Assessing the Impact of Polyethylene Terephthalate Fibre Length and Asphalt Binder Source on Low-Temperature Properties of High-Performance Asphalt Concrete

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Abstract

This study aims to enhance the low-temperature performance to create a high-performance asphalt concrete (HPAC) mix for use in a pavement's base course in cold regions. This is achieved by incorporating polyethylene terephthalate (PET) fibres of different lengths and enriching the asphalt binders (from two different sources) with asphaltenes, a by-product derived from the Alberta oil sands. Binder H is a crude oil binder with a continuous performance grading (PG) of 70.2-25.9, and Binder P is an Alberta oil sands binder with a continuous grade of PG 69.0-26.6. Both binders are modified with an optimum content of 12 % asphaltenes by weight of the binder (referred to as Binder H-A and P-A) to reach the required dynamic modulus value for HPAC of 14 GPa at 15 °C and 10 Hz. Also, an optimum dosage of waste PET fibres of 0.15 % by weight of total mixture is used to modify Binder H-A mixture using three lengths of 6, 12, and 18 mm, and using only the optimum PET dosage and length in Binder P-A mixture. The cracking resistance, represented in the fracture energy and tensile strength, is tested at low temperatures of -20, -10, and 0 °C and assessed using the creep compliance and indirect tensile strength test method. Results show that the optimal fibre length is 12 mm in that the highest fracture energy is observed in the sample with 0.15 % PET fibres that are 12 mm long. At the lowest test temperature of -20 °C, this mix shows a 12.7 % increase in the fracture energy compared to the next best-performing sample containing 6 mm PET fibres. At -10 °C, both samples with 6 mm PET and 12 mm PET fibres exhibit comparable high fracture energy values of 5,613 and 5,600 J/m^2, respectively. As for the tensile strength, the highest values of 7.4 and 6.8 MPa are recorded for mixtures containing 12 mm PET fibres at the coldest temperatures of -20 and -10 °C, respectively. With regards to the effect of binder source, enhanced cold temperature performance is evident as the two mixtures with both Binder H-A and P-A and 0.15 % of the 12 mm long fibres exhibit fracture energies surpassing those of the control mixes at -20 and -10°C. In particular, at -20 °C the Binder H-A mix attains a fracture energy of 5,261 J/m^2, while the Binder P-A mix slightly trails behind with a value of 5,121 J/m^2, holding significant potential for HPAC application.

Introduction

There is a growing interest in developing high-performance asphalt mixtures using different additives and modifiers, driven by circular economy approach. A high-performance asphalt mix, as the name implies, can help resist a broad range of traffic volumes and weights and service temperatures. In this study, a high-performance asphalt concrete (HPAC), inspired by the French high-modulus asphalt mixes,[1] is defined as having a high dynamic stiffness, superior rutting resistance, and enhanced low-temperature performance. A roadway built out of an HPAC mixture brings about multiple benefits. These include a much-enhanced thermomechanical performance in withstanding different modes of pavement distresses, low-maintenance requirements, and environmental advantages by savings in raw materials. This is believed to ensure a better whole life cost solution for such pavement systems.[2]

At the University of Alberta Pavement Research Laboratory, an initiative has been undertaken to pioneer an HPAC mix using waste and low-value materials. At an initial stage, asphaltenes which is a by-product from Athabasca bitumen of a minimal value was added to create a high modulus asphalt concrete.[3] It was found that about 12 % of asphaltenes can elevate the high-temperature performance grade sufficiently to meet high modulus requirements, albeit at a cost to the low-temperature performance grade (PG), resulting in a slight reduction in the modified mix's resistance to cracking. Nonetheless, the shift from a continuous grade of PG 70.2-25.9 to PG 82.9-21.8 suggests that the rate of increase in the high PG is more than three times that of the low PG, making the modification of asphaltenes a valuable pursuit. Based on these findings, there is a recognized need for a comprehensive solution that not only enhances high-temperature performance but also improves low-temperature performance and cracking resistance. Therefore, the authors of this study explored the integration of fibres, particularly polyethylene terephthalate (PET) fibres, which have shown empirical evidence of strengthening and enhancing cracking resistance,[4,5] offering a promising approach to not only restore but potentially enhance low-temperature performance in HPAC.

The literature extensively discusses the diverse applications and varieties of fibres used in asphalt pavement mixes, including cellulose, mineral, synthetic polymer, glass, and natural fibres.[6-8] Mineral fibres such as asbestos, carbon, and steel have limitations due to health, environmental concerns, or performance issues like corrosion. Glass fibres possess excellent properties but are brittle and prone to breakage during mixing. Natural fibres are green and cost-effective solutions but can absorb moisture, affecting asphalt binder bonding and thermal stability. Notably, engineered polymer fibres are highlighted for their high tensile strength and heat resistance. However, the focus here is on utilizing waste PET fibres due to their promising performance in enhancing cracking resistance without altering mix design, specifically addressing pavement cracking under severe winter conditions. While fibre use for pavement durability is in the research phase, this study aims to evaluate the mechanical impact of PET fibre length on HPAC's low-temperature performance. This phase of the study follows on from an earlier phase where the optimum PET fibre dosage was found to be 0.15 % by weight of total mixture. This was determined using a framework[9] the authors of this study had developed in which optimum dosage is finalised based on performance testing tailored towards enhanced low temperature resistance and dynamic stiffness. With this optimum dosage, the impact of PET fibre length is explored further. Along with fibre dispersion and dosage, fibre length plays a critical role in the strengthening effect of asphalt mixes.

With an increasing fibre length, the likelihood of bridging cracks increases, but it may also result in uneven distribution of fibres in mix.[10] In addition, different types of cracking may require different fibre lengths as these cracks occur at different pulling rates. Esfahani and Jahromi[11] evaluated the effect of several lengths of parafibres on the mechanical properties of hot mix asphalt through indirect tensile strength, Marshall strength, and resilient modulus. These authors found that out of all the lengths used (a range of 3 to 18 mm), 12 mm long parafibre added at 1 % by weight of the asphalt mixture yielded the highest results. Chin and Charoentham[12] studied the stability and drain down potential of coconut fibre-modified mixtures. The fibres used varied in length from 5 to 60 mm and were added at a dosage of 0.1, 0.3, 0.5, and 0.7 % by weight of a stone mastic asphalt. Based on the stability and drain down results, it was concluded that 0.3 % of 5-20 mm long fibres gave the optimum results. Jaskuła, Stienss, and Szydłowski[13] evaluated the bending strength of polymer fibre-modified asphalt mixture using one dosage (0.05 %) and one length (19 mm). In their bending beam experiment at a low temperature of -20 °C, it was found that the used aramid-polyalphaolefin fibres improved resistance against thermal cracking. Mirabdolazimi and Shafabakhsh[14] also used 19 mm long Forta fibres with concentrations of 0.3, 0.5 and 0.7 kilograms per ton of asphalt mix to study the dynamic creep, which showed optimum results at 0.5 %. Noorvand, Mamlouk, and Kaloush[10] modified asphalt mixtures with three types of aramid fibres and two types of nylon fibres. They determined the optimum embedded length purely based on the shear bond strength using a pullout test between fibres and the asphalt mastic, and it was determined as 20 mm.

With focus on PET fibres, in a study by Dehghan and Modarres[15], the effects of adding recycled PET fibres on the fatigue life of the modified asphalt mixtures were examined. Fibres with lengths of 10 and 20 mm and contents of 0.5, 1, 1.5, and 2 % by weight of binder were used to test for fatigue resistance at strain level of 300, 500 and 700 microstrain. It was found the optimum length, at an optimum dosage of 1 %, is 20 mm for best fatigue life results. A very recent study[5] that explored the effects of PET fibre length on the cracking resistance of asphalt mixture at a low temperature of -10 °C used two lengths of 6 and 18 mm. Based on the semi-circular bending test, it was found that longer and thicker PET fibres with a rough surface substantially improve toughness of asphalt mixtures.

Based on a detailed literature search, a common theme observed is that most of the research studies are focused on varying fibre dosage but few of those studies focus on varying fibre length. Since the effect of PET fibre length on mechanical properties of asphaltenes-enriched HPAC mixtures has not been researched, this study aims to evaluate the cracking resistance, represented in the fracture energy and tensile strength, by testing the modified mixes at low temperatures of down to -20 °C. This study is also taken a step further by exploring the effects of asphalt binder source with the same standard PG grade as the only changing variable once an optimum length is determined.

Objective

The primary objective of this study is to investigate the impact of varying lengths of PET fibres on the low-temperature response of HPAC mixtures. This will be assessed specifically through the creep compliance and indirect tensile strength testing, according to American Association of State Highway and Transportation Officials (AASHTO) T 322 test method.[16] The study aims to understand how different PET fibre lengths influence the cracking resistance and mechanical properties of HPAC mixtures at low temperatures down to -20 °C. Additionally, this research seeks to evaluate the effects of using different sources of asphalt binder on the low-temperature behavior of HPAC mixtures while maintaining the same standard PG grade. By varying the asphalt binder source, the study aims to identify potential differences in low-temperature performance, particularly focusing on cracking resistance and fracture energy.

Thus, this study aims to provide valuable insights into the mechanical impact of PET fibre length and asphalt binder source variation on HPAC's low-temperature performance. These findings will contribute to a deeper understanding of material selection considerations for enhancing the overall performance of high-performance asphalt pavement in cold climate conditions.

Materials, Additives and Mix Design

Materials and Additives

Asphalt Binder

In this research study, two asphalt binders from two different sources were used to investigate the effect of the asphalt binder source on the performance testing results. Binder H is a crude oil asphalt binder having a base continuous performance grade (PG) of 70.2-25.9 and the properties shown in Table 1. Modified Binder H was used for the control mix and the fibre-modified mix, as will be explained in the mix design section. On the other hand, Binder P is derived from Alberta oil sands bitumen, having a base continuous PG 69.0-26.6. Binder P is not commercially available, and hence its properties are not provided. Modified Binder P was only used for the fibre-modified mix.

Table 1: Specifications of the crude oil Binder H

Property	Standard	Specification		Value
		Minimum	Maximum	
Density at 15 °C, kg/L	ASTM D70[17]	-	-	1.0341
Penetration at 25 °C (100 g, 5 s), d_{mm}	ASTM D5[18]	80	100	90
Flash point (COC), °C	ASTM D92[19]	230	-	276
Ductility at 25 °C (5 cm/min), cm	ASTM D113[20]	100	-	150+
Solubility in trichloroethylene, %	ASTM D2042[21]	99.5	-	99.9
Absolute viscosity at 60 °C, Pa.s	ASTM D2171[22]	150	-	183
Viscosity at 135 °C, Pa.s	ASTM D4402[23]	-	3.00	0.42
Mass loss, %	ASTM D1754[24]	-	1.00	0.37
High performance grade, °C	AASHTO T 315[25]	-	-	70.2
Low performance grade, °C	AASHTO T 313[26]	-	-	25.9

Aggregates

Three tests were carried out to evaluate the characteristics and suitability of coarse and fine aggregates: specific gravity test, water absorption test, and Los Angeles abrasion test, as outlined in Table 2. When examining aggregates for water absorption, it was found that the results were below the maximum allowed, as defined by Denneman et al.[1] for asphalt mixes with high modulus. The Los Angeles abrasion result of 23 % for the coarse aggregates also fell within the specified range according to ASTM C131.[27] Furthermore, the specific gravity test indicated that the relative bulk density of both coarse and fine aggregates is 2.548.

Table 2: Properties of aggregates

Specific gravity				
	Aggregate portion, %	Bulk specific gravity	Bulk specific gravity (Saturated surface dry)	Apparent specific gravity
Coarse aggregate (≥ 4.75 mm)	39.7	2.618	2.652	2.666
Fine aggregate (< 4.75 mm)	60.3	2.502	2.600	2.617
Water absorption				
	Result, %		Criterion,[1] %	
Coarse aggregate (≥ 4.75 mm)	0.3		≤ 1.0	
Fine aggregate (< 4.75 mm)	0.4		≤ 1.5	
Los Angeles abrasion				
	Result, %		Standard range,[27] %	
Coarse aggregate (≥ 9.5 mm)	23		10 - 45	

Asphaltenes

The asphaltenes used was obtained as a by-product from Alberta oilsands bitumen in solid form. The asphaltenes solids were later transformed into fine powder (Figure 1) and sifted through a 150 µm sieve. This powder form ensures easier and more uniform dispersion of the asphaltenes while mixing with the asphalt binder. This conversion into powder facilitates a smoother and more consistent dispersion of the asphaltenes when mixed with the asphalt binder. The procedure for converting asphaltenes into powder and their subsequent application in modifying asphalt cement has been thoroughly discussed in a previous publication.[28]

Figure 1: Asphaltenes in solid and fine powder form

Polyethylene Terephthalate Fibres

The polyethylene terephthalate (PET) fibres used were obtained from Hi-Tech Asphalt Solutions in Mechanicsville, Virginia and were processed from recycled plastic. The fibres have three different lengths of 6, 12 and 18 mm (see Figure 2), and the properties shown in Table 3. PET fibre was used at an optimum dosage of 0.15 % by weight of total mixture, and the process for determining this specific dosage will be elaborated on in the methodology section.

Figure 2: PET fibres in three lengths of 6, 12 and 18 mm

Table 3: Physical and mechanical properties of PET fibre

Property	Value
Average length, mm	6, 12 and 18
Average diameter, µm	20
Density, g/cm^3	1.41
Tensile strength, MPa	≥500
Melting temperature, °C	≥256

Mix Design

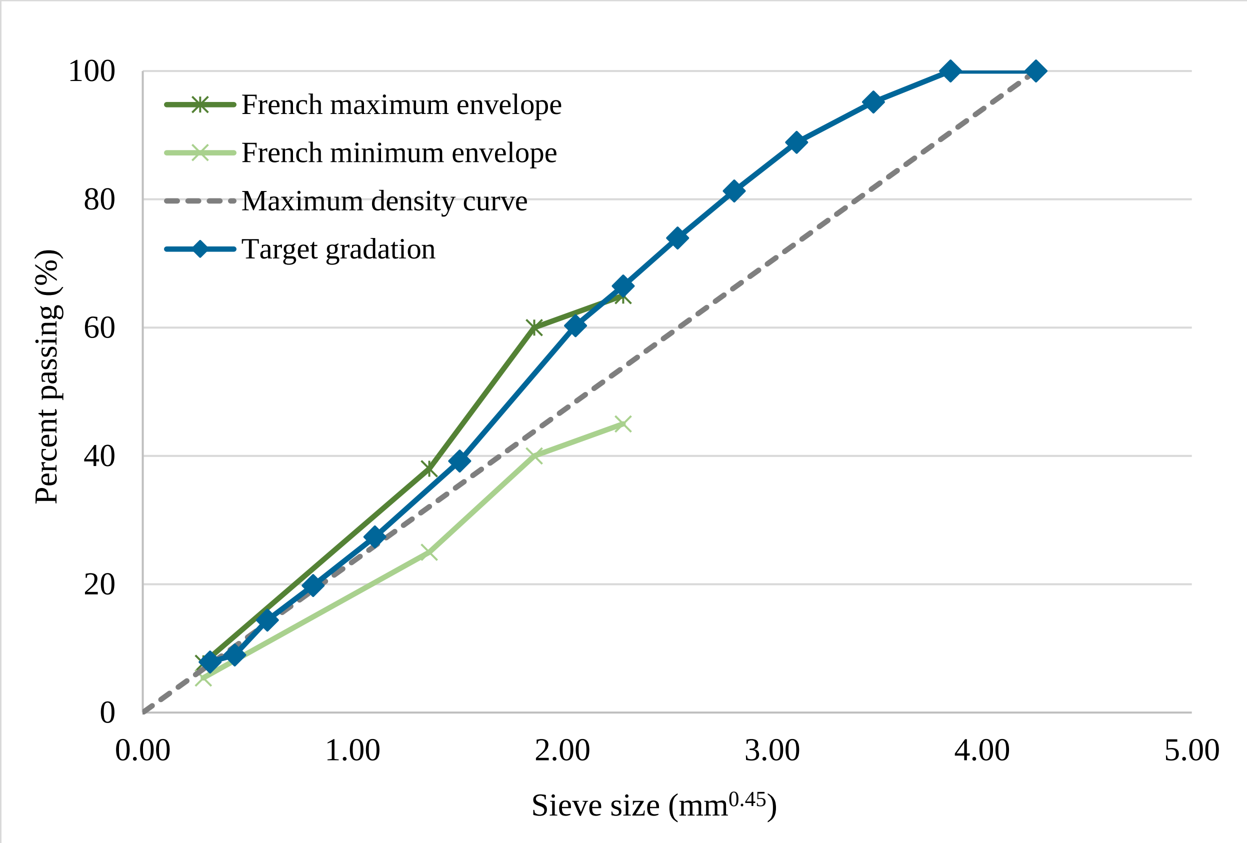
Two mixture types were prepared and tested: (*i*) *control mix*: prepared with base Binder H modified with 12 % asphaltenes and without presence of PET fibres; and (*ii*) *fibre-modified mix*: prepared with base Binders H and P modified with 12 % asphaltenes (thereafter called Binder H-A and P-A) and with incorporation of PET fibres at a dosage of 0.15 %. The reason that Binder P-A is only used in fibre mixes is for comparison purposes with fibre mixes prepared with Binder H-A. Furthermore, the reasoning for selecting 12 % asphaltenes will also be explained in the methodology section.

Aggregate Gradation and Volumetric Properties

In pioneering a high-performance asphalt concrete (HPAC), a first step was to boost the dynamic stiffness to a “high” value. Different definitions exist for what constitutes a "high modulus." The French high modulus, with a criterion of 14 GPa at 15 °C and 10 Hz[1] is one such definition used for highly fatigue-resistant mixes, and is adopted in this study due to its well-established nature. Considering that the average air temperature in Alberta is lower than France, this provides more confidence in choosing the same criteria and in allowing some tolerance if needed.

Therefore, the gradation of the control and fibre mixtures (Figure 3) designed in this research work was such that to create a high dynamic stiffness at an intermediate temperature, where it falls within the boundaries of the French envelopes,[29] meeting the desired specifications. The volumetric properties of the mix are a voids in the mineral aggregate (VMA) of 15 %, a design air void of 1.5 ± 0.5 %, and voids filled with asphalt (VFA) of 90 %.[30] The standard asphalt binder grade of both the control mix and the mix modified with fibre and asphaltenes is PG 82-16.

Figure 3: Selected aggregate grain size distribution



Binder Content

The binder content in HPAC was determined based on both the richness modulus K , signifying the thickness of the binder film covering the aggregate surfaces, and the selected aggregate gradation, according to Equation 1.[1] The mixes were formulated to be of a highly fatigue-resistant class, resulting in an optimal binder content of 5.6 % by weight of the total mixture.

$$TL_{est} = K\alpha\sqrt[5]{\Sigma} \quad (1)$$

where:

TL_{est} = percent binder by mass of total mixture (%),
K = richness modulus,
α = correction coefficient for relative density of aggregates, and
Σ = specific surface area of aggregates (m^2/kg).

Methodology

Sample Preparation

The process of preparing hot-mix asphalt (HMA) mixtures involved several steps. Firstly, the mixtures were prepared using a bucket mixer and divided into appropriate specimen sizes according to the recommendations provided in AASHTO R 47.[31] Afterward, these mixtures were evenly spread in aluminum trays to a uniform thickness. Since the samples were intended for performance testing, they underwent short-term conditioning in an oven at 135 °C for 4 hours as specified by AASHTO R 30,[32] before reaching the design compaction temperature over a maximum period of 30 minutes as specified by AASHTO T 312[33]. Based on the viscosity-temperature relationship, the design compaction temperatures were set at 160 and 164 °C for mixes modified with Binder H-A and Binder P-A, respectively. Test specimens were then compacted using a Superpave gyratory compactor (SGC) with a ram pressure of 600 kPa, an external angle of 1.25°, and 30 gyrations a minute.

Optimum addition of asphaltenes

As per the mix design and along with the chosen gradation, the most appropriate high PG grading for binders to meet the dynamic modulus requirements for application in HPAC was determined to be high PG 82.[3] This is, again, a dynamic modulus value of 14 GPa at temperature of 15 °C and a loading frequency of 10 Hz. According to Ghasemirad, Bala, and Hashemian[34], the minimum addition of asphaltenes to achieve a high PG of 82 with a colloidal index below the instability limit is 12 %. Thus, the resulting binder grade after modification with asphaltenes is a continuous PG 82.9-21.8 for Binder H-A and a continuous PG 82-21.9 for Binder P-A.

Optimum dosage of PET fibre

PET fibre was used at an optimum dosage of 0.15 % by weight of total mixture, determined in a previous study[9] using a framework that incorporates volumetric and performance testing tailored towards enhanced stiffness and low temperature performance. In short, compactibility in this framework is defined as achieving an air void content of less than 6 % after compaction using 80 gyrations by an SGC. Dynamic modulus, crucial for HPAC applications, should meet a value of 14 GPa at 15 °C and 10 Hz, with some tolerance considering Albertan climate. Lastly, to resist low-temperature cracking, the optimal combination of fracture energy and indirect tensile strength is sought. The results of the tests used for 6 mm fibres in this framework for each mix are summarised in Table 4, showing that optimum results are attained with 0.15 % of 6 mm PET fibres.

Table 4: Determination of optimum dosage of 6mm PET fibre[9]

Mix	**Air voids, %**	**Dynamic modulus, MPa**	**Indirect tensile strength at -20/-10/0 °C**	
			Tensile strength, MPa	Fracture energy, J/m^2
Control	1.48	13,379	6.4/6.2/4.7	3,917/4,619/5,389
0.05 % PET	1.48	13,414	6.5/6.1/5.1	4,389/5,283/6,294
0.10 % PET	1.44	13,768	6.8/6.4/5.1	4,542/5,432/6,561
0.15 % PET	1.44	13,824	6.9/6.2/5.3	4,669/5,613/7,138
0.20 % PET	1.16	13,584	NA	NA
0.30 % PET	-	13,572	NA	NA

Indirect Tensile Strength at Low Temperature Test

The creep compliance and the indirect tensile (IDT) strength test, as shown in Figure 4, was used to evaluate tensile strength and fracture energy of asphalt mixtures at low temperatures, according to AASHTO T 322.[16] For each mix, three specimens with a diameter of 100 mm and a thickness of 40 mm were prepared. The specimens were conditioned for 3 hours to reach a uniform temperature, before testing at three temperatures of -20, -10, and 0 °C. In addition, the load-to-fracture was applied to the specimen at a rate of 12 mm/min for each temperature. The fracture energy is calculated as per Equation 2, and the indirect tensile strength is calculated as per Equation 3.

Figure 4: IDT test setup

$$G_f = \frac{W_f}{D \times t} \times 10^6 \quad (2)$$

where:

G_f = failure energy (Joules/m^2),
W_f = work of failure (Joules), which is the area under the load-displacement curve,
D = specimen diameter (mm), and
t = specimen thickness (mm).

$$S_t = \frac{2000 \times P}{\pi \times t \times D} \quad (3)$$

where:

S_t = indirect tensile strength (kPa), and
P = maximum load (N).

Results and Discussion

Effects of length of PET fibre

Figure 5 shows the fracture energy results obtained during tests conducted at low temperatures of -20, -10, and 0 °C for Binder H-A mixes with the optimum content and varying lengths of PET fibre. All fibre-modified samples showed enhancement in the fracture energy compared to the control mix. These varied from improvements up to 34% at -20 °C, up to 22% at -10 °C, and up to 56% at 0 °C. Specifically at the coldest test temperature of -20 °C, the highest fracture energy can be observed for 12 mm PET incorporated sample with an increase of 12.7 % compared to the sample with 6 mm PET. At -10 °C, the fracture energy of both the 6 mm PET (5,613 J/m^2) and 12 mm PET (5,600 J/m^2) incorporated samples demonstrate a similarly high value. However, compared to the other two lengths, the fracture energy at 0 °C is lowest for 12 mm PET samples (6,071 J/m^2). Nevertheless, the performance under freezing temperatures is not a critical factor in Canada's cold climate.

Figure 5: Fracture energy results of Binder H-A control and fibre mixes with optimum content and three lengths

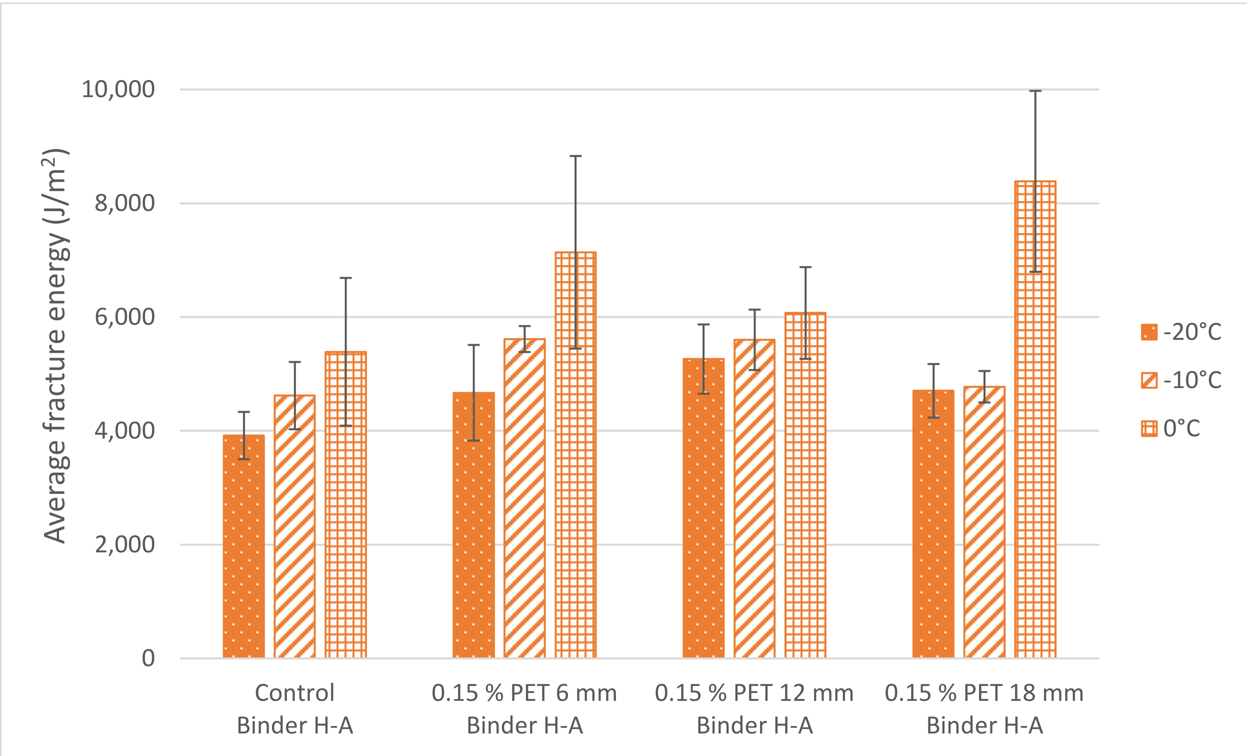
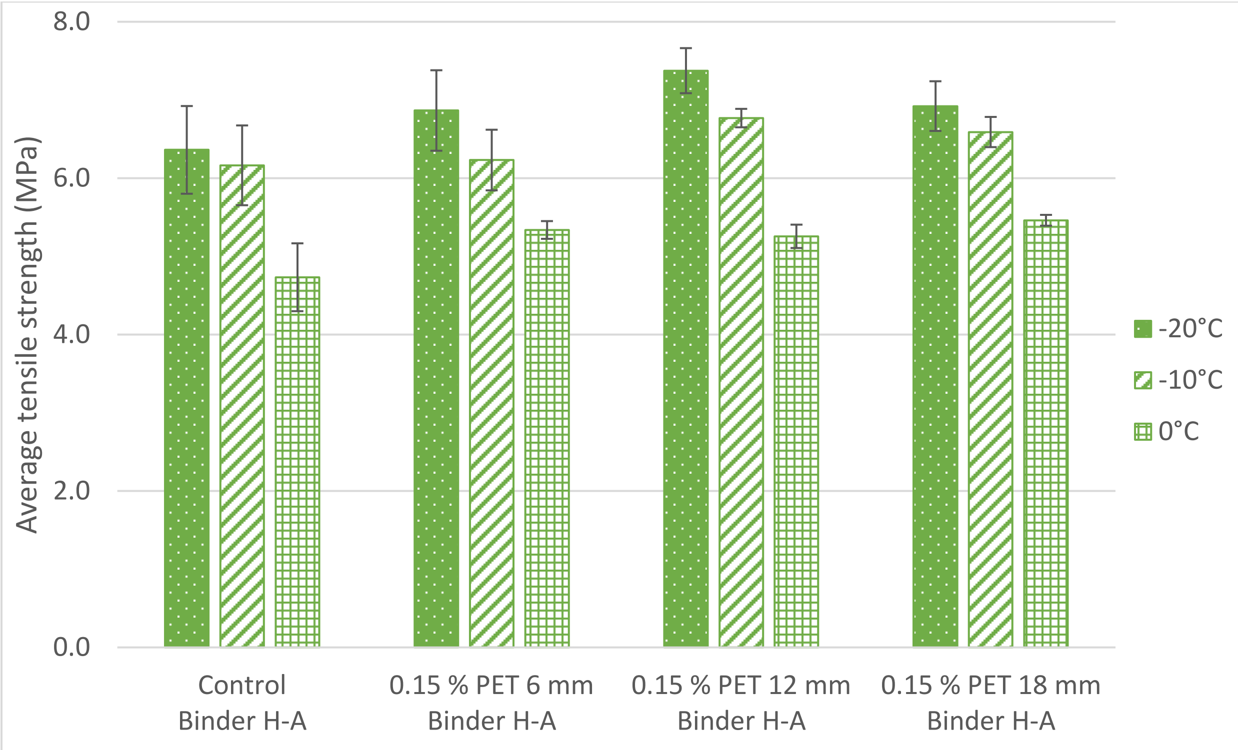


Figure 6 illustrates the indirect tensile strength results for fibre mixes with optimum content of 0.15 % and the three different lengths. The highest tensile strength of 7.4 and 6.8 MPa are observed for mixes with 12 mm PET at the test temperatures of -20 and -10°C, respectively. However, at 0 °C the mixes with three different lengths show similar results (5.3 MPa for 6 mm PET, 5.3 MPa for 12 mm PET, and 5.5 MPa for 18 mm PET samples).

Figure 6: Indirect tensile strength results of Binder H-A control and fibre mixes with optimum content and three lengths



Following this analysis of the outcomes achieved using the optimum PET content and varying PET fibre lengths, it is concluded that the most suitable PET fibre length is 12 mm. Subsequently, the test is extended to utilize a different binder type, specifically the modified Binder P, while maintaining the optimal PET fibre length and content for the next part of the study.

Effects of asphalt binder source

The comparison between the two asphalt mixes with 0.15 % 12mm PET using the two asphalt Binders H-A and P-A reveals subtle differences in their mechanical properties despite their identical compositions. With focus on the fracture energy at various temperatures, some disparities come to light. At -20 °C, Binder H-A mix attains a fracture energy of 5,261 J/m^2, while Binder P-A mix registers a slightly lower value of 5,121 J/m^2. Similarly, at -10 °C, Binder H-A mix records 5,600 J/m^2, and Binder P-A mix demonstrates a comparable value of 5,162 J/m^2 (Figure 7). Notably, the gap between the two sources persists; however, at 0 °C, Binder H-A mix reaches a lower value of 6,071 J/m^2, compared with Binder P-A mix which exhibits a considerably higher value of 7,787 J/m^2. This difference in fracture energy across temperatures shows only a small impact of asphalt binder sources on the mixes' performance. Turning attention to the tensile strength (Figure 8), at -20, -10, and 0 °C Binder H-A mix displays tensile strengths of 7.4, 6.8, and 5.3 MPa, respectively. In parallel, Binder P-A mix mirrors these strengths with values of 7.4, 6.9, and 5.6 MPa, respectively. These closely aligned tensile strength profiles highlight the limited influence of asphalt binder source on this specific mechanical property.

Figure 7: Fracture energy results of fibre mixes with optimum content and length and two sources of asphalt binder

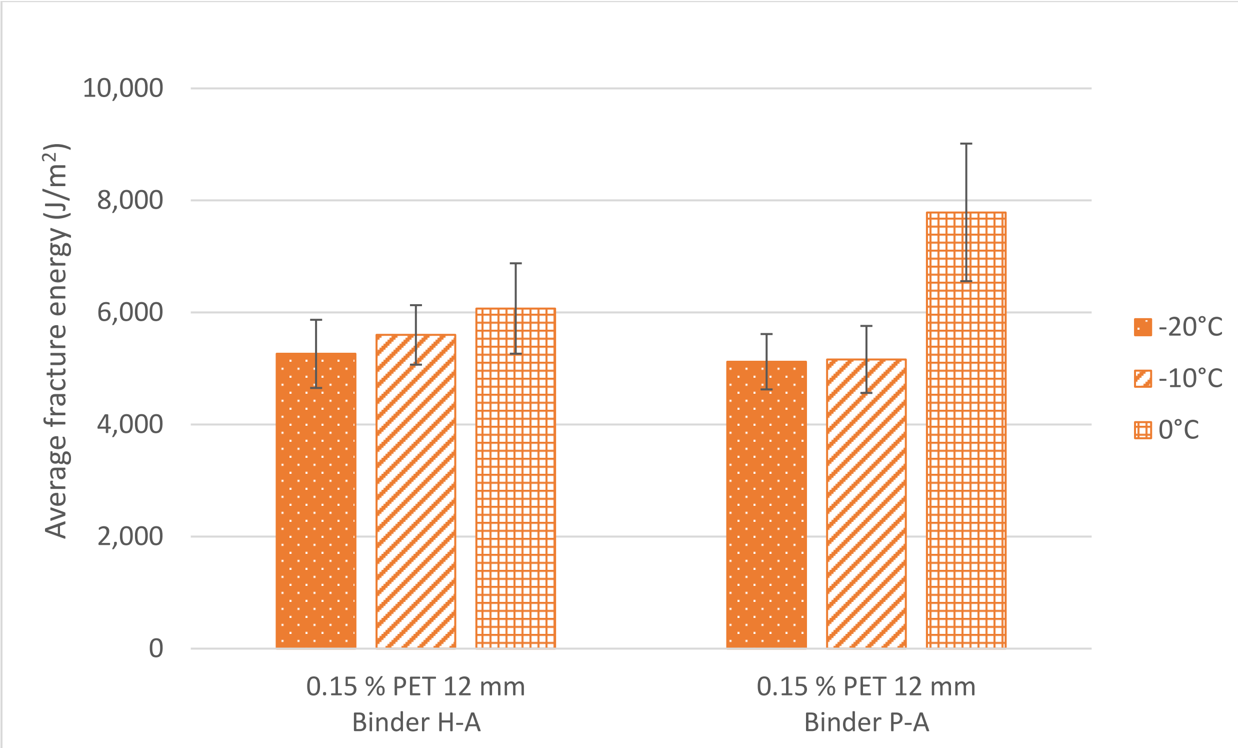
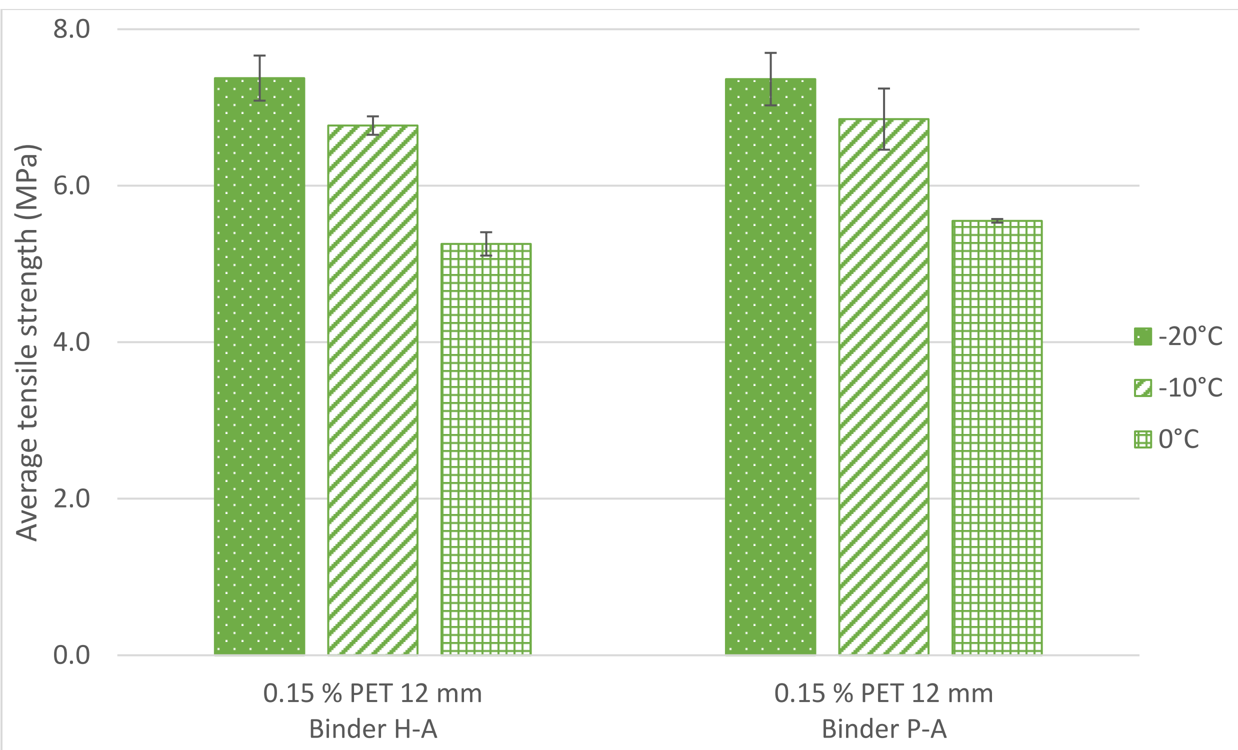


Figure 8: Indirect tensile strength results of fibre mixes with optimum content and length and two sources of asphalt binder



In aggregate, the comparison of the two asphalt mixes underscores that while there are modest differences in certain aspects of their mechanical behavior, these differences are notably marginal and unlikely to yield significant divergences in practical performance in the field. Nevertheless, in light of the minimal disparities observed in the mechanical properties between the two asphalt mixes, it becomes evident that the Binder P form Alberta oilsands binder holds significant potential for HPAC application, presenting a resource-efficient alternative to the commercial crude oil Binder H.

Conclusion

In this study, the influence of varying lengths of polyethylene terephthalate (PET) fibres and asphalt binder sources was investigated on the low-temperature performance of high-performance asphalt concrete (HPAC). Through thorough testing and analysis, the key findings are summarised below:

- All fibre-modified samples using 6, 12 and 18 mm PET fibres showed enhancement in the fracture energy compared to the control mix. These varied from improvements up to 34% at -20 °C, up to 22% at -10 °C, and up to 56% at 0 °C.
- The incorporation of PET fibres, particularly at an optimum dosage of 0.15% by weight of mix and with a length of 12 mm, significantly enhanced the cracking resistance of HPAC at low temperatures, compared with the other two lengths of 6 and 18 mm. The fracture energy and tensile strength results with 12 mm PET fibres demonstrated notable improvements, especially at -20 °C and -10 °C, highlighting the efficacy of PET fibres in mitigating cold temperature distresses.
- The exploration into two asphalt binder sources – from crude oil (Binder H) and Alberta oil sands bitumen(Binder P) – revealed minimal differences in mechanical properties. Despite the minor variations in fracture energy and tensile strength, both binders exhibited promising performance in HPAC formulations, suggesting the feasibility of utilizing alternative binder sources for sustainable pavement construction.

This study underscores the critical role of PET fibre length and asphalt binder selection in optimizing the low-temperature response of HPAC mixtures. The findings presented here contribute valuable insights for pavement engineers and practitioners, aiming to develop resilient and sustainable asphalt mixtures tailored for cold climate regions.

References

[1] Denneman, E., M. Nkgapele, J. Anochie-Boateng, and J. Maina, "Transfer of high modulus asphalt mix technology to South Africa" (paper presentation, Proceedings of the 10th conference on asphalt pavements for Southern Africa, Champagne Sports Resort, KwaZulu-Natal, South Africa, 2011).

[2] Guyot, X., "High Performance Asphalt for Airfield Pavement" (paper presentation, IOP Conference Series: Materials Science and Engineering, Kuala Lumpur, Malaysia, 2021).

[3] Ghassemirad, A., N. Bala, L. Hashemian, and A. Bayat, "Application of asphaltenes in high modulus asphalt concrete," *Construction and Building Materials* 290, (2021): 123200, doi:https://doi.org/10.1016/j.conbuildmat.2021.123200.

[4] Callomamani, L. A. P., L. Hashemian, and K. Sha, "Laboratory Investigation of the Performance Evaluation of Fiber-Modified Asphalt Mixes in Cold Regions," *Transportation Research Record* 2674, no. 7 (2020): 323-335, doi:https://doi.org/10.1177/0361198120922213.

[5] Ma, J. and S. A. Hesp, "Effect of recycled polyethylene terephthalate (PET) fiber on the fracture resistance of asphalt mixtures," *Construction and Building Materials* 342, (2022): 127944, doi:https://doi.org/10.1016/j.conbuildmat.2022.127944.

[6] McDaniel, R. S. NCHRP Synthesis 475 Fiber additives in asphalt mixtures. Report No. 0309271770, (2015).

[7] Abtahi, S. M., M. Sheikhzadeh, and S. M. Hejazi, "Fiber-reinforced asphalt-concrete – A review," *Construction and Building Materials* 24, no. 6 (2010): 871-877, doi:https://doi.org/10.1016/j.conbuildmat.2009.11.009.

[8] Slebi-Acevedo, C. J., P. Lastra-González, P. Pascual-Muñoz, and D. Castro-Fresno, "Mechanical performance of fibers in hot mix asphalt: A review," *Construction and Building Materials* 200, (2019): 756-769, doi:https://doi.org/10.1016/j.conbuildmat.2018.12.171.

[9] Saleh, M., N. Ahmed, T. B. Moghaddam, and L. Hashemian, "A novel framework for determining optimum fibre content in high-performance asphalt concrete mixes for low temperature applications." (paper presentation, Transportation Association of Canada Conference and Exhibition, Ottawa, Canada, 2023).

[10] Noorvand, H., M. Mamlouk, and K. Kaloush, "Evaluation of optimum fiber length in fiber-reinforced asphalt concrete," *Journal of Materials in Civil Engineering* 34, no. 3 (2022): 04021494.

[11] Esfahani, M. A. and M. N. Jahromi, "Optimum parafibre length according to mechanical properties in hot mix asphalt," *Road Materials and Pavement Design* 21, no. 3 (2020): 683-700.

[12] Chin, C. and N. Charoentham, "Effect of coconut fiber length and content on properties of stone mastic asphalt," *Suranaree Journal of Science & Technology* 28, no. 3 (2021).

[13] Jaskuła, P., M. Stienss, and C. Szydłowski, "Effect of polymer fibres reinforcement on selected properties of asphalt mixtures," *Procedia Engineering* 172, (2017): 441-448.

[14] Mirabdolazimi, S. and G. Shafabakhsh, "Rutting depth prediction of hot mix asphalts modified with forta fiber using artificial neural networks and genetic programming technique," *Construction and Building Materials* 148, (2017): 666-674.

[15] Dehghan, Z. and A. Modarres, "Evaluating the fatigue properties of hot mix asphalt reinforced by recycled PET fibers using 4-point bending test," *Construction and Building Materials* 139, (2017): 384-393.

[16] *Standard Method of Test for Determining the Creep Compliance and Strength of Hot Mix Asphalt (HMA) Using the Indirect Tensile Test Device*, AASHTO T 322 (Washington, DC: American Association of State Highway and Transportation Officials, 2007).

[17] *Standard Test Method for Specific Gravity and Density of Semi-Solid Asphalt Binder (Pycnometer Method)*, ASTM D70 (West Conshohocken, PA: ASTM International, 2018).

[18] *Standard Test Method for Penetration of Bituminous Materials*, ASTM D5 (West Conshohocken, PA: ASTM International, 2019).

[19] *Standard Test Method for Flash and Fire Points by Cleveland Open Cup Tester*, ASTM D92 (West Conshohocken, PA: ASTM International, 2018).

[20] *Standard Test Method for Ductility of Asphalt Materials*, ASTM D113 (West Conshohocken, PA: ASTM International, 2017).

[21] *Standard Test Method for Solubility of Asphalt Materials in Trichloroethylene or Toluene*, ASTM D2042 (West Conshohocken, PA: ASTM International, 2015).

[22] *Standard Test Method for Viscosity of Asphalts by Vacuum Capillary Viscometer*, ASTM D2171 (West Conshohocken, PA: ASTM International, 2018).

[23] *Standard Test Method for Viscosity Determination of Asphalt at Elevated Temperatures Using a Rotational Viscometer*, ASTM D4402 (West Conshohocken, PA: ASTM International, 2015).

[24] *Standard Test Method for Effect of Heat and Air on Asphaltic Materials (Thin-Film Oven Test)*, ASTM D1754 (West Conshohocken, PA: ASTM International, 2014).

[25] *Standard Method of Test for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR)*, AASHTO T 315 (Washington, DC: American Association of State Highway and Transportation Officials, 2022).

[26] *Standard Method of Test for Determining the Flexural Creep Stiffness of Asphalt Binder Using the Bending Beam Rheometer (BBR)*, AASHTO T 313 (Washington, DC: American Association of State Highway and Transportation Officials, 2022).

[27] *Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine*, ASTM C131 (West Conshohocken, PA: ASTM International, 2014).

[28] Saleh, M., N. Ahmed, T. B. Moghaddam, and L. Hashemian, "Towards a high-performance asphalt concrete for extreme climatic conditions using asphaltenes and polyethylene terephthalate fibres," *Construction and Building Materials* 420, (2024): 135573, doi:https://doi.org/10.1016/j.conbuildmat.2024.135573.

[29] Delorme, J.-L., C. De la Roche, and L. Wendling. LPC bituminous mixtures design guide. (Laboratoire Central des Ponts et Chaussées, Paris, 2007).

[30] Leiva-Villacorta, F., A. Taylor, and R. Willis. NCAT Report 17-04 High-modulus asphalt concrete (HMAC) mixtures for use as base course. (Auburn, AL, 2017).

[31] *Standard Practice for Reducing Samples of Asphalt Mixtures to Testing Size*, AASHTO R 47 (Washington, DC: American Association of State Highway and Transportation Officials, 2022).

[32] *Standard Practice for Laboratory Conditioning of Asphalt Mixtures*, AASHTO R 30 (Washington, DC: American Association of State Highway and Transportation Officials, 2022).

[33] *Standard Method of Test for Preparing and Determining the Density of Asphalt Mixture Specimens by Means of the Superpave Gyratory Compactor*, AASHTO T 312 (Washington, DC: American Association of State Highway and Transportation Officials, 2022).

[34] Ghasemirad, A., N. Bala, and L. Hashemian, "High-temperature performance evaluation of asphaltenes-modified asphalt binders," *Molecules* 25, no. 15 (2020): 3326.