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Visual Abstract

The impacts of type and proportion of five different asphalt modifiers on the low-temperature fracture toughness and fracture energy of modified HMA

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ABSTRACT. Low-temperature fracture toughness and fracture energy are two important measures that could be used to investigate the impacts of using asphalt modifiers on the performance of asphalt pavements in cold regions. The aim of this research was to identify the impacts of using various proportions of five different asphalt modifiers on the fracture toughness and the fracture energy of Hot Mix Asphalts (HMA) under mode I loading and at low environmental temperatures. The asphalt modifiers used for this purpose were: Elastoplastomer Polymer Strings (EPS), Parafiber, Sulfur Polymer, Polyolefin-Aramid Compound Structural Fibers (PACSF) and Sasobit. These modifiers were individually used at three different proportions to produce Semi-circular Bend Specimens containing vertical edge crack. Each specimen was then tested under symmetric monotonic three-point bend loading at -15°C. The results indicated that, except for the EPS, both fracture toughness and fracture energy were increased with an increase in the modifier proportion. The highest increase in both measures was observed in the specimens modified with the PACSF, closely followed by specimens modified with the Parafibers. The least increase in these two measures was observed in the specimens modified with the Sulfur Polymer. The results indicated the applicability of examined modifiers to improve the resistance of HMA to crack initiation and crack growth at low temperatures.

KEYWORDS. Mode-I Fracture Toughness; Mode-I Fracture Energy; Hot Mix Asphalt; Low-Temperature Cracking; Asphalt Modifiers.

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INTRODUCTION

The major deterioration mode of road asphalt pavements at low ambient temperatures is mainly in the form of thermal cracks and brittle fractures. This is mainly due to the solid state and elastic behavior of bitumen and subsequently asphalt mixtures at these conditions. A number of researches have previously conducted to enhance the performance of asphalt mixtures in these conditions. Fracture Mechanics is one of the analytical tools that has been widely used to evaluate the performance of asphalt mixtures at different temperatures and conditions over the last three decades [1-23]. It has also been used in researches concerned with the performance of asphalt mixtures at low temperatures [1, 2, 3, 4, 5, 6, 7]. These studies have indicated that initiation and propagation of cracks in these situations can be investigated under monotonic pure tension mode (Mode I), provided that the Linear Elastic Fracture Mechanics (LEFM) dominates the testing conditions, i.e. the testing is undertaken at subzero temperatures [2, 3, 4, 8] and under fast loading conditions [2]. At higher temperatures and under slow loading, asphalt mixtures tend to demonstrate a viscoelastic or even viscous behavior.

Using Fracture Mechanics approach, based on numerical fracture analysis and/or fracture toughness tests described in section 4, a number of studies have been undertaken to investigate the impacts of involved parameters such as asphalt mixture properties, testing temperature, loading condition, specimen shape, and applied asphalt modifier type [1-23]. A summary of major findings from such researches is described below.

In respect with the mixture properties, Behbahani et al. [9] , Aliha et al. [5] and Aliha et al. [8] in their experimental studies concluded that the fracture toughness of asphalt mixtures at low temperatures would be reduced with an increase in their air void and a decrease in their aggregate size. Aliha et al. [8] also realized that with an increase in the bitumen hardness, the mode I fracture toughness of asphalt mixtures would significantly be increased but this behavior is less pronounced when switching to mode II loading. They also concluded that with an increase in the nominal size of aggregates used in the asphalt mixtures, the mixed mode fracture toughness, especially under the dominated mode II loading, would be increased. Their findings also indicated that limestone aggregates have a higher fracture toughness than siliceous aggregates. More recently, Ren and Sun [10] investigated the impact of void characteristics (porosity, void size, and void distribution) on the fracture performance and crack propagation of HMA. A combination of experiments and heterogeneous simulations based on the discrete element method was applied. The fracture tests were performed on a series of edge cracked Semi Semi-Circular Bend (SCB) specimens fracturing under different loading modes at -6°C and 10°C. The results indicated that the fracture toughness and the time at which peak load occurs reduced as the porosity and void size increased and the impact of void size was more significant than that of porosity. At -6°C, the impact of void characteristics on crack propagation was not significant in mode I and mixed mode I/II loading.

In terms of specimen shape, the findings of a study by Ameri et al. [3] indicated that it would be easier to use SCB specimens containing vertical edge crack rather than other specimen geometries when they are used for crack propagation experiments at low temperatures. They modeled two types of SCB specimens under different loading modes using the finite element analysis and produced a wide range of shape factors. Also, Saha and Biligiri [11] in a review of previous studies concluded that the SCB geometry is a suitable shape for specimens used in the crack propagation experiments.

In terms of loading condition, Pirmohammad and Ayatollahi [6] in their experimental study on the fracture resistance of HMA under different loading modes showed that this factor would influence the fracture resistance of HMA significantly. Saha and Biligiri [11] in their research concluded that the monotonic loading can be used to obtain useful information on the fracture behavior of SCB specimens but this type of loading is not appropriate when fatigue behavior of asphalt mixtures is being investigated. Also, Aliha et al [8] in their research showed that the effects of binder and asphalt modifier on the fracture toughness were noticeable when the asphalt mixtures were subjected to pure or dominantly mode I loading condition.

In terms of testing temperature, Pirmohammad and Ayatollahi [6] in their experimental study on the fracture resistance of HMA under different testing temperatures indicated that for all of the fracture tests they performed under different loading modes, the fracture toughness increased with a decrease in temperature but below a certain temperature threshold (i.e. -20°C), it started decreasing. Aliha et al. [5] in a series of experiments performed at four different subzero temperatures (-24°C, -18°C, -12°C and -6°C) indicated that the fracture toughness would increase with a decrease in temperature. However, below a certain temperature threshold, which was identified as the lower Performance Grade (PG) limit of each bitumen, the fracture toughness would decrease with further reductions in the temperature. This reduction was attributed to the nucleation of micro cracks inside the bitumen which may lead to more brittleness of the bitumen and also reduction in the bonding between the bitumen and aggregates.

In terms of modifier type, Behbahani et al. [9] investigated the mode I fracture toughness of asphalt mixtures modified with Crumb Rubber, Sasobit, Styrene–Butadiene–Styrene (SBS), Poly-Phosphoric Acid (PPA) and Anti-Stripping Agent (ASA) at low temperatures (-15°C). The results of their experiments indicated that the highest and the lowest fracture toughness were observed when the Crumb Rubber and ASA were used as asphalt modifiers respectively. However, one proportion of Sasobit was only used in their experiments (i.e. 2.5 wt% of bitumen). As an extension to their research, Aliha et al. [5] investigated the impacts of variation in factors such as asphalt modifier type, mixture air void, testing temperature and loading mode on the fracture toughness of asphalt. Their tests were performed at -24°C, -18°C, -12°C and -6°C. The results of their experiments indicated that for both examined percentage of air voids (i.e. 3% and 7%), modified asphalt mixtures demonstrated a higher fracture toughness in comparison with the unmodified mixtures. The most increase in the fracture toughness was again observed when Crumb Rubber or SBS were used. The PPA modifier did not increase the fracture toughness considerably. In a series of experiments by Kaloush et al. [12] on the asphalt mixtures modified with the Polyolefin-Aramid Compound Structural Fibers (PACSF), the impacts of this modifier on the crack propagation was investigated. The results indicated that the fiber-reinforced mix had higher resistance to crack propagation than the control mix. However, only one proportion of this material was used in their experiments (i.e. 0.045 wt%), Moreover, disc-shaped specimens with 90° edge cracks were used and the experiments were undertaken at + 20°C. In a recent research by Fazaeli et al. [1], the performance of asphalt mixtures modified with Sasobit and PACSF was investigated. Their laboratory and field evaluations, based on fracture tests performed on SCB specimens at 0°C, indicated that asphalt mixtures modified with each one or combinations of these modifiers demonstrated higher fracture toughness than the unmodified asphalt mixtures under both monotonic and cyclic loading. They observed that initiation of cracks in modified mixtures would need more stress at the crack tip area and that the cracks are progressed more slowly in the modified samples than unmodified samples. Based on these results, they concluded that the performance of modified mixtures was better than the unmodified mixtures in terms of both crack initiation resistance and the crack growth rate. More recently, Aliha et al. [13] investigated the influence of two fibers types, namely natural jute fibers and PACSF on mode I+II fracture toughness of Warm Mix Asphalt (WMA) mixtures. The experiments were conducted on the SCB specimens modified with 3 different fiber contents and at 3 different test temperatures (0, -10 and -20°C). The results indicated that both fibers can increase in general the fracture resistance of WMA relative to the control mixture. This improvement was more pronounced when the testing temperature decreased or the fiber content increased. The PACSF provided better crack growth resistance characteristics and the performance of both fibers was more pronounced under mode I loading.

This literature review indicates that previous studies based on Fracture Mechanics have highly been successful in identifying many of underlying factors contributing to the fracture toughness of asphalt pavements and their deteriorations, especially at low-temperature conditions. As part of these studies, the impacts of some asphalt modifiers have also been investigated. However further researches in this area are still needed as e.g. no previous research on the impacts of asphalt modifiers such as Elastoplastomer Polymer Strings (EPS), Sulfur Polymer and Parafibers on the fracture toughness behavior of asphalt mixtures has been undertaken so far. Moreover, further researches on some of the previously examined asphalt modifiers such as Sasobit and PACSF are still needed to examine their performance under other testing conditions and/or other proportions of the modifier. Finally, the fracture energy behavior of HMA modified with these additives has received little attention in previous studies.

Thus, the objective of this research was to extend previous researches further, via examining and comparing the fracture toughness and the fracture energy behavior of HMA modified with 3 different proportions of each one of the following five asphalt modifiers. The asphalt modifiers used for this purpose were: Sulfur Polymer, Parafibers, EPS, PACSF and Sasobit. The performance of the first three materials has not previously been investigated in this respect. The previous researches on the remaining modifiers were also carried out under different experimental conditions or a limited range of modifier contents.

Sieve size (mm)	Requirement (Percent Passing)		Applied Percentage
	Min	Max	
19	100	100	100
12.5	90	100	95
4.75	44	74	57
2.36	28	58	43
0.3	5	21	8
0.075	2	10	4.5

Table 1: Aggregates gradation of HMA.

MATERIALS

As indicated in the previous section, five different asphalt modifiers were examined in this research. Three of these modifiers namely, EPS, Sulfur Polymer and Parafibers are produced in Iran and were provided by internal manufactures. The other two modifiers namely, PACSF and Sasobit are imported from abroad and were provided by their representative company in the country. Bitumen and aggregates were provided from a well-known local HMA production plant. The materials were then transferred to the Technical and Soil Mechanics Laboratory in Tehran which is one of the best-equipped laboratories in the fields of soil mechanics, asphalt pavement materials and cement concrete materials in Iran. The characteristics of these materials are described in the following sections.

Aggregates
Aggregates used for producing HMA fracture test samples were limestone aggregates with a nominal maximum aggregate size of 19mm. The aggregates gradation is indicated in Tab. 1 and it is in consistent with the grading No. 4 of Iranian Asphalt Road Pavements' Guidelines [14].

Bitumen
The base bitumen was a semi-hard bitumen with penetration grade of 60/70 and performance grade PG 64-22 in accordance with ASTM D5 / D5M-13 (2013) and ASTM D946-82 (2005) standards [15, 16]. Based on the Marshall mix design method [17], the optimum percentage of the base bitumen was identified as 4.2 wt% of the total HMA. For the simplicity of comparisons, all the HMA samples were produced based on this base bitumen content.

PACSF
These asphalt modifiers are comprised of compound artificial fibers such as Polyolefin fibers and Aramid fibers or similar fibers that are well known for their high strength, durability and cohesiveness. Polyolefin fibers are dissolved in the bitumen and modify its properties. On the other hand, Aramid fibers reinforce the asphalt mixture and increase its homogeneity, causing the external loads are distributed over a wider area and thereby the internal tensions are reduced in the pavement. PACSF are produced and supplied for a wide range of asphalt mixtures. The new generation of these fibers is produced and supplied in three categories for different applications including for HMA blends, Warm Mix Asphalt blends and for Patch blends.

In order to produce a more homogeneous mixture, PACSF and aggregates were initially mixed and then the bitumen was added to the mixture. In this research, the PACSF supplied for HMA blends were used. These fibers were used in three ratios namely, 0.05, 0.075 and 0.1 wt% of the asphalt mixture as was recommended by their supplier. The properties of the PACSF used in this research are presented in Tab. 2.

Color	Specific gravity (gr/cm^3)	Melting point (C°)	Flash point (C°)	Modulus of elasticity (GPa)	Tensile strength (MPa)	Diameter (mm)	Length (mm)	Water absorption	Resistance in acidic and alkaline environ.
					Aramid				
Yellow	1.44	450	-	110	2800	0.02≥	19	No	good
					Grid Polyolefin				
Cream Black White	0.91-0.96	≥120	≥590	≥4.2	570-660	0.3≥	19	No	Excellent

Table 2: Properties of applied PACSF.

EPS
In order to apply this polymer type modifier, the bitumen should initially be heated up to 155°C and then poured in a mixer where the modifier is gradually added to the melted bitumen. This modifier was tested in three different proportions, namely

5, 10 and 15 wt% of the bitumen. These percentages were selected so that the overall range recommended by its manufacture is covered. The properties of this modifier are presented in Tab. 3.

Characteristics	Description
Form	Relatively long strings with polymer granules
Color	Black
Solubility	Homogeneously dissolves in bitumen
Viscosity	Increases bitumen viscosity
Melting point	140 to 160 ° C
Chemical structure	Elastoplastomer Polymer Strings

Table 3: Properties of Elastoplastomer Polymer Strings.

Sulfur Polymer

The potential for application of sulfur to enhance the quality and performance of asphalt mixtures was first recognized in the 1970s but some health and environmental concerns prevented its wider applications worldwide. This led to the later initiatives by some researchers with the aim of its transformation to the sulfur compounds, using special additives, so that the resulting material can safely be used in asphalt pavements. The resulting product is called Sulphur Polymer that can partially be substituted with the bitumen content of asphalt mixtures. Sulphur Polymer is a compound material comprising sulfur as the base material combined with some other additives such as plasticizers, additives to change its melting and evaporation temperatures and also additives to prevent rapid solidification of the bitumen. This modifier should initially be dissolved in the bitumen. For this purpose, three different modified bitumen samples were produced in which 30, 40 and 50 wt% of the original optimum bitumen content was substituted with the Sulfur Polymer respectively. These proportions are recommended by the manufacture for application on roads with light, medium and heavy traffic loads respectively. To produce each sample, the Sulfur Polymer was dissolved in the bitumen that was previously heated up to 140°C. The properties of the applied Sulfur Polymer in this research is presented in Tab. 4.

Characteristics	Description
Form	Granules
Color	Gray
Solubility	Homogeneously dissolves in bitumen
Viscosity	Increases bitumen viscosity
Melting point	At least 90 °C
Chemical structure	A material consisted of 90% sulfur

Table 4: Properties of applied Sulfur Polymer.

Sasobit

This modifier is produced by the Sasol WAX Company and it has been in the market since 1997. It is a combination of long-chain hydrocarbons produced from coal combustion using the Fischer–Tropsch process. It is usually known as Fischer–Tropsch Paraffin Wax. According to the information provided by this company, this product is a combination of chlorine, sulfur, nitrogen and oxygen atoms and it has good stability to oxidation and aging and can be stored in large quantities over a long period of time in stock.

Application of this modifier facilitates mixing and compaction capability of asphalt mixture through a reduction in the bitumen viscosity. Furthermore, it causes that a crystal structure is formed in the bitumen at low temperatures which increases its stiffness [1].

Sasobit is similar to the Paraffin Wax which is one of the derivations of crude oil but its molecular weight is higher than Paraffin Wax. It can easily be dissolved in the bitumen at temperatures above 120°C and there would be no segregation afterward. This material has a melting temperature between 70°C and 110°C and creates a homogeneous solution with bitumen. Sasobit is supplied in two physical forms namely, tablets form (4mm diameter) and granule form (1mm diameter). In this research, Sasobit was initially dissolved in the bitumen at 120°C. It was then used at three different proportions namely, 2, 2.5, and 3 wt% of bitumen to produce HMA samples. These proportions are in the range of proportions recommended by its manufacture and are generally used in previous researches as well [1, 8, 5, 18, 19, 20] . The properties of the Sasobit used in this research is presented in Tab. 5.

Characteristics	Description
Form	Tablets form (4mm diameter) or granules form (1mm diameter)
Density of tablet shape (4 mm diameter)	622 kg/m^3
Density of granules (1 mm diameter)	590 kg/m^3
Color	Clear white
Solubility	Homogeneously dissolved in bitumen
Viscosity	Decreases bitumen viscosity
Melting point	70°C to 110°C
Chemical structure	Coal derivatives- Hydrocarbon Aliphatic

Table 5: Properties of applied Sasobit.

Parafibers

Parafibers are comprised of fibers and white powders. The ratio of the powder to the fiber is pre-determined by the manufacture. It is similarly added to the asphalt mixture as the PACSF. The only difference is the percentage in which they are added to the asphalt mixture. In this research, Parafibers were used in three different proportions namely, 0.1, 0.15 and 0.2 wt% of the asphalt mixture to produce their corresponding samples. These proportions were selected to cover the recommended range by its manufacture. The properties of Prafiber used in this research is presented in Tab. 6.

Characteristics	Description
Form	Compound Fibers and powders
Density	18.1 gr/cm^3
Color	White fiber and white powder
Powder melting point	100 °C to 110 °C
Fibers melting point	230 °C
Fibers length	12-18 mm
Fibers diameter	1.3 mm
Modulus of elasticity	6 GPa

Table 6: Properties of applied Parafibers.

SAMPLES PREPARATION

Aggregates were kept overnight in an oven with its temperature set at 110°C and then heated for 4 hours at 160°C before mixing with the bitumen. Each modifier was added to asphalt mixture in accordance with the procedure described in the previous section. An asphalt mixer was used to produce a homogeneous asphalt mixture. For each

modifier, HMA samples with 150mm diameter, 130 mm height and mix density of 2385 kg/m^3 were produced in accordance with Iranian Code [14], using a gyratory compaction apparatus.
The samples were then cut into semi-circles with 30mm thickness using a diamond circular saw. A saw with 1mm thickness was used to create a vertical crack with 1mm thickness and 20 mm length in the SCB specimens. Using this procedure, 8 semi-circle cracked specimen was produced for each percentage use of five examined modifiers in this research. Steps involved in the preparation of edge cracked SCB specimens are illustrated in Fig. 1.

MECHANICAL TESTS

In this research, the critical mode I fracture toughness (K_{IC}) and fracture energy measures were used to get a better insight into the resistance and cracking behavior of asphalt mixtures, e.g. their crack initiation and crack propagation behavior. The value of K_{IC} can be calculated using Eqn. (1) [9, 21, 22].

$$K_{IC} = Y_I \sigma \sqrt{\pi a} = \frac{F_f}{2Rt} \sqrt{\pi a} Y_I \left(a / R, S / R \right) \tag{1}$$

where K_{IC} = mode I fracture toughness ($MPa.m^{0.5}$), σ = the compression stress imposed on the specimen, Y_I = mode I shape factor, a = crack length for edge cracks or half crack length for internal cracks, F_f = maximum load, R= Radius of Semi-Circular Bend (SCB) specimen which is described below, S= half of loading span and t= specimen thickness.
It is worth mentioning that various geometric shapes have been proposed for the specimens used in the crack propagation experiments, e.g. Single-Edge Notched Beam (SENB) [22, 23, 24], Cracked Straight Through Brazilian Disc (CSTBD) or Brazilian Disc (BD) [22, 25], Disc-shaped Compact Tension (DCT) [26, 27, 28], Edge Notched Disc Bend (ENDB) [29, 30, 31] and Semi-Circular Bend (SCB) [21, 3, 32, 4, 33, 34] specimens. Among these specimen shapes, the SCB specimens have widely been used by many researchers. This is largely due to its simple geometry, ease of sample preparation from the gyratory compactor or from the field, the possibility of creating a wide range of loading modes in this specimen, ease of loading, etc. A schematic view of SCB specimen under mode I loading is indicated in Fig. 2.

Figure 1: Steps involved to produce edge cracked SCB specimens.

In order to establish the LEFM conditions for both normal and modified mixtures and also use similar temperature during the experiments, the specimens were kept in a freezer with -15°C temperature for 6 hours. This temperature is similarly used in a number previous researches on fracture resistance of HMA at low temperatures [9, 2, 5, 7]. This temperature is also in the range recommended by the AASHTO provisional specification for determining the fracture energy of asphalt mixtures using the SCB geometry which requires that these tests are performed at less than 10°C above the PG lower limit of the base bitumen used in the experiments [35]. PG lower limit corresponds to the minimum pavement design temperature in the Superpave Performance Grading system. Each specimen was then laid on the supports so that the distance between two support points was 100 mm and the crack was situated in the middle. A UTM device with the loading capacity of 15 KPa was used for loading of the specimens. In order to minimize the effects of temperature variations, the setting and loading process of the specimens was carried out rapidly and a temperature controlled chamber was used.

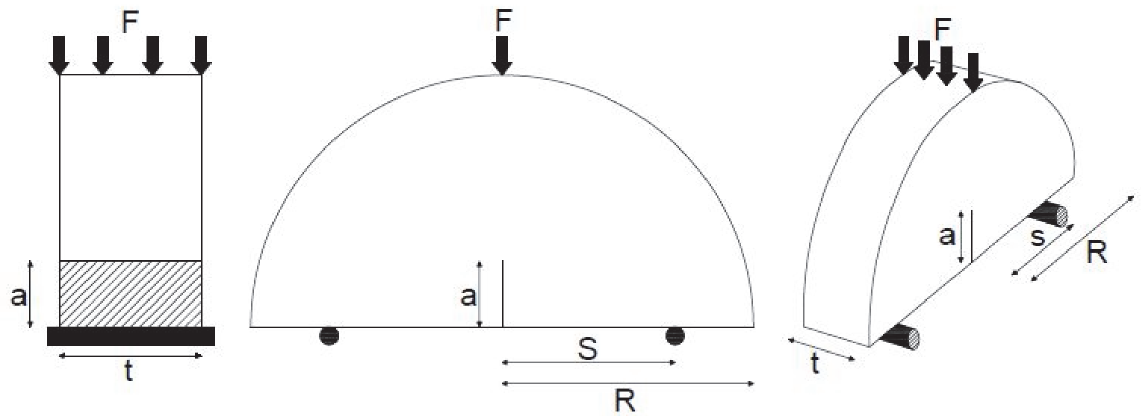

Figure 2: Schematic view of edge cracked SCB specimen under mode I loading.

Li and Marasteanu [4] in their research noticed that loading rate would have an influence on the fracture energy, i.e. the fracture energy decreases with an increase in loading rate at different temperatures. However this reduction in fracture energy was found to be more pronounced at higher test temperatures (e.g. -6°C and above), whereas the effect due to loading rate on the fracture energy was mostly diluted at lower temperatures (e.g. -18°C or -30°C).

Figure 3: Crack propagation testing process.

In this study, a load line displacement rate of 3 millimeters displacement per minute was applied as this rate has also been used in a number of similar researches [1, 2, 8, 13]. These arrangements for temperature control and loading speed were used to ensure that the experiments have been conducted under LEFM conditions. An illustration of the process involved during these experiments is presented in Fig. 3.

The maximum load for each sample was obtained from its corresponding load-displacement diagram (e.g. see from Fig. 4 to Fig.9). The fracture toughness for each specimen was then calculated using Eqn. (1). The assumed values for the parameters used in this equation are a=20mm, R=75mm, t=30mm, S=50mm, and Y_I=3.73. The shape factor value was obtained from previous research by Ameri et al. [3].

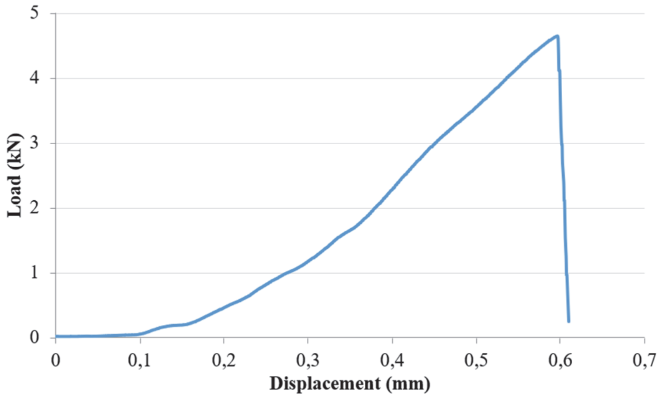

Figure 4: A load-displacement curve obtained for the Control SCB test sample.

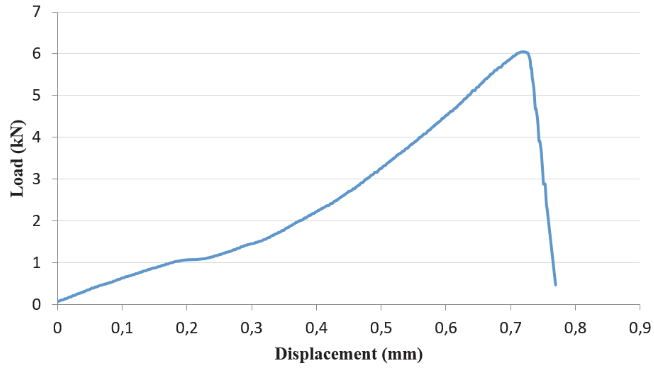

Figure 5: A load-displacement curve obtained for the SCB test sample modified with Sasobit 3.

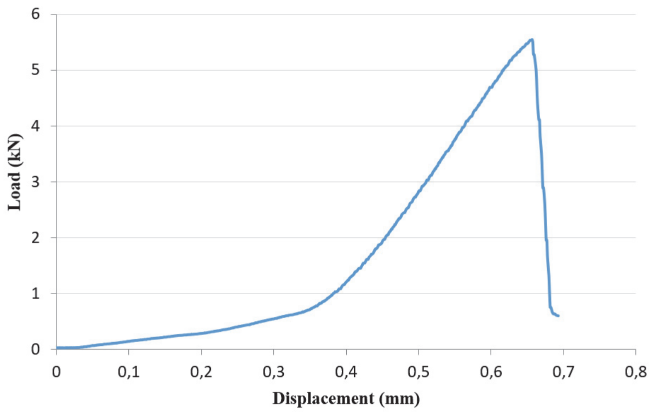

Figure 6: A load-displacement curve obtained for the SCB test sample modified with Sulfur 50.

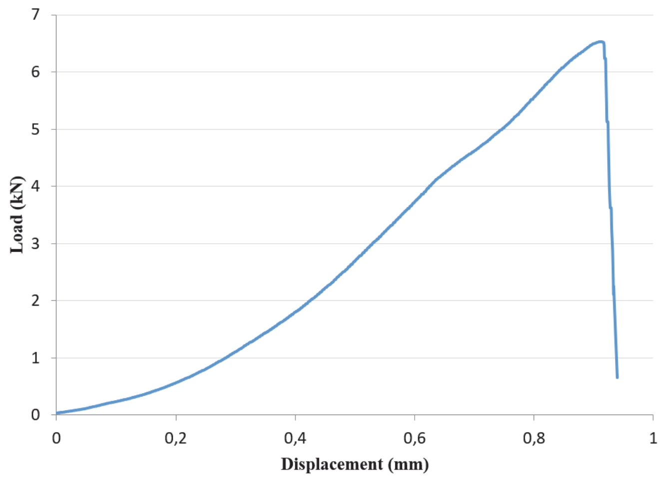

Figure 7: A load-displacement curve obtained for the SCB test sample modified with PACSF 0.1.

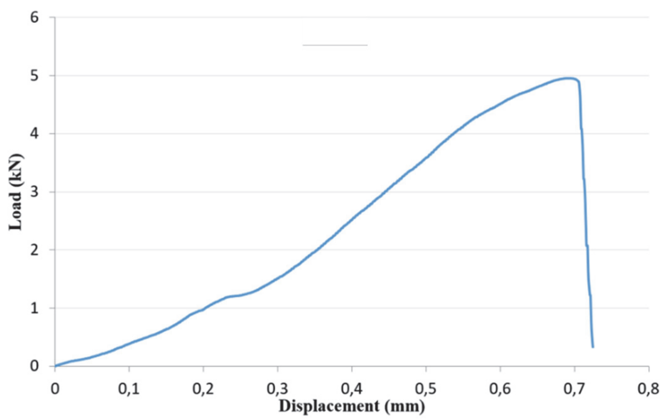

Figure 8: A load-displacement curve obtained for the SCB test sample modified with EPS 15.

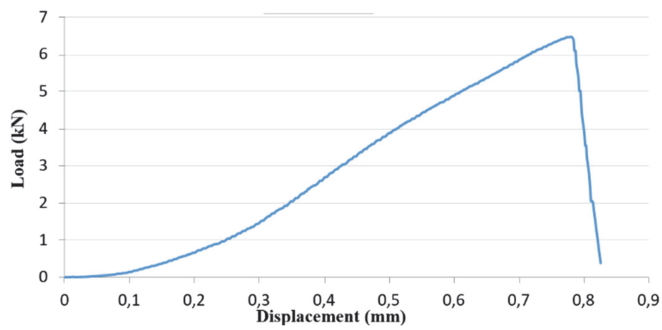

Figure 9: A load-displacement curve obtained for the SCB test sample modified with Parafiber 0.2.

The fracture energy is equal to the area under the load-displacement curve divided by the effective area of the fracture. It implies that a specimen with higher fracture energy capacity would absorb higher energy before reaching to the fracture point. It can be calculated using Eqn. (2) below.

$$G_f = \frac{W_f}{A_{lig}} \quad (2)$$

where G_f , W_f *and* A_{lig} are fracture energy, work to breakdown a specimen or the area under the load- displacement curve and ligament area, respectively.

Modified/Unmodified HMA Specimen Type	Fracture Toughness of Specimens			Fracture Energy of Specimens		
	Average (MPa.m$^{0.5}$)	COV (%)	%Change modified versus control	Average (J/m^2)	COV (%)	% Change modified versus control
Unmodified (control)	0.965	4.9	-	931	13.1	-
PACSF 0.05	1.187	15.1	22.28	1228	8.7	31.79
PACSF 0.075	1.308	11.5	35.55	1350	15.1	44.95
PACSF 0.1	1.356	6.8	40.4	1430	4.3	53.48
Sulfur Polymer 30	0.974	16.2	1	969	5.3	4.07
Sulfur Polymer 40	1.087	6.6	11.74	1007	2.4	8.15
Sulfur Polymer 50	1.152	8.4	24.14	1061	3.7	13.87
EPS 5	0.957	13	-1	1036	6.4	11.22
EPS 10	0.935	8.4	-3.3	1063	2.5	14.15
EPS 15	1.029	8.8	6.63	1125	3.1	20.73
Parafiber 0.1	1.140	8.1	13.98	1212	2.5	30.09
Parafiber 0.15	1.254	9.7	25.38	1303	5.1	39.88
Parafiber 0.2	1.344	10.3	36.78	1387	3.4	48.93
Sasobit 2	1.084	6.2	12.33	1100	7.5	18.13
Sasobit 2.5	1.156	8.9	19.84	1175	7	26.14
Sasobit 3	1.256	7.6	30.21	1279	2.6	37.37

Table 7: Average, COV and % change values of the fracture toughness and fracture energy for each specimen type.

ANALYSIS OF RESULTS AND DISCUSSION

Following the experiments, the average and covariance (COV) values of the measured fracture toughness and fracture energy for specimens with similar modifier type and proportion were calculated. Also, the percentage increase in the average fracture toughness of each specimen type in comparison with the control specimen (the similar specimen when no modifier is added) was calculated. The results are presented in Tab. 7, Fig. 10 and Fig. 11. As indicated in Tab. 7, the COV values of fracture toughness and fracture energy for all specimen types is less than 25%, indicating the repeatability of experiments. Fig. 10 indicates the observed average fracture toughness of specimens in ascending order from top to bottom. The suffix numbers assigned to each modifier type represent the percentage of applied modifier.

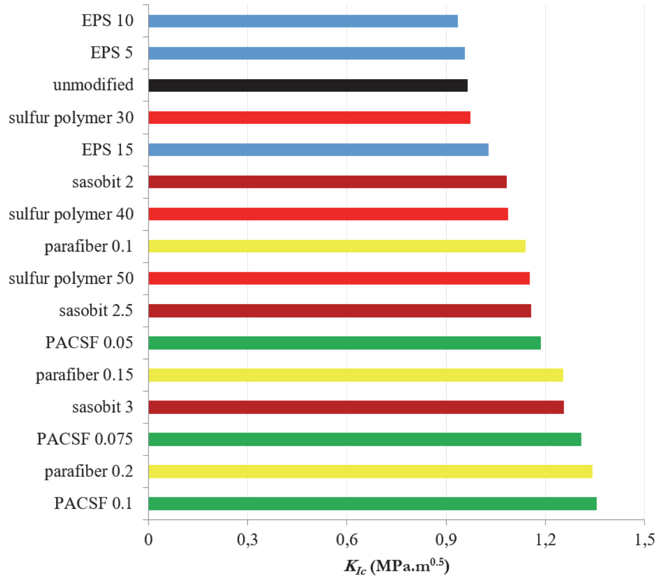

Figure 10: Bar chart of average fracture toughness of specimens.

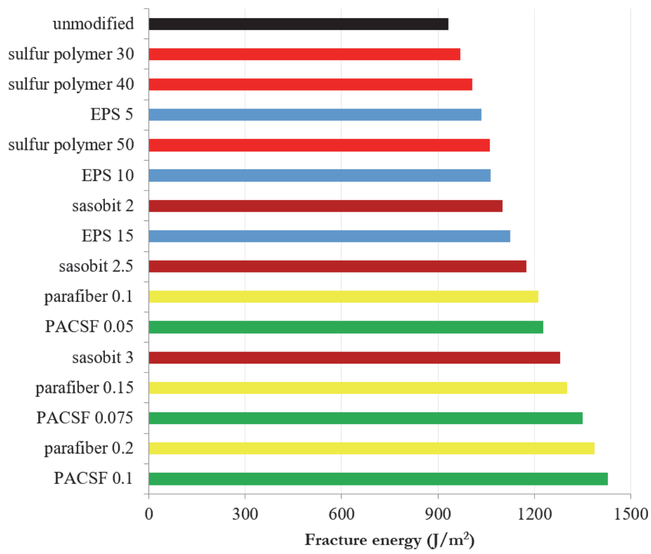

Figure 11: Bar chart of average fracture energy of specimens.

The results indicate that specimens modified with PACSF have produced the highest fracture toughness. This performance has been closely followed by specimens modified with Parafibers. This behavior can be attributed to the fact that these modifier types not only modify the bitumen but also reinforce the asphalt mixture, causing the loads are distributed over a wider area and thereby the overall tensions are reduced. This would result in a better performance for the asphalt pavements during their operational life. The results for the specimens modified with the EPS indicates that the fracture toughness initially decreased when the two lower proportions of this modifier namely, 5% and 10% were used. The fracture toughness then slightly increased when the proportion of this modifier was increased to 15%. This indicates that the asphalt mixtures modified with this modifier may produce inconsistent behavior under different percentage usage of this modifier. This behavior may be attributed to the chemical structure of this modifier and its reaction with the bitumen. However, further research is needed to explore the underlying causes of this behavior. The results for the specimens modified with other four modifier types indicates that the fracture toughness has consistently increased with an increase in the proportion of the modifier.

In respect with the fracture energy, the results presented in Tab. 7 and Fig. 11 indicate that the fracture energy has also consistently increased with an increase in the proportion of each modifier type. These results also indicate that specimens modified with PACSF and Prafibers have produced the highest fracture energy respectively. These results are in consistent with the results of the fracture toughness tests on the specimens. This performance can be attributed to the reinforcing effect of fibers in these two modifiers which would increase the ductility of their corresponding asphalt mixtures. This would extend their energy absorbance capacity before reaching to the ultimate fracture point.

The results also indicate that the fracture energy of the specimens modified with EPS has increased consistently as the percentage of these modifiers was increased from 5 to 15%. This is in contrast with the behavior observed for the fracture toughness of specimens modified with this modifier. Furthermore, the results indicate that increase in the fracture energy of specimens modified with different types and contents of modifiers has not followed the same order observed for the fracture toughness (e.g. compare Fig. 10 and Fig. 11). These results indicate that the performance of examined modifiers in terms of fracture toughness and fracture energy could be different, especially when different proportion of modifiers are used. However, the results presented in Tab. 7, Fig. 10 and Fig. 11 show that if we only consider the highest observed values for each modifier type and exclude the results for the specimens modified with EPS, the order of increase in both fracture toughness and fracture energy for asphalt mixtures modified with other four remaining modifiers has been

consistent. According to these results, the order of increase in both measures under the highest applied proportion of modifiers has been: Sulfur Polymer 50, Sasobit 3, Parafiber 0.2 and PACSF 0.1, respectively.
The relationship between the observed average fracture toughness and fracture energy of similar asphalt mixtures tested in this study is presented in Fig. 12 which indicates a high correlation between the variation of these two measures (R^2 =0.849). This figure indicates a strong and direct relationship between energy absorbance capability of modified asphalt mixtures and their fracture toughness when they are subjected to mode I loading at -15°C temperature.

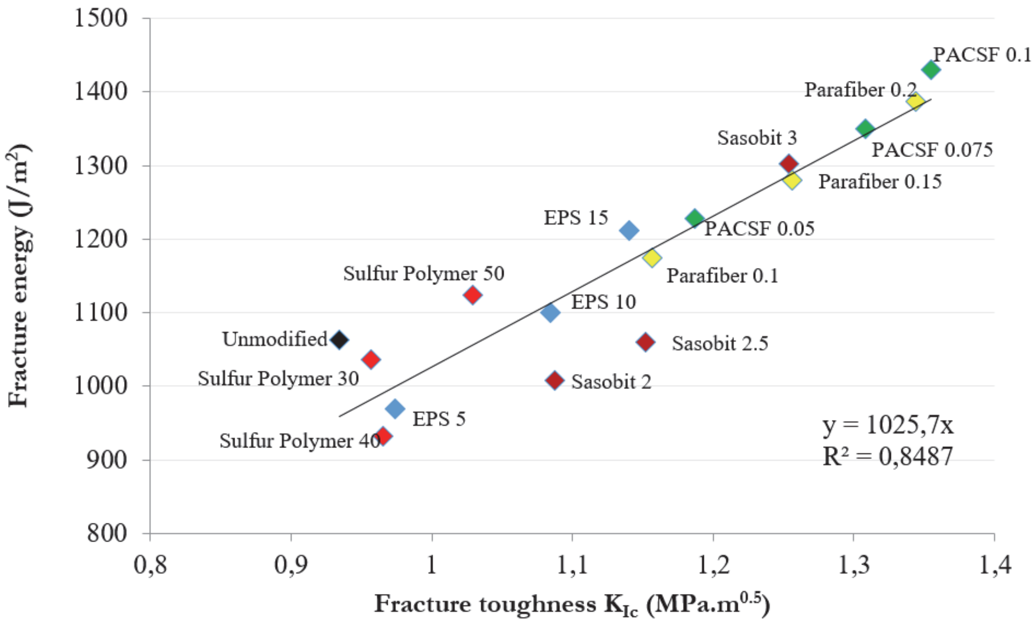

Figure 12: The relationship between the observed average fracture energy and fracture toughness of modified and unmodified asphalt mixtures.

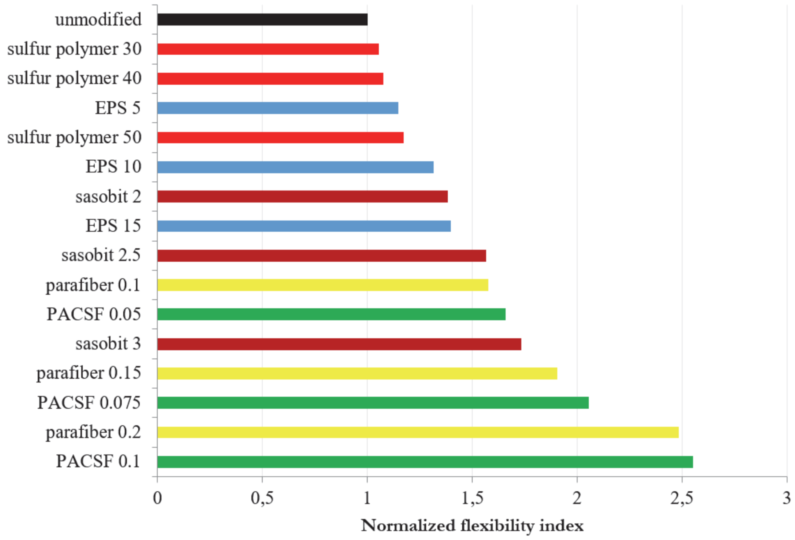

Figure 13: Flexibility Index of modified asphalt mixtures, normalized in relation to the unmodified mixture

It could be argued that although the results indicate an increase in the fracture toughness and fracture energy of the modified asphalt mixtures but increase in toughness may be attributed to the increased viscosity and stiffness of the binder. Furthermore, the fracture energy can mask the brittleness if it is very strong. Therefore, the resulting brittleness can prolong the crack initiation but can accelerate the crack propagation afterward. In order to investigate whether the modified asphalt mixtures examined in this study possess both strength and ductility, a fracture based Flexibility Index (FI) proposed by Ozer et al. [36] was also calculated for the modified and control asphalt mixtures. In this measure, the combination of post-peak slope of load-displacement curve and the fracture energy is used for characterizing the cracking potential of asphalt mixtures in addition to the fracture toughness. The FI was calculated using Eqn. (3) as suggested by them [36].

$$FI = \frac{G_{fa}}{abs(m)} \tag{3}$$

Where: G_{fa} denotes fracture energy reported in J/m² and abs(m) denotes the absolute value of the post-peak slope of the load-displacement diagram reported in kN/mm.

The results are illustrated in Fig. 13 which indicates that the normalized Flexibility Index of modified mixtures is more than 1, indicating the higher flexibility of modified asphalt mixtures in comparison with the unmodified asphalt mixture. This increase is less pronounced for asphalt mixtures modified with low and average proportions of Sulfur Polymer (i.e. 5% and 8% respectively). A comparison of Fig. 11 and Fig. 13 indicates that the order of increase in the normalized FI of tested modifiers in accordance with their type and proportion are consistently similar with the fracture energy results. According to these results, it could then be expected that these modifiers would not only improve crack initiation resistance of asphalt mixtures but also their crack growth at temperatures as low as -15°C.

A HMA Specimen Type	B % Change in Fracture Toughness (modified vs control)	C % Change in Fracture Energy (modified vs control)	D % Change in costs (US$)	E B/D ratio	F C/D ratio
Unmodified (control)	-	-	-	-	-
PACSF 0.05	22.28	31.79	12.6	1.8	2.5
PACSF 0.075	35.55	44.95	18.9	1.9	2.4
PACSF 0.1	40.4	53.48	25.2	1.6	2.1
Sulfur Polymer 30	1.0	4.07	1.2	0.8	3.4
Sulfur Polymer 40	11.74	8.15	1.6	7.3	5.1
Sulfur Polymer 50	24.14	13.87	2.2	11.0	6.3
EPS 5	-1.0	11.22	4.9	-0.2	2.3
EPS 10	-3.3	14.15	9.9	-0.3	1.4
EPS 15	6.63	20.73	14.8	0.4	1.4
Parafiber 0.1	13.98	30.09	7.1	2.0	4.2
Parafiber 0.15	25.38	39.88	10.6	2.4	3.8
Parafiber 0.2	36.78	48.93	14.1	2.6	3.5
Sasobit 2	12.33	18.13	6.5	1.9	2.8
Sasobit 2.5	19.84	26.14	8.1	2.4	3.2
Sasobit 3	30.21	37.37	9.7	3.1	3.9

Table 8: Summary of the economic assessment of modified asphalt mixtures.

It could also be argued that the application of modifiers could accelerate crack growth at low temperatures, provided that the temperature of modified bitumen drops below its glass transition temperature (T_g) which is a transition point from softening quasi-brittle to brittle behavior. This behavior could be attributed to the fact that the bitumen strength and its adhesion to the aggregates would initially be increased with a decrease in the bitumen temperature but below a certain temperature (i.e. T_g), accumulation of microcracks in the bitumen caused by its increased stiffness and brittleness, leads to reductions in the fracture toughness of the mixture as suggested by [6] as well. In this study, the results suggest that the examined modifiers have not increased the glass transition temperature or the lower PG limit of modified bitumens above the test temperature (-15°C). It is worth mentioning that the T_g of neat bitumens is also around -15°C [37, 38] and a lower T_g for the modified bitumens used in this study is expected.

The results may also imply that the lower PG limit of the modified bitumens in this study is still below the test temperature (-15°C). In a previous research by Aliha et al. [7], the performance grade of a neat bitumen similar to one used in this study (penetration grade 60/70 and PG 64-22), when modified with 2.5%wt Sasobit, was measured as 70-22, indicating no change in the lower PG limit of this modified bitumen.

In future researches, this study can further be elaborated to provide a more in-depth understanding of the underlying mechanisms behind the cracking performance of these modifiers, to investigate the chemical and rheological characterization of these modifiers and their corresponding modified binders.

The results of an economic assessment of the modifiers examined in this study is presented in Tab. 8. For this assessment, the cost of HMA was obtained from its average bid prices in the USA (i.e. $85 per ton [39]). The cost of modifiers was obtained from their representative companies. The following conclusions may be drawn from these results:

- The additional costs associated with using these modifiers varies in the range of 1.3 to 25.2%, depending on the type and the proportion of modifiers. The highest cost increase is associated with the PACSF modifier and the lowest cost increase is related to the Sulfur Polymer.
- The ratios of percentage changes in the fracture toughness and fracture energy to the percentage change in their corresponding modified HMA costs presented in Tab. 8 (B/D and C/D ratios) indicate that Sulfur Polymer has produced the most effective results in economic terms. However, this is compromised by much less improvement in the fracture toughness and fracture energy measures in comparison with PACSF, Parafiber and Sasobit modifiers.
- In highway projects with the tight budgets, it may be advisable to apply Parafiber and Sasobit to provide a balance between the fracture performance and the costs. However when the cost is not an important issue, PACSF would be the best choice.

CONCLUSIONS

- The results of fracture toughness and fracture energy experiments on the SCB specimens, produced from HMA modified with 5 different asphalt modifiers, using three different proportions for each, indicated that overall both measures were improved in comparison with similar but unmodified HMA specimens. The results indicated that with an increase in the proportion of each modifier in the bitumen, both fracture toughness and fracture energy were increased. The only exception was for the specimens containing 5 and 10 wt% EPS in which the fracture toughness was reduced.
- The results indicated that the fracture toughness and fracture energy of SCB specimens modified with two modifiers containing fiber components namely, PACSF and Parafibers, in comparison with other three modifiers were highest respectively. The increase in the fracture toughness of these specimens can be attributed to the role of reinforcement fibers in producing a more integrated structure and thereby reducing the tensions in the specimens through wider distribution of loads. The increase in the fracture energy of these specimens can be attributed to the role of reinforcement elements in increasing the ductility and energy absorbance of the asphalt mixture. The other three modifiers would mainly improve the bitumen properties.
- The other three modifiers in their descending order of increased fracture toughness were Sasobit, Sulfur Polymer and EPS respectively, when their highest modifier content was used in the asphalt mixture.
- The other three modifiers in their descending order of increased fracture energy were Sasobit, EPS and Sulfur Polymer respectively, when their highest modifier content was used in the asphalt mixture.
- If we exclude the performance of the HMA modified with EPS, the other four remaining additives, under their highest percentage usage, demonstrated a similar order of performance in terms of both fracture toughness and fracture energy.
- A higher Flexibility Index measured for modified asphalt mixtures in comparison with similar but unmodified asphalt mixtures indicated that their ductility has not been compromised. It is therefore expected that these modifiers would enhance crack initiation resistance and crack growth behavior of asphalt mixtures at low temperatures.
- A combined economic-performance based analysis indicated that depending on the extent of required improvement in the fracture behavior of HMA and available budget, the choice of appropriate modifier could be different.

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DECLARATION OF INTEREST

The authors declare that they have no commercial or financial interest in the materials discussed in this manuscript.

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NOMENCLATURE

A	Crack length for edge cracks or half crack length for internal cracks
A_{lig}	Ligament area
ASA	Anti-Stripping Agent
BD	Brazilian Disc
COV	Covariance
CSTBD	Cracked Straight Through Brazilian Disc
DCT	Disc-shaped Compact Tension

ENDB Edge Notched Disc Bend
EPS Elastoplastomer Polymer Strings
F_f Maximum load
FI Flexibility Index
G_f Fracture energy
HMA Hot Mix Asphalt
K_{IC} Mode I fracture toughness
LEFM Linear Elastic Fracture Mechanics
PACS Polyolefin-Aramid Compound Structural Fibers
PG Performance Grade
PPA Poly-Phosphoric Acid
R Radius of SCB specimen described below
S Half of loading span
SBS Styrene–Butadiene–Styrene
SCB Semi-Circular Bend specimen
SENB Single-Edge Notched Beam
s The compression stress imposed on the specimen
t Specimen thickness
T_g Glass transition temperature
W_f Work to breakdown a specimen
WMA Warm Mix Asphalt
Y_I Mode I shape factor
Y_I Mode I shape factor