EVALUATING THE SEMI-CIRCULAR BENDING TEST FOR HMA MIXTURES

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Abstract Semi-Circular Bending (SCB) Test is a fast and accurate three-point bending test, which was originally used in rock mechanics. SCB test is going to be an accepted test method for asphalt concrete pavements. Different asphalt-mixture property-values such as tensile strength, stress intensity factor and fatigue can be obtained by this test. In this study, static and dynamic tests including SCB test, Stiffness modulus and fatigue tests using Nottingham Asphalt Tester (NAT), Indirect Tensile Strength test (ITS) and Triaxial Hveem test, were conducted on asphalt concrete specimens with different bitumen and filler contents, using two standard aggregate grades. The results obtained from different common tests were compared with the semi-circular bending test; assure that, SCB is a true-accurate test for prediction of both short-term and long-term mechanical properties of asphalt mixtures.

Keywords Semi-Circular Bend Test, Asphalt Concrete, Indirect Tensile Test, Stress Intensity Factor, Hveem Test

چکیده آزمایش خمش نیم دایره، یکی از انواع آزمایش‌های خمش سه نقطه‌ای می‌باشد که از سرعت و دقت خوبی برخوردار است و به طور اساسی در مکانیک سنگ مورد استفاده قرار گرفته است. با توجه به تحقیقات انجام شده برای گسترش حوزه استفاده از این آزمایش به ارزیابی روسازی‌های آسفالتی، ویژگی‌های مختلف بتن آسفالتی مانند مقاومت کششی، ضرایب شدت تنش و مقاومت خستگی مصالح بتن آسفالتی را می توان با این آزمایش تعیین نمود. در این پژوهش، آزمایش‌های استاتیکی و دینامیکی شامل آزمایش خمش نیم دایره، آزمایش‌های دستگاه تست ناتینگهام (NAT)، آزمایش کشش غیر مستقیم و آزمایش سه محوری ویم بر روی بتن آسفالتی با درصدهای مختلف قیر و فیلر، با استفاده از دو دانه بندی استاندارد انجام شده است. مقایسه نتایج حاصل از آزمایش‌های رایج و نتایج آزمایش‌های دینامیکی و استاتیکی انجام گرفته توسط نمونه‌های خمش نیم دایره دقت و صحت نتایج آزمایش خمش نیم دایره به منظور تعیین ویژگی‌های رفتاری کوتاه-مدت و بلند-مدت بتن آسفالتی را تایید می‌نماید.

1. INTRODUCTION

The performance of asphalt pavement is influenced by a few primary factors: properly designed mixture, consistent plant production and field compaction. Neither of these factors alone can assure satisfactory pavement life [1,2].

The fundamental engineering properties of the mixture must relate to its field performance, in order to obtain properly deigned asphalt mixture. However, relating mixture's laboratory properties to its field behavior is not a simple task. Such analyses can only be made if good quality models are available. Models are presented for prediction of the strength characteristics and the resistance to cracking, fatigue and permanent deformation [3]. Asphalt mixtures are complex materials. Their behavior is strongly dependent on temperature, strain rate (quite often asphalt mixtures are thought to be loading time dependent, but actually they are strain rate dependent) and stress conditions. Given this complex behavior, lots of attention should be paid to a correct modeling of the mixture characteristics in relation to the above parameters [4].

Numerous researches have been conducted

relating the tensile strength of asphalt mixtures to the performance of asphalt pavements [5-7]. Good fracture properties are an essential requirement for asphalt pavement built in countries with cold winters in which the prevailing failure mode in cracking due to stresses such as, low-temperature shrinkage. Cracking can occur as a result of a single severe temperature drop (single event) or of multiple cycles of less severe temperature change (thermal fatigue). Low-temperature cracking is manifested as a set of surface-initiated transverse cracks of various length and width [6]. One of the most common tests to determine the fracture resistance or tensile strength of asphaltic concrete is the Marshall Stability test, but a simple test like Marshall does not fulfill all the requirements and is therefore abandoned in many countries. After Marshall Test, pavement engineers and researchers have been extensively using indirect tensile test to determine the tensile strength properties of HMA mixtures. Also in a number of recent papers, researchers have investigated the use of indirect tension test to describe the response of asphalt mixtures [7].

According to Shapery's theory of crack-growth in viscoelastic media, it suffices to know the viscoelastic compliance, the tensile strength, and the fracture energy, to characterize the resistance to crack-growth [8-10]. The viscoelastic compliance can be obtained from a frequency sweep test, e.g. the four point bend test. In principles, the tensile strength and the fracture Energy can be obtained from a tensile test. However, to date, a suitable tensile test for asphalt has not been developed. A direct tensile test is expected to yield a large variation coefficient.

Developments in performance based specifications have resulted in a search for more appropriate "fundamental" tests for instance a triaxial test. The problem with many of these tests however is that they lack simplicity and that specimens cannot easily be obtained from the pavement. Furthermore the need to do repeated load testing complicates the applicability of such tests. In Netherland, as well as in some other countries, e.g. South Africa, the possibilities of the so called semi-circular bending test are investigated since it is believed that, this test is a simple tool to obtain information on the modulus and tensile characteristics of asphalt mixtures [11-22].

This paper presents the results of a laboratory study in which the Semi-circular bending test was evaluated for its suitability to characterize the tensile strength, Fracture toughness and fatigue life of asphaltic concrete. Numerical analyses indicate a good correlation and therefore agreement between the results of the tensile strength and fracture toughness obtained from SCB test and dynamic stiffness modulus of Nottingham Asphalt Tester (NAT). It was found that SCB test is very promising for determination of asphalt concrete characteristics mainly tensile and fracture resistance while it clearly shows the asphalt-aggregate interaction in the mechanical behavior of the asphalt mixtures.

2. EXPERIMENTAL METHODS

2.1. Semi-Circular Bending Test (SCB) The principle of the semi-circular bending test to determine the tensile strength is shown in Figure 1. Monotonic load was applied to a semi-circular specimen until failure. The load and vertical deformation was recorded continuously. The loading rate was 50.8 mm/min (2in/min).

Two roller supports and a loading roller were used for loading conditions [10]. The distance between the supports in different researches were about 2s = 0.8D [14,15,17]. The horizontal length of the loading strip was 9.4 mm and the horizontal length of the support strip was 6.25 mm [15,17]. The specimens' diameters were 100 mm, resulting in a span length of 2s = 80 mm. The specimens' thicknesses were selected to be 25 mm.

Figure 2 shows the schematic view of the fracture toughness test using SCB specimens. Parameter (a) is the length of the notch crack which was about 10 mm for the prepared specimens. The other geometric parameters are all like the SCB tensile strength. Fracture toughness SCB test is developed to measure the cracking susceptibility of asphalt [9]. The static SCB test on notched specimens-used for determining the fracture toughness of the asphalt-has already been used in various projects [11,14,15,19,23]. With this material property, it is possible to calculate the critical load at which a construction with a certain crack length fails. With this parameter, it is also

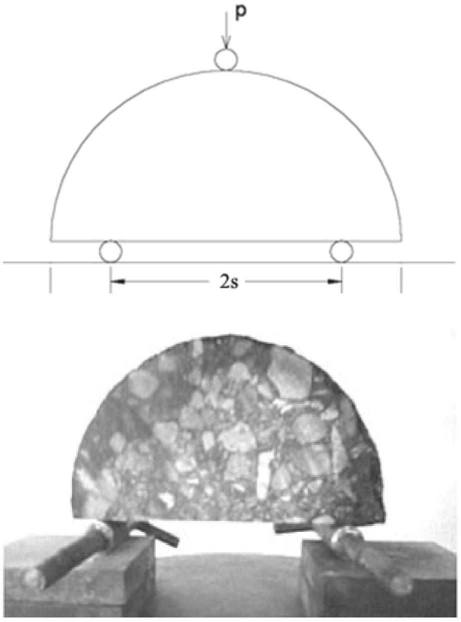


Figure 1. Principles of SCB test (tensile strength test).

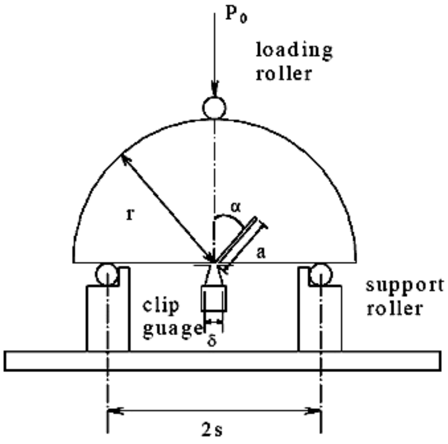


Figure 2. Schematic of the experimental setup. (fracture toughness test).

possible to predict the critical crack length at which a construction fails when a specific axle-load passes. All static SCB experiments for finding the fracture toughness value were conducted on halved asphalt concrete core at 25˚C and 0˚C. The samples were subjected to a compression load with continuous strain rate of 0.085 mm/s.

2.2. Indirect Tensile Strength Test (ITS)

The ITS test was conducted according to ASTM D4123 [24]. Specimen was loaded to fail at a 50.8 mm/min (2 inch/min) deformation rate.The indirect tension (ITS) test involves loading a cylindrical specimen with static or repeated compressive loads which act parallel to and along the vertical diametrical plane of the specimen. Figure 3 shows the loading condition of ITS test.

From the indirect tensile test we can determine the tensile strength and it’s an important property of asphalt concrete mixtures in order to identify its distresses such as crack growth from fatigue or low temperature conditions [3,4]. Although ITS has many advantages such as relative simple setup and the ease in preparing specimens, it also has some disadvantages. For example; the permanent deformation under the loading strip is undesirable for the evaluation of the tensile strength property of asphalt mixtures. In addition, the stress state during the diametrical test on a specimen under loading is complicated and not a realistic representation of the stress state in the whole pavement structure. A biaxial state of stress exists and the maximum horizontal tensile stress at the center of the specimen is one third of the vertical compressive stress at the same point [17,20].

2.3. Triaxial Hveem Test Triaxial Hveem test method is a common way to design asphalt concrete pavements. Triaxial Hveem test is done

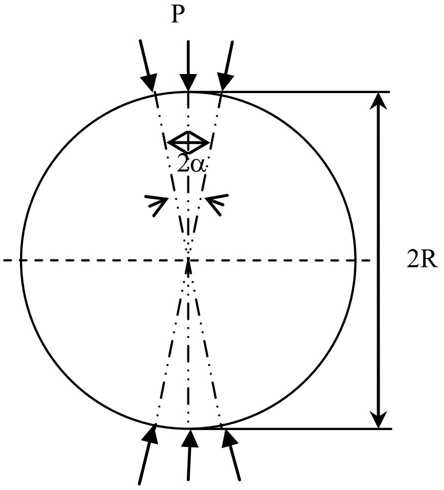


Figure 3. Applied load in indirect tensile test.

with Hveem stabilometer which is capable of measuring horizontal strain and stresses.

By performing Hveem test and using Mohr-Coloumb theory developed by McCarthy, it is possible to define the cohesion value (C) and internal friction angle (ϕ) of the asphalt concrete which is used to calculate the tensile strength, compressive strength and shearing resistance [25].

3. MATERIAL CHARACTERIZATION

3.1. Aggregate Characterization The aggregate grading used for this research is according to the Issue No.101 of technical properties of roads and pavements (Iranian Standards) [26]. In Figure 4, two aggregate gradations used for the preparation of the samples were shown.

3.2. Bitumen Characterization Bitumen that is used for preparing specimens was from Isfahan refinery. It was evaluated for rheology using penetration test at 25°C (ASTM D5 [27]), softening point test (ASTM D36 [28]), and ductility test at 25°C (ASTM D113 [29]). Some bitumen characteristics are shown in Table 1. As can be seen, the rheological characteristics of the bitumen were all within the specification limits.

4. SAMPLE PREPARING

Cement was used as the filler of the mixtures 5, 5.5, 6 and 6.5 percents of asphalt content were chosen for specimen's preparation in order to have more varied results.

The hot asphalt mixture was prepared in Marshall Test cylinders with the diameter of 100

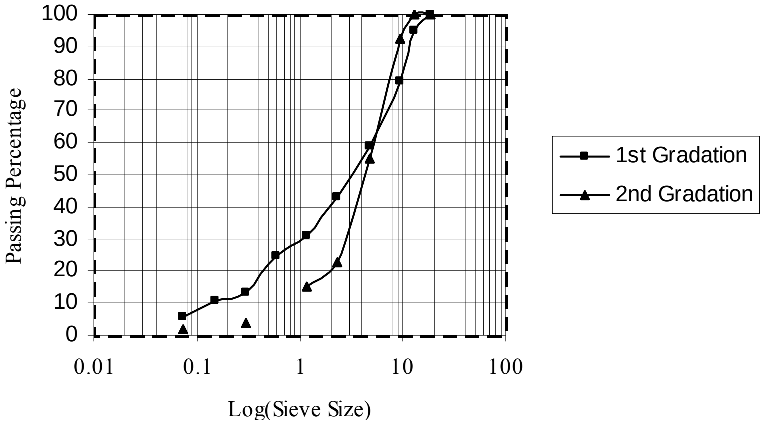


Figure 4. Aggregate gradations used for test specimens.

TABLE 1. Properties of the Bituminous Used for Test Specimens.

Total Bitumen Content	Weight Drop	Inflammation Point	Ductility	Softening Point	Penetration Index	Specific Gravity
%	%	°C	cm	°C	(mm/10)	gr/cm^3
99	0.2	262	112	51	66	1.02

mm and then compacted with 75 levels by Marshall Hammer. The specimens were cut to the specified height and diameter (25 mm height and 100 mm diameter). Afterward the asphalt concrete specimens were cut into two halves. The cutting procedure has been done with Mason-Mate device. Furthermore, indirect tensile stiffness modulus tests (ITSMT) have been conducted using Nottingham Asphalt Tester. Preparation of NAT specimens were done according to ASTM D4123 [24].

For a better comparison, the tests were performed at three different temperatures. A series of SCB and NAT tests at 25˚C and 0˚C and a series of SCB and Hveem tests at 25˚C and 60˚C were carried out. The ITS test is usually carried out at room temperature, therefore the temperature of 25˚C was selected to have a comparison between ITS and SCB tensile strength results. Furthermore the Hveem test is performed at 60˚C defined by the ASTM standard; similarly the same temperature was used for carrying out a series of SCB and Hveem test. Following this tensile strength tests, the fracture resistance tests were also performed on specimens. These tests are usually conducted at low temperatures; consequently the 0˚C and 25˚C temperatures were selected for the fracture tests. Regarding the temperature-dependent behavior of asphalt concrete, the NAT tests which were used herein as a tool to investigate the accuracy of SCB fracture resistance test, were also carried out at 0 and 25˚C.

5. RESULT AND DISCUSSION

For indirect tensile final results, the load was continuously recorded and indirect tensile strength was computed as follows:

$$S_t = \frac{2P_{ult}}{\pi Dt} \quad (1)$$

Where

S_T Tensile strength, MPa

P_{ult} Peak load, N

t Thickness of the specimen, mm

D Diameter of the specimen, mm.

For Semi circular bending test (SCB) The maximum stress at the bottom of the specimen was calculated as Equations 2 obtained from finite element analysis [15,17]:

$$\sigma_X = 3.564\frac{P_{ult}}{D.t} \quad (2)$$

Where

σ_x Tensile strength, MPa

P_{ult} Peak load, N

t Thickness of the specimen, mm

D Diameter of the specimen, mm.

Table 2 presents the ultimate load and tensile strength obtained from SCB and ITS tests. It should be noted that both tests gave consistent results. The coefficient of variation of ITS was 9 percent; where as those for SCB were within 5.5 %. The SCB tensile strength was about 2.5 times to the ITS strength.

By performing Hveem test and using Mohr-Coloumb theory we defined the cohesion value (C) and internal friction angle (ϕ) that is used to calculate the tensile strength.

In Figure 5 the procedure which is used to find the tensile strength of asphaltic concrete through Mohr-Coloumb theory and Hveem test method is shown. The parameter “TS” which is shown in 5 equals with the tensile strength of the mixture.

In Table 3, comparison between the results of SCB and Hveem tests were shown at 60˚C temperature.

During the test performance, micro-cracking damage is initiated within the area of highest bending moment at the bottom edge of the specimen and in the area above the support. It gradually extends along the bottom edge and then coalesces near the centerline of the specimen. Due to this significant coalescing of tension damage in time, intense localization of cracking along the diameter of the specimen occurs in the final stages of the test. Some distributed compressive damage can also be observed near the edge of the loading

TABLE 2. Comparison of average ITS and SCB Tensile Strength (TS) at 25˚C.

		SCB			ITS			Ratio
A.C (%)		Pmax (N)	TS (MPa)	cov (%)	Pmax (N)	TS (MPa)	cov (%)	(SCB/ITS)
1st Grad.	5	726	1.05	3.6	1256	0.32	9.4	3.28
	5.5	783	1.18	1.4	1441	0.4	7.5	2.95
	6	771	1.12	6.5	1345	0.35	5.5	3.2
2nd Grad.	5	548	0.79	6	1192	0.27	10.6	2.92
	5.5	624	0.91	4.2	1305	0.33	12.8	2.76
	6	560	0.82	3.8	1217	0.3	8.3	2.73

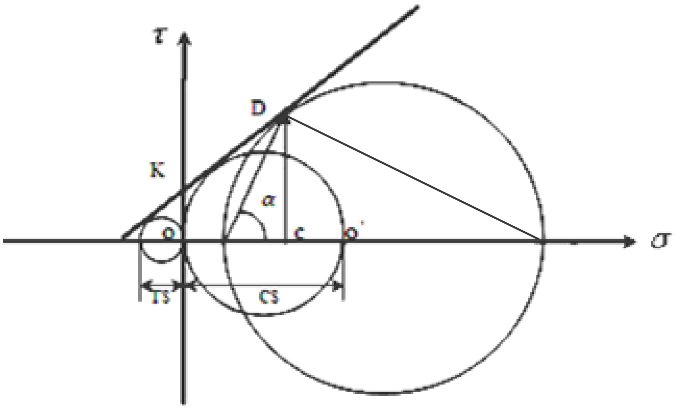


Figure 5. Determining tensile strength of asphalt concrete through triaxial Hveem method [25].

TABLE 3. Comparison of average Hveem and SCB Tensile Strength (TS) at 60˚C.

		SCB		Hveem		Ratio
A.C (%)		TS (MPa)	cov (%)	TS (MPa)	cov (%)	(Hveem/SCB)
1st Grad.	5	0.24	7.6	0.32	4.4	1.33
	5.5	0.33	5.4	0.4	5.5	1.21
	6	0.18	6.5	0.25	3.5	1.39
2nd Grad.	5	0.19	8	0.27	3.6	1.42
	5.5	0.25	9.2	0.33	7.8	1.32
	6	0.18	4.8	0.3	6.3	1.67

strip and near the support rollers also, but it is negligible compared to the tensile damage.

Stress analysis in specimen of SCB test (Figure 6) shows the large tensile stresses occurring at the bottom of the specimen and also a compressive arch develops and pure tension always occurs at the mid-point of the bottom edge of the specimen. The way in which SCB specimens fail indicates that tension might be the dominant failure mode.

Figure 6 shows the tensile and compressive stresses as calculated by means of a finite element program assuming that the material behaves linear elastic. The figure shows that indeed large tensile stresses occur at the bottom of the specimen but also that a compressive arch develops.

The stress state during the diametrical test on a specimen under loading is complicated and not a realistic representation to the stress state in the whole pavement structure (Figure 7). A biaxial state of stress exists and the maximum horizontal tensile stress at the center of the specimen is one third of the vertical compressive stress at the same point. But In SCB test, the specimen starts with a pure tensile flexural failure, which reflects a relatively "true" tensile strength of the mixture [3,4]. From the stress analyses, it appeared that significant compressive stress concentration occur under the loading strips and/or rollers. Although asphalt mixture normally have much higher compressive strength than tensile strength, excessive compressive stress concentration could still cause localized punching failure which in turn would affect the stress distributions and cause test errors. This is particular when testing asphalt mixtures at elevated temperatures or at slow loading rates. For determining the fracture toughness, if the maximum force at which the specimen fails, showed by F_{max}, the apparent fracture toughness will be obtained from the below equation derived from finite element analysis [11,14,31 and 32].

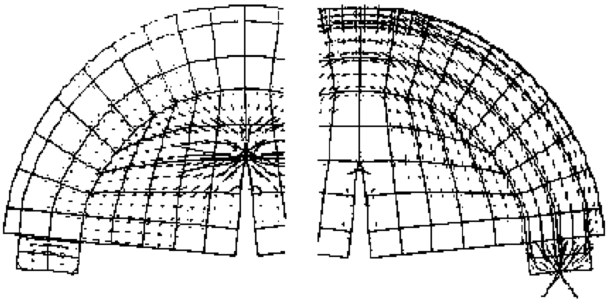


Figure 6. Left FEA diagram shows the distribution of tensile stresses right one shows the distribution of compressive stresses [14].

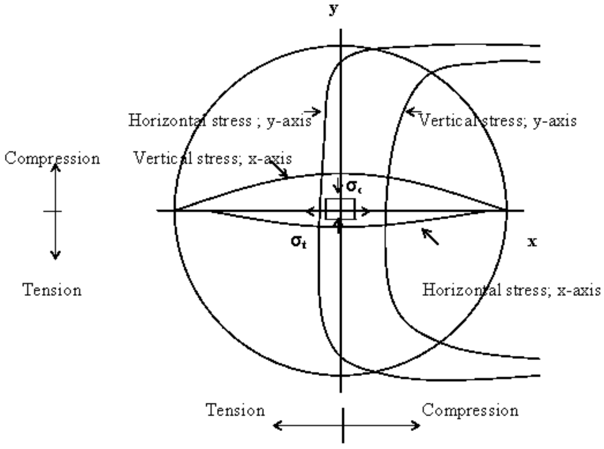


Figure 7. Stresses at the center of the ITS specimen [30].

$$K_1 = \sigma_0 \sqrt{\pi a} Y_1 \tag{3}$$

$$\sigma_0 = \frac{F_{max}}{DL} \tag{4}$$

Where D is the specimen diameter and L is the specimen thickness. Y_1 is the normalized intensity factor, which is defined from finite elements analysis done by Lim, et al [33], for different specimen geometries. The variation of the intensity factor due to changes in the specimen geometry is shown in Figure 8 Parameter Y_1 is determined from Figure 8. The main standard used in this test is ASTM E399 which is developed for the determination of the fracture toughness for metals is the [34]. To account for the heterogeneity of asphalt specimens, the fracture toughness obtained from Equation 2 should obtain the conditions (5a,d). Before K_1 is tested to see if it fulfills the conditions mentioned before, it is called apparent fracture toughness K_{IQ}. According to Lim et al, the conditions Equation 4 provides a conservative estimate of the minimum specimen size required. But the results demonstrate that there is already too much plasticity at + 15˚C causing P_{max} to become large relative to P_o [33]. It was found that the conditions 4b-4d is not critical. For example if K_{IQ}/σ_{ys} is assumed to be 1.0 and then condition (5b) requires a ≥ 2.5 mm. The notch length of 10 mm is well beyond this critical value.

However the fracture toughness value was found to be independent of the specimen thickness in the range between 25 mm and 75 mm, and independent of the specimen diameter in the range between 100 mm and 220 mm at low temperatures [11].

Results of the apparent fracture toughness obtained from SCB test are shown in Figure 9. Comparing the variation of tensile strength and fracture toughness with bitumen content and gradations revealed that fracture toughness value is more dependent on aggregate characteristics than bitumen content (mastic) of the specimens. It is the result of the facts that in asphalt mixtures, cracks propagate not only through the mastic and interface between the mastic and the aggregate, but also through the aggregate particles.

$$\frac{P_{max}}{P_o} \le 1.10 \tag{5a}$$

$$a \ge 2.5\left(\frac{K_{IQ}}{\sigma_{ys}}\right)^2 \tag{5b}$$

$$W \ge 5\left(\frac{K_{IQ}}{\sigma_{ys}}\right)^2 \tag{5c}$$

$$t \ge 2.5\left(\frac{K_{IQ}}{\sigma_{ys}}\right)^2 \tag{5d}$$

Stiffness modulus values of each specimen were obtained from the indirect tensile stiffness modulus tests using the NAT. The condition of loading and other variation was steady for all the specimens. Figure 10 shows the results of Stiffness modulus test. The Fracture toughness results must have a good correlation with the ones of the stiffness tests in order to assure the tensile strength obtained from SCB test can be used to investigate the influence of asphalt-aggregate interaction in the mechanical behavior of the bituminous mixtures.

Correlation for Fracture toughness (K_{1C}) values obtained from the SCB-specimen shows that they are in good agreement with the Stiffness modulus value of NAT tests. The results of correlation analyses on the data obtained from these two tests were shown in Figure 11. As shown in this Figure,

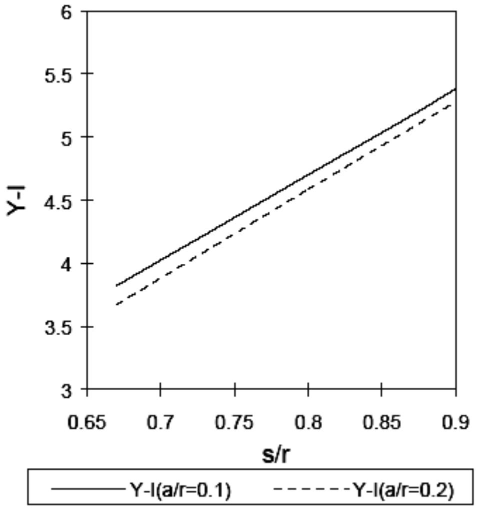
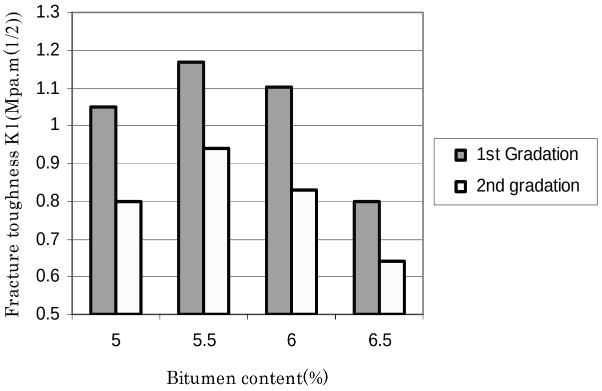
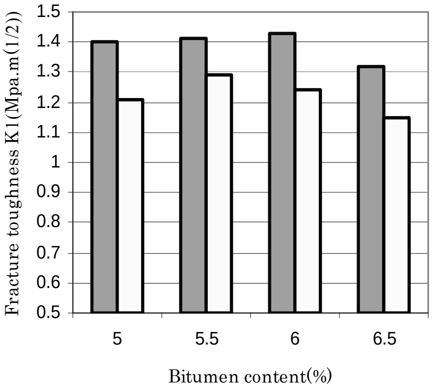


Figure 8. Normalized stress intensity factor for SCB specimen based on Lim, et al [33].

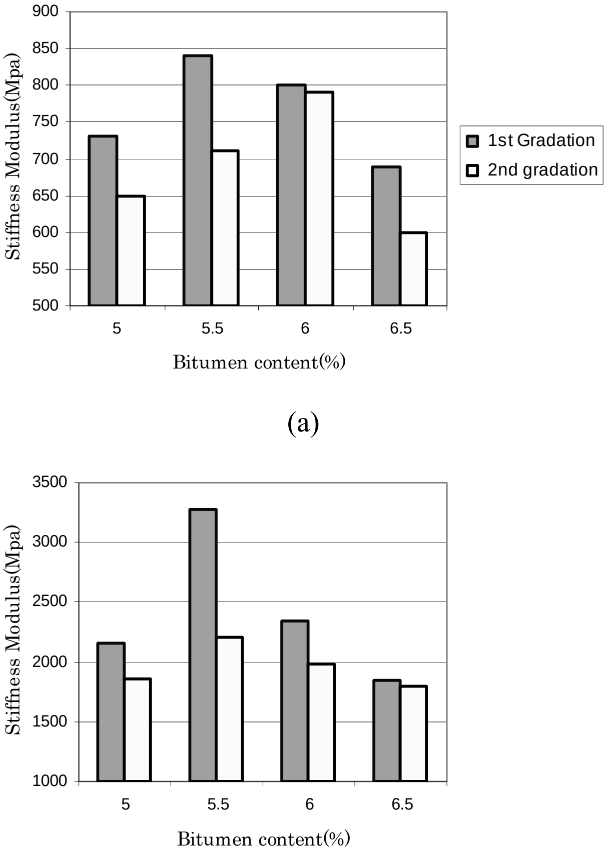


(a)



(b)

Figure 9. Variation of fracture toughness with bitumen content and gradation (a) at temperature of 25˚C and (b) at temperature of 0˚C.



(a)

(b)

Figure 10. Stiffness modulus tests (NAT) results for specimens (a) at temperature of 25°C and (b) at temperature of 0°C.

all the correlation factors (C.C; Correlation Coefficient) are in the agreement range which denoted the SCB test is very promising for the determination of asphalt concrete characteristics; mainly tensile and fracture resistance while it clearly shows the asphalt-aggregate interaction in the mechanical behavior of the mixtures.

In the next step, the Fatigue life tests on the AC specimen were applied. Figure 12 presents the results of the SCB fatigue test. Load levels were based on a fraction of the ultimate strength from the SCB tensile strength test and were applied at a frequency of 5 Hz to evaluate the fatigue characteristics of the mixtures with two different gradations. For each grading, the HMA were made at the optimum bitumen contents. Figure 13 presents the results of the NAT fatigue test. From both NAT and SCB fatigue test results it can be clearly seen that the fatigue behavior of the two tests are similar. The mixtures made of the second gradation have less fatigue resistance due to the gap-graded aggregates.

6. SUMMARY AND CONCLUSIONS

This study has been conducted to evaluate the SCB test for determining tensile and fracture resistance of asphalt concrete mixtures. For a better conclusion we perform the high validity indirect tensile stiffness modulus test on the specimens, using Nottingham asphalt tester device.

Following notes can be drawn from this investigation:

- SCB test could be used to characterize the tensile strength of asphalt mixtures with good repeatability, which makes it a potentially simple performance test for asphalt concrete mixtures.
- The results from SCB, ITS and Hveem methods, were fully comparable and convertible. The tensile strength from SCB and ITS test were different due to their different stress states under loading.
- The SCB has the big advantage over the well known ITS test, being the fact that the specimens fail much nicer. The way in which SCB specimens fail indicate that tension must be the dominant failure mode even at higher temperatures. This is contrary to the type of failure (wedging) often observed at ITS tests which indicates the specimens fail is due to a mixed mode of stress conditions.
- In the SCB test, loads can be chosen much smaller (1/5 to 1/10) than ITS test. Thereby reducing the undesirable effect of local failure close to these loads and letting the investigated phenomenon (crack growth) appear in its pure form.
- Fracture test results obtained from SCB test have a good correlation with the ones from stiffness modulus; assure that the SCB test can be used to characterize the fracture properties of HMA mixtures.

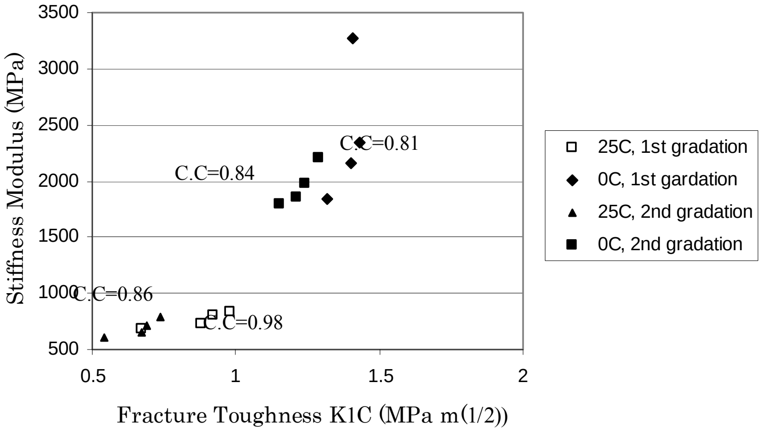


Figure 11. Correlation between the results of fracture toughness (SCB) and stiffness modulus (NAT).

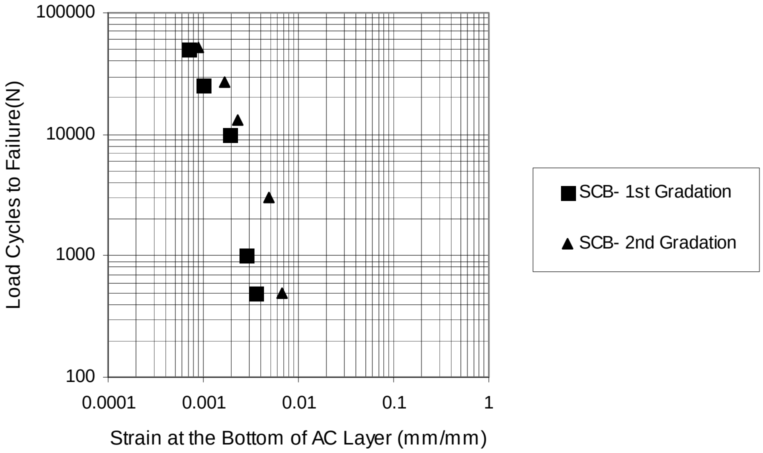


Figure 12. Number of load cycles to failure versus initial strain at the bottom of the asphalt concrete layer (SCB Test Results).

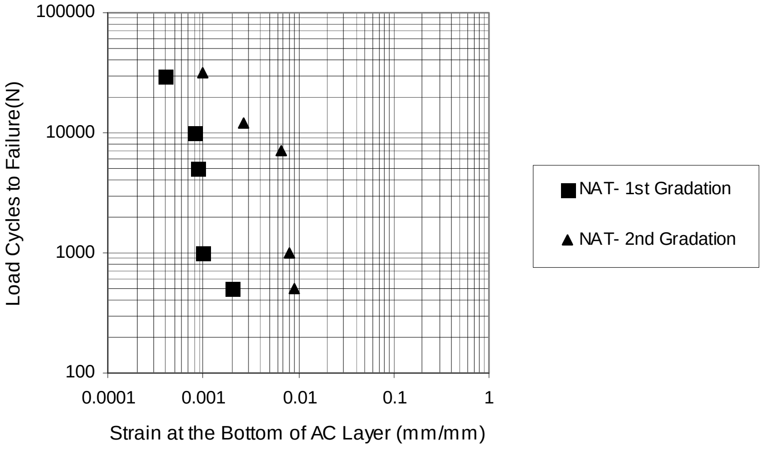


Figure 13. Number of load cycles to failure versus initial strain at the bottom of the asphalt concrete layer (NAT Test Results).

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