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## Cracking Susceptibility Assessment of Gap Graded Asphalt Concrete

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### ABSTRACT

*Tensile stresses are produced at the bottom of asphalt concrete layer due to traffic loadings. Fatigue cracks initiate and propagate through the pavement layer. Crack propagation resistance of asphalt concrete is an important issue towards understanding of the cracking mechanism and can be investigated over the service life of the pavement. In the present assessment, the cracking susceptibility of asphalt concrete was investigated in terms of mode one stress intensity factor, and fracture toughness. Asphalt concrete mixture was prepared using three percentages of binder content and two types of mineral filler. The asphalt concrete mixtures were subjected to roller compaction. Core specimens were extracted from the prepared slab samples. The core specimens were cut to semi-circular shape, notched, then tested for stress intensity factor under semi-circular bend SCB test. The specimens were tested under (20 and 0) °C environment. It was noticed that the limestone dust filler exhibits higher fracture toughness than coal flyash, while coal flyash shows higher SCB when compared with the limestone dust filler regardless of the testing temperature. However, as the testing temperature declines, the fracture toughness increases regardless of the filler type. The Fracture Toughness increases by (24.2, and 37.9) % and (31.3, and 43.7) % as the binder content increases from (4.7 to 5.2 and 5.7) % for specimens with limestone dust when the SCB specimen was tested at (20 and 0) °C respectively under a rate of loading of 25.4 mm/minutes. However, the fracture toughness increases by (76.8, and 84) % and (61.1, and 87) % when the binder content increases from (4 to 4.5 and 5) % respectively for specimens with coal flyash when the SCB specimen was tested at (20 and 0) °C respectively under a rate of loading of 25.4 mm/minutes.*

**Keywords:** Asphalt concrete, Gap, Susceptibility, Cracking, Semi-circular bend, Stress intensity factor, Fracture.

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### INTRODUCTION

Cracking of asphalt concrete pavement is a common failure mechanism. It is one of the main reasons for rehabilitation and maintenance requirements, as well as it reduces the user comfort and increases vehicle maintenance cost and fuel consumption due to high road roughness.

Biligiri, et al., [1] evaluated asphalt concrete mixtures for their crack propagation potential with the aid of the semi-circular bending test. It was observed that the mix with higher asphalt content provided better resistance to crack propagation in terms of fracture energy. The influence of applied loading type and specimen configuration on the measured fracture toughness was investigated by Yang et al., [2]. Four different testing techniques including Semi-Circular Bend, Single Edge Notch Beam, Edge Notch Disc Bend, and Edge Notch Diametral Compression disc were implemented. The prepared specimens have different shapes (full disc, semi-disc, and rectangular beam) and are loaded either with diametral compressive force or symmetric three-point bending. The tests were performed at

two low temperatures ( $-5\text{ }^{\circ}\text{C}$  and  $-25\text{ }^{\circ}\text{C}$ ). It was revealed that the fracture toughness is not significantly dependent on the shape of the test specimen. In addition, the fracture toughness values of all tested samples were increased linearly by decreasing the test temperature.

Wang et al., [3] used SCB fatigue tests under different testing temperatures and stress ratio to characterize the fatigue life of the semi flexible asphalt concrete mixture SFP, while the laboratory fatigue prediction model was established. The results show that the SFP mixture has better fatigue resistance under low stress ratio and low temperature, while the fatigue resistance under other load conditions and environment is worse than that of reference asphalt mixture.

Lu et al., [4] investigated the potential for characterization the cracking behavior of nonstandard SCB testing for asphalt mixtures. It was found that the SCB test on nonstandard specimen size of 100 mm diameter could be used to evaluate the cracking resistance of asphalt concrete mixtures. It was also found that production temperatures, notch lengths, and air voids considerably affected the cracking behavior of asphalt mixtures.

Canestrari, and Ingrassia, [5] revealed that pavements characterized by open-graded friction courses, which are very common worldwide, present critical issues in terms of cracking due to the high air void content that promotes the development of the distress. A study by Myers and Roque, [6] based on fracture mechanics theory showed that the stress intensity factor value depends on the distance between tire and crack and varies as the crack length changes. This result suggests that the critical position that produces the greatest stress intensification when the distress is in an advanced stage is different from the critical position in the initial phase when the crack depth is small.

A study of the cracking model by Ling et al., [7] showed that greater thicknesses of the asphalt pavement layer as well as a greater thickness of the base layer do not significantly affect the crack initiation time, but they can considerably reduce the longitudinal crack growth rate. Roque et al., [8] stated that as the stiffness of the base layer increases, the crack initiation is progressively delayed and the crack growth rate in depth is reduced. The viability of using three test methods for asphalt concrete mixtures were investigated by Marasteanu et al., [9]. The Bending Beam Rheometer for creep and strength of asphalt mixtures; low temperature Semi Circular Bend test for fracture energy of asphalt mixtures, and Dynamic Modulus test of asphalt mixtures using the Indirect Tensile Test configuration.

The results show that the properties of asphalt concrete are highly temperature dependent, and the ranking observed at one temperature can change at a different temperature. In addition, it was observed that materials with similar rheological properties, such as creep stiffness, do not necessarily have the same fracture resistance. It was concluded that these results confirm one more time the need for a fracture/strength test for correctly evaluating cracking resistance of asphalt materials.

Schanz and Abdulsattar, [10] evaluated the crack propagation, the potential of stress intensity factor, and the fracture toughness of asphalt concrete using the SCB test. It was observed that the fracture toughness increases by 57.5 % as the test temperature decreases; this may indicate that the asphalt concrete becomes more brittle at cold temperatures. It was concluded that as the temperature decrease, the fracture energy decreases but the fracture toughness increases.

Aliha et al., [11] revealed that the crack tip location has a marked influence on the magnitude and sign of geometry factors. On the other hand, if the crack tip is located inside the mastic part, the geometry factors will be smaller. The crack growth path was predicted using the maximum tensile stress criterion. It was shown that the aggregates gradation could change the crack growth path locally.

Vega et al., [12] investigated the influence of notch configurations and thickness on the fracture energy and stress intensity factors of asphalt concrete specimens. Three types of notch configuration and three levels of specimen thickness were investigated. The test results showed that the testing temperature and the specimen thickness did not statistically impact the stress intensity factor. However, the specimen thickness exhibits impact on fracture energy. On the other hand, the testing temperature and the notch configuration were statistically significant to the fracture energy.

Garcia, [13] introduced a systematic fracture and fatigue crack growth testing approach for hot mix asphalts. The fracture toughness and the fracture resistance of a dense-graded asphalt concrete material were experimentally evaluated at different temperatures and varying thicknesses.

It was revealed that fracture energy and fracture toughness decrease as temperature increases. It was concluded that fatigue crack length curve exhibit deviations at 25°C and more of a smooth curve at 5 °C, finally, the linear crack growth region was predicted. Coleri et al., [14] characterized the cracking performance of asphalt pavements by considering four tests to evaluate fatigue cracking resistance. The impact of asphalt concrete mixture properties, aggregate gradation, asphalt binder content, air-void content, and aging, on cracking performance of asphalt mixtures was investigated. Recommended strategies were proposed to address the issue of early pavement fatigue failure based on the test results, statistical analysis, and life cycle cost analysis.

Fuan et al., [15] compared the consistency of fracture toughness test results obtained from Semi-circular bend SCB and edge notch disc bend ENDB on a typical asphalt concrete mixture. The thickness of the specimens, the testing temperature, and the loading rate are considered as variable. It was found that the fracture toughness values obtained from both testing methods are in good agreement. It was revealed that the load carrying capacity and the fracture toughness of asphalt mixture increases by increasing the specimen thickness, and the loading rate, and by decreasing the test temperature.

Pirmohammad and Ayatollahi, [16] assessed the influence of testing temperature and loading mode on the fracture resistance of asphalt concretes under static loading. It was revealed that both loading modes and temperature influence the fracture resistance of asphalt concrete significantly. It was concluded that the fracture resistance of asphalt concretes first increased and then below a temperature of (-20 °C) decreased. Reliability of semi-circular bending (SCB) specimen for measuring the fracture behavior of asphalt pavement materials under static loading has been examined by Mubaraki and Sallam, [17]. The relation between the stress intensity factor and the crack mouth opening displacement has been examined and a good relation is found through the whole life of SCB specimen.

The aim of the present investigation is to assess the cracking susceptibility of gap graded asphalt concrete in terms of fracture toughness, and stress intensity factor. The influence of two types of mineral filler, three percentages of binder content, and two testing temperature

on the cracking phenomena will be assessed. The semi-circular bend SCB test will be implemented for this investigation.

## MATERIALS AND METHODS

### Asphalt Cement

Asphalt cement binder of 40-50 penetration grads was implemented in this work. It was obtained from AL-Nasiriya oil Refinery. The physical properties of the asphalt binder are listed in Table 1.

**Table 1. Physical Properties of Asphalt Cement Binder**

Physical Properties	ASTM, [18] Designation	Asphalt cement
Penetration	D5-06	42
Softening Point °C	D36-95	49
Ductility Cm	D113-99	150+
Specific Gravity	D70	1.04
Flash Point °C	D92-05	269
<b>After thin film oven test</b>		
Retained Penetration of Residue	D5-06	33
Loss in weight (163°C, 50g,5h) %	D-1754	0.175
Ductility of Residue	D113-99	130 cm

### Fine and Coarse Aggregates

Crushed coarse aggregates having a nominal maximum size of 19 mm and retained on sieve No. 4 was obtained from AL-Ukhaider quarry. Crushed and natural sand mixture was implemented as Fine aggregate (passing sieve No.4 and retained on sieve No.200). It was obtained from the same source. The aggregates were washed, air dried and separated into different sizes by sieving. The physical properties of aggregates are shown in Table 2.

**Table 2. The Physical Properties of Coarse and Fine Aggregate as per ASTM, [18]**

Property	Coarse Aggregate	Fine Aggregate
Bulk Specific Gravity (ASTM C 127 and C 128).	2.642	2.658
Percent Water Absorption (ASTM C 127 and C 128)	1.07	1.83
Percent Wear (Los-Angeles Abrasion) (ASTM C 131)	18 %	-

### Mineral Filler

Two types of mineral filler are implemented in the present investigation; the first one is the limestone dust which was obtained from Karbala governorate. The physical properties of the limestone dust mineral filler are presented in Table 3. The second type is coal fly ash class F which was obtained from local market. The physical properties of the fly ash mineral filler are listed in Table 4.

**Table 3. The Physical Properties of Limestone Dust Mineral Filler**

Property	Value
Bulk specific gravity	2.617
% Passing Sieve No.200	94

**Table 4. Physical Properties of Coal Fly Ash Mineral Filler**

Maximum Sieve Size (micron)	% Passing	Specific gravity	Specific Surface Area (m <sup>2</sup> / kg)
0.075	98	2.645	650

### Selection of Aggregates Combined Gradation

One types of aggregates gradation was selected in the present investigation. It follows Road Note 31, [19] of the British standard specification for Gap graded wearing course pavement layer with 12.5 mm nominal maximum size of aggregates. Figure 1 shows the selected aggregate gradation and the limitations of the specification.

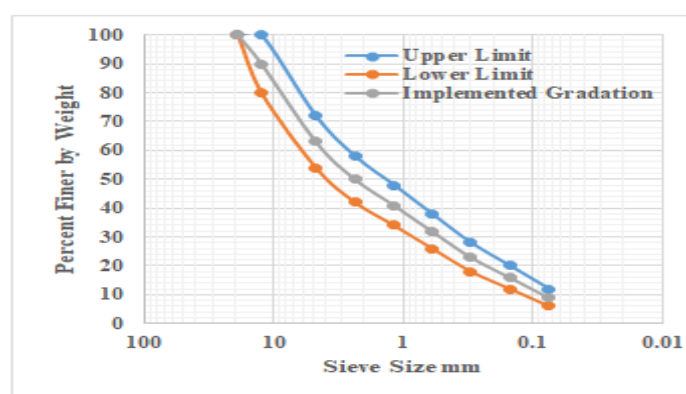


Fig. 1. Combined Gradation Adopted

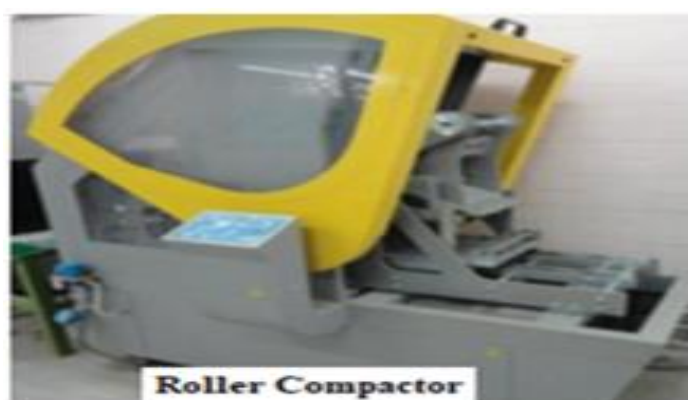
### Preparation of Asphalt Concrete Mixture and Specimens

The fine and coarse aggregates were combined with mineral filler to meet the specified gradation for wearing course. The combined aggregates were then heated to 160 °C before mixing with asphalt cement. The asphalt cement binder was heated to 150 °C then, the binder was added to the heated combined aggregates to the desired amount and mixed thoroughly by hand using a spatula for two minutes so that the aggregate particles are coated with a thin film of the binder. The optimum asphalt content of (4.7, and 4.5) % for mixtures with limestone dust and coal fly ash filler types respectively. The optimum binder percentage was determined based on Marshall trial mixes using various asphalt percentages. Details of obtaining the optimum binder content could be found in Sarsam and Sultan, [20]. Table 5 presents the Marshall properties of the prepared asphalt concrete mixtures.

**Table 5. Marshall Properties of the Prepared Mixtures**

Filler Type	Limestone Dust	Coal Flyash
Optimum Binder Content %	4.7	4.5
Marshall Stability kN	9.5	12.5
Marshall Flow mm	3.3	3.1
Bulk Density gm/cm <sup>3</sup>	2.295	2.301
V <sub>v</sub> %	4	4.1
VMA %	14.3	14.4
VFB %	72	70.4

The mixtures were casted in a slab mold of (400 x 300 x 63) mm and subjected to roller compaction to the target bulk density for each binder content according to EN12697-33, [21]. The applied static load was 5 kN while the number of load passes depended on the asphalt content and target bulk density of the mixture and was determined based on trial-and-error process. Details of the compaction process could be referred to Sarsam, [22]. The compaction temperature was maintained to 150 °C. Slab samples were left to cool overnight. Core specimens of 50±2 mm high and 102 mm diameter were obtained from the compacted slab sample using the Diamond core bit. The total number of core specimens obtained was twelve, while the number of casted slabs was four. The core specimens were cut to semi-circular shape using a diamond saw. The semi-circular specimens were subjected to SCB three point bending test as per AASHTO, TP105- 13, [23] after introducing a notch of 10 mm length. Figure 2 exhibit the roller compactor implemented, while Figure 3 presents the SCB test.



*Fig. 2. The roller compactor*

All the testing program was conducted at (0, and 20) °C environment. Specimens were tested in triplicate and the average value was considered for analysis. The mode one stress intensity factor which represents cracking in the tensile stresses plane was implemented to predict and describe the stress intensity near the tip of a crack caused by loading. The magnitude of the stress intensity factor depends on the specimen geometry, size and location of the crack, magnitude of load, and distribution of load. It is related to the rate of crack growth, and it is implemented to establish failure criteria due to fracture. The fracture toughness ( $\text{MPa}\cdot\text{m}^{0.5}$ ) is obtained as the stress intensity factor at the critical load. The critical load is assumed to be the maximum load at failure recorded during testing.



*Fig. 3. SCB Specimen with Notch*

## RESULTS AND DISCUSSIONS

### Influence of Filler Type on Fracture Toughness – SCB Relationship of Asphalt Concrete

Figure 4 demonstrates the fracture toughness-semi-circular bend (SCB) strength relationship, it can be noticed that the limestone dust filler exhibits higher fracture toughness than coal flyash, while coal flyash shows higher SCB when compared with the limestone dust filler regardless of the testing temperature. However, as the testing temperature declines, the fracture toughness increases regardless of the filler type. This may be attributed to the reduction in the binder’s viscosity at low temperature which leads to stiffer mixture. On the other hand, the fine flyash gradation can fill more voids with asphalt and increases the bending resistance. It can be revealed that test results of the SCB test at the temperature of 0° C were inconclusive and got much scatter. This may be attributed to the fact that, at the temperature of 0° C, during the SCB test with a constant rate of deformation, fracture of the specimens suddenly happens due to the notch provided along with the initiation of the crack. Such behavior agrees well with the work reported by Li and Marasteanu, [24], and Li and Marasteanu, [25].

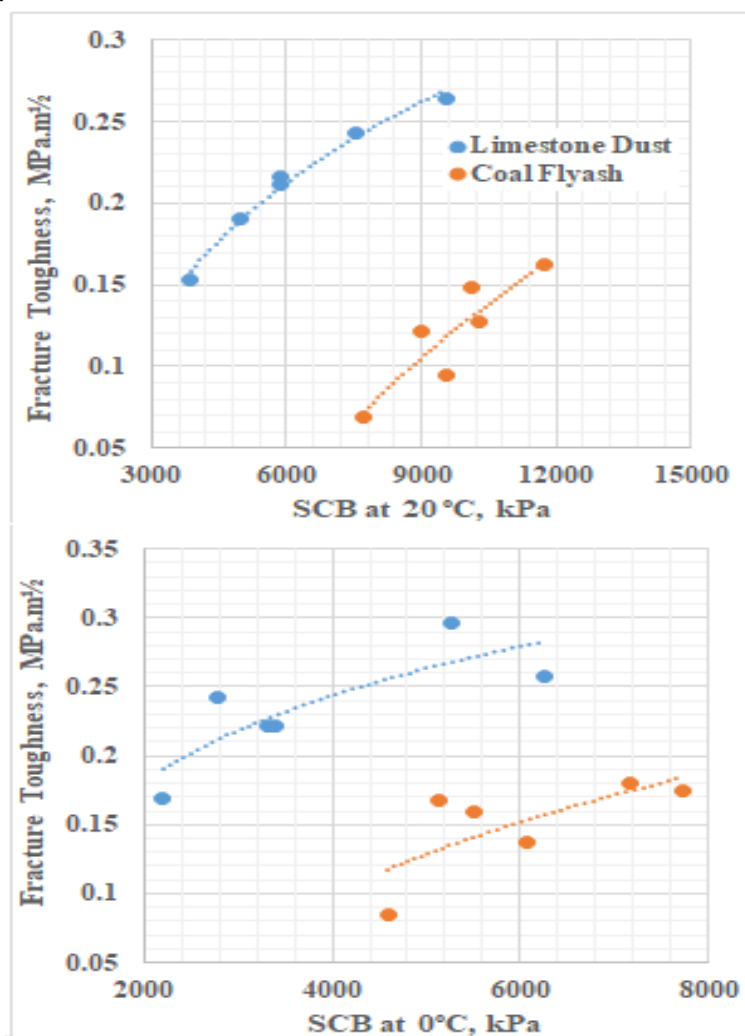


Fig. 4. Fracture Toughness- SCB Relationship

Table 6 exhibits the obtained mathematical models relating the SCB strength with the fracture toughness for both filler types and testing temperatures. It can be observed that when implementing limestone dust or coal flyash into the asphalt concrete mixture, it exhibits

higher coefficient of determination with a reasonable scatter of data around the model curve when the specimens are tested under 20 °C environment. However, the scatter of data when testing under 0 °C environment is more regardless of the filler type. Similar modeling behavior was reported by Sarsam, [26].

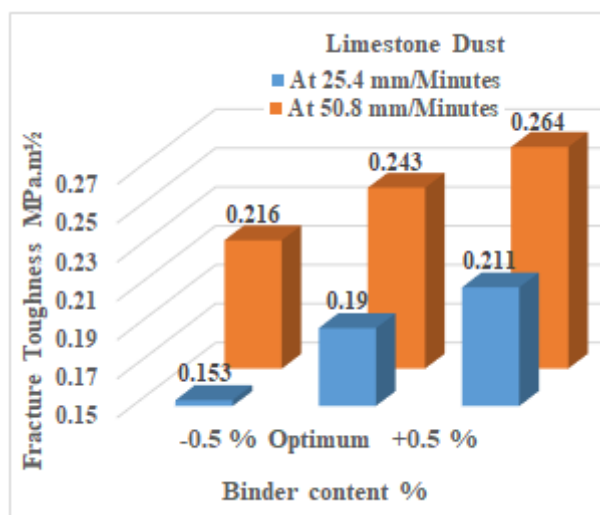
**Table 6. Fracture Toughness- SCB Mathematical Models**

Testing Temperature	Filler type	Mathematical Model	R <sup>2</sup>
20 °C	Limestone Dust	$Y = 0.1228 \ln(x) - 0.8556$	0.986
	Coal Flyash	$Y = 0.2171 \ln(x) - 1.8709$	0.798
0 °C	Limestone Dust	$Y = 0.8861 \ln(x) - 0.4908$	0.669
	Coal Flyash	$Y = 0.1277 \ln(x) - 0.9591$	0.511

$Y = \text{Fracture Toughness (MPa.m}^{0.5}\text{)}, \quad x = \text{Semi-circular bend strength (kPa)}$

**Influence of binder content and loading rate on Fracture Toughness of specimens with limestone dust**

Figure 5 demonstrates the influence of binder content and rate of loading on the Fracture Toughness of asphalt concrete prepared by implementing limestone dust as a filler when tested at 20°C environment under semi-circular bend test. It can be noticed that the Fracture Toughness increases by (24.2, and 37.9) % as the binder content increases from (4.7 to 5.2 and 5.7) % respectively when the SCB specimen was tested under a rate of loading of 25.4 mm/minutes. However, the Fracture Toughness increases by (12.5, and 22.2) % as the binder content increases from (4.7 to 5.2 and 5.7) % respectively when the SCB specimen was tested under a rate of loading of 50.8 mm/minutes. On the other hand, doubling the rate of loading exhibit an increase in the Fracture Toughness by (41.1, 27.8, and 25.1) % for binder content of (4.7, 5.2, and 5.7) % respectively. Such behavior may be attributed to the better adhesion created between the binder and aggregates and lower voids as the binder content increases.



*Fig. 5. Fracture Toughness @ 20°C*

When the testing temperature decreases to 0°C, the Fracture Toughness increases regardless of the binder content or loading rate as exhibited in Figure 6. This can be attributed to the fact that asphalt mixture is stiffer when cold and requires more stress to initiate cracking. It can be noticed that the Fracture Toughness increases by (31.3, and 43.7) % as the binder content increases from (4.7 to 5.2 and 5.7) % respectively when the SCB specimen was tested under a rate of loading of 25.4 mm/minutes. However, the Fracture Toughness increases by (16.2,

and 33.3) % as the binder content increases from (4.7 to 5.2 and 5.7) % respectively when the SCB specimen was tested under a rate of loading of 50.8 mm/minutes. Doubling the rate of loading exhibit an increase in the Fracture Toughness by (31.3, 16.2, and 21.8) % for binder content of (4.7, 5.2, and 5.7) % respectively. At optimum binder content of 4.7 %, the Fracture Toughness increases by (16.8 and 6.1) % for mixtures tested under (25.4 and 50.8) mm/minutes respectively when the testing temperature decreases from (20 to 0) °C. Similar behavior was reported by Teshale, [27].

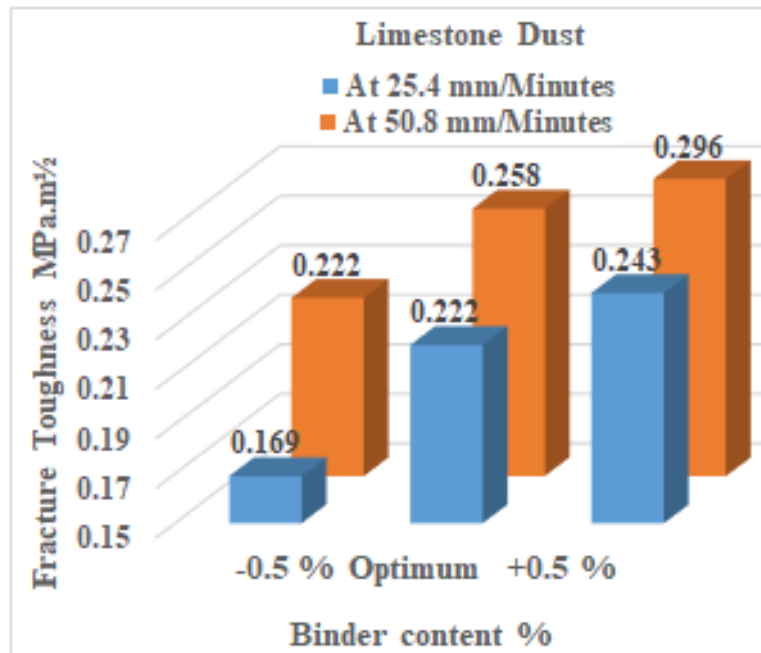


Fig. 6. Fracture Toughness @ 0°C

### **Influence of binder content and loading rate on Fracture Toughness of specimens with Coal Flyash**

As demonstrated in Figures 7 and 8, the fracture toughness increases as the binder content increase within the limitations of the test regardless of the testing temperature or the rate of loading. When the SCB specimens are tested at 20°C environment, the fracture stiffness increases by (55.7, and 71.5) % and (76.8, and 84) % when the binder content increases from (4 to 4.5 and 5) % respectively for (50.8 and 25.4) mm/minutes rate of loading.

However, when the rate of loading is doubled, the fracture toughness increases by (37.6, 21.3, and 28.3) % for specimens constructed with (4, 4.5 and 5) % binder contents respectively. On the other hand, when the specimens are tested at 0°C environment, the fracture toughness increases by (3.5, and 7.1) % and (61.1, and 87) % when the binder content increases from (4 to 4.5 and 5) % respectively. However, when doubling the rate of loading, the fracture toughness increases by (97.6, 27, and 13.2) % for specimens constructed with (4, 4.5 and 5) % binder contents respectively.

In general, the fracture toughness of asphalt concrete specimens is higher at low testing temperature regardless of the type of filler or the rate of loading. At optimum binder content, the fracture toughness declines by (14.9 and 10.9) % when the specimens were tested under (50.8 and 25.4) mm/minutes respectively at 20°C as compared with specimens tested at 0°C. Similar findings were reported by Schanz and Abdulsattar, [10].

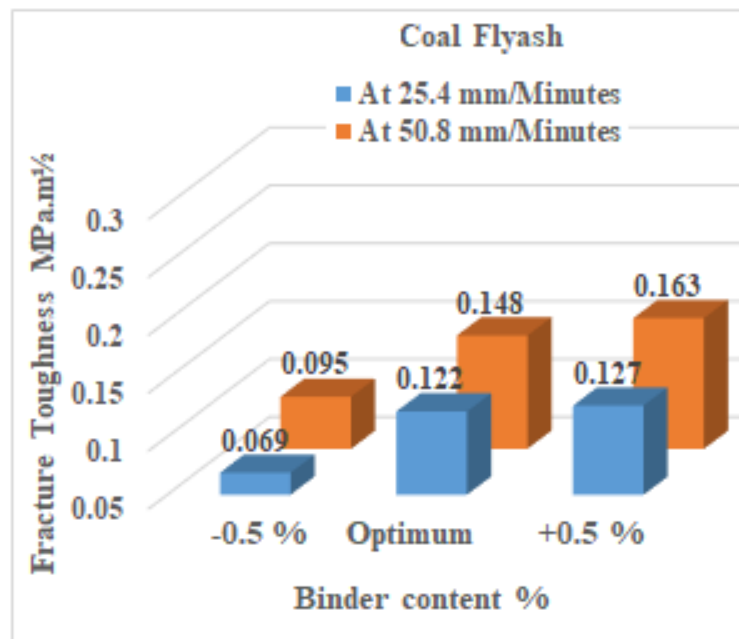


Fig. 7. Fracture Toughness @ 20°C

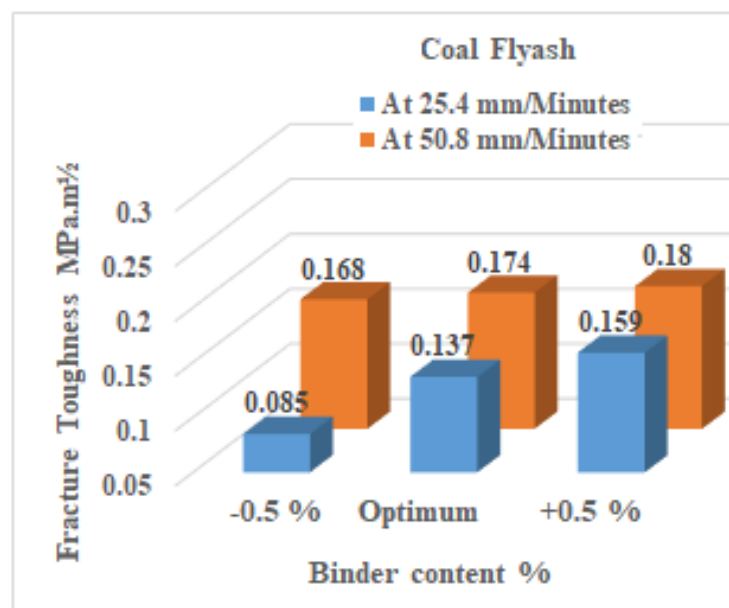


Fig. 8. Fracture Toughness @ 0°C

## CONCLUSION

Based on the testing and materials limitations, the following could be addressed.

- 1) The limestone dust filler exhibits higher fracture toughness than coal flyash, while coal flyash shows higher SCB when compared with the limestone dust filler regardless of the testing temperature.
- 2) Fracture Toughness increases by (24.2, and 37.9) % and (31.3, and 43.7) % as the binder content increases from (4.7 to 5.2 and 5.7) % respectively when the SCB specimen prepared with limestone dust was tested under a rate of loading of 25.4 mm/minutes at (20 and 0) °C respectively.

- 3) Fracture Toughness increases by (76.8, and 84) % and (61.1, and 87) % as the binder content increases from (4.7 to 5.2 and 5.7) % respectively when the SCB specimen prepared with coal flyash was tested under a rate of loading of 25.4 mm/minutes at (20 and 0) °C respectively.
- 4) At optimum binder content of 4.7 %, the Fracture Toughness increases by (16.8 and 6.1) % for mixtures with limestone dust tested under (25.4 and 50.8) mm/minutes respectively when the testing temperature decreases from (20 to 0) °C.
- 5) At optimum binder content, the fracture toughness declines by (14.9 and 10.9) % when the specimens with coal flyash were tested under (50.8 and 25.4) mm/minutes respectively at 20°C as compared with specimens tested at 0°C.

## REFERENCES

- 1) Biligiri K., Said S., Hakim H. *Asphalt mixtures' crack propagation assessment using semi-circular bending tests*. International Journal of Pavement Research and Technology 5(4):209-217. January 2012. <https://www.researchgate.net/publication/279625181>.
- 2) Yang D., Karimi H., and Aliha M. *Comparison of testing method effects on cracking resistance of asphalt concrete mixtures*. Appl. Sci. 2021, 11, 5094. MDPI. <https://doi.org/10.3390/app11115094>.
- 3) Wang S., Zhou H., Chen X., Gong M., Hong J., and Shi X. *Fatigue resistance and cracking mechanism of semi-flexible pavement mixture*. Materials, 2021, 14, 5277. MDPI. <https://doi.org/10.3390/ma14185277>.
- 4) Lu D., Saleh M., and Nguyen N. *Evaluation of fracture and fatigue cracking characterization ability of non-standardized semicircular-bending test for asphalt concrete*. ASCE Journal of Materials in Civil Engineering. Volume 32 Issue 8 - August 2020.
- 5) Canestrari F., Ingrassia L. *A review of top-down cracking in asphalt pavements: Causes, models, experimental tools, and future challenges*. journal of traffic and transportation engineering (English edition)2020; 7(5): 541e572. [www.keaipublishing.com](http://www.keaipublishing.com).
- 6) Myers L., and Roque R. *Top-down crack propagation in bituminous pavements and implications for pavement management*. Journal of the Association of Asphalt Paving Technologists 71, 651e670. 2002.
- 7) Ling M., Luo X., Chen Y., Hu S., Lytton R. *A calibrated mechanics-based model for top-down cracking of asphalt pavements*. Construction and Building Materials, Elsevier, Volume 208, 30 May 2019, Pages 102-112. <https://doi.org/10.1016/j.conbuildmat.2019.02.090>.
- 8) Roque R., Zou J., Kim Y., Baek C., Thirunavukkarasu S., Underwood B., Guddati M. *Top-Down Cracking of Hot-Mix Asphalt Layers: Models for Initiation and Propagation*. NCHRP 162, TRB 2010. <http://www.trb.org/Publications/Blurbs/164029.aspx>.
- 9) Marasteanu M., Turos M., Ghosh D., Matias de Oliveira J., Yan T. *Investigation of Cracking Resistance of Asphalt Mixtures and Binders*. Technical report MN/RC 2019-03, January 2019, Civil, Environmental, and Geo- Engineering University of Minnesota. <http://mndot.gov/research/reports/2019/201903.pdf>.
- 10) Schanz H., and Abdulsattar Z. *Stress Intensity Parameter and Crack Growth of Iraqi Hot Mix Asphalt Mixtures*. Asian Journal of Engineering and Technology (ISSN: 2321 – 2462) Volume 01– Issue 05, December 2013. [www.ajouronline.com](http://www.ajouronline.com).
- 11) Aliha M., Ziari H., Mojaradi B., Sarbijan J. *Modes I and II stress intensity factors of semi-circular bend specimen computed for two-phase aggregate/mastic asphalt mixtures*. Theoretical and Applied Fracture Mechanics. Elsevier, Volume 106, April 2020, 102437. <https://doi.org/10.1016/j.tafmec.2019.102437>.

- 12) Vega A., Yang S., Braham A. *Evaluation of Semicircular Bend Geometric Properties for Asphalt Concrete Testing*. ASCE Journal of Materials in Civil Engineering. Volume 33 Issue 12 - December 2021.
- 13) Garcia E. *Test methods for the fracture and fatigue crack growth behavior of hot mix asphalts*. Open Access Theses & Dissertations. University of Texas at El Paso, 455. 2017. [https://digitalcommons.utep.edu/open\\_etd/455](https://digitalcommons.utep.edu/open_etd/455).
- 14) Coleri E., Sreedhar S., Haddadi S., Wruck B. *Adjusting asphalt mixes for increased durability, and implementation of a performance tester to evaluate fatigue cracking of asphalt*. Report No. FHWA-OR-RD-18-06. Final report SPR 785. Oregon Department of Transportation, Research Section. USA. January 2018.
- 15) Fuan S., Ke M., Kanghe L., Kun L., Aliha M. *Influence of specimen geometry on mode I fracture toughness of asphalt concrete*. Constr. Build. Mater. 2021, 276, 122181. <https://doi.org/10.1016/j.conbuildmat.2020.122181>.
- 16) Pirmohammad S.; Ayatollahi M. *Fracture resistance of asphalt concrete under different loading modes and temperature conditions*. Elsevier, Constr. Build. Mater. 2014, 53, P. 235–242. <https://doi.org/10.1016/j.conbuildmat.2013.11.096>.
- 17) Mubarak M., Sallam H. *Reliability study on fracture and fatigue behavior of pavement materials using SCB specimen*. Taylor and Francis, Int. J. Pavement Eng. 2020, 21, Issue 13, P. 1563–1575. <https://doi.org/10.1080/10298436.2018.1555332>.
- 18) ASTM American Society for Testing and Materials, ASTM: *Road and Paving Material, Vehicle- Pavement System*, Annual Book of ASTM Standards, Vol. 04.03. 2016. [www.astm.org](http://www.astm.org).
- 19) TRL. *A guide to the structural design of bitumen surfaced roads in tropical and sup tropical countries*, ROAD NOTE 31, Transport research laboratory, Crowthorne, Berkshire, United Kingdom.1993.
- 20) Sarsam S. I. and Sultan K. H. *Impact of Aggregate Gradation and Filler Type on Marshall Properties of Asphalt Concrete*. Journal of Engineering, Volume 21 Number 9, P. 34-46, September 2015.
- 21) EN 12697 – 33. *Bituminous Mixtures – Test Methods for Hot Mix Asphalt – part 33: Specimen prepared by Roller Compactor*, European Committee for Standardization. 2007.
- 22) Sarsam S. I. *Influence of Aging, Temperature and Moisture Damage on the Stiffness of Asphalt Concrete through the Fatigue Process*. International Journal of Scientific Research in Knowledge, 4(4), 2016. P. 077-084, <http://www.ijsrpub.com/ijsrk>.
- 23) AASHTO. TP105- 13. *Provisional Standard Method of Test for Determining the Fracture Energy of Asphalt Mixtures Using the Semi-circular Bend Geometry (SCB)*. 2013. Washington DC.
- 24) Li X, Marasteanu M. *Evaluation of the low temperature fracture resistance of asphalt mixtures using the semi-circular bend test*. Journal of the Association of Asphalt Paving Technologist, 73: 401-426. 2004.
- 25) Li XJ, Marasteanu M. *Using semicircular bending test to evaluate low temperature fracture resistance for asphalt concrete*. Exp Mech., 50: 867–76. 2010.
- 26) Sarsam S. I. *Flexural and Cracking Behavior of Roller Compacted Asphalt Concrete*. Journal of Engineering and Development, 9(4). 2005.
- 27) Teshale E. *Low-Temperature Fracture Behavior of Asphalt Concrete in Semi-Circular Bend Test*. PhD. Dissertation, University of Minnesota. 2012.