The Impact of Polyethylene Terephthalate (PET) Fibres on the Cracking Resistance of High-Performance Asphalt Concrete (HPAC)

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ABSTRACT

The safety of a road network highly influences its overall productivity and efficiency. High-performance asphalt concrete (HPAC) is an innovative paving mixture in the design and construction of high-traffic roads in North America, which has high strength, good fatigue life, and excellent rutting resistance. However, the HPAC application is limited in colder regions because of the material's low flexibility and stress relaxation capacity. A road pavement undergoes different types of defects and failures throughout its design life, and cracking is one of them. Cracking in the asphalt pavement is introduced by numerous causes, such as heavy traffic, low temperature, and poor drainage. Cracking in the asphalt pavement negatively affects a road's lifespan and increases the maintenance cost of a road. Therefore, the objectives of this study are to evaluate the impact of asphalt mix modification in terms of resistance to cracking and improvement of cracking tolerance in high-performance asphalt concrete with the utilization of Polyethylene Terephthalate (PET) fibres in the mixes. Three different lengths of PET fibres (6 mm, 12 mm, and 18 mm) are used in the mixes. A binder source-H with PG 70-22 is used for fabricating the HPAC throughout this research, which is modified with 12% asphaltenes (by the weight of binder). An indirect tensile cracking test (IDEAL-CT) at an intermediate temperature of 25℃ and at 37℃ according to the PG grading of the binder as per ASTM D8225 for all the asphalt mixes is carried out to determine the cracking tolerance (CT) index values, failure energy, and indirect tensile strength. The analysis of the test results shows that the failure energy and the indirect tensile strength properties of the asphalt mixes are improved with the addition of PET fibres in comparison with the control mixes at 25℃. However, it is observed that increasing the fibre length improves the CT_{Index}, failure energy, and indirect tensile strength when the specimens are tested at the temperature of 37℃.

Keywords: High Performance Asphalt Concrete, Polyethylene Terephthalate (PET) Fibre, CT_{Index}, Cracking Resistance, Failure Energy, Indirect Tensile Strength.

1. INTRODUCTION

The most widely used pavement type around the world is flexible pavement. In North America, Canada, for example, has a long network of 95% asphalt paved roads throughout the country [1]. The effect of traffic overload and climatic factors create premature distresses in the pavement, which can cause a service life reduction of the asphalt pavement if not maintained properly. The most common distress type found in asphalt paved roads in Canada is cracking which can occur for various of reasons [2]. Consequently, billions of dollars is spent for the purpose of rehabilitation and construction of new asphalt pavements every year [2]. Numerous research has been performed continuously over the years for alternatives and innovative materials to enhance pavement performance. The overall performance of asphalt pavements can be improved by modifying either the asphalt binder or the asphalt mixture.

Waste materials such as asphaltenes are recently utilized in the asphalt binder modification due to the sustainability and cost reduction. Asphaltenes have a relatively higher rate of production in refineries, with the potential to be used in asphalt binder modification applications [3].On the other hand, the addition of fibres as a reinforcement in asphalt pavement has been in use for a very long time as per the National Cooperative Highway Research Program (NCHRP) report 475 [4]. However, it has traditionally been used to control the drain down of the asphalt cement [5]. There is a broad discussion going on in the literature which is concerned with the particular applications and types (such as materials, sources, dimensions) of fibres in asphalt mixes [5]. In addition to cellulose fibres, other types include mineral, synthetic polymer, glass, waste or recycled, and plant-based fibres [5]. The inclusion of fibres in asphalt mixes is considered most promising due to their high mechanical properties [6]. The aramid fibres are fibres with high enough tensile and modulus strength to be used as reinforcement in advanced composites [7]. The polypropylene and aramid fibres is used in hot mix asphalt to improve the performance of asphalt pavements against common distresses such as rutting, fatigue, and reflective cracking [8]. Basalt fibres that are produced from basalt rocks have been used to enhance the load bearing capacity of the surface layer of pavement, which are directly subjected to the traffic effects [9]. Polyethylene terephthalate fibre generated from plastic wastes have been used as binder additive or in the asphalt mixture in several studies to improve the mechanical performance of hot mix asphalt [10,11]. 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 [12].

High-performance Asphalt Concrete (HPAC) is an advanced paving material that provides excellent performance in terms of durability and resistance to deformation. Although it has superior properties, cracking may still occur in the pavement which eventually can minimise its lifespan and performance. Addition of fibres such as Polyethylene Terephthalate (PET) in the asphalt mixes can help overcoming this issue. Polyethylene Terephthalate (PET) fibres are the most important among the polyester fibres. They have high tensile strength and good resistance to chemical and environmental degradation, for which they are commonly used as a reinforcing material in asphalt concrete [13].

In this research a binder source-H with PG 70-22 is used for fabricating the High-performance Asphalt Concrete (HPAC), which is modified with 12% asphaltenes (by the weight of binder). Three different lengths of PET fibres (6 mm, 12 mm, and 18 mm) are used with optimum fibre content of 0.15% (by total weight of the mix) as per the previous study conducted in the University of Alberta. According to ASTM D8225 [14], the IDEAL-CT test can be carried out at the intermediate temperatures of 25°C and at a temperature based on the PG grading of the binder (in this study, it is 37°C for asphaltenes-modified binder). Both test temperatures are adopted in this research as the test temperature could have high impact on the performance of asphalt mixes.

2. OBJECTIVE

This study is subjected to evaluate the effect of fibre addition on the cracking behavior of HPAC using ideal cracking test (IDEAL-CT) at an intermediate test temperature of 25°C, and at 37°C for mixes with asphaltenes-modified binder. Test specimens are prepared for unmodified asphalt binder, modified asphalt binder with the inclusion of different PET fibre lengths. Therefore, the main objective of this study is to conduct an in-depth investigation of how the addition of the PET fibres affect the cracking performance of High-performance Asphalt Concrete (HPAC).

3. METHODOLOGY

The ideal cracking test (IDEAL-CT) is done to obtain the parameters including cracking tolerance index, failure energy, pre-crack failure energy, post-crack failure energy, and indirect tensile strength. These parameters are analyzed to determine the impact of fibres addition in the asphalt mixes. Figure 1 shows the methodological steps conducted during this research.

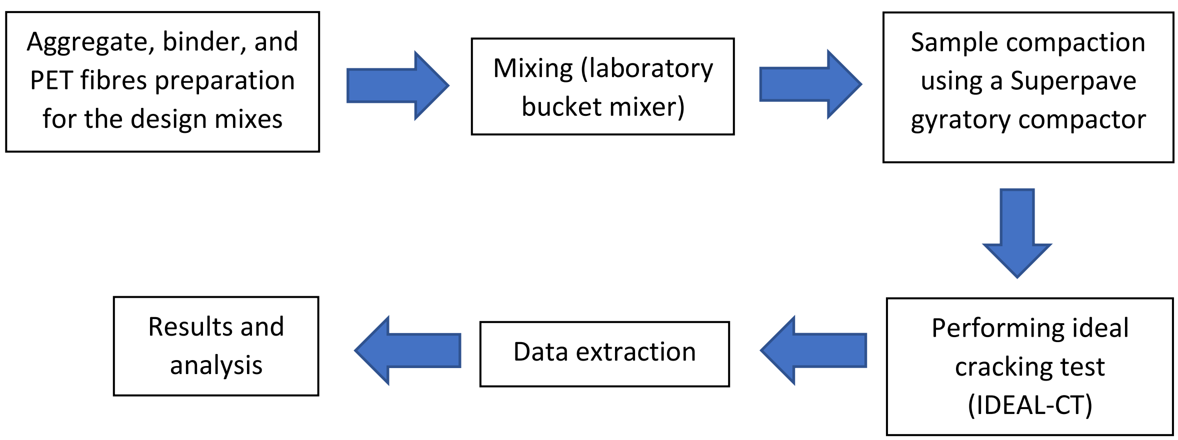


Figure 1: Methodological flowchart

4. EXPERIMENTAL PROCEDURE

4.1 Materials and Mix Design

4.1.1 Asphaltenes

Asphaltenes is the most responsible component in elastic behavior of asphalt binder [15]. Asphaltenes, a waste with insignificant importance in the oil industry, has different rich sources including crude oil, asphaltite, oilsands, tar sand, and bituminous coal [16]. Asphaltenes is extracted from their source, using solvent extraction, or solvent deasphalting, is majorly used [17]. The asphaltenes used in this study is received in chunk form, which is then ground and sieved into powder form (Figure 2) to be mixed with asphalt binder from source-H using a high shear mixer. This method of modifying asphalt binder with asphaltenes is adopted from a study conducted by Sultana and Bhasin [18].

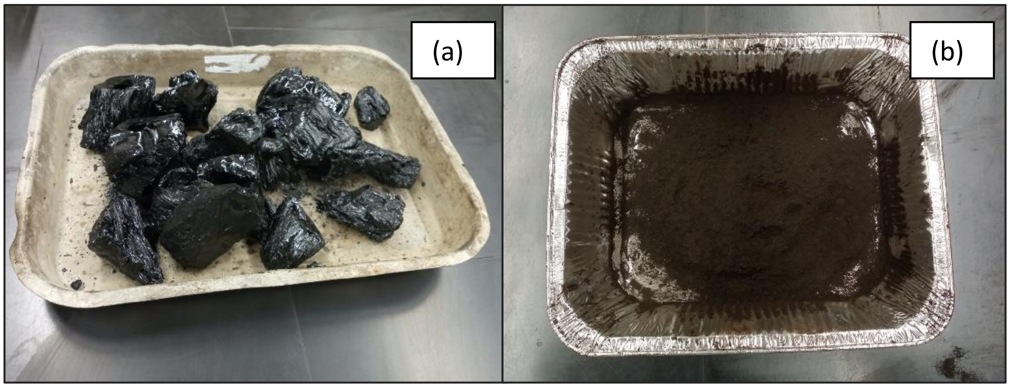


Figure 2: Asphaltenes (a) in Chunk form, (b) in powder form

4.1.2 Polyethylene terephthalate (PET) fibres

Addition of PET fibres (Figure 3) as reinforcement in asphalt mix is relatively new. Polyethylene Terephthalate (PET) fibres are semi-crystalline, thermoplastic, and non- biodegradable polymer. PET fibres are originated from a group of polyesters. The PET properties are not altered even when they are subjected to different conditions such as extreme heat, loading, which makes them a recyclable product [13].

Figure 3: PET fibres in different lengths (6 mm, 12mm, 18 mm)

4.1.3 Mixture volumetric properties

The volumetric properties (Table 1) used for the mixes are adopted from a study conducted by Leiva-Villacorta, Taylor, and Willis [19].

Table 1: Volumetric properties of HPAC mixes with nominal maximum aggregate size of 19 mm [19]

Property	Value
Binder grade	PG 82-16
Design air void (%)	1.5±0.5
Voids in the mineral aggregate (VMA) (%)	15
Voids filled with asphalt (VFA) (%)	90
Effective binder content by volume (%)	13.5±0.5

4.1.4 Asphalt Binder

The binder used in this study from a source-H is a crude oil binder which is readily available in the market. The binder has a base performance grade of PG 70-22. The binder is modified with 12% asphaltenes (by the weight of binder) to produce a performance grade of PG 82-16. The binder content for high performance asphalt concrete is calculated following an outline developed by Denneman et al. [20]. In the outline the richness modulus K and the type of aggregate gradation are used to calculate the binder content for the mixture design. The optimum binder content for this study is 5.6% by the weight of the total mixture.

4.2 Asphalt Mixture Preparation

The mixing temperature for the mixes are 158°C (for unmodified binder), and 173°C (for asphaltenes modified binder) as per the viscometer test. A laboratory bucket mixer is used for mixing aggregates, binder and fibres. The asphalt mixture is then divided accordingly into flat aluminum trays. The trays with the mixture are then put into the oven for 4 hours at 135°C for conditioning as per AASHTO R 30 [21]. The oven temperatures are set to 145°C (for unmodified binder) and 160°C (for asphaltenes modified binder) for 30 minutes before the compaction.

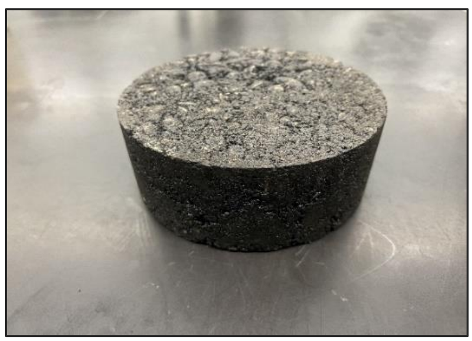


Figure 4: A Superpave gyratory compacted test specimen for IDEAL-CT

Three Superpave gyratory compacted samples are prepared for each control, and PET fibre lengths (6 mm, 12 mm, and 18 mm) using a Superpave gyratory compactor. Control unmodified (CU) samples are prepared with unmodified asphalt binder without the addition of PET fibres, while control modified (CM) samples are prepared with asphaltenes modified binder with no PET fibres added in the mix. Asphaltenes modified binder is used for all the specimens fabricated with PET fibres. A Superpave gyratory compacted sample with a diameter of 150$\pm$2 mm and thickness of 62$\pm$1 mm for IDEAL-CT is shown in Figure 4.

4.3 IDEAL-CT test

The IDEAL-CT is a simple (without any cutting, gluing, drilling, or notching of test specimens), practical (minimum training is required for regular operation), and efficient (test is usually completed within a minute) test. The proposed test has a much lower coefficient of variation compared to traditional repeated load cracking tests [22]. The IDEAL-CT test is carried out as per ASTM D8225 [14]. The specimen size for this test is kept at 150 ± 2 mm in diameter and 62 ± 1 mm in height. The width of the loading strips is 19.05 ± 0.3 mm. Three specimens are prepared at 1.5% ± 0.5% air void content. The test specimens are preconditioned in an environmental chamber at an intermediate test temperature of 25°C and at a temperature based on the PG grading of the binder (in this study, it is 37°C) for 2 hours. The second temperature is calculated as per Equation 1 [14].

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

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).

The specimen is centered in the fixture, and it is observed that the specimen is making uniform contact on the support. A constant compressive load with a rate of 50 ± 2 mm/min is applied during the test. The test temperature of 25°C is maintained as the load and displacement are measured. The test is stopped when the load drops below 100 N. The time, load and load-line displacement (LLD) data are collected at minimum rate of 40 sampling data points per second for a smooth load-LLD curve. The IDEAL-CT test setup is shown in Figure 5.

Figure 5: IDEAL-CT test setup

Failure energy is calculated using the area under the load-displacement graph following Equation 2. Equation 3 is used to calculate the CT_{Index} values [14].

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

where,

G_f = failure energy (Joules/m^2),
W_f = work of failure (Joules), which is 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) is calculated using Equation 4, according to ASTM D6931 [23].

$$ITS = \frac{2000 \times P}{\pi \times t \times D} \quad (4)$$

where,

ITS = indirect tensile strength (kPa),

P = maximum load (N),

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

D = specimen diameter (mm).

5. RESULTS AND DISCUSSION

5.1 Results of IDEAL-CT test

The IDEAL-CT test is used to define the crack indices of the asphalt mixes which helps to find out the mix design with the most crack-resistant. The test was carried out for all the test specimens using a universal testing machine (UTM), and the load-displacement graph is plotted for each mixture.

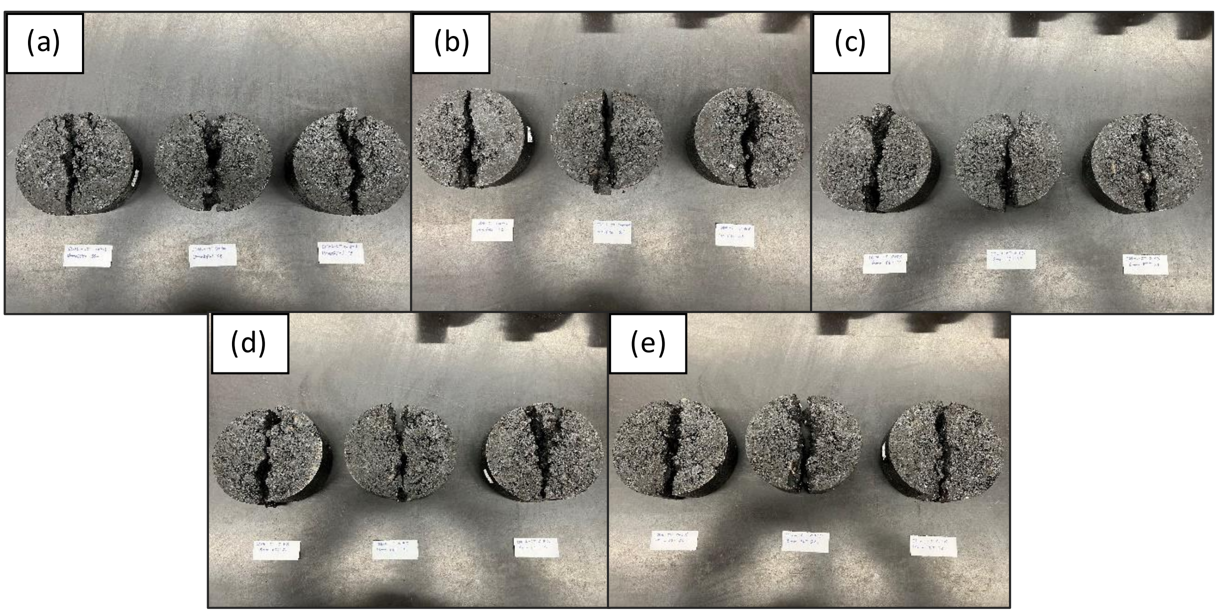


Figure 6: (a) Control unmodified, (b) control modified, (c) 0.15% PET 6mm, (d) 0.15% PET 12mm, (e) 0.15% PET 18mm

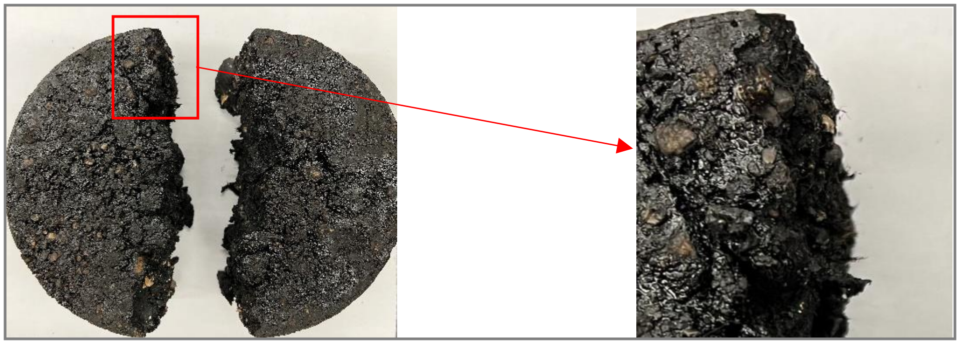
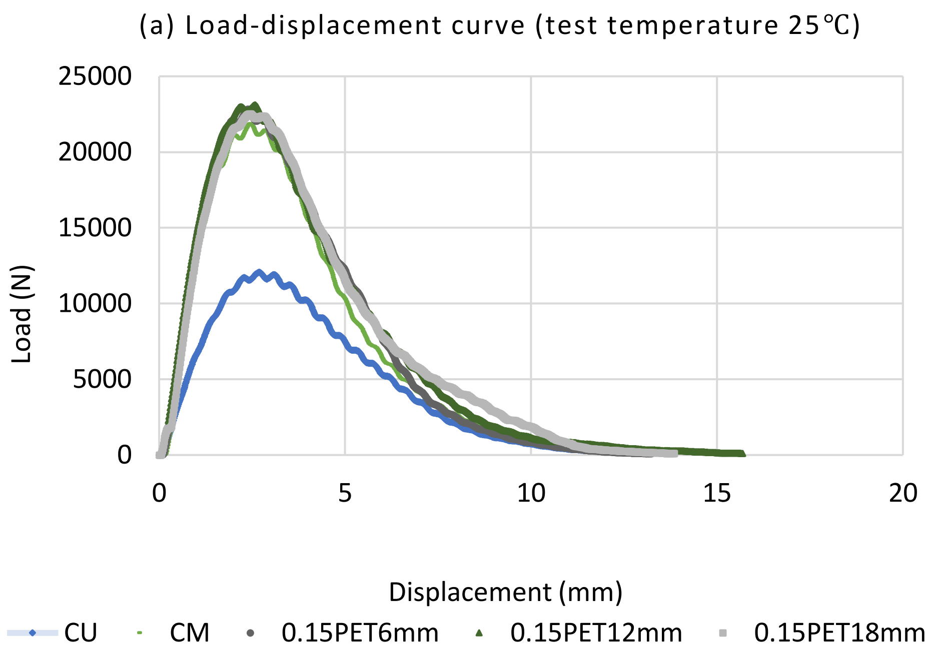


Figure 7: Close-up view showing fibrils bonding in the modified mix

Figure 6 shows the fractured control and PET fibre-modified samples after testing. In addition, close inspection of the modified sample revealed hair-like fibrils bonding to the small granules and aggregates (Figure 7).

The load-displacement graphs for all the test specimens tested at 25℃, and 37℃ are shown in Figure 8(a), and 8(b), respectively. As can be seen in Figure 8(a), at 25℃, the failure load for the control unmodified samples (11.57 kN) is found to be lower than that of the control modified (22.25 kN) and fibre-modified samples (23.09 kN, 22.94 kN, and 22.52 kN for 6 mm, 12 mm, and 18 mm samples, respectively); however, the crack propagation is slower in the post-crack stage for the control unmodified samples due to lower slope of the post-crack curve. The failure load values notably dropped for all asphaltenes-modified samples (10.66 kN, 11.96 kN, 11.91 kN, and 11.03 kN for control modified, 6 mm, 12 mm, and 18 mm samples respectively) when they are tested at a test temperature of 37℃ (Figure 8(b)). Nevertheless, crack propagation rate is comparatively slower in all the tested specimens modified with asphaltenes during the post-crack stage at the testing temperature of 37℃.



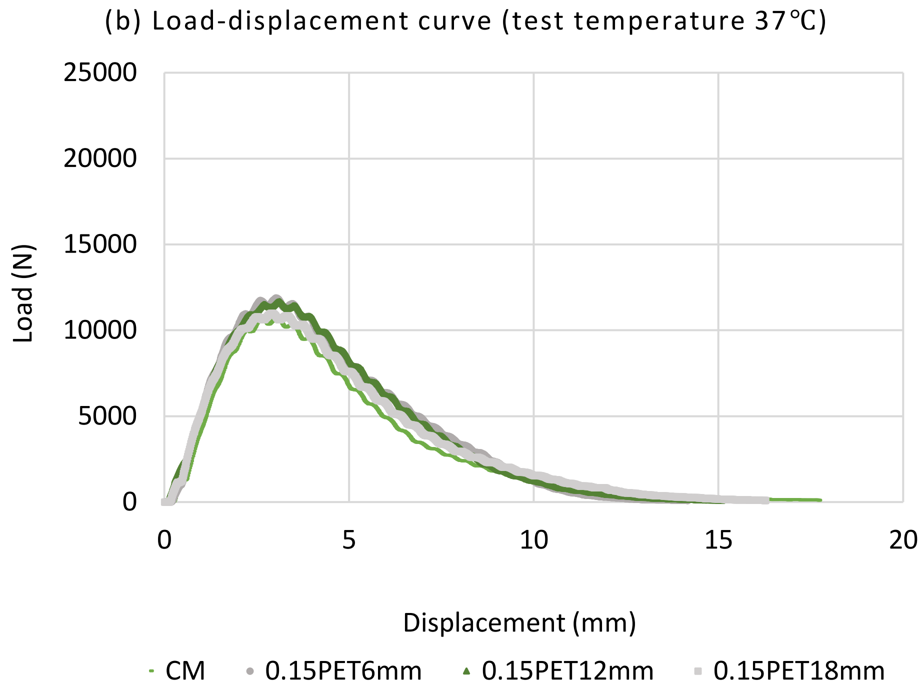


Figure 8: Load displacement curve for all test specimen (a) 25℃, (b) 37℃

Figure 9 shows the comparison of cracking tolerance (CT) index values, it can be observed that the CT_{Index} value is higher for the control unmodified samples than the other mixes. The value decreased to 42 for the samples with asphaltenes modification. However, an increasing trend can be seen with the addition of fibres. A 11.9% increase was observed when 0.15% PET 6mm fibres are added. The percentage of increase is around 17% for 12 mm length of PET fibres. At the testing temperature of 37℃, it can be illustrated that the CT_{Index} values had a significant rise for all the asphaltenes-modified samples. A significant increase of 72% can be seen in the 12 mm PET fabricated samples compared to the control modified samples. The CT_{Index} value for 18 mm PET samples is 99 which is very close to the 12 mm PET samples (105).

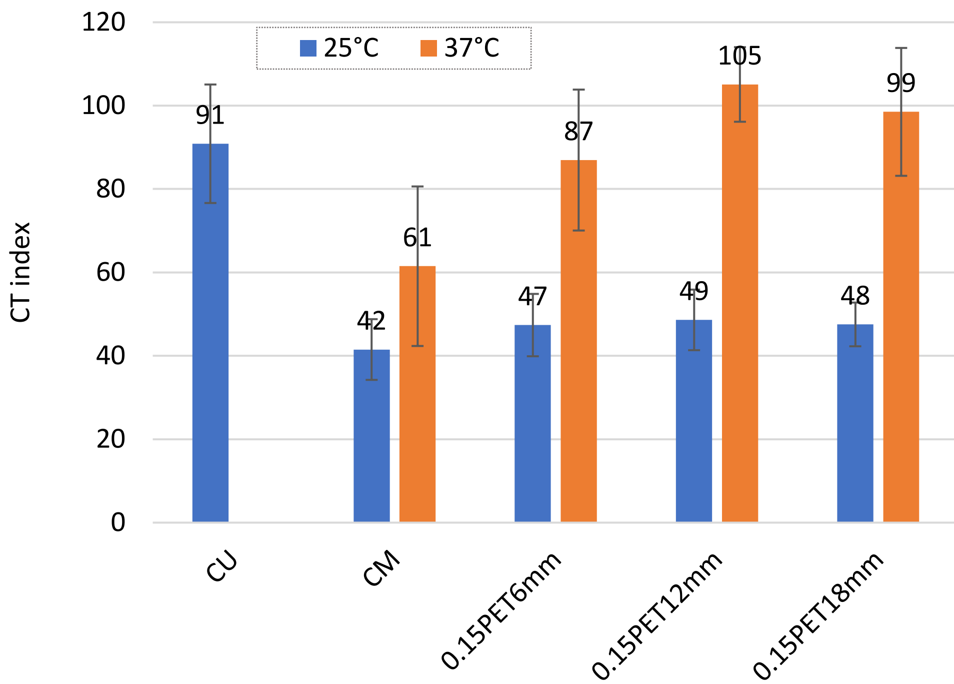
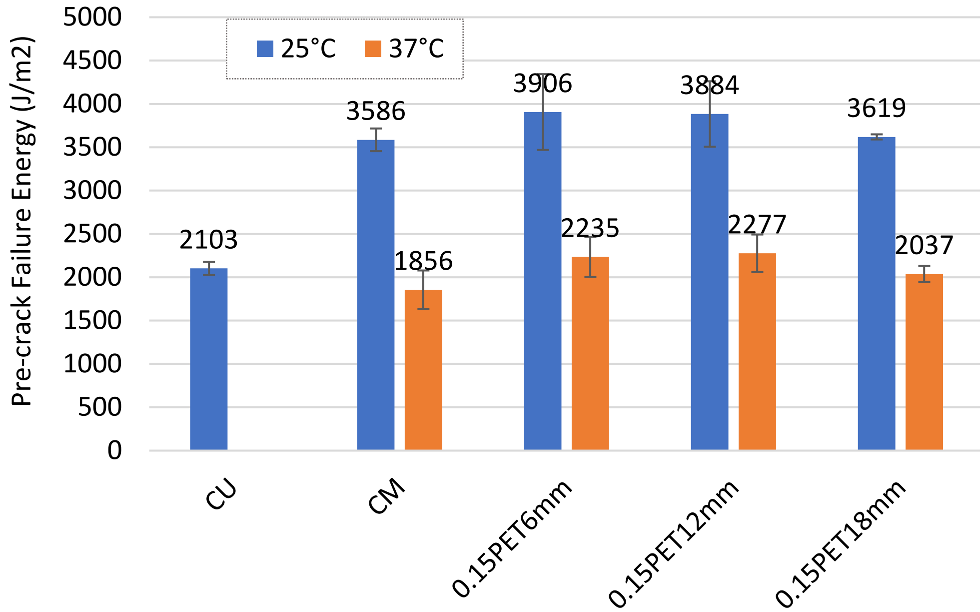


Figure 9: Comparison of CT_{Index} values

Total failure energy is the sum of the pre-crack failure energy and the post-crack failure energy. The former is the strain energy, which indicates the cracking resistance, while post-crack failure energy is a representative of energy dissipation, and can be used for crack propagation assessment in the mix [24]. A trend of increment can be seen from both pre-crack failure energy (Figure 10(a)) and post-crack failure energy (Figure 10(b)) graphs. The highest increase of 8.92% is observed for the fabricated specimens with 6-mm PET in term of pre-crack failure energy compared to the specimens with asphaltenes modification, while the highest increase is 14.84% for the samples with the length of 18 mm PET fibres regarding post-crack failure energy result. The energy values for both pre-crack and post-crack failures exhibited a notable decrease when the asphaltenes modified specimens are tested at 37℃. However, a trend of increment in the failure energy values can be observed with the inclusion of PET fibres in the mixes. The pre-crack failure energy peaks at 2277 Joules/m^2, showing a 23% increase compared to the control modified samples, specifically in case of the 12 mm PET-modified samples. Post-crack failure energy reached to 4728 Joules/m^2 for 12 mm PET fabricated specimens, closely resembling 18 mm PET samples (4864 Joules/m^2) tested at 37℃.

(a)



(b)

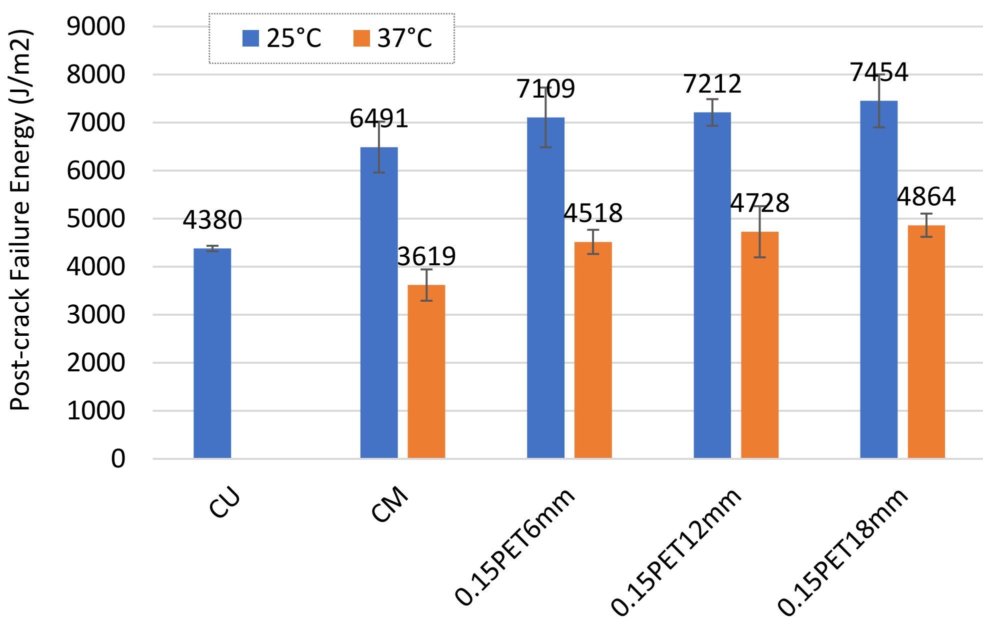


Figure 10: Comparison of (a) pre-crack failure energy ($joules/m^2$), (b) post-crack failure energy ($joules/m^2$) results

The assessment of the potential for cracking in an asphalt mix also relies on the consideration of total failure energy. As depicted in Figure 11, at an intermediate test temperature of 25℃, the total failure energy has a jump of 9.3% for the 6-mm PET modified mixes when compared to the control modified samples. The addition of 12-mm PET fibres demonstrates the highest increase, approximately 10%. A similar percentage of increase is observed for the mix containing 18-mm PET fibres. Furthermore, at a test temperature of 37℃, a substantial rise of 28% is observed in samples fabricated with 12 mm PET fibres in comparison to the control modified samples.

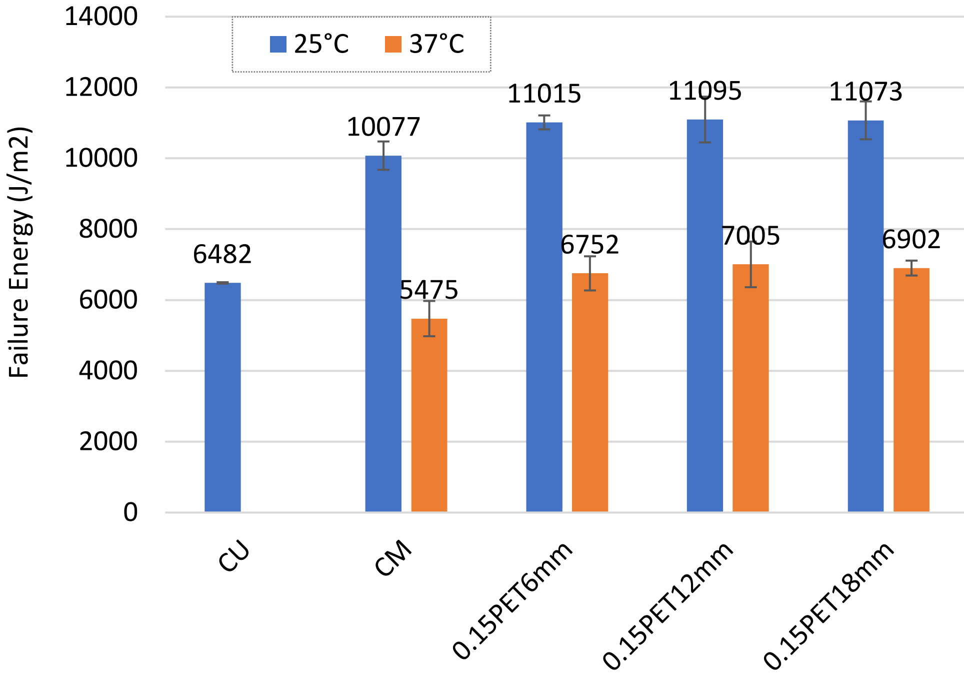


Figure 11: Comparison of failure energy ($joules/m^2$) results

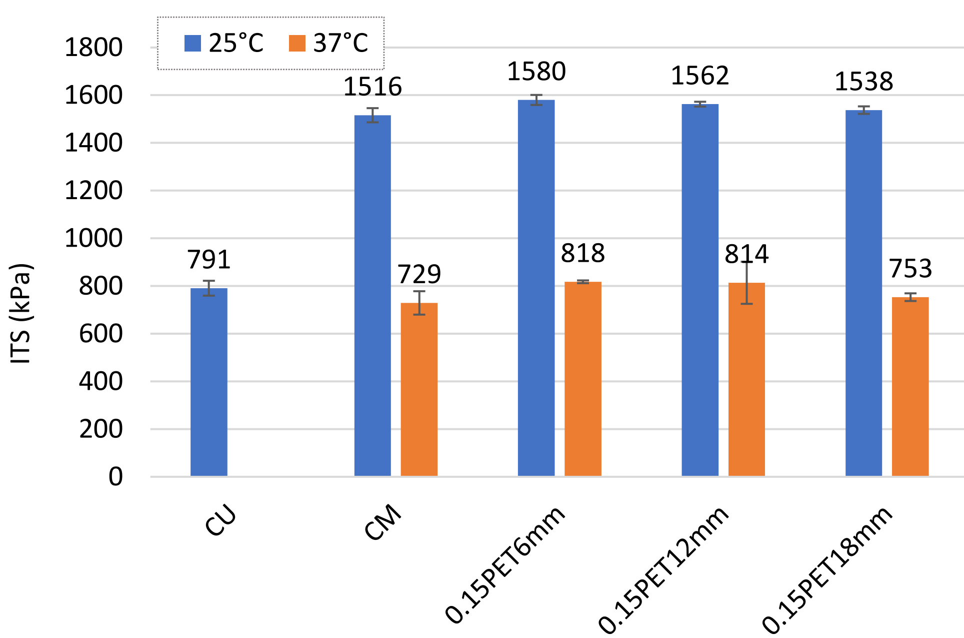


Figure 12: Comparison of indirect tensile strength (kPa) results

Regarding the outcomes of indirect tensile strength (ITS), it can be observed from Figure 12 that all PET fibre-modified specimens exhibit slightly higher values compared to the control modified samples at the test temperature of 25℃. When the test temperature is increased to 37℃, the ITS values are reduced to half of those obtained at 25℃. Among the various PET fibre lengths, the mixtures containing 6, and 12 mm PET fibres demonstrate the higher ITS values with 818, and 814 kPa, respectively. However, for mixes fabricated with 18 mm PET fibres, the ITS value decreases to 753 kPa.

6. CONCLUSION

In this study, a performance test IDEAL-CT is performed to evaluate the cracking property of asphalt mixes fabricated with Polyethylene Terephthalate (PET) fibres and a comparison is carried out with the control samples. The specimens are tested at two test temperatures, one is 25℃ which is considered as an intermediate temperature, and the other test temperature is chosen as 37℃ considering the PG grading of the asphaltenes-modified binder. The following conclusion can be made based on the results discussed in the above section:

- Considering the results of the samples tested at 25℃ temperature, better results are observed with the addition of PET fibres in terms of failure energy and indirect tensile strength. Around 10% increase is seen in total failure energy for 12 mm PET fabricated asphalt mix, while the post-crack failure energy increment is around 15% for 18 mm PET fabricated samples. A slight increase (around 5% for 6 mm PET) can be seen in the indirect tensile strength value of PET modified asphalt mix compared to the control modified mix. However, no impact of different lengths of PET fibres modification is observed with same dosage.
- The impact of adding PET fibres of various lengths becomes more apparent when the test temperature is raised to 37℃. As the length of the PET fibres increases up to 12 mm, there is a noticeable positive trend in different parameters. The specimens modified with 12 mm PET fibres exhibit the highest CT_{Index} value of 105. The specimens with 12 mm PET fabrication also demonstrate the highest pre-crack failure energy, with a 23% increase, as well as a 28% increase in total failure energy compared to the control modified samples. Consequently, it can be concluded that the specimens modified with 12 mm PET fibres outperform the other test specimens in all aspects of the study.
- When the test temperature is increased from 25℃ to 37℃, the ITS values significantly decrease, making the influence of various PET fibre lengths more noticeable. Consequently, to achieve more reliable results in IDEAL-CT tests, it is recommended to determine the test temperature based on the PG grading of the binder.

For future research, other performance tests such as IDT creep and compliance test at lower temperature, Hamburg wheel-tracking (HWT) test can be performed to better understand the effects of the addition of PET fibres in the asphalt mixture.

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