Evaluation of Cracking Resistance and Permanent Deformation of Control and Fibre-modified Plant-produced Hot-mix Asphalt

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ABSTRACT

The addition of elastomeric polymers to asphalt mixtures is a common practice for preventing premature distresses in asphalt pavements. Polymer enhances the asphalt binder to improve its rutting and cracking resistance. In cold temperatures, thermal stress in asphalt pavement builds up to the point that it can exceed the pavement's tensile strength, causing cracks on the surface. Given the severe cold seen in Alberta's winters, the City of Calgary is seeking to address asphalt pavement cracking issues by investigating the impact of polymer (dry) fibres on pavement cracking resistance. In the present study, a trial road section having been constructed in Calgary using aramid and wax polymer fibre-modified hot-mix asphalt adjacent to a control section, the hot-mix asphalt is modified using 0.0065% fibres by weight of asphalt mix. (Note this amount is much less than cellulose fiber, for example.) Representative samples of the fibre-modified and control mixes are collected from the asphalt plant and transferred to the University of Alberta asphalt laboratory for testing. The cracking property and rutting performance of the modified and unmodified asphalt mixes are assessed through IDEAL Cracking Test and Hamburg wheel-tracking test, respectively. The results show that the average cracking tolerance index for the control sample is found to be 123.7, whereas, for the fibre-modified sample, the value is 178.2. These findings suggest that the cracking resistance of the samples can be increased by up to 44% as a result of modification. Furthermore, the average indirect tensile strength for the control sample is found to be 789 kPa, while that of the fibre-modified sample is just 735 kPa; however, the load-displacement plots show higher post-cracking energy resulting in slower crack propagation for the reinforced mix. In addition, the Hamburg wheel-tracking test results show that, after 20,000 of wheel passes, the average rut depth of the fibre-modified sample is 4.58 mm, whereas, for the control sample, the rutting is 4.93 mm, indicating a decrease in rut depth by 7.1% as a result of the addition of fibre.

Keywords: Aramid Fibre, Asphalt Mixture Performance Tests, CT-Index, Fracture Energy, Moisture Susceptibility, Rutting, Stripping Inflection Point, Tensile Strength.

1. INTRODUCTION

1.1 Background

Asphalt pavements are layered structures, with every layer functioning to decrease the stress exerted on the layers beneath it with materials of inferior quality. Asphalt mixtures are mainly composed of asphalt binder, aggregates, and filler. In recent years, with increasing traffic loads and intense climatic conditions, the addition of modifiers to asphalt mixtures is a common practice for preventing premature distresses in asphalt pavements. In regions with cold temperatures, and in addition to vehicular loading, thermal stress in asphalt pavement builds up to the point where it can exceed the pavement's tensile strength, causing cracks on the surface [1]. The challenge in pavement mix and structural design is that asphalt pavements need to be stiff enough to resist rutting, but also need to be of sufficient resilience and flexibility to prevent cracking. Cracking of the pavement, in particular, is an increasing concern in many jurisdictions and, consequently, the development of solutions to improve cracking resistance will prove beneficial. One such solution to address the thermal cracking issue is the use of fibres in the asphalt mix [2]. Fibres used in asphalt mix modification come in many different types and forms, with each type having benefits and disadvantages that make them more suitable for some applications than others. For example, although they are weak in tension, cellulose fibres have been very commonly and successfully used in stone matrix asphalt and porous (or open-graded) mixtures to prevent drain down of the binder from the aggregate particles [3].

A rich discussion is ongoing in the literature concerning the particular applications and types (materials, sources, dimensions) of fibres in asphalt mixes [3,4,5]. In addition to cellulose fibres, other types include mineral, synthetic polymer, glass, waste or recycled, and plant-based fibres. Mineral fibres include, for example, asbestos, carbon, and steel. Use of asbestos was banned in the 1960s because of health and environmental concerns. Steel fibres, meanwhile, have been found to be ineffective in terms of long-term performance because of their vulnerability to corrosion upon exposure to water. Glass fibres, although they have excellent mechanical and physical properties such as high tensile strength, elastic recovery, softening point and low elongation, are brittle and may break during mixing and compaction or where they cross each other. Moreover, natural fibres are low cost, sustainable, and have acceptable strength, but they tend to absorb moisture, causing them to swell. This, in turn, affects the bonding between the asphalt binder and the fibres. In addition to their susceptibility to moisture, natural fibres can degrade at high temperatures. Of particular relevance to the present study are engineered, polymer fibres, with the different types of polymer fibres ranging in terms of melt point but all generally having a high tensile strength. Among the most commonly used polymer fibres is aramid fibre [3]. Aramid – short for aromatic polyamides – is a type of polymer fibre with hair-like fibrils and has two types: meta-aramid and para-aramid. The former is mainly used in heat resistant applications and the latter is used in applications requiring both heat resistance and strength [6]. Although some studies have used aramid fibre for improvement of thermal resistance—such as Kaloush et al. [7], who used a blend of polypropylene and aramid fibres—very few studies have used a standalone aramid fibre for enhancement of thermal cracking. The most recent research study in this area was conducted by Callomamani et al. [8], who used uncoated aramid fibres of 38 ± 1.3 mm in length and 15 µm in diameter. In their analysis, they found that using 0.065% of uncoated aramid fibre by total weight of the mix made the freeze/thaw-conditioned asphalt mixture more resistant to moisture damage and slowed down the crack propagation of the mixture at low temperatures [8]. Similarly, Kaloush et al. [7] reported in their study that, at high temperatures, aramid fibres contract, making the pavement more resistant to deformation.

In this paper we report on the findings of a study that used aramid and wax fibre as an asphalt mix modifier. The aramid and wax fibre is an engineered, dry para-aramid polymer for hot-mix asphalt (HMA), coated with a Sasobit wax so that the fibres appear in hair-like fibrils when dispersed into the mix. The main motivation underlying the use of this fibre was the need to address pavement cracking issues under severe winter conditions without changing the mix design. To investigate the impact of dry polymer fibres on pavement cracking resistance, two adjacent trial road sections—one with a regular (control) mix and the other with an aramid and wax fibre-modified mix on the surface wearing layer—were constructed in September 2021, in Calgary, Alberta.

Although fibres have been used in other studies to improve cracking and rutting resistance, these applications are still considered to be at the research and development stage [9]. Thus, the main objective of our laboratory testing on mix samples obtained from the asphalt plant was to conduct an in-depth laboratory evaluation of how the addition of this synthetic fibre affects the mechanical performance of plant-produced HMA modified with the aramid and wax fibre.

1.2 Site Location

The constructed road sections we investigated are part of a local ring road in southwest Calgary comprising Woodfield Road SW and Woodbine Boulevard SW, as shown in Fig. 1. The total length of the control and fibre-modified sections is approximately 1.5 km and 1 km, respectively. The road sections are local residential roads with maximum latest recorded daily traffic counts between 936 and 6,133 in one direction (i.e., Eastbound versus Westbound and Northbound versus Southbound) and a truck volume percentage of less than 1% [10].

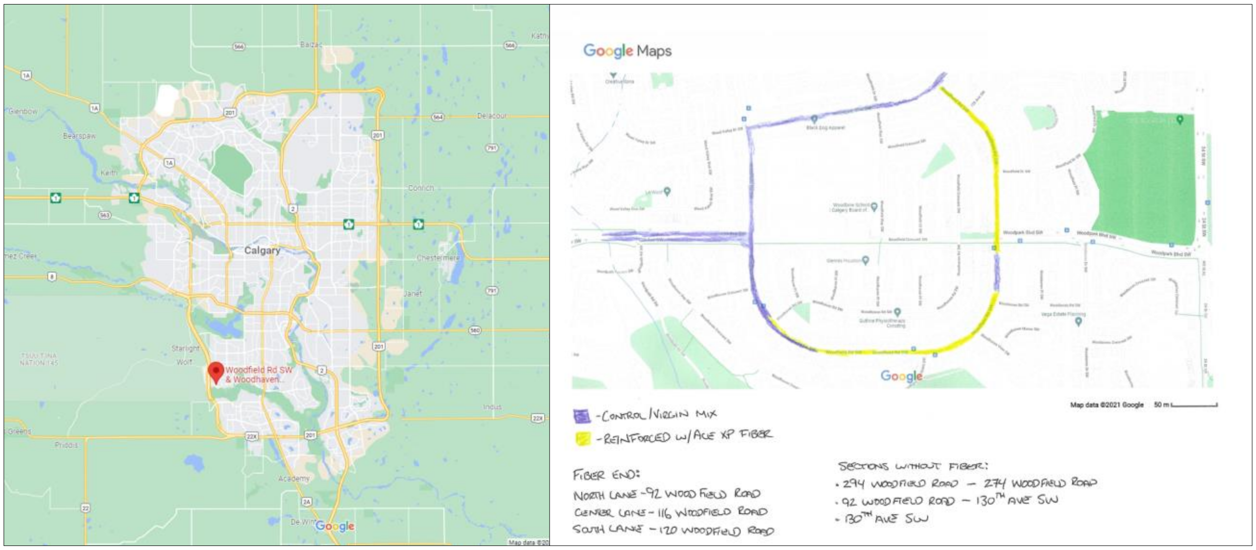

Fig. 1. Project site showing control and fibre-modified road sections

1.3 Sampling of Control and Fibre-modified Asphalt Mixes

Representative samples of unmodified (control) and fibre-modified asphalt mixtures were collected from stockpiles built from haul trucks before leaving the City of Calgary Manchester asphalt plant . A quartermaster splitting device was used to quickly quarter samples into four different boxes (constituting one sampling batch). Relevant standards, including ASTM D979/D979M [11], AASHTO T 168 [12], AASHTO R 97 [13], and ATT-3796 of Alberta Transportation [14], were consulted to ensure an unbiased sampling process. As illustrated in Fig. 2, the stockpile's top material was first removed and discarded. A bucket (provided with the quartermaster) was then used to fill the top section of the quartermaster's hopper. Next, the gate of the quartermaster was opened to allow free flow of the HMA and the split HMA to be collected in the four corner boxes. Afterward, the hopper section was cleaned of any residuals into the relevant boxes before spreading the mix evenly to a uniform thickness. This process was repeated until the required amount of control and fibre-modified material for laboratory testing had been collected. Approximately 300 kg of fibre-modified samples and 90 kg of control samples were collected for the testing at the University of Alberta asphalt laboratory.

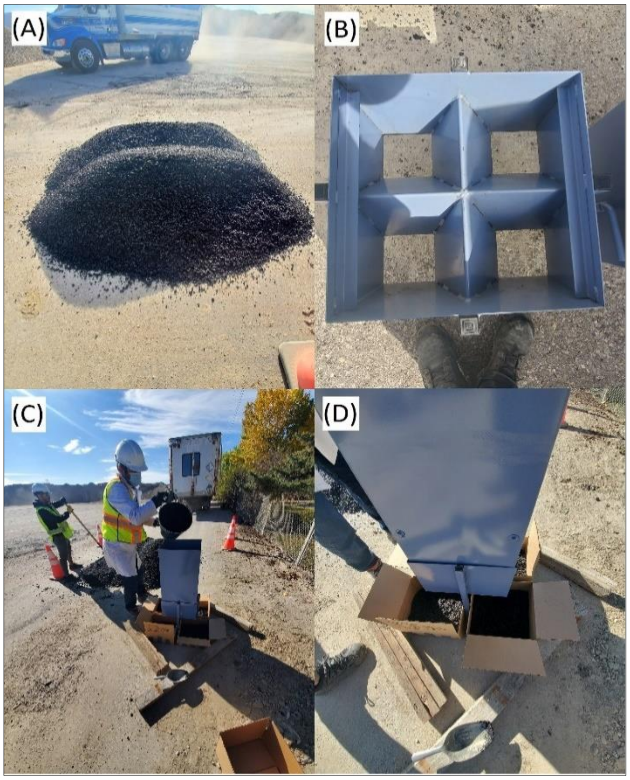

Fig. 2. (A) Asphalt mix stockpile at HMA plant; (B) Quartermaster base unit; (C) Loading process; (D) Sample collection in the cardboard boxes

2. OBJECTIVE AND SCOPE

As noted above, the main objective of this study was to evaluate the mechanical performance properties of plant-produced aramid and wax fibre-modified asphalt mixes through various laboratory tests. For this purpose, the impact of fibres on the cracking property and rutting performance of asphalt mixes before and after fibre modification was analyzed. Cracking resistance was assessed using the indirect tensile asphalt cracking test (IDEAL-CT) [15] at an intermediate temperature, while rutting resistance was assessed using the Hamburg wheel-tracking (HWT) test [16] at a high temperature.

3. EXPERIMENTAL PROCEDURE

3.1 Materials and Mix Design

The aramid and wax polymer fibre used in this project was composed of 50% aramid fibre by weight and 50% Sasobit wax binder to improve dispersion of fibres into the asphalt mix. Aramid fibre is a synthetic, high-performance dry polymer with a tensile strength of 2,700 MPa, which is five times that of steel. On the other hand, the Sasobit wax is soluble and negligible in the liquid asphalt binder [17]. The melting points of the aramid fibre and wax binder are 425 °C and 77 °C, respectively. A 65 g/tonne concentration of aramid fibre and 65 g/tonne wax binder were mixed, and the resulting aramid and wax fibres were produced in 38 mm-long bundles with 12,000 fibres per bundle. This mix resulted in over 10 million fibres being dispersed into one tonne of mix material. Fig. 3 shows the constituent materials of the aramid and wax fibre and the resulting fibre bundles.

Fig. 3. Aramid and wax polymer fibre composition, adapted from [17]

The plant mix was prepared manually using an in-line air conveyor system (see Fig. 4). The polymer fibres were blended in the mixture using the dry process in which fibres are added to the heated dry aggregates and mixed before adding the asphalt binder and completing the mixing process [4]. When the aramid and wax fibre entered the asphalt mixing chamber, the wax melted to disperse the aramid fibres into the asphalt mix. In this process, the fibres were mixed and distributed manually to ultimately travel the pipeline system and arrive at the asphalt mix chamber. The combined aramid and wax dosage was 130 g per metric tonne of mixture, which translates to a percentage of 0.0065% of aramid by total weight of the mix.

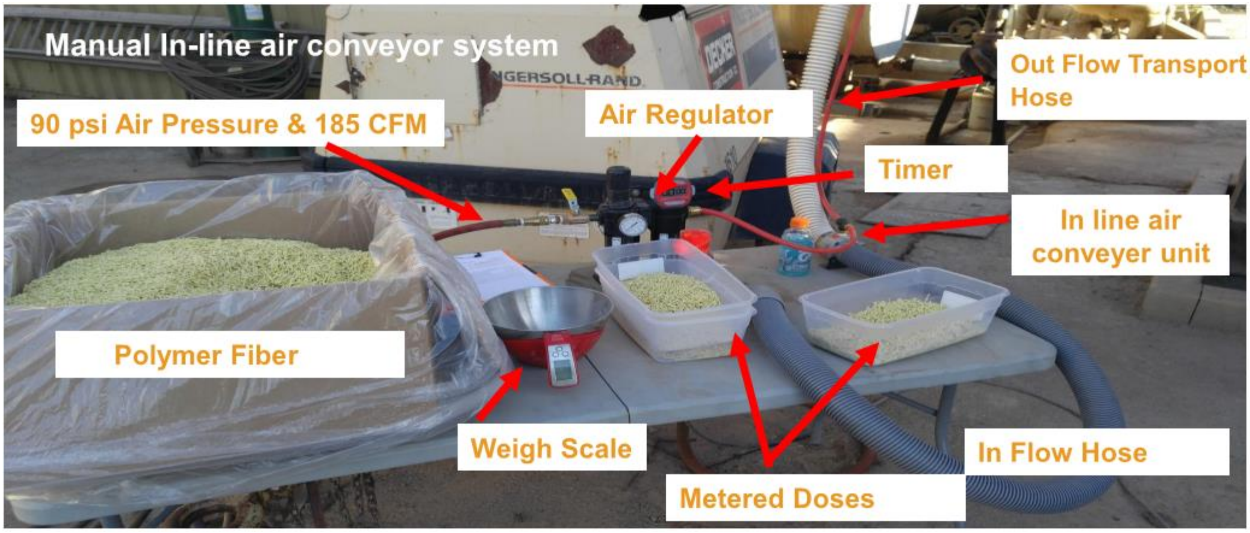

Fig. 4. Aramid and wax fibre mixing process through manual in-line air conveyor system

As noted above, the laboratory tests were carried out at the University of Alberta asphalt laboratory and were implemented using a Superpave fine-graded mix with a 12.5 mm nominal maximum aggregate size (NMAS), a Husky PG 64-34 asphalt binder, and design traffic (20 years) of more than 5 million equivalent single-axle loads (ESALs). The asphalt mix design was conducted in accordance with the City of Calgary's 2015 Roads Construction Standard Specifications [18]. The aggregate size distribution used for both the control and the fibre-modified mixes is shown in Table 1.

Table 1: Plant-produced asphalt mix design combined aggregate gradation

Sieve size (mm)	% Passing	Design limits		The City of Calgary limits [18]		
				Aggregate gradation control points 12.5 mm NMAS – Fine graded		Tolerance +/−
		min	max	Min	max	
25.000	100.0	100.0	100.0			4
20.000	100.0	100.0	100.0	100	100	4
16.000	100.0	100.0	100.0			4
12.500	95.0	91.0	99.0	90	100	4
10.000	82.0	78.0	86.0		90	4
5.000	64.0	60.0	68.0			4
2.500	47.0	44.0	50.0	39	58	3
1.250	36.0	33.0	39.0			3
0.630	26.0	24.0	28.0			2
0.315	13.6	12.0	16.0			2
0.160	7.8	6.0	10.0			2
0.080	5.1	4.1	6.1	2	10	1

Table 2 shows the full range of the mix properties, including composition, binder and aggregate properties, as well as volumetric ratios and densities.

Table 2: Plant-produced asphalt mix design characteristics and volumetric properties

Property	Mix design results	The City of Calgary limits [18]
A.C. "binder" Content (% total mix)	5.3	
Film Thickness (microns)	8.6	-
Dust Ratio (0.080 mm)	1.09	0.6 – 1.2
G_{mb} (N_{design}) kg/m^3	2,372	-
G_{mm}	2.465	-
% G_{mm} ($N_{initial}$)	88.9%	89% max
% G_{mm} (N_{design})	96.2%	
% G_{mm} (N_{max})	97.5%	98% max
Air Voids (%)	3.8%	3.8% - 4.2%
VMA (%)	14.5%	14% min
Voids Filled (%)	74.1%	65% - 75%
Tensile Strength Ratio	77%	75% min
Fractured Aggregate: +5 mm: 2 faces + (%)	91%	90% min
+5 mm: 1 faces + (%)	96%	95% min
Manufactured Sand (TLT 314))	76%	70% min
Fine Aggregate Angularity	46%	45% min
Flat and Elongated Particles	0.8%	10% max
Sand Equivalent Test (ASTM D 2419)	71%	45% min

3.2 Preparation of Specimens

The plant-produced mixtures were reheated in an oven at 135 °C until they were sufficiently workable to be divided into appropriate specimen sizes (an average of 3 kg). The sample was reduced using a quartermaster to obtain representative samples of approximately the required specimen size. The split HMA was collected in flat-bottom trays and spread evenly to approximately 40 mm to 60 mm in thickness. In addition, the design compaction temperature was set to 140 °C as per the mix design. Test specimens were prepared using a Superpave gyratory compactor with a ram pressure of 600 kPa, an average internal angle of 1.25°, and 30 gyrations per minute throughout compaction. The moulds and other necessary equipment used in the process of compacting specimens were heated at the compaction temperature, and the mould was charged with the mix, avoiding segregation of the mixture. Since the mixtures used in this study were plant-mixed and laboratory-compacted (PMLC) mixes, no additional aging was required prior to testing.

During the mix preparation and material collection, some fibre clustering was observed. Fig. 5 shows an example of this clustering effect in one of the samples, where clustering is indicative of incomplete dispersion of the fibres in the mix. While the performance tests indicated that cracking resistance with aramid fiber was greatly improved (Section 4), the clusters can cause concern because they can be seen. Understanding that there are thousands of individual fibers in a sample of mix, this becomes more of a perception than a real concern. If this is seen in production, additional mixing time is recommended to reduce or eliminate these clusters. It should be noted that the clustering was not observed during the sampling of the fibre reinforced mix at the plant.

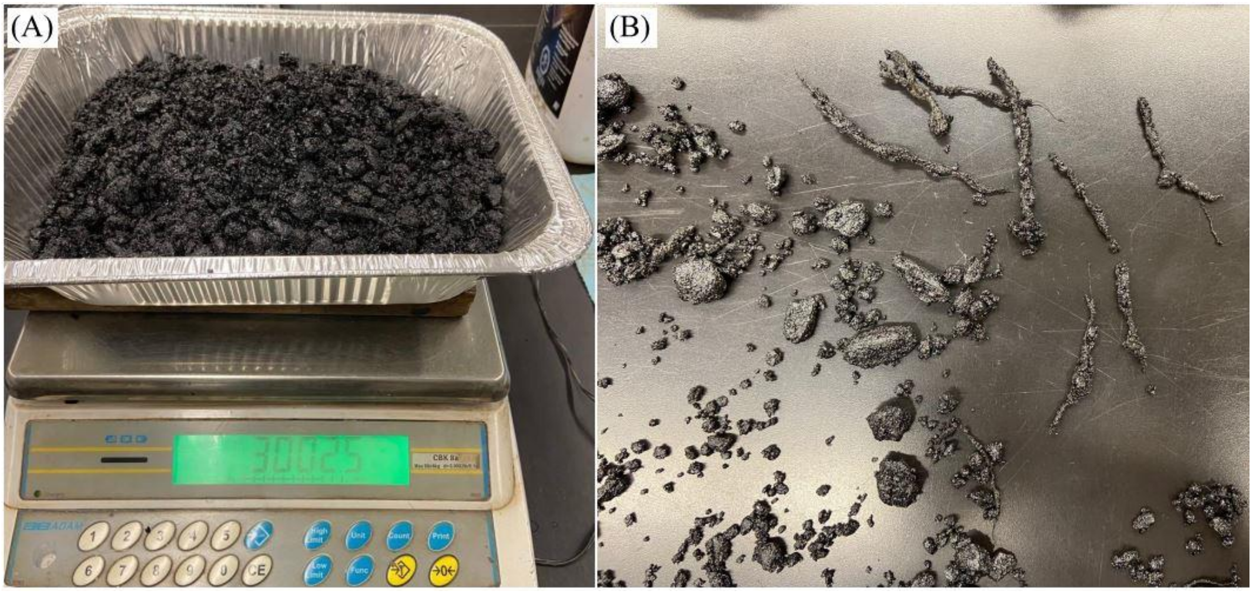

Fig. 5: (A) Loose mixture and (B) fibre clustering (after heating at the laboratory oven for splitting)

3.3 Laboratory Testing

Two laboratory tests were conducted as part of this study—the IDEAL-CT, and the HWT test. These tests can be used to determine in a balanced manner whether a given asphalt mix meets cracking and rutting performance criteria, respectively. Further information about these respective test methods and the number of specimens used is provided in the following subsections.

3.3.1 Indirect Tensile Strength and IDEAL-CT Test

The IDEAL-CT test was conducted according to ASTM D8225 [15]. The sample size for this test was kept at 150 ± 2 mm in diameter and 62 ± 1 mm in height (jaw size: 19.05 ± 0.3 mm). Three specimens were prepared at 7.0% air void content ± 0.5%, as specified by the standard. The test specimens were preconditioned in an environmental chamber at a test temperature of 19 °C for 2 h. This test temperature was calculated as per Equation 1 [15]. Inside the test machine, a constant load-line displacement rate of 50 ± 2 mm/min was applied. The test temperature was maintained at 19 °C as the load and displacement were measured, and the fracture energy and cracking tolerance index (CT-index) were calculated accordingly. Fig. 6 shows the IDEAL-CT test setup.

$$PG\ IT = \frac{PG\ HT + PG\ LT}{2} + 4 \tag{1}$$

where

$PG\ IT$ = intermediate performance grade temperature (°C),

$PG\ HT$ = climatic high-performance grade temperature (°C), and

$PG\ LT$ = climatic low-performance grade temperature (°C).

Fig. 6: Indirect tensile strength and IDEAL-CT test setup

Each sample's fracture energy was determined using the area under the load-displacement graph as per Equation 2, and the CT-Index was calculated as per Equation 3 [15].

$$G_f = \frac{W_f}{D \times t} \times 10^6 \tag{2}$$

where

G_f = failure energy (Joules/m^2),

W_f = work of failure (Joules), which is simply the area under the load-displacement curve,

D = specimen diameter (mm), and

t = specimen thickness (mm).

$$CT_{Index} = \frac{t}{62} \times \frac{l_{75}}{D} \times \frac{G_f}{|m_{75}|} \times 10^6 \tag{3}$$

where

CT_{Index} = cracking tolerance index,

G_f = failure energy (Joules/m^2) as defined in Equation 2,

$|m_{75}|$ = absolute value of the post-peak slope m_{75} (N/m),

l_{75} = displacement at 75% the peak load after the peak (mm),

D = specimen diameter (mm),

t = specimen thickness (mm), and

$\frac{t}{62}$ = unitless correction factor for specimen thickness.

The indirect tensile strength (ITS) was calculated as per Equation 4 below, provided in ASTM D6931 [19].

$$ITS = \frac{2000 \times P}{\pi \times t \times D} \times 10^6 \tag{4}$$

where

ITS = indirect tensile strength (kPa),

P = maximum load (N),

t = specimen height immediately before test (mm), and

D = specimen diameter (mm).

3.3.2 Hamburg Wheel-tracking Test

Permanent deformation (i.e., rutting) is one of the major distress modes of asphalt pavements under high temperature conditions. Moisture susceptibility, meanwhile, refers to the vulnerability of the bituminous mixture to water damage [20], manifested in the debonding between the aggregates and asphalt binder (which, in turn, accelerates other kinds of distress). In this context, in our study an HWT device was used to evaluate four HMA samples (two pairs of each type of mix) for rutting performance and moisture susceptibility in accordance with AASHTO T324 [16].

This test was carried out by tracking a 703 ± 4.5 N, 47 mm-wide steel wheel across an HMA sample submerged in water at a frequency of 52 ± 2 passes per minute and a maximum speed of 0.305 m/s at the midpoint for 20,000 passes, or until a rut depth of 12.5 mm was reached—whichever was reached first. Each specimen was saw-cut along a secant line to maintain a maximum gap of 7.5 mm between the high-density polyethylene (HDPE) moulds. The temperature was kept as 45 °C during the test (based on average pavement temperature in Calgary), and the specimens were preconditioned in the water bath at the test temperature for 30 minutes immediately prior to testing. Two linear variable displacement transducers (LVDTs) were used to measure the depth of the wheel’s impression, i.e., rut depth. Fig. 7 shows the HWT device used in the study, as well as the test setup.

Fig. 7. Hamburg wheel-tracking device and test setup

4. RESULTS AND DISCUSSION

4.1 Results of Indirect Tensile Strength and IDEAL-CT Test

The IDEAL-CT test is used to define the crack indices of mixes, and it aids in determining which mix design is the most crack-resistant. The IDEAL-CT tests focus on intermediate temperature cracking of asphalt mixtures. Samples prepared for the IDEAL-CT were tested using a universal testing machine (UTM), and ITS values and load-displacement graphs were extracted and plotted accordingly. Fig. 8 shows the fractured control and fibre-modified samples after testing. This figure shows that, based on a qualitative comparison, the fibre-modified sample exhibited less damage than the control sample under the same testing load and conditions. In addition, close inspection of the sample revealed hair-like fibrils bonding to the small granules and aggregates (Fig. 9). Table 3 shows the CT-Index and the ITS values calculated based on the ITS and IDEAL-CT test.

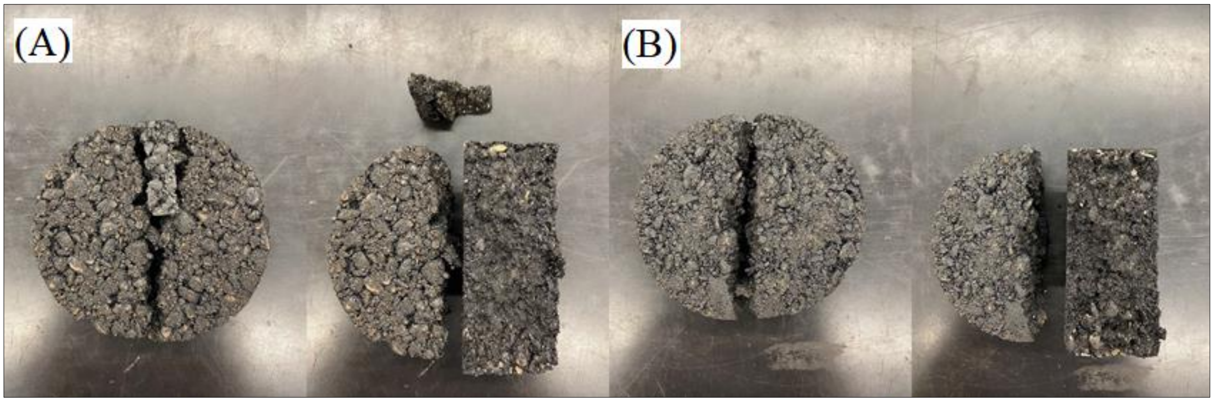

Fig. 8. (A) Control samples and (B) fibre-modified samples after testing

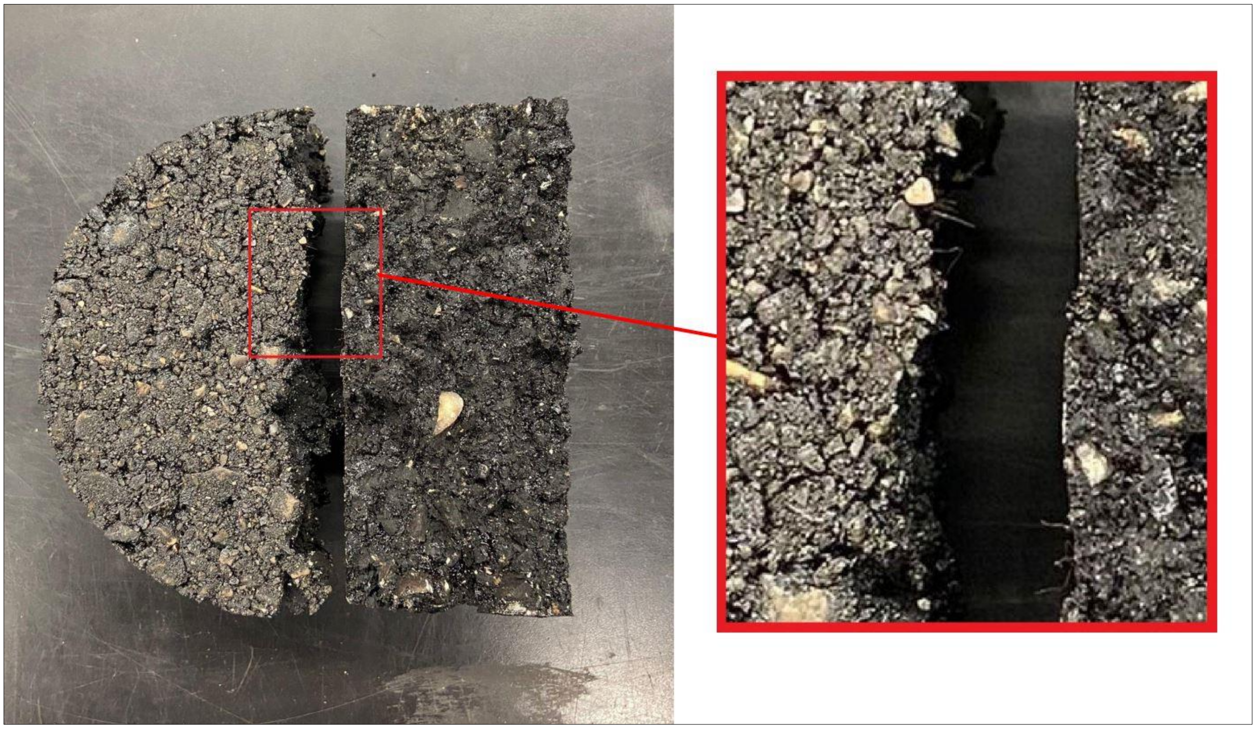

Fig. 9. Close-up view showing fibrils bonding to the mix aggregates

The average CT-Index of the control sample was 123.7, whereas for the fibre-modified sample, the average CT-Index was 178.2 (i.e., 44% higher). This is an indicator that the aramid fibre mixture should out-perform the control over time. Moreover, a comparison of the coefficients of variation of the CT-Index values calculated for each mix type shows similar variability in both data sets.

Table 3: IDEAL-CT, ITS and fracture energy test results for all control and fibre-modified mix samples

Sample ID	Average thickness, mm	CT-Index	ITS, kPa	Pre-cracking energy J/m²	Post-cracking energy J/m²	Fracture energy, J/m²
C1	62.10	142.3	837.5	3,401	4,721	8,122
C2	61.93	117.4	762.3	3,020	4,108	7,128
C3	61.92	111.5	767.8	2,668	4,291	6,959
Average	-	123.7	789.2	-	-	7403
Standard deviation	-	16.3	41.9	-	-	628.4
Coefficient of variation	-	13.2%	5.3%	-	-	8.5%
F1	61.97	173.7	720.5	2,390	5,099	7,489
F2	62.13	154.1	705.9	2,650	4,627	7,278
F3	62.09	206.6	779.2	3,122	5,572	8,694
Average	-	178.2	735.2	-	-	7820
Standard deviation	-	26.5	38.8	-	-	763.9
Coefficient of variation	-	14.9%	5.3%	-	-	9.8%

The load-displacement graphs for select control and fibre-modified samples are shown in Fig. 10. As can be seen, the failure load for the control sample was found to be higher than that of the fibre-modified sample; however, the slope of the curve portion after the failure point decreased for the fibre-modified sample. The significance of the lower (flatter) slope of the post-crack curve is that it indicates slower crack propagation and improved mixture cohesion for fibre-modified samples as compared with the control samples. A similar result was observed in the case of the fracture energy results.

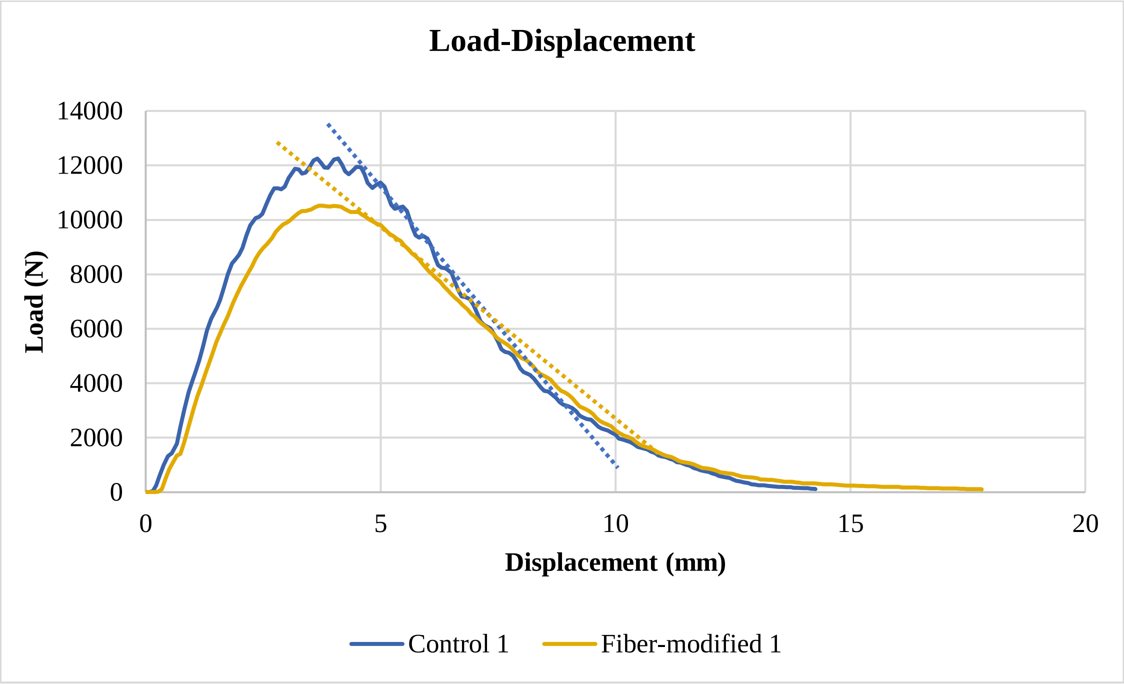

Fig. 10. Load-displacement graph for control and fibre-modified samples (dashed lines indicate slope of post-peak stage curve)

Table 3 shows the total fracture energy, which is the sum of the pre-cracking energy and the post-cracking energy. The former is the strain energy, indicative of the cracking resistance, while the latter is the dissipated energy, and can be used to assess the crack propagation in the mix [21]. The fracture energy also signifies the cracking potential of an asphalt mix. As can be seen from the table, the average fracture energy of the fibre-modified mix was found to be 5.5% higher than that of the control mix, implying a lower cracking potential. Furthermore, as mentioned above, although the peak strength of the control mix is higher (and hence it has higher pre-cracking energy), the average post-cracking energy of the fibre-modified mix is 16.5% higher than that of the control mix, which is in agreement with the mild post-peak curve slope indicating slower crack propagation, providing a more cohesive mix. While this is not a true fracture energy of the sample since the actual crack opening is not measured, it is an "index" that can be useful as seen in this analysis.

4.2 Results of Hamburg Wheel-tracking Test

The HWT test was run at 45 °C, with the samples before and after the HWT test shown in Fig. 11. The rut depth was plotted against the number of passes to investigate the resistance of the asphalt mix to permanent deformation and moisture damage. Moisture damage typically begins to take effect at the stripping inflection point (SIP), accelerating the deformation, and this phenomenon is evidenced by a change in the concavity of the graph. An HMA with an SIP occurring at several load cycles less than 10,000 passes may be susceptible to moisture damage [22].

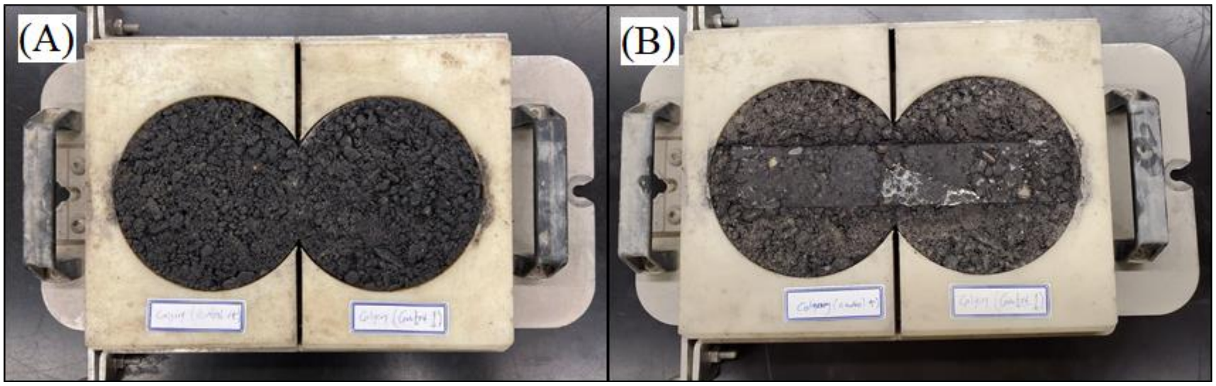

Fig. 11. Control samples (A) before and (B) after Hamburg wheel-tracking test

The plots for depth of rutting versus the number of passes for select control and fibre-modified samples are shown in Fig. 12. The results show that, at 20,000 passes, the average rut depth of the fibre-modified samples was 4.58 mm, whereas, for the control samples, the average rutting depth was found to be slightly higher at 4.93 mm. This result indicates that the rut depth decreased by about 7.1% for 20,000 passes as a result of adding the fibre to the mix. Moreover, an SIP point was not observed for either of the two mixtures, implying that neither is moisture susceptible.

Overall, these mixtures are extremely rut and moisture resistant. It should be noted that any value less than about 12.5 mm of rutting is considered extremely rut resistant in the United States. When less than 5 mm, we are approaching the threshold of 0 mm and it is difficult to measure an added benefit between mixtures.

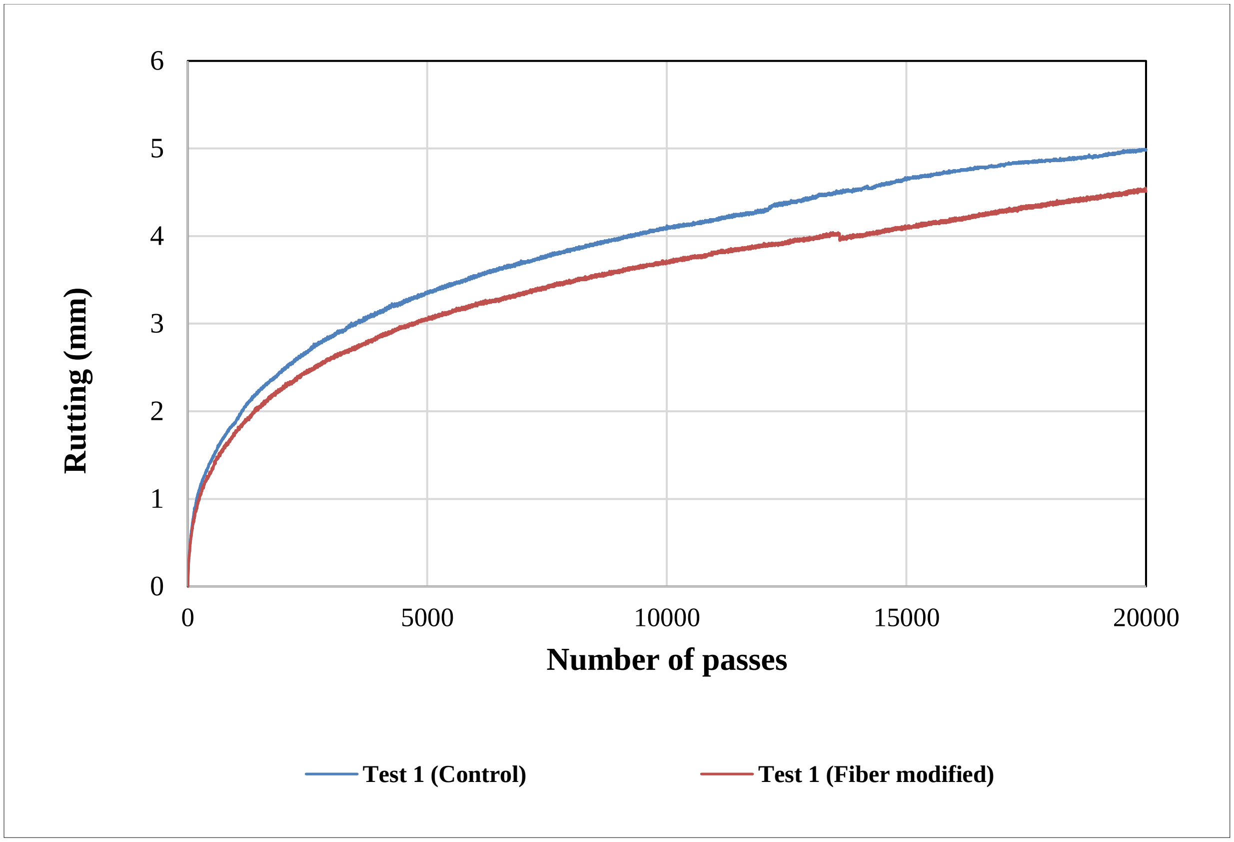

Fig. 12. Hamburg wheel-tracking test rutting depth for control and fibre-modified mix samples

5. CONCLUSIONS, RECOMMENDATIONS, AND FUTURE WORK

In this study, two performance tests were performed to evaluate the mechanical properties of plant-produced asphalt mixes modified with aramid-wax coated polymer fibre and compare them with the control samples. The conclusions of this study are summarized as follows:

- The IDEAL-CT test found that CT-Index of the aramid fibre-modified samples to be higher than that of the control samples, suggesting that the cracking resistance can be increased by up to 44% as a result of aramid fibre modification.
- According to the load-displacement results the fracture energy was found to be 5.5% higher in the case of the aramid fibre-modified mix, implying that the modified mix has a lower cracking potential. Moreover, the average post-cracking energy of the fibre-modified mix was improved by about 16.5% compared to the control, indicating slower crack propagation. The peak strength, however, was found to be higher for the control mix.
- The HWT test showed a decrease in the rut depth by about 7.1% for 20,000 passes, as a result of adding aramid fibre. Moreover, moisture susceptibility (as indicated by the appearance of an SIP in the plot) was not observed for either of the two mixtures.

Future performance tests are recommended to better understand the effects of the addition of fibre to the asphalt mixture. The recommendations for future work are summarized as follows:

- The results of IDEAL-CT and HWT tests revealed that aramid fibre-modified mixes have better intermediate cracking and high-temperature rutting resistance than unmodified mixes. A similar comparison between control and aramid fibre-modified mixes is recommended for additional testing methods, including dynamic modulus, flow number, and bending beam fatigue tests.
- Considering the higher cracking resistance of fibre-modified mixes compared with the control mix at an intermediate temperature, investigation and comparison of low-temperature cracking resistance is also recommended. IDT creep and compliance and/or disk-shaped compaction tension (DCT) can be used for this analysis.
- In order to better understand fibre dispersion, it is recommended that future work includes dispersion analysis which could be as simple as a microscopic evaluation of enlarged fractured specimen faces.
- Naturally, the above tests and falling weight deflectometer in-field testing are recommended to fully document potential benefits. These findings can then be used in life cycle cost analysis (LCCA) to better understand the pavement economics.

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