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Evaluating cracking resistance of fibre-reinforced asphalt mixes using a repeated cyclic SCB test

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Abstract

Cracking resistance is a critical performance attribute of asphalt concrete mixtures and is essential for achieving durable and long-lasting pavements. Balanced Mix Design (BMD) seeks to optimise this performance by ensuring sufficient stiffness to resist permanent deformation while maintaining adequate flexibility to mitigate cracking. Fibre reinforcement is well established as an effective means of improving cracking resistance, whereas higher air void content generally leads to reduced cracking performance. However, many existing cracking test protocols fail to reliably capture these effects. This study compares current monotonic tests such as the Ideal Cracking Test (Ideal-CT) and the Semi-Circular Bend (SCB) test with a newly developed repeated cyclic SCB test. The proposed cyclic SCB test was conducted under load-controlled conditions using a haversine waveform at a frequency of 10 Hz. Dense-graded AC14 asphalt mixtures were produced using PG64-16 and PG58-22 binders and compacted with a Superpave gyratory compactor. Both control and aramid fibre-reinforced mixtures were evaluated across a range of air void contents (%VTM). The results show that the monotonic Ideal-CT and SCB tests did not consistently capture the effects of air void content or fibre reinforcement on cracking resistance. In contrast, the cyclic SCB test effectively distinguished both influences. Fibre-reinforced mixtures exhibited significantly enhanced cracking resistance, evidenced by higher cracking numbers (CN) and lower crack growth rates (CGR), demonstrating the ability of fibres to reduce crack propagation. Furthermore, the cyclic test reliably reflected the expected reduction in cracking resistance with increasing air void content. Overall, the cyclic SCB test demonstrates strong potential method to evaluate cracking resistance for asphalt concrete mixture.

Keywords: repeated cyclic SCB; cracking behaviour; HMA; fibre; aramid cracking resistance

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1. Background

Cracking in hot mix asphalt (HMA) pavements is a major distress that undermines long-term performance and serviceability of asphalt pavements. It manifests primarily as fatigue cracking, thermal cracking, and reflective cracking, each governed by distinct mechanism. Fatigue cracking develops under repeated tensile strains, typically initiating at the bottom of the asphalt layer due to traffic loading. Its progression depends on mixture stiffness, air void content, binder properties, and pavement structure (Huang, 2004). In thin pavements subjected to high tyre pressures, fatigue cracking may also occur from the surface downward creaking top-down cracks. Thermal cracking results from temperature-induced contraction when tensile stress exceeds mixture strength, especially in cold climates, and is strongly affected by binder stiffness and mixture volumetrics. Reflective cracking arises in overlays when movement from underlying joints or cracks propagates through the new surface, influenced by structural discontinuities and thermal shifts.

Several test methods have been developed to characterize asphalt cracking resistance. The Disk-Shaped Compact Tension (DCT) test (ASTM D7313, 2020) is widely used for low-temperature cracking, providing fracture energy and crack propagation resistance. The Overlay Tester (OT), developed by the Texas Department of Transportation, evaluates reflective cracking through repeated opening and closing cycles, showing strong field correlation (Zhou et al., 2007). Jianming et al. (2019) proposed a reflective cracking test using the Joint Motion Simulation System, effectively capturing traffic and thermal load effects with good repeatability and sensitivity.

The Semi-Circular Bending (SCB) test has gained wide adoption for its simplicity and cost-effectiveness and is standardized under AASHTO TP 124 and ASTM D8044-16 (ASTM2016). Conducted at 25 °C under a displacement rate of 0.5 mm/min, it provides indices such as fracture energy (U), strain energy release rate (Jc), flexibility index (FI), and fracture toughness (Ozer et al., 2016; Zhou et al., 2017). These indices quantify crack initiation and propagation resistance and allow comparison across mixtures with reclaimed asphalt pavement (RAP), polymer modification, and different aging conditions. Lu et al. (2019) showed that non-standard 100 mm SCB specimens, validated through experiments and DEM modeling, can reliably match standard results. More recently, Lu et al. (2025) compared four indices namely, FI, cracking resistance index (CRI), cracking tolerance index (SCB-CTI), and rate-dependent cracking index (RDCI), and found CRI most effective using machine learning sensitivity analysis, though all exhibited limitations.

Other common methods include the Indirect Tensile Strength (ITS) test, which measures tensile strength but is less representative of field conditions and unreliable at high temperatures, and the Ideal-CT test (ASTM D8225-19), a crack tolerance method based on indirect tensile loading at 50 °C (Im and Zhou, 2017).

Recent advances have emphasized cyclic SCB testing to better simulate traffic loading. Zhang et al. (2018), Yongjin et al. (2022), and Ye et al. (2024) applied cyclic SCB with digital image correlation to sulfur-extended asphalt mixtures, showing strong Paris law consistency, improved repeatability, and sensitivity to sulfur dosage. Zou et al. (2017) used monotonic and cyclic SCB to assess RAP mixtures, reporting consistent reductions in fracture energy, crack initiation energy, fatigue indices, and overall cracking resistance with higher RAP content.

2. Main objectives of this research

The primary objective of this research is to compare standardized monotonic test protocols namely the Crack Tolerance Index (CT_{Index}) test according to ASTM D8225-19 (ASTM, 2019) and the Semi-Circular Bending (SCB) test (ASTM D8044-16) with a simple performance-based repeated cyclic SCB test. The aim is to evaluate the effectiveness of the new cyclic test protocol in assessing the cracking resistance of asphalt mixtures and to determine its sensitivity to fibre modification and air void content in compacted mixes. To achieve this, dense-graded AC14 asphalt mixtures were prepared using two binder types: PG64-16 (60/70 penetration grade) and PG58-22 (80/100 penetration grade). Specimens were compacted to different target air void contents to capture the influence of air voids content. Two groups of mixes were evaluated: a control group containing only the plain binder and a fibre modified group reinforced with Aramid ACE fibres at dosages of 66 g/tonne and 132 g/tonne. All mixtures were tested using the SCB protocol in accordance with ASTM D8044, and their performance was compared with parameters derived from the proposed repeated cyclic SCB test. This comparison was conducted to assess the reliability and practicality of the cyclic method for characterizing cracking resistance.

3. Specimen geometry

For the Crack Tolerance Index (Ideal_CT) test, cylindrical specimens with a diameter of 100 mm and a height of 65 mm were prepared using a gyratory compactor, applying a ram pressure of 600 kPa and an external angle of gyration of 1.25°. For the Semi-Circular Bending (SCB) test, cylindrical asphalt specimens were moulded and trimmed to dimensions of 100 mm in diameter and 30 ± 1 mm in height. Each specimen was then cut into two halves to produce semi-circular samples. Vertical notches with depths of 5 mm, 10 mm, and 15 mm were introduced at the midpoint of the flat edge to create the SCB test configuration, as illustrated in Fig.1. The span length between the two steel supports was fixed at 80 mm for all tests. Two replicates were tested for each asphalt mixture and notch depth. All SCB tests were conducted using a Universal Testing Machine (UTM-30) equipped with the SCB jig as shown Fig. 1. (a). Prior to testing, specimens were conditioned in a temperature-controlled chamber at 25 °C for 90 minutes to ensure thermal equilibrium.

(a) (b)

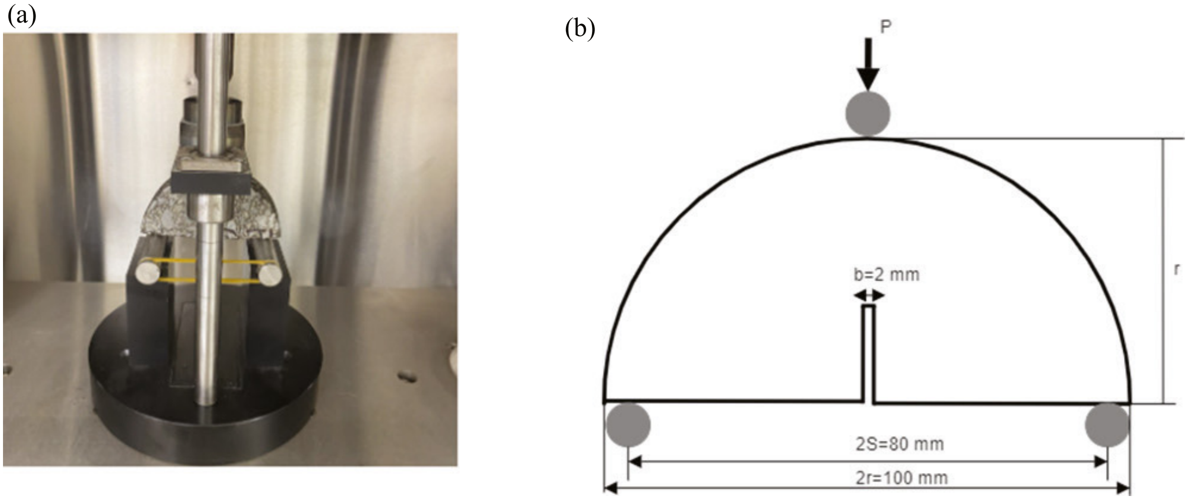


Fig.1. (a) Semicircular Bending Test Specimen Loading Assembly, (b) Specimen Geometry

4. Experimental testing programme

The crack tolerance test (Ideal-CT) was conducted according to ASTMD8225 at 25 C for dense graded asphalt mix with maximum nominal aggregate size 14 mm (AC14) mix. The test was conducted on control specimens and Aramaid fibres using 132 g/tonne. Two types of binders were used PG 64-16 or 60/70 penetration grade and softer type binder PG58-22 or 80/100 penetration grade. All mixes were made at 5.1% binder content with air voids ranged from as low as 3.0% to 7.73%. The test results are shown in Table 1 below. For the semicircular bending test, Table 2 shows different combinations of air voids content and notch depth for fibre modified mix tested according to the standard ASTMD8044 SCB monotonic loading at 0.5 mm/min loading rate. Fibre modified specimens for SCB tests were prepared at 66g/tonne dose.

Table 1. Ideal CT test results for control and fibre modified mix

Binder Content (%BC)	Fibre, g/ton	Binder	Air Void, %	CT_{index_total}
5.1	Control	PG64-16	5.6	116.2
5.1	Control	PG64-16	4.5	123.3
5.1	Control	PG64-16	4.9	68.7
5.1	Control	PG64-16	3.0	59.0
5.1	132	PG64-16	7.7	145.2
5.1	132	PG64-16	6.4	255.6
5.1	132	PG64-16	7.2	189.9
5.1	132	PG64-16	6.2	173.1
5.1	Control	PG58-22	5.3	86.4
5.1	Control	PG58-22	4.1	113.5
5.1	Control	PG58-22	4.3	90.3
5.1	Control	PG58-22	4.2	59.5
5.1	132	PG58-22	4.8	56.3
5.1	132	PG58-22	3.5	43.0
5.1	132	PG58-22	4.5	70.4
5.1	132	PG58-22	3.4	67.6

Table 2. Semicircular test data for monotonic loading at 0.5 mm/min for fibre modified mix with 66g/tonne dose

Air Voids (%)	Notch Length (mm)	Sample Thickness (mm)	$U_{failure}$ (kJ)	IFIT (FI)[1]	Fracture Toughness ($MPa.m^{0.5}$)
3.3	5	30.1	0.00015	3.9	0.052
3.3	5	30.4	0.00007	2.8	0.030
3.4	10	30.2	0.00011	5.8	0.059
3.4	10	30.0	0.00015	7.0	0.070
3.6	15	30.7	0.00010	5.3	0.080
3.6	15	30.6	0.00010	4.8	0.078
4.8	5	31.3	0.00017	5.3	0.058
4.8	5	31.2	0.00016	4.4	0.057
4.9	10	30.9	0.00007	4.9	0.043
4.9	10	30.9	0.00009	6.4	0.047
5.5	15	30.6	0.00008	8.8	0.068
5.5	15	30.5	0.00001	1.3	0.022
7.4	5	31.2	0.00013	7.5	0.033
7.4	5	31.1	0.00013	9.8	0.037
7.9	10	30.6	0.00007	9.0	0.035
7.9	10	30.7	0.00006	4.8	0.031
9	15	29.1	0.00003	9.3	0.029
9	15	29.4	0.00005	15.0	0.031

[1]IFIT or FI = Illinois Flexibility Index

5. Results and analysis

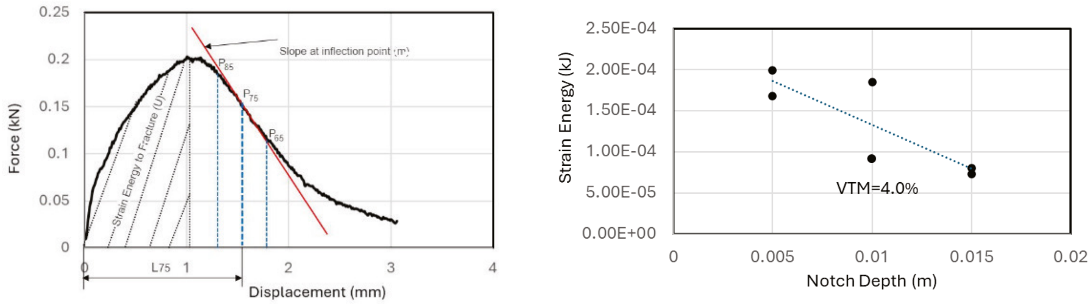
5.1 Crack tolerance index

The crack tolerance index is determined from force displacement curve as shown in Fig. 2(a) measured in the indirect tensile strength test at 25 ºC and at constant displacement rate of 50 mm/min. Equations 1 and 2 are used to calculate the crack tolerance index.

$$CT_{index} = \frac{b}{62} * \frac{G_f}{|m_{75}|} * \frac{\ell_{75}}{D} * 10^6 \tag{1}$$

$$|m_{75}| = \left|\frac{ppp_{85}-ppp_{65}}{\ell_{85}-\ell_{65}}\right| \tag{2}$$

CT_{index}= Crack tolerance Index
b is the thickness of the specimen in mm
G_f= fracture energy per unit area of fracture face
D= Diameter of the specimen
ℓ_{75}= displacement at 75% of the peak load
m75 = the slope of the curve post cracking between 65 % to 85 % of the peak force as shown in Figure 2a



(a) (b)

Fig. 2. (a) Force Displacement Relationship (b) Stain Energy Versus Notch Depth

Fig.3.(a) presents the Crack Tolerance Index (CTindex) results for mixtures with varying percentage air voids in the compacted mix (%VTM) using both hard (PG64-16) and soft (PG58-22) binders without fibre modification. The results indicate no performance advantage in terms of cracking resistance of the softer PG58-22 binder over the harder PG64-16 binder. Moreover, for both binder types of binders, the CTindex increased with higher air void content in the compacted mix which is an unexpected and counterintuitive trend, which represents a major limitation of this test method. Fig.3.(b) compares fibre-modified mixtures with the corresponding control mixtures. While the CTindex increased for PG64-16 mixes with fibre, no significant difference was observed for PG58-22 mixes. This suggests that the fibre's effect may have been masked by the influence of air void content.

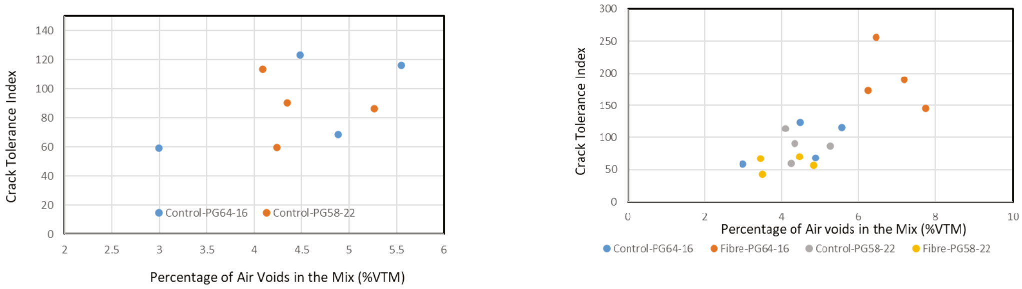


Fig. 3. Ideal_CT index for (a) control mixes, (b) control and fibre modified mix

5.2 Semicircular bending test

The SCB specimens were subjected to the standard monotonic test. The monotonic loading was performed according to the ASTM D8044 at a constant displacement rate of 0.5 mm/min. The load–displacement data were recorded for each specimen to determine peak load capacity, fracture energy, post peak slope, fracture toughness and flexibility index. The area under the curve between zero load and the peak load is designated as the strain energy to failure (U) as shown in Fig.2.(a). The test is conducted using three different notch depth 5, 10 and 15 mm. The critical value of J integral (Jc) is determined as per Equation 3:

$$J_c = \frac{-1}{b} * \frac{dU}{da} \tag{3}$$

J_c=Critical Strain energy release rate kJ/m^2
b = Specimen thickness (m)
a = Notch depth (m)
$\frac{dU}{da}$ = the slope of the strain energy relative to the notch length as shown in Figure 2b

Fracture toughness is another parameter used in this study to analyse the crack resistance of the asphalt specimens tested in the SCB standard monotonic test. Equations 4 to 6 are used to calculate KI which is the plane strain fracture toughness, or critical value of stress intensity factor. KI is the material property measuring the fracture cracking resistance of an asphalt mixture. σmax is the maximum applied stress; Pmax is the maximum applied load; r and b are radius and thickness of test sample, respectively. YI is the normalised mode I stress intensity factor. Equation 4 is used for the ratio of s/r = 0.8.

$$K_I = \sigma_{max} Y_I \sqrt{\pi a} \tag{4}$$

$$\sigma_{max} = \frac{P_{max}}{2r*b} \quad and\ Y_I = 4.782 - 1.219\left(\frac{a}{r}\right) + 0.063exp\left(7.045\left(\frac{a}{r}\right)\right) \tag{5}$$

The flexibility index is calculated as per Equation (6)

$$Illinois\ Flexibility\ Index\ (IFIT)\ or\ FI = A * \frac{G_f}{|m|} \quad and \quad G_f = \frac{W_f}{b*L} \tag{6}$$

where $|m|$ is the absolute value of the slope at the inflection point in kN/mm as shown in Fig.2.(a).
A = 0.01 is unit conversion and scaling factor;
b is thickness of sample in m,
L is ligament length in m.
W_f (N.mm) is fracture work;
G_f = the fracture energy per unit area in Joules/m^2

Fracture toughness for both unmodified and fibre-modified specimens was evaluated across different air void contents and notch depths, as shown in Fig.4. (a) and (b). The results showed a more logical trend compared to the Jc parameter: fracture toughness generally decreased with increasing air void content, aligning with expected material behaviour. However, the fracture toughness did not show any significant effect of fibre modifications as shown in Fig.4.(a). In addition, inconsistencies were noted, for example, at percentage of air voids 3.4% the fracture toughness increased with the increase with the notch depth as shown in Fig.4.(b) which is counterintuitive. This further underscores the limitations of the monotonic SCB test in reliably distinguishing the influence of reinforcement on cracking performance, and notch depth.

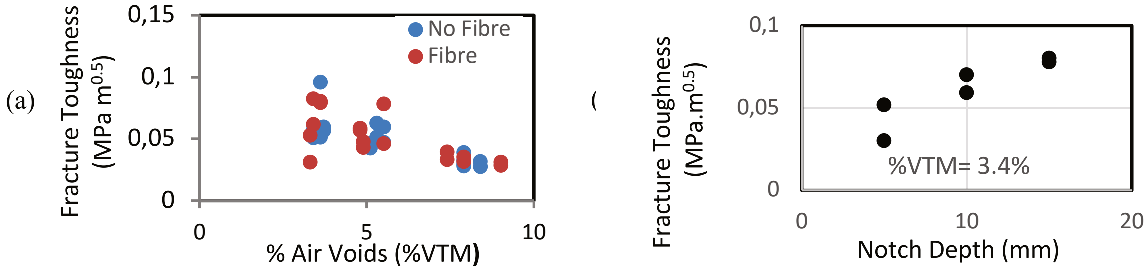


Fig. 4. (a) Effect of %VTM on Fracture toughness (b) Effect of Notch Depth on Fracture Toughness

Illinois Flexibility index (IFIT) or shortly Flexibility Index (FI) was also investigated against air voids content and notch depth, and it showed similar limitations to those of the stain energy rate Jc and the fracture toughness as shown in Fig.5.(a) and (b). These results clearly demonstrate the limitation of the monotonic tests regardless of the parameter used in
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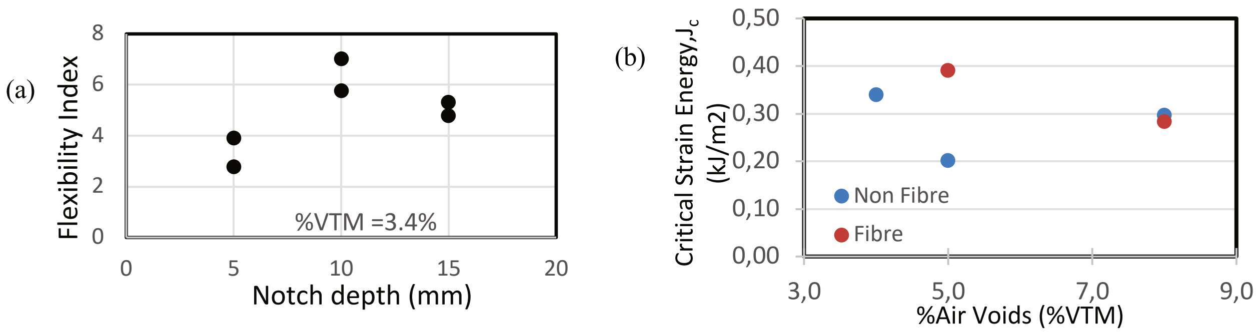
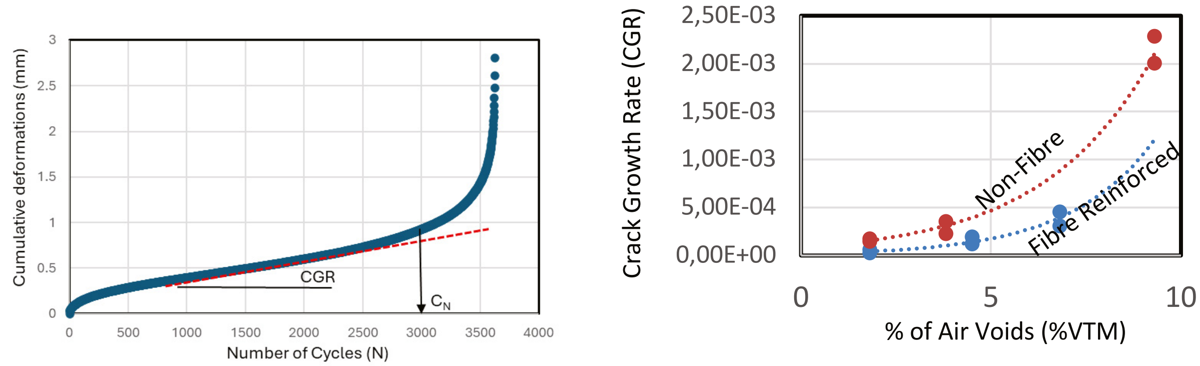


Fig. 5. (a) Effect of Notch depth on Flexibility Index (b) Effect of air voids content on Jc

6. Repeated cyclic load

The repeated cyclic Semi-Circular Bend (SCB) test developed in this study was conducted on 100 mm diameter semicircular specimens under load-controlled conditions using a haversine waveform at 10 Hz. The applied load was set at 50% of the peak load obtained from the standard monotonic SCB test. Cumulative deformation and the number of loading cycles were recorded as shown in Fig.6(a). The response curve exhibited three distinct phases, resembling the behaviour observed in dynamic creep tests, but measured here at an intermediate temperature of 25 °C using semicircular specimens (Fig.6.(a). The linear portion of the curve was analyzed to determine the Crack Growth Rate (CGR), where a steeper slope indicates reduced crack resistance. The inflection point of the curve, defined as the Cracking Number (CN), was also identified. A higher CN value reflects greater cracking resistance of the asphalt mixture. Fig.6.(b) shows that the Crack Growth Rate (CGR) increases with higher air void content, while the Cracking

Number (CN) decreases as air voids increase which is an expected trend for both parameters. Fig.7.(a) and (b) illustrate the CGR of fibre-reinforced and unmodified AC14 mixtures as a function of air void content. The results demonstrate that, although higher air voids consistently accelerate crack growth in both mixtures, fibre reinforcement effectively slows crack propagation, lowers the CGR, and enhances cracking resistance, thereby extending pavement service life.



(a) (b)

Fig. 6. (a) Repeated Cyclic test (b) % Cracking number CN and Crack Growth Rate CGR versus %VTM

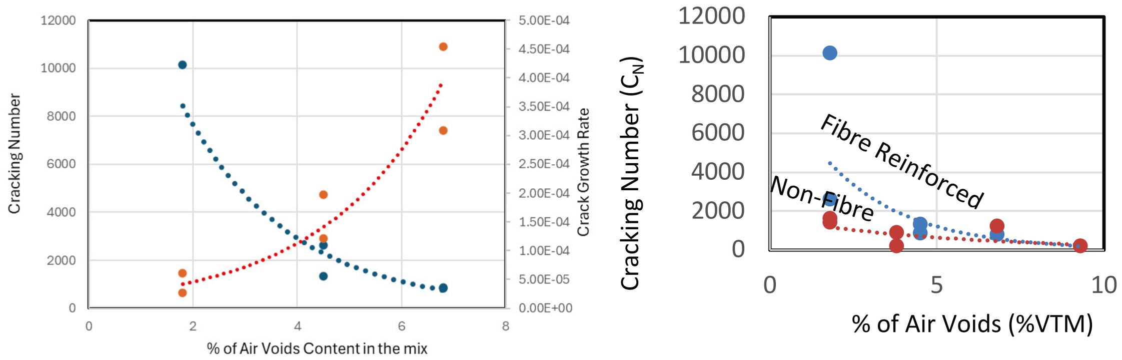


Fig. 7. Control specimens versus fibre modified (a) CN versus %VTM (b) CGR versus %VTM

7. Conclusions

In this study, both the Ideal-CT test and the monotonic semicircular bend (SCB) test were applied to controlled asphalt mixes and aramid fibre modified dense-graded AC14 mixtures. Parameters such as the Crack Tolerance Index (Ideal-CT), critical strain energy release rate (Jc), fracture toughness, and flexibility index were evaluated. However, these indices demonstrated limitations, including inability to reliably predict the influence of air voids, inconsistency with notch depth effects, and insensitivity to fibre reinforcement. In contrast, the repeated cyclic SCB test showed greater reliability, effectively capturing the influence of air voids and reflecting the benefits of fibre reinforcement through the cracking index and crack growth factor.

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