Performance Evaluation of Fiber Modified Asphalt Mixes in Cold Regions

Authors:

Luis Alberto Perca
MSc Student, University of Alberta
1-060 Markin/CNRL Natural Resources Engineering Facility
9105 116th St.
Edmonton, AB Canada T6G 2W2
(e-mail) lperca@ualberta.ca

Leila Hashemian, Ph.D. (corresponding author)
Assistant Professor, University of Alberta
7-255, Donadeo Innovation Centre for Engineering
9211 116th St., University of Alberta
Edmonton, AB, Canada T6G 1H9
(e-mail) hashemia@ualberta.ca
780-492-8934

Jintao Liu
Undergrad Student, University of Alberta
1-060 Markin/CNRL Natural Resources Engineering Facility
9105 116th St.
Edmonton, AB Canada T6G 2W2
(e-mail) jintao5@ualberta.ca @ualberta.ca

Jay Kwon
Undergrad Student, University of Alberta
1-060 Markin/CNRL Natural Resources Engineering Facility
9105 116th St.
Edmonton, AB Canada T6G 2W2
(e-mail) boemjoon@ualberta.ca@ualberta.ca

Paper prepared for presentation at the

Innovations in Pavement Management, Engineering and Technologies Session of the 2019 TAC-ITS Canada Joint Conference

Halifax, NS

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, 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.

Keywords: fiber modified asphalt, aramids, PET, PAN, fracture energy, tensile strength, thermal cracking

INTRODUCTION AND BACKGROUND

Asphalt concrete withstands forces very well in compression but not in tension (Mcdaniel, 2015). 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 (Muftah et al. 2017, Park et al. 2015). Thermal cracking is a distress that is particularly concerning 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 (Zofka et al. 2011, Jung and Vinson, 1994).

Fibers have already been used to reinforce paving materials for many decades in various parts of the world (Abtahi et al. 2010, Klinsky et al. 2018) and their main application in asphalt mixes has been to prevent drain-down of the binder from the aggregate particles (Tripathi, 2018). 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 (Park et al. 2015, Kaloush et al. 2018, Yee et al. 2015). The most commonly used polymer fibers are polyester, Polyethylene Terephthalate (PET), polypropylene, aramid, and combinations of these (Muftah et al. 2017; Hatta and Hashim, 2017; Button and Hunter, 1984; Piggott, 2016). 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 (Yee et al. 2015).

There is a broad discussion about the use of different fibers in asphalt mixes in the literature (Mcdaniel, 2015; Abtahi et al. 2010; Slebi-Acevedo et al. 2019; Xu et al. 2010). 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 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 (Dehghan and Modarres, 2017; Barman et al. 2018), tensile strength (Park et al. 2015, Vasconcelos and Bernucci, 2012; Chen and Lin, 2005), and freeze-thaw resistance (Xu et al. 2010), while decreasing cracking potential (Park et al. 2015; Chen and Lin, 2005; Maurer and Malasheskie, 1989) and rutting distress (Tripathi, 2018; Kaloush et al. 2018). 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 CO_2 emissions (Stempihar et al. 2012). Finally, PET fibers, that is part of a group of polyesters, are affordable fibers that show similar or better improvements in asphalt mixes (Ahmad et al. 2017). Beyond the consideration of its mechanical properties, PET use may help to reduce the impact of waste plastic material by re-using waste materials (Usman et al. 2016).

OBJECTIVE AND SCOPE

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 Indirect Tensile Strength test (ITS) by the conditioning the samples using freeze and thaw cycles. 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 -20°C.

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 1. The properties of the control mix are summarized in Table 2.

Table 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 2: Mix Design and Volumetric Properties

Mix Design Properties	Actual	Specifications
Number of gyrations	100.0	100.0
Asphalt Cement (A.C.)% of Total Mix	5.5	-
Gmm (kg/m3)	2431.0	
Gmb (kg/m3)	2337.0	
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 1. The basic properties of fibers are given in Table 3.

Table 3: Fiber properties

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

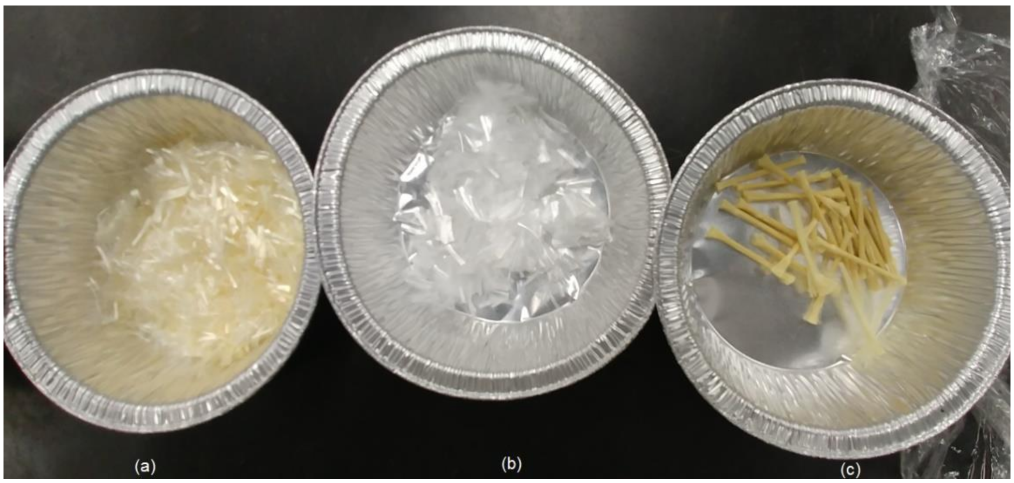

Figure 1: Photo of fibers selected for the study: (a) polyacrylonitrile(PAN) fibers (b) polyethylene terephthalate (PET) fibers (c) uncoated aramid fibers

According to (Abtahi et al. 2010), the most common methods for introduction of fibers in HMA samples are the wet process and the dry process. In the first case, fibers are blended with the binder previous to 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.

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 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 per cent. To increase the PET content to 0.2%, the mix design should be modified by adding 0.5% of asphalt cement.

Table 5 shows the impact of adding PAN fiber to the volumetric properties of the asphalt mix. From Table 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 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 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, there 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 amount of aramid fibers used was reduced 10 times, testing Asphalt Concrete mixes with a comparative dosage of 0.00065% by weight.

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 (AASHTO T-283, 2016). 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 (AASHTO T-283, 2016). 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 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 (Ahmadinia et al. 2012).

The results of the ITS test are shown in Table 6. As it 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 75%, indicating that all mixes may have adequate resistance against damage induced by moisture. From literature review, minimum TSR values are above 70-75% (Ahmadinia et al. 2012, Klinsky et al. 2018, Alberta Transportation, 2002).

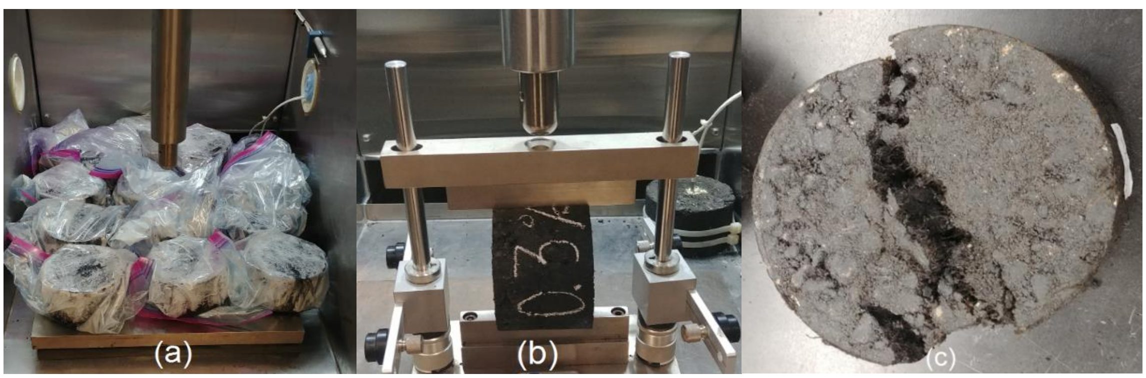

Figure 2: ITS test process: (a) frozen samples, (b) application of force to the sample, and (c) a broken sample

Table 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

Determination of Cracking Tolerance Index of Asphalt Mixtures (IDEAL CT Test)

The standard ASTM D8225-19 (Road and Materials, 2019) 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:

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

Where $\mathbf{CT_{Index}}$ is the cracking tolerance index, **t** is the specimen thickness (mm), $\mathbf{l_{75}}$ is the displacement at 75% of the peak load after the peak (mm), **D** is the specimen diameter (mm), $\mathbf{G_f}$ is the fracture energy (J/m2), and $\mathbf{m_{75}}$ is the post-peak slope around the 75% peak load point after the peak (N/m). Further reference of parameters is shown in Figure 3.

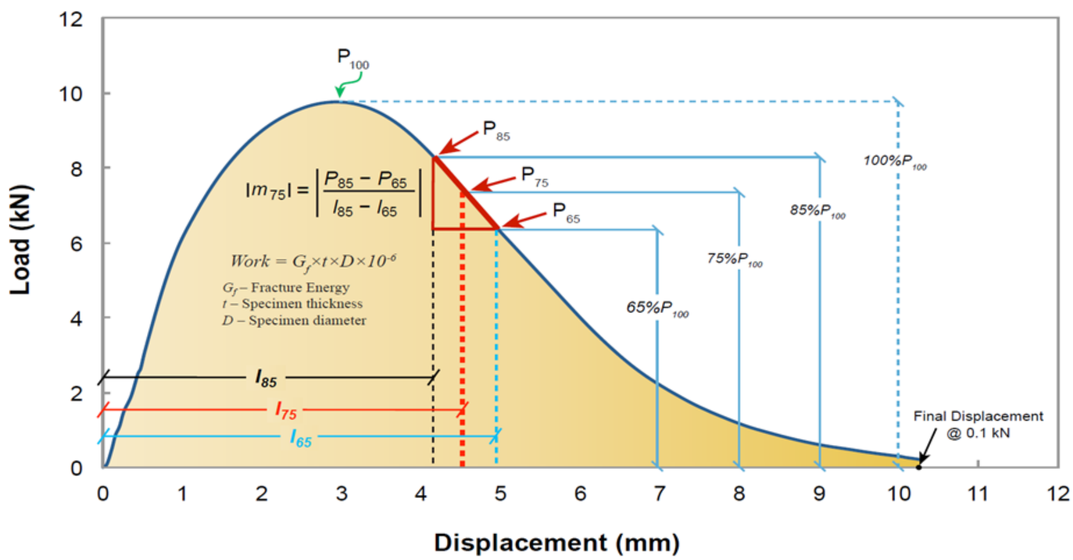

Figure 3: Parameters within the force-displacement curve, ASTM D8225 (Road and Materials, 2019)

The work of fracture (W_f) is estimated as the area under the force-displacement curve (see Figure 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 4). The results of the calculation are shown in Table 7.

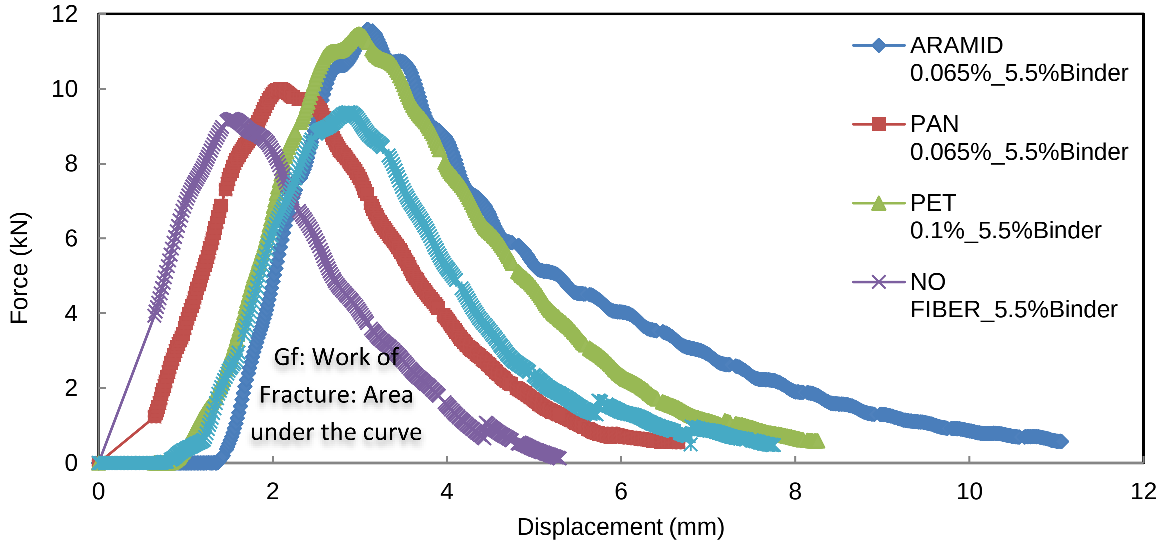

Figure 4: Force-Displacement curve: work of failure (W_f) - area under the curve

Using Figure 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 (Park et al. 2015, Vasconcelos and Bernucci, 2012).

The results of the calculation are given in Table 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 indeces 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 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

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 (AASHTO T322, 2011). 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 5).

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

Figure 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.

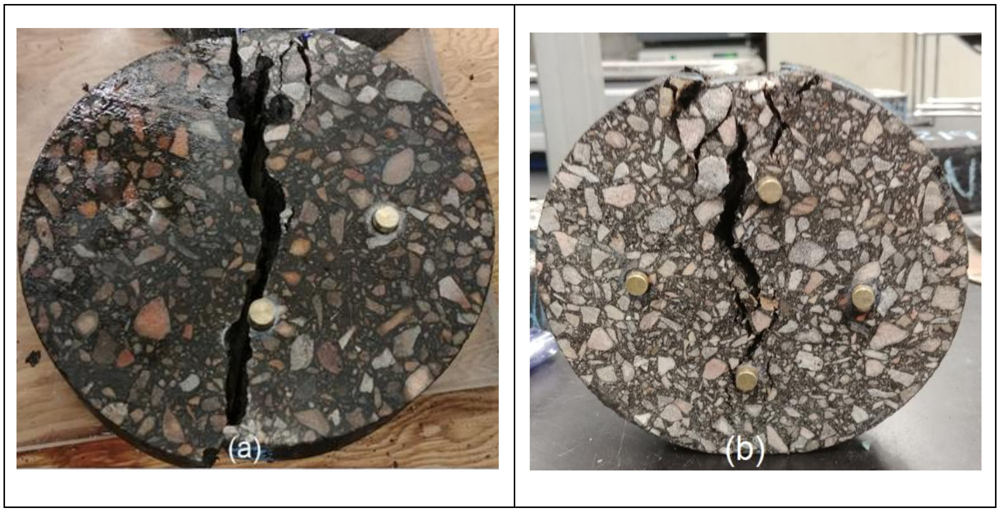

Figure 6: IDT test results at -20°C: (a) control mix, (b) PET (0.1 %wt) and aramid (0.065 % wt) fiber modified mix

The summary of IDT test results is given in Table 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 temperature compared to the control mix.

Table 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

CONCLUSIONS AND FUTURE WORK

The conclusions of this study are summarized as follows:

1- 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 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.

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 temperature.

ACKNOWLEDGEMENTS

The authors want to thank Phillip Blankenship from SurfaceTech Corporation, for his assistance in conducting the laboratory investigations. Also, the authors would like to acknowledge SurfaceTech Corporation (USA) and Pioneer Scientific Industry Corporation (China) for providing samples of the fiber materials.

REFERENCES

AASHTO T-283. (2016). Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage Standard Method of Test for Resistance of Compacted Asphalt Mixtures to Moisture-Induced Damage

AASHTO T322. (2011). Standard Method of Test for Determining the Creep Compliance and Strength of Hot Mix Asphalt (HMA) Using the Indirect Tensile Test Device Determining the Creep Compliance and Indirect Tensile Test Device. *American Association of State Highway and Transportation Officials*, 1–11

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

Ahmad, A. F., Razali, A. R., Kaneto, K., & Yoshino, K. (2017). Utilization of polyethylene terephthalate (PET) in bituminous mixture for improved performance of roads

Ahmadinia, E., Zargar, M., Karim, M. R., Abdelaziz, M., & Ahmadinia, E. (2012). Performance evaluation of utilization of waste Polyethylene Terephthalate (PET) in stone mastic asphalt. *Construction and Building Materials*, *36*, 984–989. https://doi.org/10.1016/j.conbuildmat.2012.06.015

Barman, M., Ghabchi, R., Singh, D., Zaman, M., & Commuri, S. (2018). An alternative analysis of indirect tensile test results for evaluating fatigue characteristics of asphalt mixes. *Construction and Building Materials*, *166*, 204–213. https://doi.org/10.1016/j.conbuildmat.2018.01.049

Button, J. W., & Hunter, T. G. (1984). Synthetic Fibers in Asphalt Paving Mixtures, *7*(2)

Chen, J. S., & Lin, K. Y. I. (2005). Mechanism and behavior of bitumen strength reinforcement using fibers. *Journal of Materials Science*. https://doi.org/10.1007/s10853-005-5691-4

Dehghan, Z., & Modarres, A. (2017). Evaluating the fatigue properties of hot mix asphalt reinforced by recycled PET fibers using 4-point bending test. *Construction and Building Materials*, *139*, 384–393. https://doi.org/10.1016/j.conbuildmat.2017.02.082

Hatta, M. N. M., & Hashim, M. S. (2017). Utilization of polyethylene terephthalate (PET) in asphalt pavement : A review

Jung, D. H., & Vinson, T. S. (1994). *Low -Temperature Cracking : Test Selection*. Washington,DC

Kaloush, K. E., Biligiri, K. P., Zeiada, W. A., Rodezno, M. C., & Reed, J. X. (2018). Evaluation of Fiber-Reinforced Asphalt Mixtures Using Advanced Material Characterization Tests, *38*(4), 400–411

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

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

Mcdaniel, R. S. (2015). Fiber Additives in Asphalt Mixtures- NCHRP. https://doi.org/10.17226/22191

Muftah, A., Bahadori, A., Bayomy, F., & Kassem, E. (2017). Fiber-Reinforced Hot-Mix Asphalt: Idaho Case Study. *Transportation Research Record: Journal of the Transportation Research Board*, *2633*(1), 98–107. https://doi.org/10.3141/2633-12

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

Piggott, M. R. (2016). *Load Bearing Fibre Composites Second Edition*.

Road, I., & Materials, P. (2019). Standard Test Method for Determination of Cracking Tolerance Index of Asphalt Mixture Using the Indirect Tensile Cracking Test at, (April), 1–6. https://doi.org/10.1520/D8225-19

Slebi-Acevedo, C. J., Lastra-González, P., Pascual-Muñoz, P., & Castro-Fresno, D. (2019). Mechanical performance of fibers in hot mix asphalt: A review. *Construction and Building Materials*. https://doi.org/10.1016/j.conbuildmat.2018.12.171

Stempihar, J. J., Souliman, M. I., & Kaloush, K. E. (2012). Fiber-Reinforced Asphalt Concrete as Sustainable

Paving Material for Airfields. https://doi.org/10.3141/2266-07

Transportation, Alberta(2002.). TENSILE STRENGTH RATIO (TSR) SPECIFICATIONS- AMENDMENT TO SPECIFICATION 3.50. Retrieved from http://www.transportation.alberta.ca/Content/docType29/production/AMC_S262(Sec_3-50).pdf

Tripathi, A. (2018). Mechanistic Analysis and Economic Benefits of Fiber-Reinforced Asphalt Mixtures

Usman, N., Masirin, M. I. B. M., Ahmad, K. A., & Wurochekke, A. A. (2016). Reinforcement of asphalt concrete mixture using recycle polyethylene terephthalate fibre. *Indian Journal of Science and Technology*, *9*(46). https://doi.org/10.17485/ijst/2016/v9i46/107143

Vasconcelos, K. L., & Bernucci, L. B. (2012). Effect of Temperature on the Indirect Tensile Strength Test of Asphalt Mixtures, (June 2012), 13–15

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

Yee, P., Aida, B., Hesp, S. A. M., Marks, P., & Tam, K. K. (2015). Analysis of Premature Low-Temperature Cracking in Three Ontario , Canada , Pavements, (January 2006). https://doi.org/10.3141/1962-06

Zofka, A., Marasteanu, M., Turos, M., Zofka, A., Marasteanu, M., & Turos, M. (2011). Investigation of Asphalt Mixture Creep Compliance at Low Temperatures Investigation of Asphalt Mixture Creep Compliance at Low Temperatures, *0629*. https://doi.org/10.3166/RMPD.9HS.269-285