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Asphalt Mixtures' Crack Propagation Assessment using Semi-Circular Bending Tests

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Abstract: The main objective of this study was to evaluate asphalt mixtures for their crack propagation potential using the semi-circular bending (SCB) test. The work encompassed two major tasks: first, preparing two laboratory blended asphalt mixes and obtaining relevant fracture characteristics of those mixtures using the SCB tests; and second, implementing the laboratory test methodology in studying the actual field test sections for their crack propagation potential by utilizing SCB tests on the procured field-cored samples. For the laboratory-prepared mixes, the mix with higher binder content provided better resistance to crack propagation in terms of fracture energy. For the field-cored samples, the mix with an additional binder provided significantly higher resistance to fatigue cracking and propagation. The modified mix (with an additional binder percentage) and the reference mix had significantly different fracture energy characteristics. At all test temperatures, the modified mix was 50% higher in magnitude than the reference mix. This was also confirmed from the previously conducted routine fatigue cracking tests. Overall, the SCB tests and analytical methodologies provided insight in understanding the comprehensive picture of the fatigue criteria and in the prediction of the design service lives of the two different road base layers essential for pavement design. It is envisioned that the procedure developed in this study can be useful for a comprehensive fatigue evaluation of the asphalt mixtures and aid in their pavement design methodology in forecasting the residual life of the flexible pavement.

Key words*: Asphalt concrete; Crack propagation; Fatigue design criteria; Semi-circular bending test; Service life.*

Introduction

Traffic loading on pavement surfaces produces tensile stresses among the other stresses at the bottom of the asphalt concrete (AC) layers. As traffic loading continues, fatigue cracks begin and then propagate through the AC layer. Crack propagation is important towards the understanding of the cracking mechanism because it can be investigated over a period of time, unlike crack initiation and the total failure criteria, which are instantaneous. Furthermore, regular monitoring and assessment of crack propagation (and resistance) of the actual pavement sections in the field is deemed important for national and local agencies. In addition, AC reflective cracking resistance is one of the most significant distresses imminent at the rehabilitation stage of the fatigued roads. The low resistance materials used in overlaying the pavement sections to counter reflective cracking can be thoroughly cracked within a very short duration.

Simple methods such as the semi-circular bending (SCB) test were devised to study fracture mechanics of rocks in the early 1990s [1]. Later, SCB techniques were utilized to understand crack resistance and fracture of asphalt mixtures [2]. Since then, the simplicity of the methodology has provided a suitable platform for researchers around the world to characterize asphalt mixtures' fracture and fatigue properties. In addition, the SCB test was used to evaluate stiffness modulus of asphalt mixtures apart from estimating the ultimate stresses / strength [3]. To understand fatigue damage parameters, advancements in the investigations of fracture characteristics of modified asphalt mixes using SCB tests at both monotonic and cyclic loadings have been ongoing [4]. Recently, the SCB test has been approved as a regular standard by the European Committee for Standardization (CEN) to determine the tensile strength or fracture toughness of an asphalt mixture for the assessment of crack propagation potential [5].

This paper presents a research study that was undertaken to understand crack propagation of asphalt mixtures in Sweden; previously, no studies had been reported in this area. In 2010, Swedish Transport Administration and VTI-Swedish National Road & Transport Research Institute jointly aimed to develop a simple tool to assess crack propagation and comprehensively evaluate fatigue criteria of the AC mixes. The premise was that the methodology should be able to assess field cores taken directly from actual road sections.

Objective & Scope of the Work

The main objective of this study was to evaluate asphalt mixtures for their crack propagation potential using the SCB test. The scope of work included two parts. In the first portion of the study, SCB tests were utilized on two laboratory-blended asphalt mixes to obtain relevant fracture characteristics of those mixtures. With the first task underway, researchers envisioned that the results emanating from that study would assist in the implementation of the laboratory test methodology used to study the actual field test sections for their crack propagation potential. Thus, the second task of the study was to use SCB test methodology on the field-cored samples for their crack propagation assessment.

It is envisioned that the procedure developed in this study can be

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Table 1. Summary of the Current Literature on Crack Propagation Evaluation.

Author(s)	Test Methodology	Output Parameters	Mixture Properties
Lim *et al* [1]	Semi Circular Bending	Fracture Toughness Stress Intensity Factors	Rocks
Mobasher *et al* [6]	3-point Flexural Bending Beam	Fracture Toughness, Critical Stress-intensity Factor	Conventional and Asphalt Rubber Mixes Beam Specimens: 406 x 89 x 89 mm Test Temperature: -7 and -1^{o}C
Molenaar *et al* [2]	Uniaxial Tensile Semi Circular Bending Indirect Tensile	Fracture Toughness, Tensile Strength	Hot Mix Asphalt, Test Temperature: 0^{o}C
Li and Marasteanu [8]	Semi Circular Bending	Fracture Toughness, Fracture Energy	Superpave Mixes in MnRoad Facility 19 mm NMAS, 5.8% AC, 4% AV Performance Grades: PG 58-40, PG 58-28 Test Temperature: -30 and -40^{o}C
Huang *et al* [9]	Semi Circular Bending, Indirect Diametral Tensile	Tensile Strength	Sixteen Mixes with Three Replicates Each SCB test: 25 mm Thickness IDT: 100 mm Diameter, 63 mm Height
Khalid and Monney [10]	Semi Circular Bending	Effects of Moisture Ingress Fracture Toughness Fracture Energy	Hot Mix Asphalt, Cold-laid Grave Emulsion AC Mix
Roque *et al* [11]	Semi Circular Bending	Fracture Properties	Asphalt Mix with 150 mm Diameter

useful for a comprehensive evaluation of the fatigue characteristics of the asphalt mixtures and aid in their pavement design methodology. In addition, the procedure can act as a tool to estimate/forecast the residual life of the flexible pavement during its design period.

Evaluation of Crack Propagation Phenomenon

This project focused on documenting the currently available techniques, test methodologies, and analytical procedures for the assessment of the crack propagation of asphalt mixtures. This effort also necessitated the description of the tests being used to generate laboratory experimental data. Table 1 summarizes the different testing methodologies and tests used by the various researchers around the world [1, 6-11].

Lim *et al* found that the SCB specimen under three-point bending technique is a versatile, cost-effective and reliable method for determining the mixed-mode (I and II) fracture toughness envelope of rocks [1]. The authors discussed a numerical work to cover a wide range of possible specimen geometries of experimental interest to compute the stress intensity factors. The various observations relevant to the study of stress intensity factors for the SCB test was documented in the study. A numerical convergence study was performed for the SCB test with the normalized crack length of (a/r) = 0.5, the normalized span (s/r) = 0.8 and the crack inclination angle of $\alpha = 0^{o}$, where a = crack length, r = radius of the specimen, 2s = support span. Various mathematical functions for the normalized stress intensity at a given span ratio s/r were found, which were also a function of normalized crack length ratio(a/r). The study found a generic form to estimate a stress intensity factor using the normalized stress intensity at a given span ratio, stress value, and normalized crack length. The investigation revealed that the SCB technique enables the entire range of mixed-mode I and II to be applied for analyses. However, it is important to note that mode I represents cracking in the tensile stresses plane; as such, this might be the only portion that requires analyses for crack propagation phenomenon.

Mobasher *et al* evaluated low temperature fracture parameters of conventional asphalt concrete and asphalt rubber mixtures to assess for their crack propagation properties [6]. Beam specimens with dimensions of 406 x 89 x 89 mm were prepared with different asphalt contents and tested under three-point bending flexural conditions at two test temperatures: -7 and -1^{o}C. It was found that asphalt rubber mixtures had higher fracture toughness and consequently higher resistance to cracking than conventional asphalt mixes. Additionally, increasing the binder content increased the toughness values for both the mixtures. There were large differences between the average critical stress-intensity factors for the two mixes.

Molenaar *et al* determined the tensile strength of asphalt mixtures by uniaxial tensile test, SCB test, and indirect tensile test (IDT) [7]. In the SCB test, an un-notched specimen and a notched specimen were used. It was found that the tensile strength in the different test methods was not greatly different. The SCB test was found to be a suitable methodology for the determination of the fracture toughness and the tensile strength of the AC mix. The study also included finite element calculations, which revealed that the state of stresses of the SCB test specimens was suitable to determine the tensile strength of the asphalt mixes.

Li and Marasteanu investigated the use of the SCB test as a candidate for a low-temperature cracking specification [8]. The study proposed methodologies to prepare test specimens and develop a standard and methods to calculate fracture toughness and fracture energy. Three similar Superpave mixtures (with nominal maximum size of 19 mm, 5.8% asphalt content, and 4% air voids) with different performance grade asphalt binders were utilized in the

MnRoad pavement facility. The tests were performed at -30 and -40°C and fracture properties such as stiffness, fracture toughness and fracture energy were obtained at those temperatures. The results showed that, for the calculated stiffness, neither the binder type nor the specimen location was significant. Furthermore, for fracture toughness and fracture energy, the binder type effect was significant.

Huang *et al* used the SCB test to evaluate its suitability to characterize the tensile strength of the HMA mixtures [9]. Analytical and numerical simulations were employed to interpret the experimental results. IDT was compared with the SCB test. The results from this study indicated that SCB test was capable to provide consistent results with reasonable variability. The researchers found that the SCB test exhibited several advantages over IDT in characterizing HMA mixtures, such as the ability to test mixtures at elevated temperatures. Compared to the IDT, SCB test was found to have several advantages, such as requiring much less loading applied to the loading strip and at least doubling the testing specimens. Sixteen mixtures compacted at an air voids level of 5% were tested by both SCB and IDT techniques in this study.

Khalid and Monney studied the effects of moisture ingress on the mechanical properties of a cold-laid grave emulsion asphalt concrete mixture [10]. Semi-circular specimens loaded in a three-point bending test were used to determine fracture properties such as fracture toughness and fracture energy. Results showed that, although the hot mixture had good fracture properties, the cold mixture's results were only marginally lower.

Roque *et al* identified a few problems in using the SCB test [11]. The SCB test arrangement for asphalt mixture with a 150 mm diameter semi-circular sample supported by two rollers with a span of 120 mm led to a relatively short fracture ligament. The authors believed that the initial ligament length should be as large as possible to produce reliable fracture properties.

Theory of Semi-Circular Bending Test

The SCB test includes testing of a half cylindrical asphalt concrete test specimen with a center crack loaded in three-point bending in such a way that the middle of the base of the test piece is subjected to a tensile stress. The test is normally conducted at a constant deformation rate at different test temperatures.

The maximum load, F_{max}, and the vertical deformation, ΔW are determined from the test results. The strain at maximum force, ε_{max}, is determined as follows.

$$\varepsilon_{max} = \frac{\Delta W}{W} \times 100\% \quad (1)$$

where:
W = Height (mm)
ΔW = Vertical displacement at maximum force (mm)

The maximum horizontal stress σ_{max} is given by [5]:

$$\sigma_{max} = \frac{4.263 \times Fmax}{D \times t}\ N/mm^2 \quad (2)$$

where:
D = Diameter (mm)
t = Thickness (mm)
F_{max} = Maximum Force (N)

For un-notched SCB specimens, the tensile strength is equal to the maximum stress. For notched SCB specimens with (s/r) = 0.8, the fracture toughness, K_{Ic} of the material is as follows [1].

$$K_{Ic} = \sigma_{max}\sqrt{\pi \times a} \times f\left(\frac{a}{W}\right)\ \text{N/mm}^{3/2} \quad (3)$$

where:
W = Height (mm)
a = Notch depth (mm)
σ_{max} = Stress at failure (N/mm²)
$f\left(\frac{a}{w}\right)$ = Geometric factor
$= 4.782 - [1.219(a/r)] + \left[0.063e^{\{7.045(a/r)\}}\right]$
s = half of spacing between rollers = 60 mm
r = radius of the specimen = 75 mm

Fracture Energy of the material can be calculated as follows [10].

$$\Gamma = Force \times displacement$$

$$\Gamma = \frac{Work}{Unit\ Area\ of\ Ligament} = \frac{\int P\ du}{Unit\ Area\ of\ Ligament} \quad (4)$$

where:
Fracture energy = work done on a material to increase the fractured surface with a unit area
Work = Area under load–deformation curve
Area of Ligament = sample thickness x (sample radius ~ notch depth)

Experimental Design–Laboratory Blended Mixtures

As mentioned previously, the first portion of this research study was to understand the crack propagation phenomenon using SCB tests in the laboratory. Before the implementation of SCB tests on actual field test sections, researchers deemed it important to perform investigation of crack propagation on the laboratory prepared asphalt mixtures.

The scope of work in the laboratory experimental program included preparation of two different types of asphalt mixtures: one mix with 4.4% asphalt content and 2% target air voids; the second mix with 5.4% asphalt content and 1% target air voids. Table 2 presents the two mixture types and the various properties of the mixes, including the type of asphalt binder, asphalt content, air voids, maximum theoretical specific gravity (G_{mm}), and bulk specific gravity (G_{mb}). Both mixes had similar aggregate gradation, which was basically a Swedish typical mix ABb16 (16 mm nominal maximum aggregate size).

Cylindrical gyratory plugs of diameter and height equal to 150 mm were prepared using the two mix designs. From the center of each gyratory plug, two discs were cut with approximately 50 mm thickness. Each disc was cut into two equal semi-circular specimens through the middle with final sample dimensions: diameter ~ 150 mm, thickness ~ 50 mm, and height ~ 75 mm. A notch was cut to a width of about 2 mm and a depth of about 15 mm; the notch was cut at mid-point in the direction of the loading from the central axis of the flatter side of the sample. A test frame with roller bearings was manufactured at the Swedish National Road and Transport Research Institute (VTI), and metal bearing strips of dimensions 50 x 20 x 2

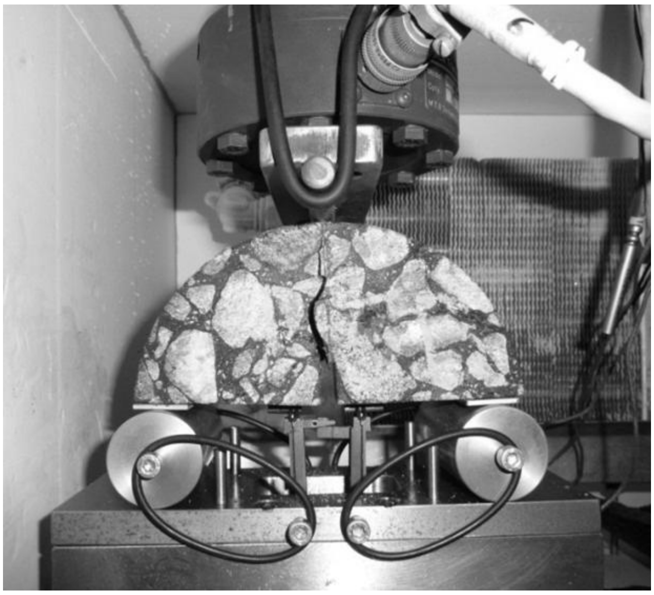

Fig. 1. Actual Semi-circular Bending Test Setup; The Sample Also Shows Cracks That Initiated at The Tip of The Notch and Propagated to The Top of The Specimen During The Experiment.

Table 2. Mixture Characteristics.

Mix Type	Binder Type	*Asphalt Content (%)*	*Air Voids (%)*	G_{mm} (g/cc)	G_{mb} (g/cc)
1	Pen 70/100	4.4	2.0	2.472	2.645
2	Pen 70/100	5.4	1.0	2.428	2.645

mm were glued to the specimens, which rested on the rollers used for testing. Tests were conducted at three temperatures: 10°C, 0°C, and -10°C. Twelve samples were prepared per mix so as to use four specimens per test temperature. Samples were placed in the temperature chamber for about four hours before testing as part of the sample-conditioning process. Since the current European Standard (EN) was not published when the tests were conducted, a deformation rate of 1 mm/min [10] was used instead of the one mentioned in the standard (equal to 5 mm/min) [5]. Fig. 1 shows an example of the actual test setup. As seen in the figure (based on the visual inspection), the crack initiated at the tip of the crack opening (or notch) and continued (propagated) to the top of the specimen due to a continuous axial loading, as expected.

Experimental Program and Test Results

Table 3 presents the experimental program matrix, including average values (four sample replicates) of the sample dimensions, notch depth and width, and the corresponding average air voids levels of the samples used for each temperature and the two different mixtures. Table 4 presents the test results (average of four samples) for the laboratory blended asphalt mixtures, which include: maximum stress, maximum vertical strain, fracture toughness (stress intensity factor), fracture energy until failure and total fracture energy.

As observed in Table 4, at the three test temperatures, the mix with lower asphalt content (4.4%) had higher maximum stress than the mix with higher asphalt content (5.4%). This is as expected and indicative of the fact that the lower the binder content in the mix (for the same aggregate gradation), the stiffer the mix. Nonetheless, the increased maximum stress in the mix may be less susceptible to fatigue cracking. Insofar as the strains are concerned, one can observe that the mix with higher asphalt content incurred higher tensile strains, indicating that the mix with lower binder content was

Table 3. Semi-Circular Bending Test Experimental Matrix, Laboratory Blended Mixes.

Mix Type	*Temp* (°C)	*AV* (%)	*a* (mm)	*W* (mm)	*T* (mm)	***W*** (mm)	***D*** (mm)
ABb 16, 4.4%AC	10	2.2	16.0	2.2	47.3	73.3	149.7
	0	2.2	16.0	2.1	49.8	74.0	149.4
	-10	2.1	15.8	2.1	49.8	73.1	149.8
ABb 16, 5.4%AC	10	0.9	16.1	2.1	49.4	73.8	149.8
	0	1.0	16.0	2.2	49.0	72.9	149.0
	-10	0.9	16.1	2.1	50.0	73.4	149.8

AV = Air Voids; a = Notch Depth; w = Notch Width; t = Sample Thickness; W = Sample Height; D = Sample Diameter;

Table 4. Semi-Circular Bending Test Results, Laboratory Blended Mixes.

Mix Type	*Temp* (°C)	σ_{max} (MPa)	ε_{max}	K_{IC} (N/mm$^{3/2}$)	Γ_{total} N/mm	$\Gamma_{failure}$ N/mm
ABb 16, 4.4%AC	10	0.61	4.74	21	2605	533
	0	0.91	3.63	31	1528	261
	-10	1.06	1.82	36	1225	241
ABb 16, 5.4%AC	10	0.50	5.82	17	3610	662
	0	0.78	5.31	26	2156	246
	-10	0.94	1.88	32	1102	189

σ_{max}= Maximum Stress; ε_{max} = Maximum Vertical Strain; K_{Ic} = Stress Intensity Factor;
Γ_{total} = Total Fracture Energy; $\Gamma_{failure}$ = Fracture Energy until Failure (@ max. stress)

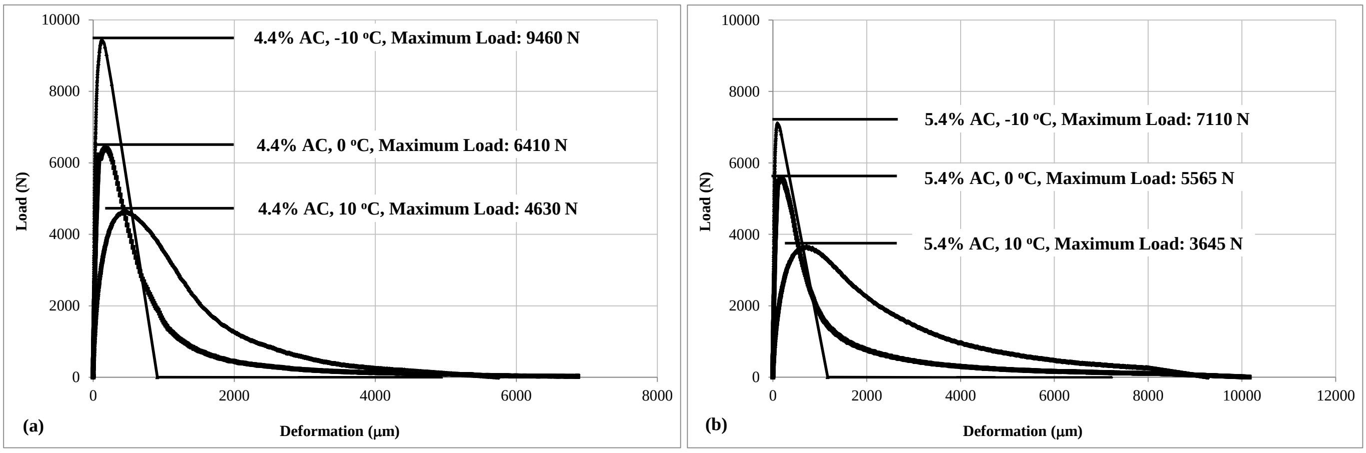

Fig. 2. Load–Deformation Relationships for Laboratory Blended Mixes at Different Temperatures for: (a) 4.4% Asphalt Content (b) 5.4% Asphalt Content.

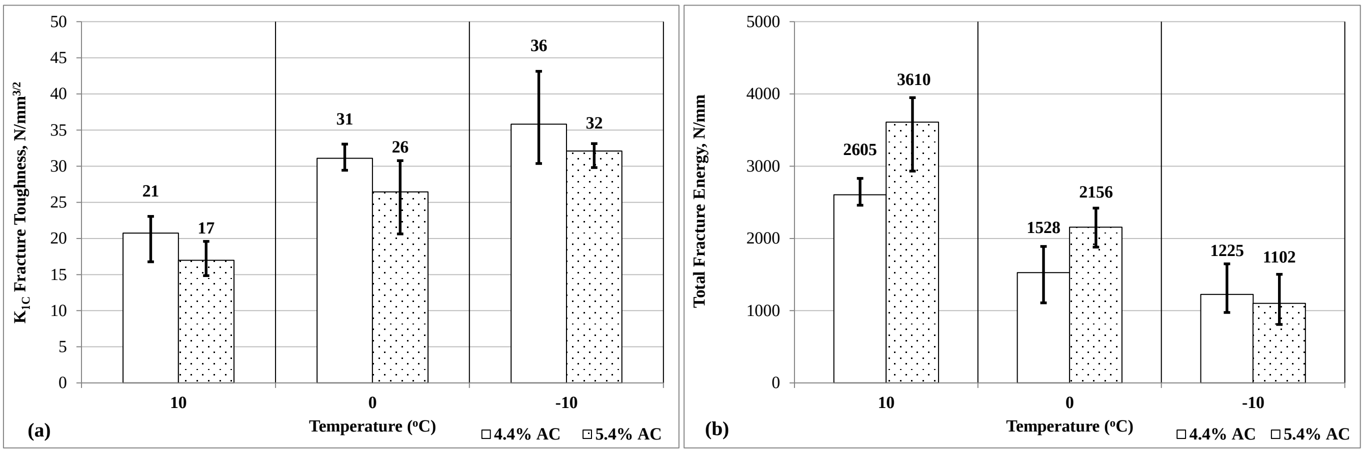

Fig. 3. SCB Test Results for The Laboratory Blended Mixes: (a) K_{IC}, Fracture Toughness (Stress Intensity Factor) (b) Total Fracture Energy.

brittle and could not accommodate deformation before failure. Higher binder content in the mix provided higher resistance to fatigue cracking in the mix.

During the actual test, it was observed that cracks started to propagate from the tip of the notch where the concentration of stresses was highest. The cracks tended to propagate in the direction of the applied load, perpendicular to the maximum principal tensile stress. This helped in drawing relationships between the applied load and deformation for both the mixes at the three tested temperatures.

Fig. 2 (a) and (b) shows the load-deformation curves for the two laboratory-blended asphalt mixes with two different asphalt contents at the three test temperatures. The figures also mention the maximum load at failure for the three temperatures. As observed, the relationship is generally linear but transforms into a non-linear relationship a few time intervals before and after the maximum load is reached. The non-linear responses were more pronounced at higher temperatures, where the mixes transitioned from hard (brittle/elastic) to soft (viscous) nature. As expected, at all the three temperatures, the mix with higher asphalt content (softer mix) had lower maximum load values than the mix with lower asphalt content (brittle mix). It is clear that in the zone of maximum load attainment, the behavior of the mixes changes from elastic (brittle) to elasto-plastic with an increase in asphalt content from 4.4 to 5.4%.

Fig. 3 (a) presents the results of fracture toughness (stress intensity factor) for both the mixes. There is a definite trend in the values between the two mixes and also within the temperature range. With increase in temperature, there was a decrease in fracture toughness for any mix; and between the two mixes, there was a decrease in fracture toughness with an increase in asphalt content from 4.4 to 5.4%. This was indicative that an increase in asphalt content compromised the mix's toughness and its ability to resist higher traffic loads, in turn reducing the mix's fatigue cracking resistance and life span. It is noteworthy that a similar trend was observed for the maximum stress values of the mixes, meaning that stresses at failure decreased with increasing asphalt content at all tested temperatures.

Using the load-deformation relationships of the two mixtures, fracture energy until failure and total fracture energy were estimated owing to a better understanding of the materials' post-peak (residual) properties using the energy concept. Fracture energies were calculated using Eq. (4) and are presented in Table 4. Fig. 3 (b) presents total fracture energies for the two mixtures at the three test temperatures. It must be noted that for fatigue cracking evaluation for Swedish climate, 10°C is considered standard. As observed, at 10°C, the highest energy is provided by the mix with higher asphalt content, both in terms of fracture energy until failure (Table 4) and total fracture energy (Fig. 3 b). The same trend was observed for

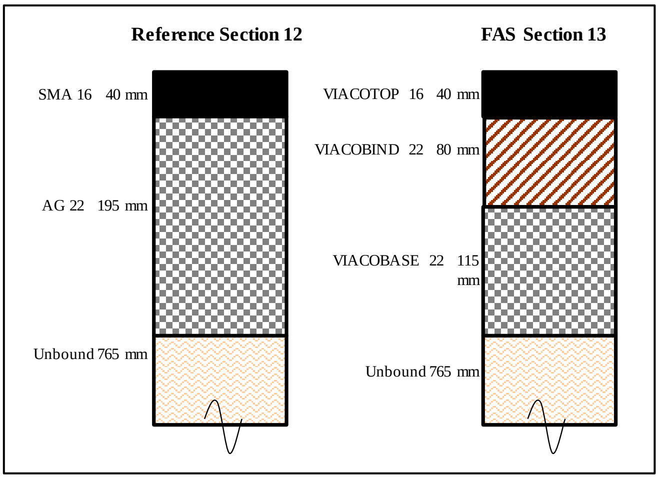

Fig. 4. Pavement Structures of the Reference and the FAS Road Sections on The Swedish E6 Highway [12].

0°C, but for the lowest temperature, i.e., at -10°C, there was an insignificant difference between the energy values of the mixes.

It must be noted that although the average maximum peak load (in turn, stress at failure) was higher for the mix with lower asphalt content, the energy dissipated by the mix with higher asphalt content was higher, mainly attributed to the viscous property of the asphalt binder. The differences between the two mixes at the other test temperatures have been found to be of less significance for the fatigue evaluation in Sweden.

Fatigue Life Predictions of Field Sections

As noted before, it was envisaged that the laboratory results emanating from the first portion of the research study would assist in the implementation of the laboratory test methodology in studying the actual field test sections for their crack propagation potential. Thus, SCB tests were conducted on the actual field cored samples to validate the laboratory test methodology and hence develop fatigue criteria of the existing test sections. This section provides the test results of the SCB tests conducted on the field cored samples.

Field Test Sections

The field cored samples were collected from the test road built on the E6 highway in western Sweden. Two full-scale test sections were built with similar structures, except for the type of bituminous layer. Fig. 4 presents the pavement structures of the two full-scale test sections [12]. The Reference Section 12 is a common type of pavement structure used in Sweden, built as a gravel-bitumen pavement. The pavement system consisted of a wearing course built with a Stone Mastic Asphalt (SMA) of 40-mm thickness overlaid on the 195-mm Swedish typical base course mix AG 22 with binder grade Pen 160/220 (4.2% asphalt content and 3% air voids), which was placed on the subgrade soil.

The modified pavement system, FAS Section 13 had the same thickness as the reference section. However, all the bitumen-bound layers in the FAS structure were a type of SMA Mix. The wearing course VIACOTOP 16 was a 40-mm SMA Mix, overlaid on the 80-mm thick SMA binder layer VIACOBIND 22, which was overlaid on the 115-mm SMA base layer VIACOBASE 22 with binder grade Pen 70/100 (5% asphalt content and 2% air voids). The unbound pavement layers of both sections were identical.

Experimental Program and Results

Field-cored samples were collected from the field test sections. Three cores were available for each layer, so each core was used to obtain two semi-circular samples. In total, 30 samples were available for testing from five different pavement layers; these were tested at three temperatures with two samples per layer. SCB tests were conducted on all samples at 10, 0, and -10 °C; a strain rate of 1 mm/min was used, similar to the one used for laboratory blended mixtures.

Table 5 presents the experimental program matrix of the field

Table 5. Semi-Circular Bending Test Experimental Matrix for the Different Pavement Layers, Swedish Field-Cored Mixtures.

Pavement Layer	*AV* (%)	*Temp* (°C)	*a* (mm)	*w* (mm)	*t* (mm)	*W* (mm)	*D* (mm)
VIACOTOP 16	~ 3.0	10	16.0	2.3	33.6	73.1	144.0
		0	15.6	2.5	41.2	73.3	149.4
		-10	15.7	2.1	32.1	70.6	144.4
VIACOBIND 22	~ 3.0	10	16.0	2.5	44.0	70.2	144.1
		0	16.1	2.4	45.1	70.5	143.9
		-10	15.8	2.2	44.9	70.5	144.0
VIACOBASE 22	~ 2.0	10	16.0	2.3	44.3	71.5	144.2
		0	16.0	2.3	45.0	70.5	143.6
		-10	15.8	2.2	45.0	70.3	143.7
SMA16	~ 2.0	10	14.9	2.6	38.4	73.8	149.6
		0	15.5	2.4	38.7	73.8	149.7
		-10	15.4	2.7	37.8	73.3	149.7
AG22	~ 3.0	10	15.4	2.8	41.4	73.4	149.6
		0	15.5	2.5	40.9	72.7	149.6
		-10	14.8	2.5	40.8	74.4	149.6

AV = Air Voids; a = Notch Depth; w = Notch Width; t = Sample Thickness; W = Sample Height; D = Sample Diameter;

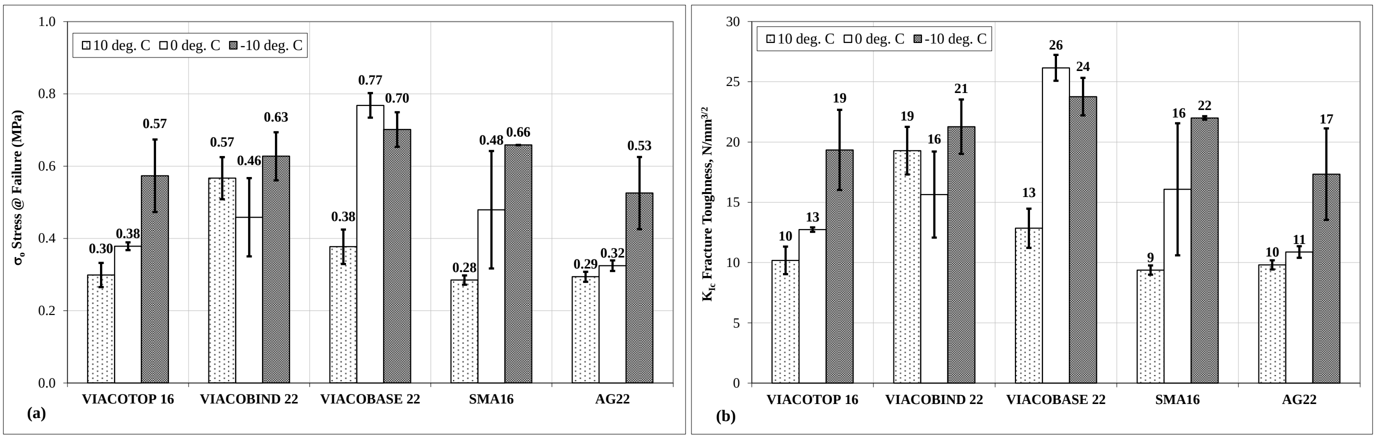

Fig. 5. SCB Test Results for The Field-cored Mixes for the Different Layers: (a) σ_o, Stress at Failure; (b) K_{IC}, Fracture Toughness (Stress Intensity Factor).

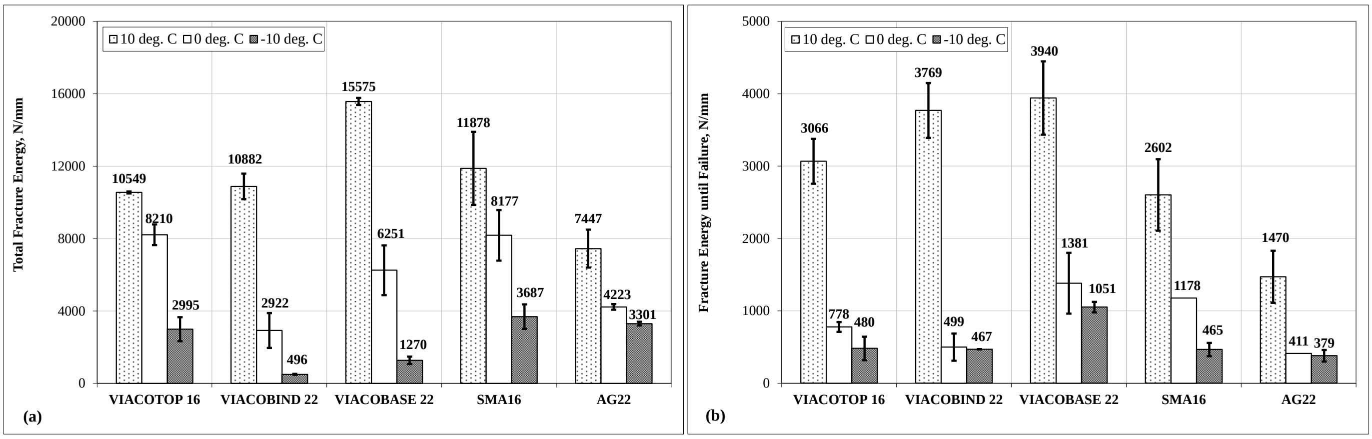

Fig. 6. SCB Test Results for The Field-cored Mixes for The Different Layers: (a) Total Fracture Energy; (b) Fracture Energy Until Failure.

cored samples used in the SCB tests. The table includes average values (two sample replicates) of the sample dimensions, notch depth and width, and the corresponding average air voids levels of the samples used for each temperature and the three different mixtures.

Fig. 5 (a) presents the average (two sample replicates) maximum stress values for the different field-cored mixes. Generally for all the mix types, as observed, stress values increased with decreasing temperature, indicative of the mixtures' susceptibility to temperature (owing to the viscoelastic properties of the asphalt mixes). It is noteworthy that the stiff binder (Pen 70/100) in the VIACO mixes had higher stresses at failure when compared to the AG 22 mix with softer binder (Pen 160/220). Fig. 5 (b) shows the average fracture toughness values for the different mixes. Higher toughness values were provided by the VIACO mixes in the FAS Section 13; in particular, the highest values were obtained for the VIACOBASE 22 mix in comparison to both SMA 16 and AG 22 mixes, the layers encompassing the Reference section 12.

Load-deformation relationships for all the mixes were established; hence, fracture energies until failure and total fracture energies were estimated using Eq. (4). Fig. 6 (a) and (b) presents average total fracture energies and fracture energies until failure for all the mixtures at the three test temperatures. As mentioned previously, 10^{o}C is considered standard for fatigue cracking evaluation for Swedish climate,. However, for completeness, the results for the two other temperatures are also presented. A general trend observed during the assessment of fracture energies is that there was a significant change in the values between FAS Section and the Reference Section pavement layers.

The VIACO mixes had significantly higher values than the Reference mixes, at least by 50% at all temperatures. When comparing the fracture characteristics of the two base layers—VIACOBASE 22 and AG 22—that are deemed important to evaluate fatigue cracking and propagation phenomena, there is a change of at least a magnitude of 2 between the energies dissipated during the design lives. At 10^{o}C, the VIACOBASE 22 is anticipated to provide at least twice the amount of additional service life than the AG 22 mix, mainly due to additional binder content in the mix.

It was interesting to note that an additional 0.8% binder with only 2% air voids in the VIACOBASE 22 mix provided much more fatigue resistance despite using a stiffer binder grade in comparison to AG 22 mix, which had lower asphalt content (4.2%) and higher air voids. Thus, higher binder content and lower air voids in the mix provided higher resistance to fatigue cracking in the mix.

Fig. 7 (a) and (b) provides a more comprehensive evaluation of the fatigue criteria for the two road base mixes. Fig. 7 (a) presents an estimation of the number of load applications for the two mixes at different strain levels at 10^{o}C [12]. For instance, if one estimates the fatigue lives of the two mixes at 150 micro-strains, there is a

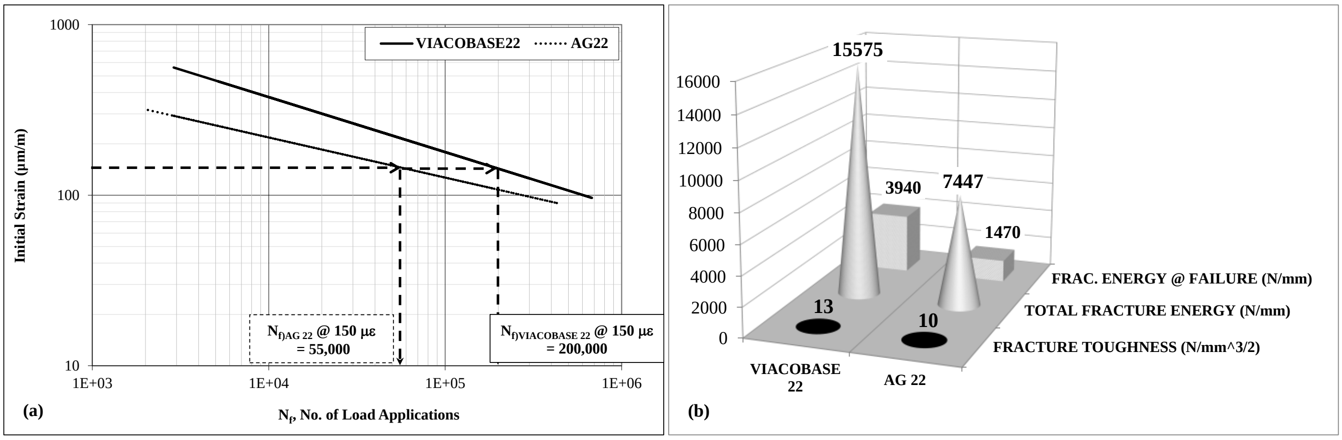

Fig. 7. (a) Fatigue Relationships for VIACOBASE 22 and AG 22 Estimated from Fatigue Tests at 10^{o}C [12]; (b) Fracture Characteristics for VIACOBASE 22 and AG 22 from SCB Tests.

shift magnitude of approximately 4 between the VIACOBASE 22 and AG 22 mixes, where the VIACOBASE mix would provide a longer service life. This shift would vary depending on the strain level accounted for; for example, the shift would be higher at higher strains and lower at lower strains. Fig. 7 (b) presents a schematic of the change in each of the fracture characteristics for the two road base layers. The conclusions of the fatigue relationships are confirmed by the change in the fracture characteristics between the two road base mixtures. Overall, the SCB tests and analytical methodologies provided an insight to understanding the comprehensive picture of the fatigue criteria and in the prediction of the design service lives of the two different road base layers essential for pavement design and rehabilitation.

Summary and Conclusions

The main objective of this study was to evaluate asphalt mixtures for their crack propagation potential using the SCB test. The work encompassed two major tasks: one, the preparation of two laboratory blended asphalt mixes and obtaining relevant fracture characteristics of those mixtures using the SCB tests; and second, the implementation of the laboratory test methodology in studying the actual field test sections for their crack propagation potential by utilizing SCB tests on the procured field-cored samples.

The major findings of the SCB tests on the laboratory blended mixtures are as follows:

- In the zone of maximum load attainment, the behavior of the mixes changes from elastic (brittle) to elasto-plastic with an increase in asphalt content from 4.4 to 5.4%. Between the two mixes, there was a decrease in fracture toughness with increase in asphalt content from 4.4 to 5.4%. This indicated that an increase in asphalt content compromised the mix’s toughness and its ability to resist higher traffic loads, in turn reducing the mix’s fatigue cracking resistance and life.
- At 10^{o}C (standard for fatigue evaluation in Sweden), the highest energy was provided by the mix with higher asphalt content, both in terms of fracture energy until failure and total fracture energy.

The major findings of the SCB tests on the field-cored mixtures are as follows:

- Higher toughness values were provided by the VIACO mixes in the modified section; in particular, the highest values were obtained for the VIACOBASE 22 mix in comparison to the AG 22 road base mix of the reference section. An additional 0.8% binder with only 2% air voids in the VIACOBASE 22 mix provided much more fatigue resistance despite using a stiffer binder grade in comparison to AG 22 mix, which had lower asphalt content (4.2%) and higher air voids. Thus, higher binder content and lower air voids in the mix provided higher resistance to fatigue cracking in the mix.
- The modified mix (with an additional binder percentage) and the reference mix had significantly different fracture energy characteristics. At all test temperatures, the modified mix was 50% higher in magnitude than the reference mix. When the two base layers VIACOBASE 22 and AG 22 that are deemed important to evaluate fatigue cracking and propagation phenomena are compared for their fracture characteristics, there was a change of a range of magnitude of 1 to 3 between the energies dissipated during the design lives. At 10^{o}C, the VIACOBASE 22 is anticipated to provide at least twice the amount of additional service life than the AG 22 mix, mainly due to additional binder content in the mix.
- The conclusions of the fatigue relationships are confirmed by the change in the fracture characteristics between the two road base mixtures, where the modified mix is anticipated to provide a longer service life.
- Overall, the SCB tests and analytical methodologies provided insight in understanding the comprehensive picture of the fatigue criteria and in the prediction of the design service lives of the two different road base layers essential for pavement design and rehabilitation.

It is envisioned that the procedure developed in this study can be useful for a comprehensive evaluation of the fatigue characteristics of the asphalt mixtures and aid in their pavement design methodology. In addition, the procedure can act as a tool to estimate/forecast the residual life of the flexible pavement during its design period. Although this study is limited in terms of experimental program, further investigations would be useful to understand the effect of cyclic loading on the different asphalt mixes, including modified mixes.

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