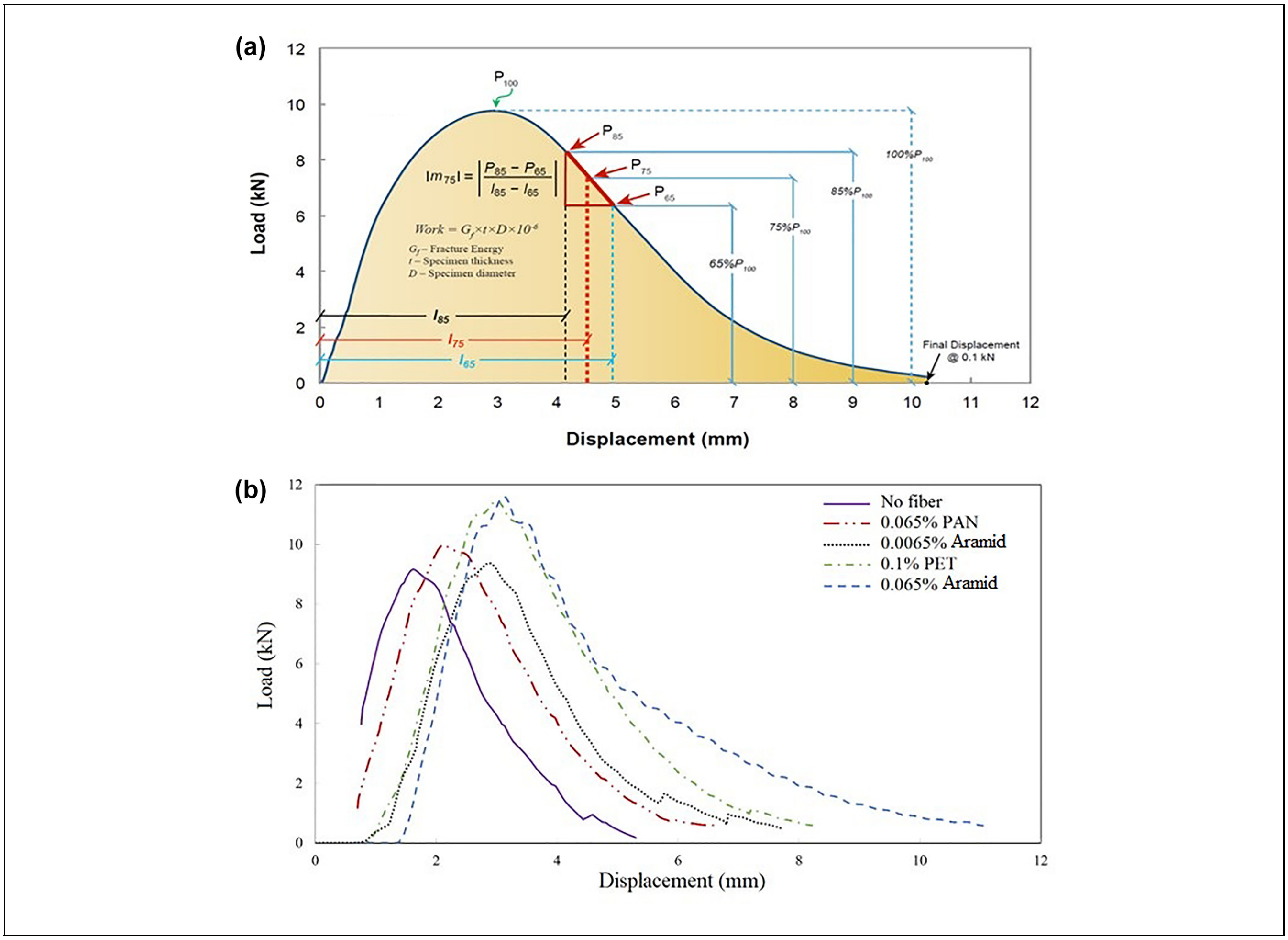

Figure 5. (*a*) Parameters within the force-displacement curve, ASTM D8225 and (*b*) force-displacement curve: work of failure (W_f) = area under the curve.
Note: PAN = polyacrylonitrile; PET = polyethylene terephthalate.

Determination of CT Index of Asphalt Mixtures

The standard ASTM D8225-19 (*33*) was used to calculate the cracking resistance of the asphalt mixtures, based on fracture mechanics theory. The CT index is obtained from the fracture energy (Gf), which has a proportional relationship to the cracking resistance and is defined in Equation 1:

$$CT_{Index} = \frac{t}{62} * \frac{l_{75}}{D} * \frac{G_f}{|m_{75}|} * 10^6 \quad (1)$$

where CT_{Index} is the CT index, t is the specimen thickness (mm), l_{75} is the vertical displacement at 75% of the peak load after the peak (mm), D is the specimen diameter (mm), Gf 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 Figure 5, including the work of failure (W_f) as the area under the force-vertical displacement curve (Figure 5*a*), which was extracted from ASTM D8225 (*33*). 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 horizontal displacement graphs from the dry ITS test were used (Figure 5*b*). 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 mixes (*9, 18*).

The results of the calculation are given below (Table 6), which shows a significant difference between the

Table 6. CT Index Results for Different Fiber Mixes

Mixture	Pre-crack toughness (J)	Post-crack toughness (J)	Work of failure (J)	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

Note: CT = cracking test; PAN = polyacrylonitrile fibers; PET = polyethylene terephthalate fibers.

fracture energy of the fiber-reinforced asphalt mixes compared with the control mix. Aramid fiber (0.065 wt%) and PET fiber (0.1 wt%) showed a significant increase in fracture energy (between 70% and 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 with the control mix. Table 6 shows that, for higher amounts of PET and PAN fiber, CT indices improve significantly which could be partly 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 with the control mix; however, there was no significant change in the pre-crack toughness.

The CT index of each mix is presented in Table 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 (*34*).

Determination of ITS at Low Temperature

ITS and creep compliance of HMA mixes are the two main outputs of the Indirect Tensile Test (IDT) test based on AASHTO T 322-07 (*35*). 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 3 h 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 s, 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 mounted on brass gauge points with a gauge length of 75 mm on each face of the specimen (Figure 6, *a* and *b*).

The results also show a qualitative comparison between a cracked fiber-modified sample and the control mix after an IDT test (Figure 6, *c* and *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 relation to slowing down crack propagation.

Table 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 with the control mix at the same temperature. For all the fiber-modified mixes, there was an inverse relationship with temperature: when temperature decreased, the tensile strength increased. On the other hand, all fiber-modified samples had higher fracture energy compared with 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 temperature compared with the control mix. Moreover, the fracture energy followed a direct relationship with temperature: when the temperature increased, the fracture energy increased.

At all three of the temperatures tested, aramid fiber (0.065 wt%) and PET fiber (0.1 wt%) presented a 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 because of the fibers holding the specimen together.

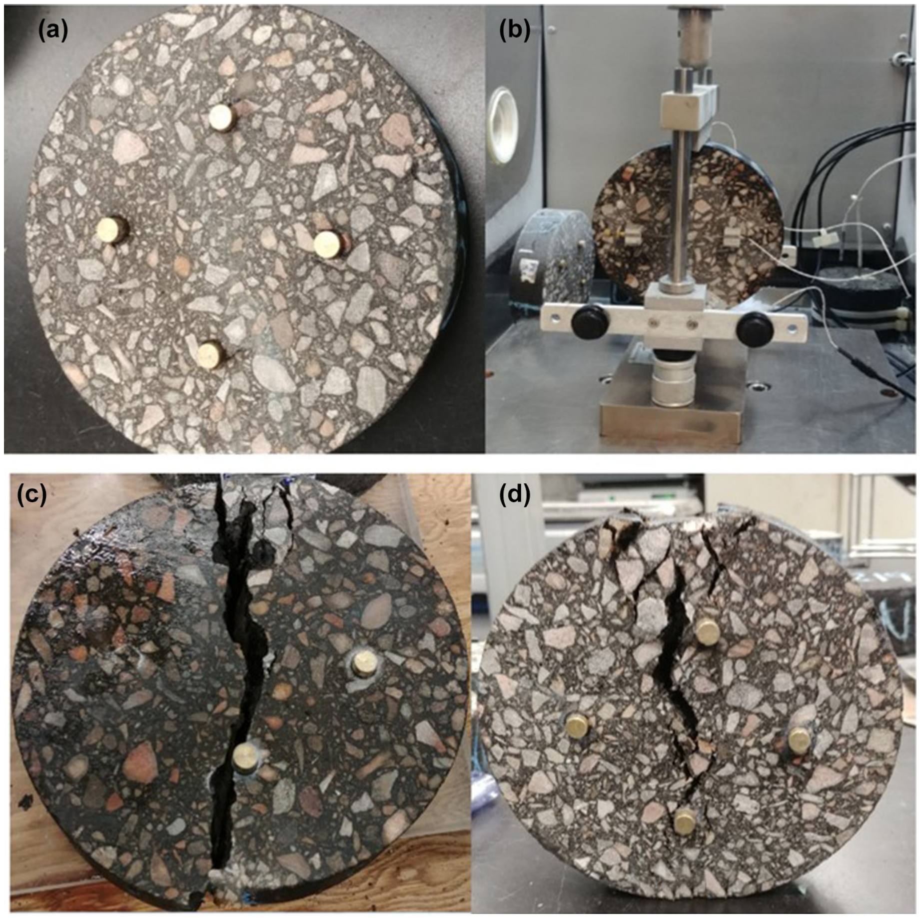

Figure 6. (*a*) Sample prepared for Indirect Tensile Test (IDT) testing, (*b*) IDT test configuration, (*c*) fracture path of the control mix, and (*d*) fracture path of a fiber-modified mix.

Table 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 (J)	Post-crack toughness (J)	Work (J)	Fracture energy (J/m^2)
No fiber, 5.5% binder	3.7	38.5	11.4	49.9	8,630.6
0.0065% aramid, 5.5% binder	4.0	37.1	29.4	66.5	9,319.3
0.065% aramid, 5.5% binder	2.9	30.9	53.8	84.8	12,450.5
0.1% PET, 5.5% binder	3.6	36.3	40.3	76.7	11,756.9
0.065% PAN, 5.5% binder	3.5	34.6	26.7	61.3	8,824.5
(*b*) Asphalt mixes at –10°C					
No fiber, 5.5% binder	3.9	51.1	14.3	65.4	9,824.3
0.0065% aramid, 5.5% binder	3.9	57.5	9.0	66.5	9,706.4
0.065% aramid, 5.5% binder	2.8	38.9	51.6	90.6	13,822.2
0.1% PET, 5.5% binder	3.4	46.3	34.1	80.4	12,015.3
0.065% PAN, 5.5% binder	3.5	26.3	30.7	57.1	9,949.2
(*c*) Asphalt mixes at 0°C					
no fiber, _5.5% binder	2.7	41.5	31.4	72.9	10,594.1
0.0065% aramid, 5.5% binder	3.5	52.4	15.6	68.0	9,842.0
0.065% aramid, 5.5% binder	2.5	50.0	56.7	106.7	14,521.5
0.1% PET, 5.5% binder	2.5	35.0	55.4	90.4	13,891.2
0.065% PAN, 5.5% binder	2.6	33.5	52.4	85.9	13,286.5

Note: PAN = polyacrylonitrile fibers; PET = polyethylene terephthalate fibers.

Table 8. Cost Comparison of Control Mix and Fiber-Modified Mixes

	Unit	$/unit	Total cost (USD/ton)
(*a*) No fiber, 5.5% binder (USD [$] per ton)			
High traffic (HT) –10 mm (ton)	0.945	40.00	$37.80
PG 58-31 binder (ton)	0.055	765.00	$42.08
Cost per ton of HMA mixture ($/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

Note: HMA = hot mix asphalt; PAN = polyacrylonitrile fibers; PET = polyethylene terephthalate fibers.
*The aramid pricing depicted here is fully commercialized; it includes not just fiber, as do the other test materials. Cost includes other applicable raw materials as a complete commercialized product that also includes pricing for dosing into hot or warm mix asphalt.

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 U.S. dollars (USD [$]), and all fiber dosages are in kilograms (kg). The cost analysis mainly considered the original binder content at 5.5%, according to the mix design. To increase the fiber dosage, however, 6.0% binder was included in the PET fiber (0.3 wt%) and PAN fiber (0.2 wt%) mixes.

Table 8 the unit prices of aramid fibers are as determined based on the study by Muftah et al. (*16*), which

Table 9. Cost-Benefit Analysis of Control Mix and Fiber-Modified Mixes: Cost per Ton of HMA Mixture versus Improvement of Mechanical Properties

Type of fiber	Cost/ton of HMA mixture	Cost overrun (%)	Fracture energy increase (J/m^2) at –20°C (%)	CT index improvement at room temperature	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	Not applied	529.48%	Not applied
0.3% PET, 6.0% binder	$89.35	11.86	Not applied	987.28%	Not applied

Note: HMA = hot mix asphalt; PAN = polyacrylonitrile fibers; PET = polyethylene terephthalate fibers.

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 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.

A summary (Table 9) shows 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, and so forth. 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.

Conclusions and Future Work

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 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 with 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 at 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 understand better the effects of adding fiber to asphalt concrete mixes. Microscopic investigation to ensure the fibers are well dispersed in the asphalt mix, the impact of fiber length on mixture properties, and determination of the fatigue life of fiber-modified asphalt mixes are the next steps of this research. It should be noted that all the conclusions for this research are based on laboratory investigations. It is also necessary to validate these results with field performance.

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Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: L. Hashemian; data collection: L. Perca and K. Sha; analysis and interpretation of results: L. Perca and L. Hashemian; draft manuscript preparation: L. Perca and L. Hashemian. All authors reviewed the results and approved the final version of the manuscript.

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