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MIXTURE DESIGN AND TEST PARAMETER EFFECT ON FRACTURE PERFORMANCE OF ASPHALT: A REVIEW

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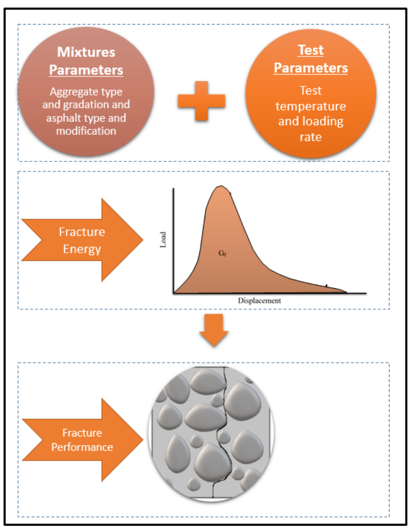
Graphical abstract



Abstract

Fracture energy is critical for crack evaluation and asphalt mixture design. Thus, the fracture mechanics of asphalt materials should be further investigated. Fracture energy is significantly correlated with factors related to mixture design and testing parameters, as shown in prior studies. Mixture design factors include aggregate gradation and asphalt modification, and test parameters include testing temperature and loading rate. In this systematic review, related studies on the effect of these parameters on the fracture energy of asphalt mixtures are discussed from the perspective of fracture mechanics. Strong relationships between asphalt mixtures' testing parameters and fracture energy are found in the literature. Moreover, selecting an appropriate loading rate and testing temperature related to the in-service conditions is crucial in evaluating the fracture energy of asphalt mixtures. Good understanding of these relationships can aid in eliminating the fluctuation in the fracture energy results determined in the laboratory. In turn, asphalt's resistance against cracking can be characterised further.

Keywords: Polymeric Fracture Energy, Asphalt mixture, Aggregate gradation, Polymer Modifiers

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1.0 INTRODUCTION

One of the significant concerns in roadway construction is that pavement service life in most of the time is shorter than initially designed. Distresses necessitate frequent rehabilitation, which raises the overall cost of the sections, including the cost of the time lost by drivers in work zones. Cracking is the most common distress mode in asphalt pavement around the world. Cracks accelerate pavement deterioration, resulting in short service life and ultimately maintenance needs [1], [2]. Thus, parameter evaluation and identification are significant to improve pavement performance and resistance against cracking. Fracture mechanic has been applied to define the resistance of asphalt mixture against cracking as early as the 1960s [3]. In this approach, fracture energy is a significant factor in evaluating the fracture resistance of asphalt mixtures. It represents the energy consumed to separate an object into two parts [4]. Thus, it is considered a material property to indicate the asphalt mixture's strength against cracking. Studies investigated various parameters that affect the fracture energy of various asphalt mixtures [5]–[8]. Most of these studies highlighted the significant effect of asphalt mixture parameters along with the test parameters. The asphalt parameters include factors that affect the produced mixture, such as bitumen type and content, aggregate gradation, aggregate type, size and polymer modifiers. While the test parameters include the test temperature and loading rate. Mixture parameters reviewed in this study significantly affect the fracture resistance of asphalt mixtures [9]. For example, polymers are considered the best modifiers for improving the resistance of asphalt mixtures against cracking [10]. Therefore, various polymer modifiers are also discussed in this review on the perspective of fracture mechanic.

The asphalt mixture is an inhomogeneous system that mainly consists of binder and aggregate. This composition reflects the mechanical behaviour of the asphalt mixture under loading. The mechanical properties of asphalt mixtures mainly depend on the adhesive and cohesive forces and internal friction. The former is highly affected by the binder properties and modification. The latter represents the embedding force between the aggregate particles. It particularly considers the designed gradation and aggregate particle size [11].

On the other hand, the quality of the asphalt mixture is also highly affected by the selection of proper test conditions and input parameters related to the test type and the required output parameters. The asphalt mixture is a viscoelastic rheological composite material. Its behaviour is significantly related to the testing temperature and loading rate [12], [13]. The viscous behaviour represents the time-dependent properties of these materials. Thus, the most appropriate testing temperature and loading rate that reflect the real condition of asphalt pavement in the field should be selected to evaluate potential occurrences of cracks. Failure to do so can create considerable fluctuation and deviation in the test results compared with the real climatic condition.

2.0 BINDER TYPE AND COMPOSITION

An asphalt mixture is composed of 5%–10% asphalt binder and 90%–95% aggregate. Given its rheological and adhesive properties, the asphalt binder can hold the components of asphalt mixture together, providing an adequate strength to resist the applied loads. A prior study showed that the asphalt binder type is significantly related to the fracture energy as it is a key property of the mixture's resistance against cracking [14], [15]. Li et al. [16] used six different performance grades to show the effect of the asphalt binder type on fracture energy. Their study included two levels of binder content: the optimum binder content and the optimum binder with an extra 0.5%. The result significantly highlighted the relationship obtained for the rheological behaviour, which represents the performance grade of the binder tested at different temperatures. These results can be justified based on the effect of the asphalt binder on the skeleton ability of asphalt mixtures on consuming the applied energy. In other words, softer or higher content of asphalt binder contributes to increasing the materials ability to resist cracking propagation by increasing the amount of the dissipated energy in the plastic zone [17]. The same conclusion is revealed by Alvarez et al. [18] by adopting fracture energy indices as fracture parameters to discriminate the fracture potentials of asphalt mixture in the laboratory. Their study characterised the cracking resistance of ten different mixtures with three different binder types. The result showed that stiff asphalt binder and high asphalt content improved fracture energy, proving the significance of fracture energy parameters in evaluating the resistance of asphalt mixtures against fracture. Several studies have reported that asphalt binder and penetration grade of binder correlates with the susceptibility of the asphalt concrete to fracture [19], [20]. As well as, Asphalt mixtures with high percentage of asphalt binder have the same behaviour of asphalt mixtures with softer asphalt binder. Mixtures with high asphalt content have ductile behaviour under loading, which can be observed in the load-displacement curve of these mixtures. Meroni et al [21]. investigate the effect of asphalt content on the shape of the load-displacement curve of asphalt mixture with high RAP content (Figure 1). As shown in the Figure, asphalt mixtures with higher asphalt content have a flatter load-displacement curve and higher displacement at peak load. Higher displacement at peak load refers to higher resistance to failure [22]. Meroni reveals the same conclusion that increasing asphalt content contributes in increasing the cracking resistance of asphalt mixtures. Another study used two penetration grade binders to evaluate the effect of asphalt stiffness on resistance against cracking and fatigue [23]. The result showed a difference in the fracture energy of both asphalt types. The asphalt mixtures with a binder penetration grade of 160/220 showed lower fracture energy than those produced with 70/100 pen asphalt grade. Chaiwat et al. [24] used compact disk-shaped tension (DCT) fracture test to obtain the fracture energy, fracture strength and total fracture work of five different asphalt mixtures with different compositions of Reclaimed Asphalt Pavement (RAP). The studied asphalt mixtures had different asphalt binder types and contents with different RAP percentages. The result showed that the mixture variables affected the determined fracture performance of tested asphalt mixtures. Moreover, the fracture energy increased when soft and high-percentage asphalt was used in the mixtures.

Soft behaviour of asphalt mixture promotes the ductile behaviour of asphalt mixture hence increasing the permanent deformation. In other words, soft binder increases the plastic zone around the crack tip, consequently, more energy will dissipate in plastic deformation around the crack tip rather than in crack initiation and propagation. The effect of various asphalt binder types and contents on fracture energy are summarised in Table 1.

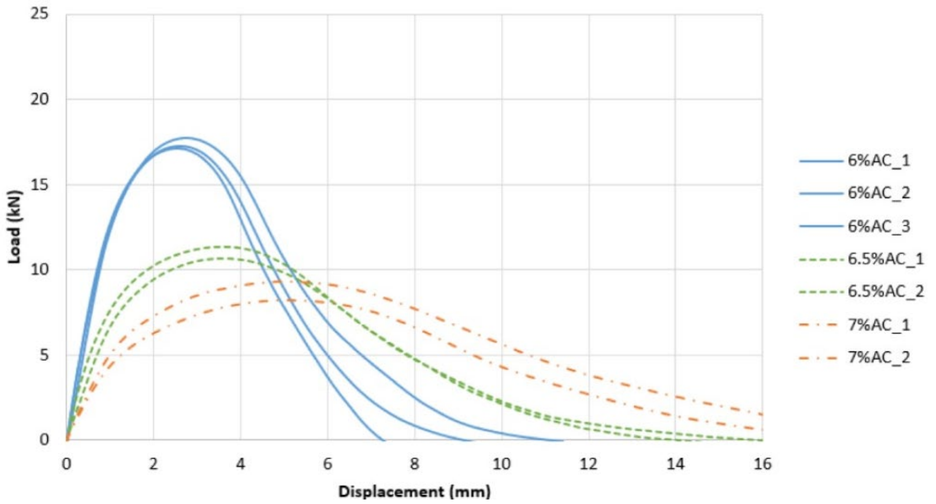

Figure 1 Effect of asphalt binder content on the load-displacement curve [21]

Table 1 Result of fracture energy of different asphalt binder contents and types.

References	Asphalt Mixture/Mix Method	Fracture Test	Test Temperature (°C)	Loading Rate (mm/min)	Fracture Energy (J/m^2)	Findings
[25]	HMA[1] PG[2] 64–22 NMAS[3] = 9.5 mm	DCT[5] T[6]= 50mm N[7] = 35 mm Fracture mode I	0	1	480	• High penetration value means soft asphalt and high deformation potential, leading to high consumption of fracture energy. • High asphalt content leads to high consumption of fracture energy due to increment of ductile behaviour of asphalt mixtures.
			−10		350	
			−20		210	
	HMA PG 58–22 NMAS = 9.5 m		0		625	
			−10		410	
			−20		300	
[26]	HMA + 10% Rubber PG 58–28 NMAS = 12.5 mm	DCT T= 50 mm N= 35 mm Fracture mode I	−12	1	785	
			−18		673	
	HMA + 10% Rubber PG 46–34 NMAS = 12.5 mm		−12		980	
			−18		862	
[24]	HMA, PG 58-22, AC[4] 4.5 % NMAS = 19 mm	DCT T =50mm N= 35 mm Fracture mode I	−12	—	365	
	HMA, PG 64-22, AC 4.5 % NMAS = 19 mm				360	
	HMA, PG 58-28, AC 4.7 % NMAS = 19 mm				414	
	HMA, PG 58-22, AC 5.0 % NMAS = 19 mm				420	
	HMA, PG 76-28, AC 5.8% NMAS = 16 mm				560	

[1] Hot Mix Asphalt, [2] Performance Grade, [3] Nominal Maximum Aggregate Size, [4] Asphalt Content, [5] Disk-Shaped Compact Tension Test, and [6] Thickness, [7] Notch Length.

3.0 AGGREGATE GRADATION AND SIZE

Aggregate interlock helps prevent premature cracking and effectively improves the frictional strength of asphalt mixtures [27]–[30]. In the asphalt mixture design, cracking resistance may be improved by reaching an appropriate particle size along with proper aggregate gradation [30], [31]. Aggregate gradation can strongly influence the aggregate interlock, which affects the cracking resistance of asphalt mixtures. Aggregate interlock can influence the resistance of materials against cracking by promoting high friction force between the aggregate particles. The optimum gradation refers to the mechanical distribution of aggregate throughout the sample, in which the asphalt mixture can handle more stress and strain before failure. However, the aggregate materials are much stronger than the asphalt mortar. Thus, the maximum interlocking force should be provided between these components. It can be reached by properly adjusting the aggregate gradation and particle size. This process properly interlocks aggregate particles to form the skeleton of a mixture structure. The aggregate gradation and particle size with the asphalt mortar produce the final skeleton, which includes fine aggregate, filler, asphalt binder and voids [27], [32]. The fine aggregates also have a crucial effect on the fracture strength of asphalt mixtures [33].

Proper interlocking provides a high friction area and improves the mixture's cracking resistance with high fracture energy. If the fine aggregate proportion is extremely low, the coarse particles will not properly interlock. The formation of voids between the same size and shape of aggregate particles is shown in Figure 2. The fine aggregate can fill up the voids and increase the interlocking friction between the coarse aggregate particles. To sum up, the fine aggregate can contribute a frictional strength to the final aggregate skeleton even though it does not support any load [34].

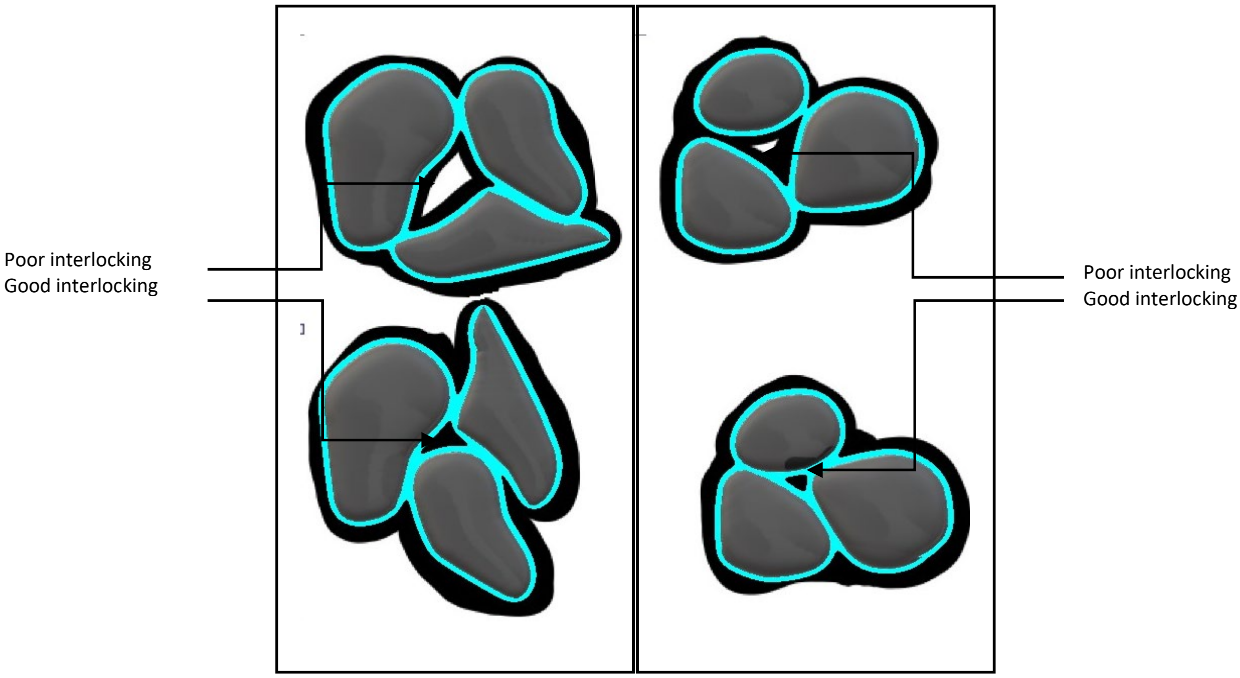

Figure 2 Aggregate interlocking and void generated due to different forms of interlock between particles

A decrease in the points of contact between the aggregate particles will result in a low resistance of the asphalt mixture against cracking. Therefore, a proper aggregate gradation will provide an asphalt mixture with high fracture energy and cracking resistance [35]–[37]. Tran and Takahashi [38] evaluated the effect of aggregate gradation on the resistance of asphalt mixtures against cracking by examining the crack initiation and crack propagation stages, which are directly related to the fracture energy parameter. Their study used the parameters as the continuous maximum density of aggregate gradation and the Dominant Aggregate Size Range (DASR) model. The DASR model shows that aggregate gradation and nominal aggregate size are associated with the mixture's resistance against cracking. The result demonstrated a strong relationship between the gradation-based Cracking Resistance Index (GCI) and the cracking resistance during the cracking initiation stage. Cracking resistance increased with the increment of the GCI value. Using the same method, Al Shamsi et al. [34] described the relationships of power-law gradation parameters and mixture compactibility. Their study focused on the compaction and performance characteristics of asphalt mixtures with aggregate structures that were designed using the Bailey method. The Bailey method is a systematic approach to mixing aggregates. It provides the aggregation as a structural backbone and a balanced continuous gradation that completes the mixture. The indirect tensile strength test and semi-circular fracture tests were conducted to determine the laboratory performance properties. The result showed a high correlation between mixture performance and the gradation parameters under different loading and environmental conditions. The related findings of the above studies on the effect of various mixture parameters on fracture energy of the asphalt are summarised in Table 2. The fracture energy parameter was used to evaluate the effect of aggregate gradation and size on the cracking resistance of the asphalt mixtures.

Table 2. Effect of Mixture Parameters on Fracture Energy of Asphalt

Mixture Parameter	References	Aggregate Gradation	Asphalt Mixture	Fracture Test	Test Temperature (°C)	Loading Rate (mm/min)	Fracture Energy (J/m^2)	Findings
Aggregate gradation	[38]	Dense graded NMAS= 12.5mm	HMA[2] Pen[3] 60/80	(SCB)[5] T[6]=50mm N[7]=25mm Fracture mode I	30	2	~320	• Gap graded has the highest fracture energy amongst all the gradations. • The failure at intermediate temperature take place around the aggregate particles, indicating that the failure path will be longer and require more energy in case of coarse aggregate [39].
		Coarse graded NMAS= 12.5mm					~346	
		Fine graded NMAS= 12.5mm					~378	
	[40]	Gap graded NMAS=16mm	HMA Binder: Pen 80–100, (AC[4] 5.7%)	SCB T=50mm N=22.5mm Fracture mode I	−10	50	1800	
		Continuously Graded NMAS=16mm	HMA Binder: Pen 80–100, (AC 4.7 %)				1650	
Aggregate Size	[41]	NMAS[1]=11 mm Dense graded	HMA Binder: Pen 35/50 (AC 5.0%)	Fénix test T=50mm N= 6 mm Fracture mode I	5	—	450	
		NMAS = 8 mm Open graded					780	
		NMAS = 4 mm Open graded					730	
	[36]	NMAS=16 mm Continuously graded	HMA Pen 87.5 (AC 5.0%) Continuously graded	SINB[7] N=16 mm Fracture mode I	−10	0.05	398.3	
		NMAS= 13mm Continuously graded	HMA SK 90, Pen 87.5 (AC 4.6%) Continuously graded				271.0	
		NMAS=16mm Gap graded	Modified HMA SBS + SK 90, Pen 87.5 (AC 6.0%) Gap graded				448.9	

[1] Nominal Maximum Aggregate Size, [2] Hot Mix Asphalt, [3] Penetration Grade, [4] Asphalt Content, [5] Semi-Circular Bending Test, [6] Thickness and [7] Single Edged Notched Beam, [7] Notch Length.

4.0 POLYMER MODIFIERS

The performance of asphalt mixture can be modified using polymer materials, which modify the viscoelastic behaviour of asphalt binder. Polymers include a wide range of plastomers and elastomers, which are commonly used in asphalt mixture modification. They significantly affect the properties of asphalt mixture [42]–[48] through the chemical reaction between the asphalt and the additives [48] or the hyperplastic properties of these materials [47]. The virtuous elastic properties of polymer modification received considerable attention from the academe and industry. The effect of polymers on the resistance of asphalt mixtures against cracking has been extensively investigated [49]–[53]. The elastic behaviour of polymers can affect the fracture energy of asphalt materials under the applied stress. Polymers are added to the asphalt mixture through two modification methods. The first one is termed as wet process where polymers are used to modify the asphalt binder prior to mixing with the aggregate. The second method is termed as dry process where polymers are directly mixed with the asphalt binder and aggregate during the asphalt mixture production. However, the enhanced properties are mostly verified for the mixture modified by the wet method than the dry method [54]–[57]. In this section, the effect of common polymer additives, including thermoplastic elastomers, polymer recycled material and thermosetting polymers, on the fracture energy of asphalt mixtures is discussed. These polymers play an important role in the production of improved asphalt mixtures [58]–[60].

Increasing the resistance of the asphalt mixture requires enhancing two main components in the asphalt mixtures; the asphalt binder and the aggregate properties. For the first component, the asphalt binder playing a crucial role in improving the cracking resistance by improving the adhesive and adhesion properties between the components of the mixtures. High adhesive and adhesion properties can increase the stresses thresholding at the crack tip resulted in higher resistance to crack initiation. Nemours studies explore this type of modification to investigate its impact on the cracking resistance. Hadidy et al. [61] investigated the effect of 5% styrene–butadiene–styrene polymer (SBS) and revealed that the polymer improved the resistance of the asphalt mixture against cracking. Such results are attributed to the role of SBS modifier on increasing the cohesive and adhesive properties of produced asphalt binder, which increases the fracture energy of the modified mixture [11]. An effort by Yan et al. [52] revealed the same conclusion when evaluated the effect of SBS on the fracture performance of asphalt mixtures using the Superpave indirect tension test. The result showed that asphalt modified with SBS has better fracture performance. SBS is more effective when added using the wet process, wherein the asphalt binder is modified with polymers before mixing the aggregate.

Another type of polymer commonly used for improving the resistance of asphalt mixture against cracking is the crumb rubber. Crumb rubber is produced by shredding the automobile tires into the required particle size [57]. Rubber has the necessary chemical properties that allow it to interact with the asphalt materials within the mixture. These properties have a significant role in producing asphalt mixture with improved properties, particularly when added using the wet process [62]–[64]. In the wet process, the rubberised binder has a high resistance to tensile stress and force. High tensile strength can increase the ability of materials to resist the initiation stage of cracking [73], at this stage, the cracks initiated at point where weak adhesive and adhesion points are generated between aggregate and asphalt binder under loading. Thus, most of the asphalt mixtures modifiers promote high performance when being added by the wet method. The modification is targeting the weakest point in the skeleton bonding structure of asphalt mixtures which is the asphalt binder. In a comprehensive review, Venudharan et al. [65] showed that the asphalt mixtures modified with crumb rubber improved the performance of open-graded, dense and gap-graded mixtures for the surface layer of asphalt pavement. However, the rubberised mixture was proven to be ideal for the open and gap-graded mixtures [31]. Such gradations have adequate spaces in the aggregate skeleton to accommodate the rubber particles [66]. On the other hand, others studies investigated the impact the size of shreded rubber on the fracture energy of asphalt mixtures [67]–[70]. Nemeorus studies revealed that using fine particles to modify asphalt mixtures can boost the interaction between asphalt binder and the used modifiers. Adequate interaction improves the resistance of asphalt mixture against cracking, particularly when modified by crumb rubber [62]. The same conclusion is observed by Razmi and Mirsayar [68] for the effect of crumb rubber particle size on fracture energy. Their study revealed that fracture energy increased with the decrease of the crumb rubber sizes. Moreover, the crumb rubber powder could produce a modified asphalt mixture with improved resistance against low temperature cracking [71]–[73]. The mechanisms of crumb rubber effect on the cracking resistance include two main stages: crack initiation and crack propagation [67], [69]. Crumb rubber particles increase the elastic zone of the materials. This process can lead to a long service time regardless of fatigue stresses. Rubber affects the elastic zone and the plastic stage under loading in the plastic deformation of the rubberised mixture. The mechanism of asphalt modification on cracking resistance could be easily cleared from the perspective of fracture mechanics. For the dry method, the rubber particles can be located at the tip of the cracks, increasing the magnitude of polar coordinate '*r*'. An increase in the magnitude of polar coordinate will dissipate the stress at the crack vicinity[74]. Consequently, the crack will no longer propagate. However, the stress will deform around the rubber particles (crack tip) or branch out in another direction as illustrated in Figure 3. In turn, the fracture energy needed for crack propagation will increase. The reason is that the energy has been consumed by the deformation within the crack process zone. The stress intensity and applied stress have a direct relationship with *r*, as shown in Figure. 4. The stress field equation (Eq. 1) is derived from Irwin [75]. The crack tip stresses reach infinite values (stress singularity) as the plastic zone size approaches zero [76].

$$\sigma = K/(\sqrt{2\pi r})\ F \quad (1)$$

where
σ = applied stress
K = stress intensity factor
r = polar coordinate
F = shape coefficient

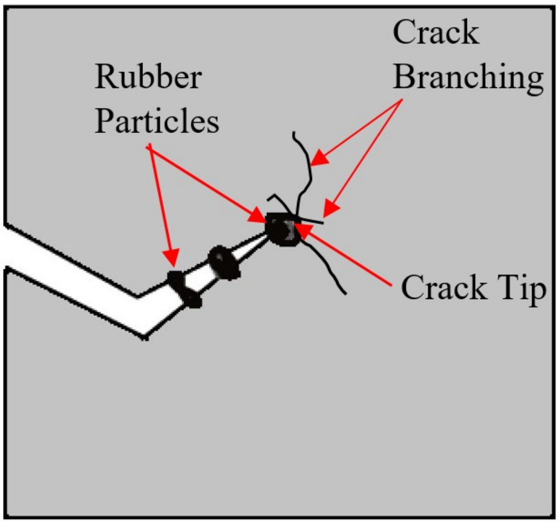

Figure 3 Illustration of crack propagation near the crack tip.

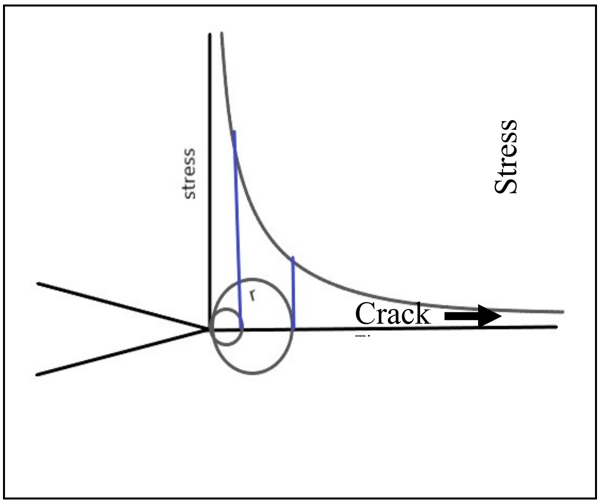

Figure 4 Relationship between a polar coordinate (r) and stress intensity (k) according to Irwin[75].

The materials with large plastic zone exhibited high deformation and consumed more energy to the failure [77]. Small *r* means high concentration for stresses, and the materials have high-stress intensity. The crack initiates when the stress concentration achieves the energy needed to separate two atoms of the materials. When rubber is used, the rubber particles can distribute the applied stress and cause the energy to dissipate in other forms (plastic deformation energy) [31], [78]. Thermoplastics can be categorised into polypropylene (PP) and polyethene (PE). The latter includes two types: high-density PE (HDPE) and low-density PE (LDPE), which are commonly used polymers in asphalt. Recycled PE is recovered from low-density domestic waste PE carry bags and considered the cheapest polymer. Polyolefinic plastomers, also known as thermoplastics, include PE, PP, ethylene vinyl acetate, ethylene butyl acrylate and polyvinyl chloride. Additional PE (plastic waste) improves the stiffness of asphalt mixture when added using the wet and dry methods [43]. Khurshid et al. [64] investigated the effect of plastic waste (plastic bottles) on the top–down cracking. The result showed that using 0.2% plastic content by weight of aggregate enhanced the cracking resistance of modified mixtures.

Table 3 Effect of polymer modifiers on the result of fracture energy.

Asphalt Mixture/Mix Method	References	Modifier Type/Content	Fracture Test	Mixing Method	Test Temperature (°C)	Loading Rate (mm/min)	Fracture Energy	Findings
HMA[2] + 10% RAB[1] Binder: PG 46–34 Quartzite Aggregate NMAS[2]: 12.5 mm	[26]	SBS + Rubber	DCT[5] T[6]=50mm N[9]=35mm Fracture mode I	Terminal Blend	−12	1	2073 J/m^2	• Polymers work on improving the mechanical and chemical properties of the resulted mixtures. • The wet process produces a mixture with higher fracture energy than the dry process. • The undesirable effect of crumb rubber is evident when coarse rubber particles are used in the mixtures. • Fracture energy of rubberised gap-graded mixture is higher than the dense-graded asphalt mixture.
					−18		1160 J/m^2	
		Crumb Rubber		Dry Method	−12		1001 J/m^2	
					−18		906 J/m^2	
HMA, PG 58–28 (AC[3] 5.2%), dense graded	[79]	Virgin	SCB[7] T = 50mm N =15mm Fracture mode I	Wet Method	20	5	2200 J/m^2	
HMA, PG 76–22 (AC 5.2%), dense graded							2400 J/m^2	
HMA, PG 58–28 + 10% CRM[4], AC 5.5%, dense graded		Crumb Rubber					2000 J/m^2	
HMA, PG 58–28 + 15% CRM, AC 5.7, dense graded		Crumb Rubber					200 J/m^2	
HMA, PG 64–22 + 10% CRM, AC 5.5, dense graded		Crumb Rubber					1750 J/m^2	
HMA, Binder 5% Granitic Aggregates and Hydrated Lime NMAS: 9.5 mm	[80]	Control	IDT[9] T = 60mm N= 35mm Fracture mode I	Dry Method	10	50	56 kJ/m^3	
		Waste Plastic/2%					58 kJ/m^3	
		Waste Plastic/2%					62 kJ/m^3	
		Waste Plastic/2%					69 kJ/m^3	

[1] Reclaimed Asphalt Pavement, [2] Hot Mix Asphalt, [3] Asphalt Content, [4] Crumb Rubber, [5] Disk-Shaped Compact Tension Test, [6] Thickness,[7] Semi-Circular Bending Test and [8] Indirect Tensile Strength, [9] Notch Length.

For the dry method, the effect of plastic particles is similar to that of the crumb rubber. Asphalt mixtures modified by plastic waste have high resistance to cracking potential and consume high fracture energy, as the plastic significantly improves the physical and chemical properties of the asphalt. The same results are observed by White et al. [81] for the effect of adding the shredded recycled waste plastics to asphalt. The result showed that plastic waste enhanced the resistance of the modified mixture against fracture. Angelone et al. [80] used PE from silo bags to modify an asphalt mixture using the dry process. The result showed that using 2% silo bags improved the fracture energy over the control mixture. On the other hand, the low bonding properties of plastic modified mixtures by the dry method may results in inconsistent properties and performance of the produced mixtures. This inconsistency can be due to poor interaction between asphalt and plastic during the mixing process. However, Radeef et al. [82] proposed a new method for optimising the interaction between plastic, asphalt and aggregate which provide high adhesion and bonding properties between the components of asphalt mixtures. Radeef used 20% of the total weight of binder for preparing the asphalt mixtures. The results showed significant enhancement in the cracking properties of mixtures. For the wet process, the resulted asphalt modified by plastic exhibited an improved elasticity and adhesivity due to the elastic behaviour of polymers [55], [83], [84]. The resulted asphalt mixture had high resistance against cracking as the failure of asphalt materials starts within the asphalt paste and propagate around the coarse aggregate particles [31], [85], [86]. The high adhesivity of modified asphalt binder promotes resistance of the asphalt mortar to crack propagation. It also increases the fracture energy of the produced mixtures [87]–[89]. The results of the above studies on the effect of polymer modifiers on the asphalt's fracture energy are summarised in Table 3.

5.0 TEST TEMPERATURE AND LOADING RATE

Selecting the test temperature and the appropriate loading rate to simulate the field condition in measuring the crack potential of asphalt pavement is a challenge, particularly for laboratory testing. The temperature has a major effect on the properties of the asphalt binder. In general, the asphalt binder modulus decreases as the temperature increases. Therefore, when the asphalt mixture is tested at a low temperature, the mixture will become brittle compared with those tested at intermediate and high temperature [90]–[93]. Moreover, the failure mechanisms in the asphalt mixture significantly depend on the testing temperature. At low temperature, the asphalt mixture has brittle behaviour. Cracks are induced throughout the mineral particles and asphalt binder, as shown in Figure 2a. At intermediate and high temperature, the crack path will be around the mineral particles. It will run throughout the asphalt-fine aggregate mortar, as shown in Figure 2b [14]. Im et al. [94] evaluated the effect of test temperature and loading rate on the fracture energy of asphalt mixtures. Their study examined the cracking performance under different test temperature and loading rates. The results showed that the loading rate affected the measured fracture energy of asphalt at low testing temperature due to the linear elastic behaviour. This effect became crucial with the increase in temperature. Moreover, the behaviour of asphalt mixture changed to viscoelastic when the temperature increased to 5 °C. The effect of loading rate and test temperature on the fracture properties of asphalt mixtures are mainly related to the change in the rheological properties of the asphalt binder. The time and thermo-dependent behaviour of asphalt binder vary based on the loading time and test temperature mirrored by the final response of asphalt mixtures under loading. Thus, asphalt mixtures behaviour is stiffer under high loading rates and low test temperature. In contrast, its behaviour becomes softer at a high loading rate and test temperature based on the viscus behaviour of the used asphalt binder [13], [95].

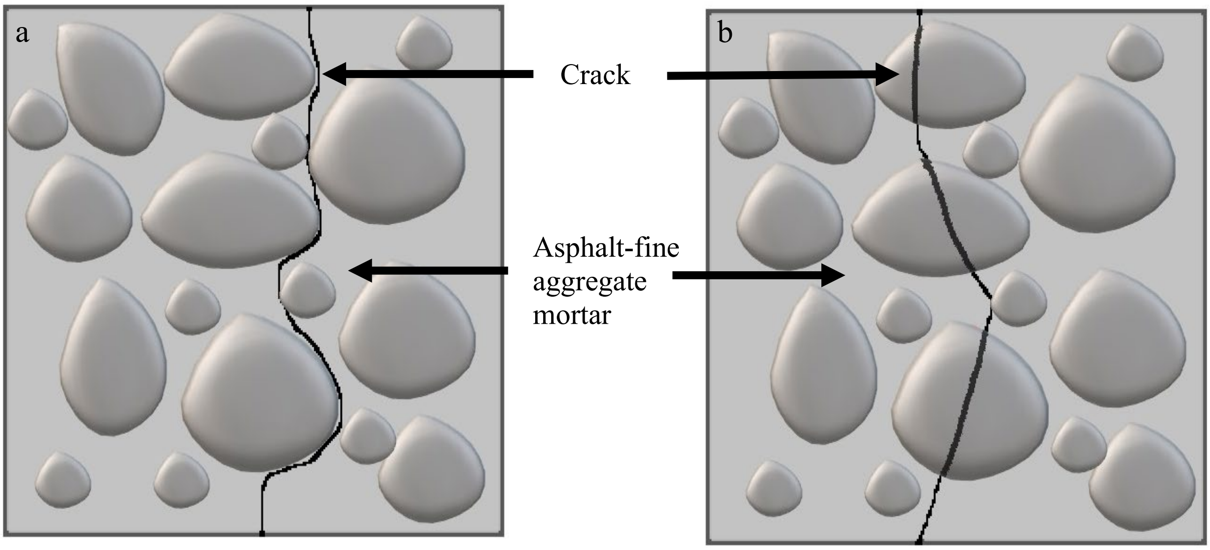

Figure 2 (a) Fracture path at intermediate and high temperature and low loading rate. (b) Fracture path at low temperature and high loading rate.

This variance in the behaviour of asphalt mixtures called the attention tio investigate its impact on the fracture properties of asphalt mixtures. Different studies reported that fracture energy decreases with the increase in loading rate at sub-zero temperatures [94], [96]. In contrast, fracture energy increases at a high loading rate when an intermediate temperature ranging from 21 °C to 30 °C is reached [97]–[100]. The same results were observed in the recent studies of the fracture behaviour characterisation of polymer materials [6]. The fracture behaviour of asphalt mixtures is greatly influenced by various asphalt evaluation standards. This finding is especially evident at low and intermediate temperatures. However, the effect of the loading rate on the fracture energy at low temperature is unclear [101].

Table 4 Effect of different test temperature and loading rates on the fracture energy of asphalt

Mixture Parameters	References	Asphalt mixture	Fracture test	Test Temperature (°C)	Loading Rate (mm/min)	Fracture Energy (J/m²)	Findings
Test temperature	[102]	HMA[1] Agg.[2]: Dense-graded binder: 50/70 PG (AC[3]: 5.26%) NMAS: 16 mm	SCB[5] T = 50 mm N[6] = 15 mm Fracture mode I	−15	0.3	300	• Increment in testing temperature increases the fracture energy (applies for low loading rate and up to 20 °C) [5]. • At a low temperature of less than −5 °C, the asphalt transforms from ductile to brittle behaviour with low fracture energy [36]. • The loading rate significantly affects the fracture energy of asphalt mixtures at intermediate and high temperature. This finding is due to the viscoelastic behaviour of asphalt. • Fracture energy increases with increasing loading rate at intermediate temperature. • The effect of the loading rate on the fracture energy at low temperature is unclear [101].
				−5		680	
				5		700	
	[103]	HMA Binder: PG 76–22 NMAS[4]: 9.5 mm	SCB T[6] = 50 mm N= 15 mm Fracture mode I	13	1.86	1700	
				13	50	1661	
				25		2655	
	[104]	HMA +35% RAP Binder: PG 64-34 NMAS: 12.5mm	SCB T = 50 mm N= 15 mm Fracture mode I	15	5	1500	
				21		1400	
				40		400	
Loading rate	[6]	HMA Agg.: Silica/dense-graded binder: PG 64–22 (5.2%) NMAS: 12.5mm	SCB T= 50 mm N= 25 mm Fracture mode I	5	1	350	
					5	565	
					10	400	
					50	280	
	[104]	HMA+35% RAP Binder: PG 64-34 NMAS: 12.5mm	SCB T = 50 mm N= 25 mm Fracture mode I	21	0.1	600	
					0.5	1000	
					1	1200	
					5	1400	
					10	1500	

[1] Hot Mix Asphalt, [2] Aggregate, [3] Asphalt Content, [4] Nominal Maximum Aggregate Size and [5] Sample Thickness, [6] Notch Length.

Fakhri et al. [6] evaluated the effect of different variables, including loading rate, testing temperature, air void content and aggregate gradation, on the fracture energy of asphalt mixtures. The result showed that fracture energy increased with the increase in the loading rate when tested at intermediate temperature but fluctuated at a low temperature of 5 °C. Fakhri's results showed the same trend as those presented in previous studies [104], [105]. Pérez-Jiménez et al. [102] presented the Fenix and Semi-Circular Bending (SCB) test results under different testing temperature and loading rates for characterising the fracture strength of different asphalt mixtures. Their study concluded that lowering the temperature and/or increasing the loading rate produced a stiffening effect of the mixture and the test response differs scarcely.

High loading rate can lead to brittle failure at low test temperature while ductile behaviour can present at low loading rate for the same testing temperature. This can be related to the time available for the cracks to overcome the adhesion and adhesive forces and propagate around the aggregate particles as discussed above. Consequently low loading rate will allow for more energy to be consumed in creep deformation rather than fracture process [97]. Other study by Nsengiyumva et al. [104] investigated the effect of testing parameters on the fracture energy of asphalt mixtures. The parameters include the test temperature and loading rate on the repeatability of the SCB results. The study revealed that fracture energy is affected by the loading rate and test temperature. Moreover, it was declared that lower loading rate has the least effect on fracture energy results. This is due to the compatibility of compliance response of the asphalt mixtures with slower loading rate whereas at faster loading rates, the mixtures presented more brittle responses with higher peak load [94], [106], [107]. Three different testing temperatures were selected i.e., 15, 21, and 40°C. Other testing variables were maintained: thickness of a specimen 50, and the loading rate 5 mm/min with notch length of 15 mm. The results indicated that fracture energy was inversely proportional to the test temperature at low loading rate. Moreover, the test temperature of 21°C appears to be reasonable for asphalt evaluation when one considers practical applications of the SCB test method for engineering purposes. In addition, Haslett et al. [103] also investigated the effect of test temperature and loading rate on the fracture energy of asphalt mixtures with different RAP percentages by using SCB test. The study includes three different test temperatures and three loading rates. The study revealed that increasing test temperature will increase the fracture energy of asphalt at high loading rate. Therefore, both studies by Nsengiyumva and Haslett, supported that the fracture energy increases with the increase in testing temperature at high loading rate [104], wherein the fracture energy decreases when the test temperature increases at low loading rate [103]. This shows the importance of loading rate as a testing parameter in determining the fracture energy due to the viscoelastic and time dependent properties of asphalt mixture. The effects of different loading rate and test temperature on the resistance of asphalt mixtures against cracking are summarised in Table 4.

6.0 CONCLUSIONS

From the review, a few important highlights can be concluded as follows:

1. Varying asphalt binder types and contents significantly affect the fracture performance of asphalt mixtures. The fracture energy increases when a softer and higher percentage of asphalt binder is used and vice versa.
2. Aggregate gradation and interlocking influence the cracking resistance of asphalt mixtures. Aggregate gradation and particle size with the asphalt mortar create a structural network and produce the final skeleton, which can be obtained with dense and fine gradations.
3. The addition of polymers (different sizes and contents) in asphalt can increase the fracture energy of the produced mixture through dry and wet methods. For example, the fine crumb rubber can produce a better crack resistance asphalt than the conventional mixture.
4. The cracking resistance and fracture energy are directly affected by the changes in test temperature. The asphalt mixture has brittle behaviour at low temperature, initiating the propagation of cracks throughout the coarse aggregate particles and asphalt-fine aggregate mortar. At intermediate and high temperature, cracks will be induced around the coarse aggregate particles throughout the asphalt-fine aggregate mortar.
5. The increment of loading rate at an intermediate temperature increases the fracture energy of asphalt mixtures. However, fluctuation trends were also observed by different studies for the effect of loading rate on fracture energy at low testing temperature.

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