FATIGUE CHARACTERISTICS OF AN ASPHALT MIX CONTAINING A GEOTEXTILE

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Abstract : The main objective of this research was to evaluate the laboratory fatigue characteristics of asphalt concrete specimens without and with a geotextile using the Dartec machine. The tests were conducted in the controlled-stress sinusoidal loading mode using the four-point bending flexural fatigue test. Only one geotextile type i.e. Trevira Spunbond 011/140 and one location i.e. 1.0 cm from the bottom of the specimen, was investigated. All tests were carried out at room temperature. The results of the research indicated that including a geotextile in the asphalt concrete improved its fatigue characteristics. The effectiveness factor, i.e. the ratio of the number of cycle to failure for specimens with and without a geotextile at a given stress level ranges from 6.01 to 8.83.

Key words : Fatigue, Asphalt Concrete, Geotextile, Effectiveness Factor, Cracking Mechanism.

1. INTRODUCTION

1.1 Background

Failure of the road under traffic occurs when there is extensive cracking of the asphalt layer and excessive deformation of the surface. When the deformation is great it may also lead to cracking of the surface layer. Cracking not only destroys the structural integrity of the bound layer but allows water to enter the pavement with serious consequences for the performance of unbound material. Cracks are initiated by repetitions of tensile strain at the bottom of the layer and the cracks subsequently propagate upward through the asphalt layer.

In general, continuously-graded asphalt concrete (AC) has good resistance to permanent deformation but less resistant to cracking. It appears that the aggregate interlock and interparticle friction in asphalt concrete mix play an important role. In certain road sections in Java Island, when asphalt concrete is used as a pavement surface layer, the predominant failure mode is cracking, not rutting. The reasons could be the mix cannot withstand the combined effect of heavy traffic and thermal stress for a significant period of time. Then, a stronger asphalt layer is needed to withstand the combination of heavy axle loads and highly temperatures .

One way of possibly strengthening the asphalt layer is by using a geotextile material. Use of a geotextile in the asphalt layer is expected to reduce strain or deflection so that a thinner than conventional asphalt layer can be used or alternatively a longer pavement service life can be achieved at the same thickness.

1.2 Research Objectives

The objectives of this research program were:

a. To assess the laboratory fatigue characteristics of asphalt concrete specimens made without and with a geotextile using the Dartec machine.
b. To study the influence of a geotextile on the cracking mechanism and determine its effect on the number of cycles required for crack propagation.
c. To determine the effectiveness factor i.e. the ratio of the fatigue lives determined for specimens with (N_{fr}) and without (N_{fn}) a geotextile, N_{fr}/N_{fn}.

1.3 Scope of Work

Due to time constraints, this investigation was limited to the following:

a. The test was conducted in the controlled-stress sinusoidal loading mode using the four-point bending flexural fatigue test.
b. Only one location of the geotextile was investigated i.e. 1.0 cm from the bottom of the specimen.
c. Only one loading frequency (10 Hz) was used.
d. All tests were carried out at constantly room temperature.
e. To establish the fatigue relationships for specimens with and without a geotextile, five stress levels were investigated and not less than three specimens were tested at each stress level.

2. LITERATURE REVIEW

2.1 Fatigue Characteristics of Bituminous Mixtures

Under repeated traffic loading, the bottom of the asphalt layer in a flexible pavement experiences tensile strain that raises the possibility of fatigue cracking. The magnitude of the tensile stress or strain is dependent on the wheel load and on the overall stiffness and nature of the pavement.
Referring to Cooper et al (1974), for a mix tested under conditions of constant temperature and speed of loading, and where stress is the independent test variable, it was found that a reasonably linear relationship exists between applied stress and cycles to failure when plotted on a logarithmic basis.

The relationship can be expressed as:

$$N = K\,(1/\sigma)^n \qquad \text{.............. (1)}$$

Where : N = Number of cycles to failure at a particular dynamic stress level
σ = Maximum amplitude of the applied dynamic stress
K = Constant which depends on temperature and type of mix.
n = Slope factor of fatigue line

Mix variables which affect the stiffness are also going to affect the fatigue life of asphalt mixes. These variables are aggregate type and grading including filler, binder type and hardness, binder content, degree of mix compaction and resulting air void content. The two factors which appear to be of primary importance are binder content and voids content.

2.2 Geotextiles

The type of geotextile that is investigated in this research is called Trevira Spunbond 011/140. For the purposes of this research, the geotextile was cut into sheets of a dimensions 39 cm x 30 cm; the sheet was located one centimetre from the bottom of the asphalt specimen.
Trevira Spunbond 011/140 is 100% continuous filament polyester nonwoven needlepunched engineering fabric. Polyester can withstand temperatures up to 220°C (425°F) without significant shrinkage, thereby providing a "factor of safety" against potential fabric shrinkage caused by high asphalt temperatures. Additionally, Trevira polyester is resistant to hydrocarbons, permitting the use of cutbacks as tack and binder coats. The needlepunched continuous filament nonwoven structure provides high tensile strength and high elongation properties which allow the fabric to conform the road surface and to be installed in curves with a minimum of wrinkles. Trevira Spunbond 011/140 has been proven recyclable.

Tack coat is necessary to bond the geotextile to the pavement surface and to form a waterproof layer. Sufficient tack coat must be applied to insure adequate bond between the geotextile and the pavement surface and to saturate the geotextile. Trevira Spunbond 011/140 will absorb approximately 0,95 L/m^2 (0,20 gal/yd^2) of asphalt cement.

Affandi (1996) investigated the performance of Trevira 11/30 at different depths in a beam specimen of asphalt mix using the cyclic loading test. He reported that the different positions of the geotextile influence the deflection significantly. He concluded that locating the geotextile at 1/4 to 1/5 of the thickness from the bottom of the specimen resulted in the best performance.

3. LABORATORY PROCEDURES

3.1 Test of Materials

The bituminous mix investigated was asphalt concrete consisting of crushed aggregate combined with 60/70-penetration grade bitumen. The aggregate grading conformed to the Indonesian National Standard, SNI No: 1737-1989-F, mix Type II for wearing, levelling and binder courses as given in Table 1 and illustrated in Figure 1.
The coarse aggregate, fine aggregate and mineral filler used in this research were Banjaran crushed rock obtained from a quarry at Banjaran, Kabupaten Bandung.
The results of tests of the physical properties of the coarse aggregate, fine aggregate and filler are given in Table 2. It can be seen that all the quality meets the Bina Marga requirements for materials used in hot mix asphalt.
Measurement of the specific gravity of the aggregate based on back calculation of the maximum theoretical specific gravity of the actual mix indicated the specific gravity of the mixed aggregate to be 2.669.
The bitumen used in this study was 60/70-penetration grade, produced by Pertamina Cilacap. The results of tests on bitumen, given in Tables 3, 4, 5 and illustrated on Figure 2, showed that all the material meets the Bina Marga specifications.

3.2 Marshall Tests

The specimens for Marshall mix design were compacted using a standard Marshall hammer for heavily trafficked roads (75 blows to each face of the specimen). A summary of the mix properties at the optimum bitumen content is given in Table 6.

Table 6 indicates that the optimum percentage of 60/70 pen-grade bitumen is 6.125% by weight of mix. It can be seen also that the quality of the mix meets the Bina Marga requirements for asphalt concrete.

3.3 Fatigue Tests

All beam specimens used for the tests were sawed from a slab of 39 cm long, 30 cm wide, and 5 cm deep, prepared in the rolling-wheel compaction apparatus. Beam specimens dimensions are 30 cm long, 15 cm wide and 5 cm deep. The specimens were designated according to type as specimen without geotextile (NGT) and specimen with geotextile (GT).
In preparing the GT sprecimens, before placing the geotextile, the asphalt mix was lightly compacted in the steel mould to a thickness of one centimetre. Before the geotextile was placed on this layer, the surface was sprayed by a bitumen to make a bond between the geotextile and asphalt mix. Once the geotextile was placed, the remaining asphalt mix was added in the mould and the wheel compactor apllied to obtain a density comparable to Marshall's mix denstity.

The laboratory fatigue tests were conducted using the Dartec equipment located in the Aerodynamic Laboratory of the Bandung Institute of Technology. Because the temperature control facility was not available, all tests were carried out at nearly-constant room temperature (26 to 27°C), checked regularly by a manual temperature measurement.
Specimens were tested at five levels of stress in the controlled-stress mode of loading. In a preliminary investigation to determine the stress levels that would result in fatigue lives ranging from 1,000 to 100,000 cycles, 7 NGT specimens and 3 GT specimens were tested over a range of stress levels. All tests were conducted at a frequency of 10 Hz (ten cycles per second) under a sinusoidal wave load.
The initial peak-to-peak load amplitude and deformation magnitudes were recorded and automatically saved on the computer hard drive. The test terminated when the specimen was completely fractured or when the actuator of the equipment did not respond. Failure was defined at the point where there was a significant change in the slope of the deflection curve versus cycles as shown schematically on the Figure 3.

4. FATIGUE TEST RESULTS

The parameters used to evaluate the fatigue characteristics of the mix without and with a geotextile were the number of cycles to failure (N_f) and the effectiveness factor (EF), the initial strain (ε) and the initial stiffness (S), the number of cycles needed to initiate and propagate cracks (N_i and N_p, respectively), and the cracking mechanism. The results were shown from Figure 4 to Figure 9).

4.1 Cycles to Failure

The analysis of fatigue data given in Tables 7 and 8 indicates that asphalt concrete without and with geotextile (NGT and GT) have significant differences in the number of cycles to failure (N_f). At a given stress level, the number of cycles to failure of the NGT specimens is less than that of the NGT specimens (see Figure 4).
The ratio of cycles to failure for GT specimens to that for NGT specimens is described in terms of the effectiveness factor, EF. The values of EF at each stress level indicate that the effect of the geotextile is to increase the fatigue life of the bituminous mixture. The EF value reduces as the magnitude of the stress increases and ranges from 6.01 to 8.83 (see Figure 9).

As with all fatigue testing, there is some scatter in the test data. While all specimen tested at a given set of condition are nominally identical, nevertheless in reality all will not be the same. In bituminous material, the distribution of air voids and aggregate particle is random.

4.2 The Initial Strain, Stiffness and Cycles to Crack Propagation.

The initial strain (ε) was calculated using the dynamic deflection value at the 50th cycle (SHRP-A-404, 1994) and the equation for the four-point flexural beam test given in Appendix A. During the test, the deflection at the 50th cycle of every specimen was recorded.
Based on the simple equation $\sigma = S.\varepsilon$, the initial stiffness (S) is defined as the slope of the regression line of the stress – initial strain relationship. Using this linear relationship equation the initial stiffness can be determined. At each stress level the NGT and GT specimens have initial strain and stiffness values that are not significantly different.
The initial stiffness (S) of asphalt concrete without geotextile (NGT) is 2,738 MPa and the initial strain (ε) ranges from 0.9928×10^{-4} to 2.7457×10^{-4}. The initial stiffness (S) of asphalt concrete with geotextile (GT) is 2,940 MPa and the initial strain (ε) ranges from 0.9740×10^{-4} to 2.6067×10^{-4} (see Figure 5 and Tables 9 and 10).
The ratio between the initial stiffness of the GT and the NGT specimens is 1.07 and the ratio between the initial strain of the GT and the NGT specimens ranges from 0.95 to 0.98. The inclusion of a geotextile in asphalt concrete appears not to influence the initial stiffness (see Figure 6).
The number of cycles required to propagate cracks (N_p) in asphalt concrete with and without geotextile was measured from observation of the initial crack at the bottom of the specimen until failure. The investigation indicates a significant difference in the number of crack propagation cycles for the two types of specimen.The NGT specimen shows a lower number of cycles for crack propagation (N_p) than the GT specimen (see Figure 7).

4.4 Cracking Mechanism in Specimens

The cracking mechanism under repeated load of specimens without a geotextile is illustrated in Figure 10 which shows the propagation of the crack from the bottom upward. This specimen type has a short crack propagation time; cracking always occurs in the area of maximum bending moment and propagates from the bottom to the top. This mechanism indicates that the specimen failure always as a result of the maximum stress applied. The number of cycles for initial cracking (at the bottom) varies depending on the stress level, but generally, the initial crack always occurs when the cumulative deflection is approximately 20 mm.
The cracking mechanism under repeated load of specimens with a geotextile (GT) is illustrated in Figure 11. The crack propagation was influenced by the geotextile which forms an interface between the one centimetre thick bottom layer and the four centimetre thick top layer. The initial crack occurs at the bottom in the area of maximum bending moment. At the same stress level, the number of cycles at which the initial cracking occurs is higher than for specimens without the geotextile as shown in Figure 6. The inclusion of a geotextile in the asphalt concrete improves its elastic recovery as indicated by the fact that the number of cycles for initial cracking (at the bottom of the beam) was longer. The magnitude of the cumulative deflection at initial cracking is approximately 20 mm. The propagation of cracking follows the pattern shown in Figure 10 and 11. The initial crack occurs at the bottom in the area of maximum bending moment and propagates upward to the bottom of the geotextile. In the second stage of propagation, the crack is arrested by the reinforcing layer for a certain number of cycles. In this stage, the bitumen-bonding layer has a significant

influence. In the next stage, the crack continues to propagate upward to the surface in the area of maximum bending moment. This test was terminated when the crack reaches the surface; failure was defined as the point where there was a significant increase in the slope of the deflection curve versus cycles.

5. CONCLUSIONS

Within the limits of this study, the following principal conclusions can be summarised:

a. Use of a geotextile in asphalt concrete improves its fatigue characteristics. The ratio of the number of cycles to failure for the asphalt concrete with and without the geotextile is described in terms of the effectiveness factor, EF, and ranges from 6.01 to 8.83, depending on stress level.
b. The inclusion of a geotextile in the asphalt concrete appears not to influence significantly the initial stiffness and initial strain of the fatigue test results.
c. The number of cycles for crack propagation (Np) of the asphalt concrete with a geotextile is greater than that of the asphalt concrete without a geotextile. The ratio of the number of cycles for crack propagation for the asphalt concrete with and without a geotextile, ranges from 38.74 to 43.37. At a given stress level the number of cycles to crack initiation for the specimen without a geotextile is greater than the specimen containing a geotextile, although in both cases, crack initiation occurs when cumulative deflection is approximately 20 mm.
d. Analysis of the cracking mechanism in the asphalt concrete specimen without a geotextile showed that the cracking always occurs in the area of maximum bending moment and propagates from the bottom to the top. This mechanism indicates that the specimen failure always as a result of the maximum stress applied. In the asphalt concrete with a geotextilet, the initial cracking occurs at the bottom in the area of maximum bending moment, propagates upward to the bottom of the geotextile and then the crack is arrested by the geotextile for a certain number of cycles. After that, the crack continues to propagate upward to the surface in the area of maximum bending moment.
e. The application of this research to the field design needs a full scale tests of pavement structure, in order to observe the "bonding" characteristics of pavement layer and to develop a "calibrated" model for predicting the fatigue life of the pavement.

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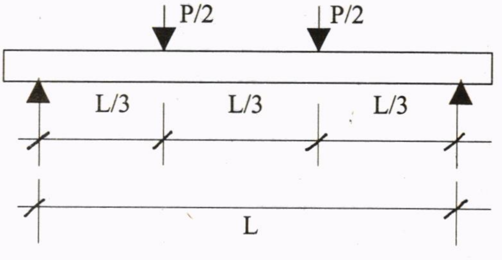
APPENDIX

FORMULAE USED IN THE ANALYSIS

Formulas used to calculate the tensile stress, strain and stiffness of a fatigue specimen, based on 4-point bending test, as shown, are :



Stress, $\sigma = M/W \rightarrow W = bh^2 / 6$, Initial Strain, $\in = 108\ h\ \delta_{50} / (23L^2)$

Initial Stiffness, $S = \sigma/\in$

Where :

M	=	the maximum bending moment
b	=	the width of the specimen
L	=	the length of the specimen
h	=	the thickness of the specimen
P	=	load
σ	=	maximum stress
$\in$	=	initial strain
S	=	initial stiffness
δ_{50}	=	the dynamic deflection at the 50^{th} cycle

Table 1 Grading Limits for Gradation Type II of the Bina Marga Specification

Sieve Size	Grading Band (%)	Middle	
		Passing (%)	Retained (%)
3/4" (19.10 mm)	100	100	0
1/2" (12.70 mm)	75 - 100	87.5	12.5
3/8" (9.520 mm)	60 - 85	72.5	15
No.4 (4.760 mm)	35 - 55	45	27.5
No.8 (2.380 mm)	20 - 35	27.5	17.5
No.30 (0.590 mm)	10 - 22	16	11.5
No.50 (0.279 mm)	6 - 16	11	5
No.100 (0.149 mm)	4 - 12	8	3
No.200 (0.074 mm)	2 - 8	5	3
PAN			5
			100

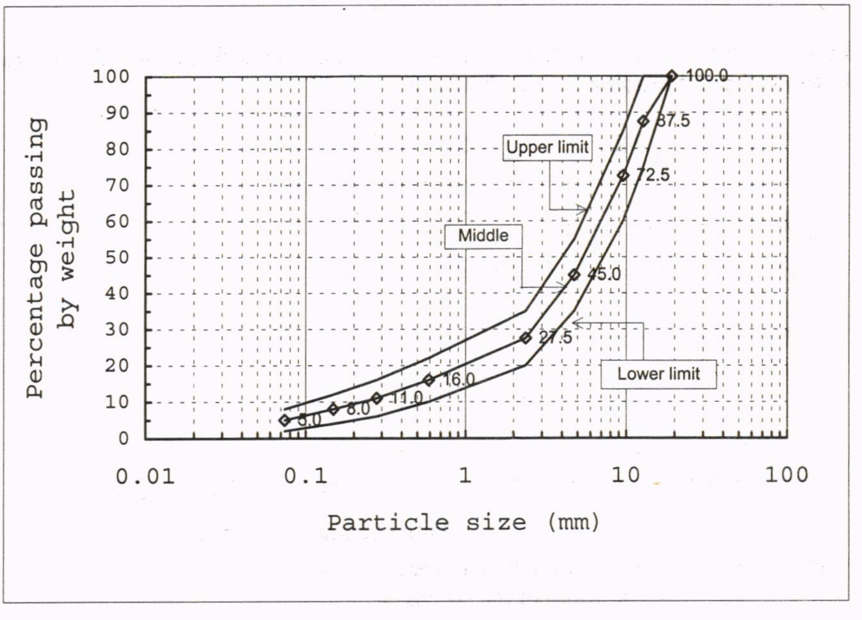


Figure 1 Grading Limits for Gradation Type II of the Bina Marga Specification

Table 2 Properties of Aggregates and Filler

Material	Property	Units	Sample 1	Sample 2	Sample 3	Average	Specification Min	Specification Max	Method of Test
Coarse aggregate	Specific Gravity:								
	- Bulk	-	2.657	2.665	-	2.661	2.5	-	SNI 1969 - 1990 F
	- SSD	-	2.703	2.704	-	2.703	-	-	SNI 1969 - 1990 F
	- Apparent	-	2.784	2.774	-	2.779	-	-	SNI 1969 - 1990 F
	Absorption	%	2.001	2.093	-	2.047	-	3.0	SNI 1969 - 1990 F
	Abrasion	%	19.040	21.500	-	20.270	-	40.0	SNI 3-2417-1990 F
	Affinity for bitumen	%	>95	>95	-	>95	95	-	SNI 1726 - 1990 F
	Flakiness index	%	19.900	20.900	-	20.400	-	25.0	BS - 892-1975
Fine aggregate	Specific Gravity:								
	- Bulk	-	2.657	2.665	-	2.661	2.5	-	SNI 1969 - 1990 F
	- SSD	-	2.703	2.704	-	2.703	-	-	SNI 1969 - 1990 F
	- Apparent	-	2.784	2.704	-	2.744	-	-	SNI 1969 - 1990 F
	Absorption	%	1.709	1.482	-	1.595	-	5.0	SNI 1969 - 1990 F
	Sand equivalent	%	64.840	-	-	64.840	-	50.0	AASHTO T-176-81
Filler	Specific Gravity	-	2.710	2.712	2.696	2.706	2.5	-	SNI 1969 - 1990 F

Table 3 Properties of 60/70 Pen-Grade Bitumen

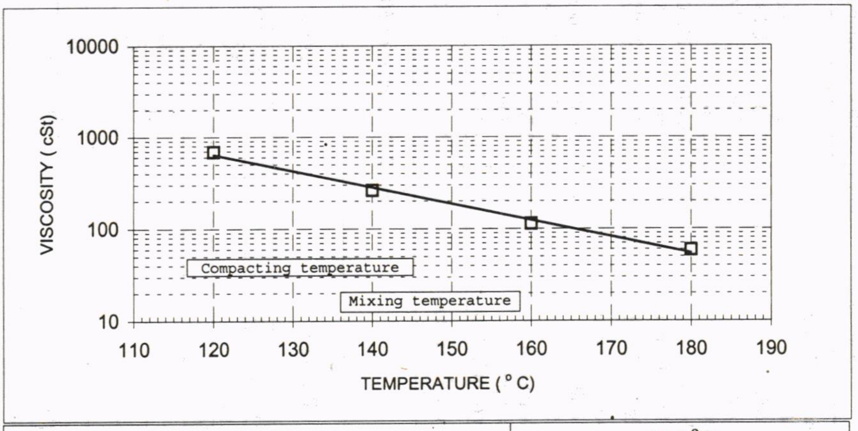
Property	Units	Test Results	Specification Min	Specification Max	Method of Test
Penetration at 25 C, 100 g, 5 sec.	0.1 mm	65.8	60	79	SNI 06 - 2456 -1991
Softening point ($T_{R\&B}$)	°C	49.4	48	58	SNI 06 - 2434 -1991
Ductility, 25 C, 5 cm/minute	cm	>140	100	-	SNI 06 - 2432 -1991
Solubility(C_2HCl_3)	%	>99	99	-	ASTM D 2042
Flash point	°C	323	200	-	SNI 06 - 2433 -1991
Specific gravity	-	1.0308	1.0	-	SNI 06 - 2488 -1991
Thin Film Oven Test, 163 C, 5 hrs. °	%	0.0018	-	0.8	SNI 06 - 2441 -1991
Mixing temperature (Visc.170 cSt)	°C	152	-	-	-
Compacting temperature(Visc.280 cSt)	°C .	140	-	-	-
after Thin Film Oven Test (TFOT)					
Penetration at 25 C, 100 g,° 5 sec.	%Original	83.6	54	-	SNI 06 - 2456 -1991
	0.1 mm	55	-	-	
Softening point ($T_{R\&B}$)	°C	50.8	-	-	SNI 06 - 2434 -1991

Table 4 Penetration and Temperature Susceptibility of Bitumen, Before and After TFOT

Penetration (100 gr, 5 seconds, 0.1 mm)			Slope of log Pen-Temp (A) and Penetration Index (PI)	
Temperature (°C)	Before TFOT	After TFOT	25 °C - 35 °C	
			Before TFOT	
		% original	A	PI
25	65.8	55	0.03596	0.722
		83.6	After TFOT	
35	150.6	135	A	PI
		89.6	0.03900	0.170

Table 5 Determination of Mixing and Compacting Temperatures

Temperature (°C)	Time (seconds)	cSt
120	326	690
140	126	263
160	56	114
180	30	59



Mixing temperature (170 cSt)	152 °C
Compacting temperature (280 cSt)	140 °C

Figure 2 The Kinematic Viscosity-Temperature Relationship

Table 6 Summary of Results of Marshall Analysis

Mix Properties	Units	Value
Optimum Bitumen Content	%	6.125
Voids in Mineral Aggregate	%	17.658
Voids Filled with Bitumen	%	73.613
Voids in Mix	%	4.667
Unit Weight	gr/cm^3	2.230
Stability	kg	893.752
Flow	mm	3.814
Marshall Quotient	kg/mm	238

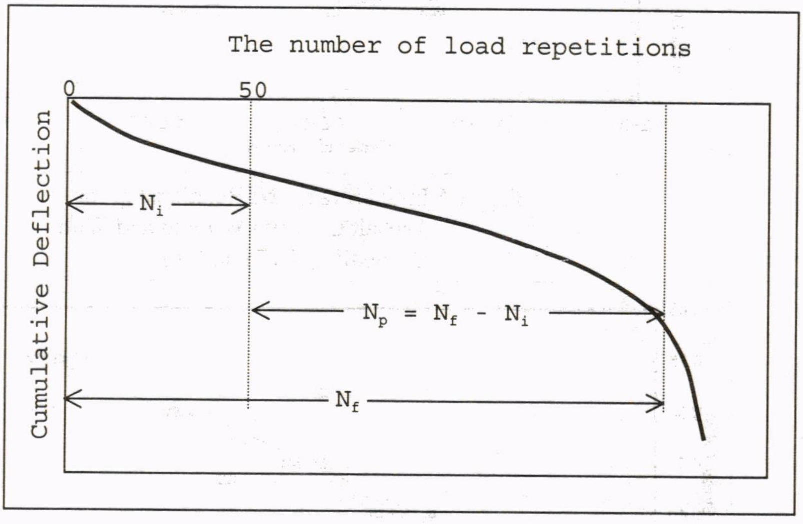


Figure 3 Definition of Initial and Failer Condition

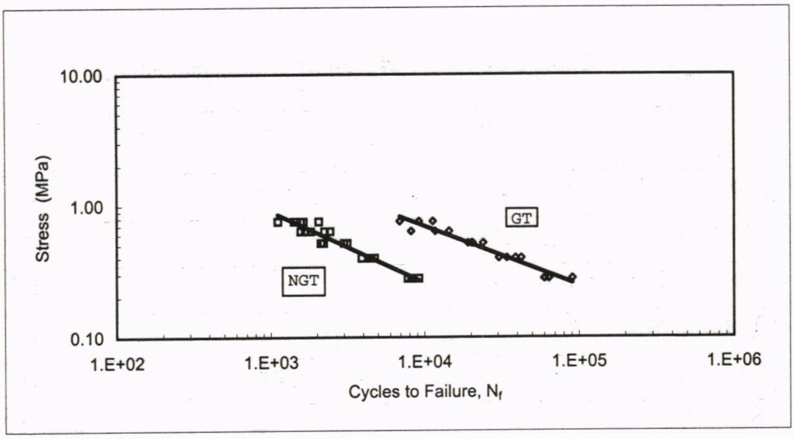


Figure 4 Stress - Nf Relationship for Asphalt Concrete Without and With Geotextile (NGT and GT)

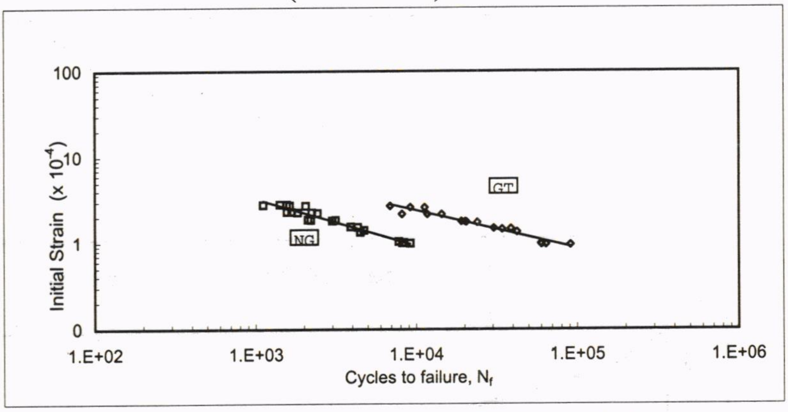


Figure 5 Initial Strain - Nf Relationship for Asphalt Concrete Without and With Geotextile (NGT and GT)

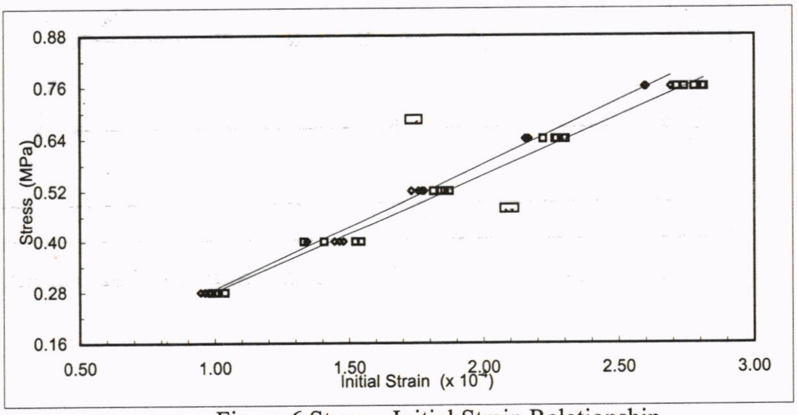


Figure 6 Stress - Initial Strain Relationship for Asphalt Concrete Without and With

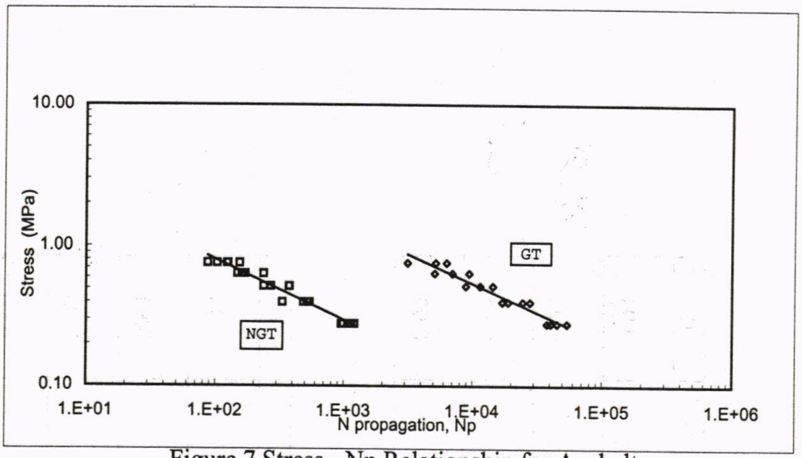


Figure 7 Stress - Np Relationship for Asphalt Concrete Without and With Geotextile (NGT and GT)

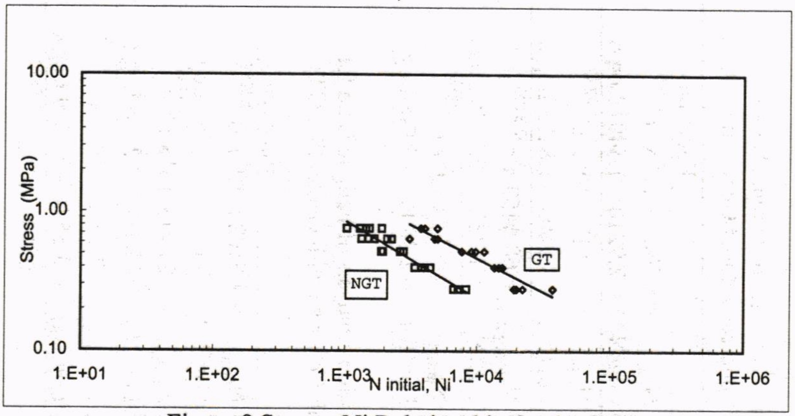


Figure 8 Stress - Ni Relationship for Asphalt Concrete Without and With Geotextile (NGT and GT)

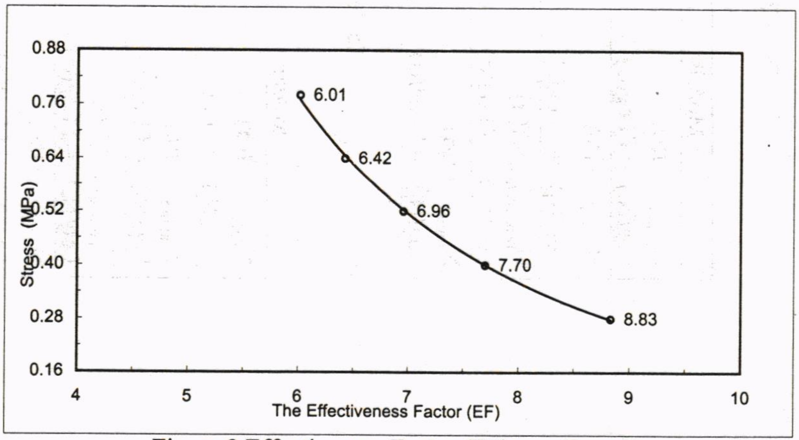


Figure 9 Effectiveness Factor (EF) as a Function

Table 7 Regression Analysis of Fatigue Data for Asphalt Concrete without Geotextile (NGT)

Models	Equation	R^2
$N_{failure} = f(\sigma)$ $Log(N_f) = f\ Log(\sigma)$	$N_{failure} = 8.3364 \times 10^2 \times \sigma^{-1.8401}$ $Log(N_f) = 2.9210 - 1.8401\ Log\ \sigma$	0.94
$N_{failure} = f(\varepsilon)$ $Log(N_f) = f\ Log(\varepsilon)$	$N_{failure} = 8.7147 \times 10^3 \times \varepsilon^{-1.8283}$ $Log(N_f) = 3.9403 - 1.8283\ Log\ \varepsilon$	0.94
$N_{propagation} = f(\sigma)$ $Log(N_p) = f\ Log(\sigma)$	$N_{propagation} = 60.6459 \times \sigma^{-2.3106}$ $Log(N_p) = 1.7828 - 2.3106\ Log\ \sigma$	0.95
$N_{initial} = f(\sigma)$ $Log(N_i) = f\ Log(\sigma)$	$N_{initial} = 7.5971 \times 10^2 \times \sigma^{-1.8148}$ $Log(N_i) = 2.8806 - 1.8148\ Log\ \sigma$	0.92

Table 8 Regression Analysis of Fatigue Data for Asphalt Concrete with Geotextile (GT)

Models	Equation	R^2
$N_{failure} = f(\sigma)$ $Log(N_f) = f\ Log(\sigma)$	$N_{failure} = 4.5102 \times 10^3 \times \sigma^{-2.2252}$ $Log(N_f) = 3.6542 - 2.2252\ Log\ \sigma$	0.94
$N_{failure} = f(\varepsilon)$ $Log(N_f) = f\ Log(\varepsilon)$	$N_{failure} = 7.2140 \times 10^4 \times \varepsilon^{-2.2576}$ $Log(N_f) = 4.8582 - 2.2576\ Log\ \varepsilon$	0.94
$N_{propagation} = f(\sigma)$ $Log(N_p) = f\ Log(\sigma)$	$N_{propagation} = 2.2773 \times 10^3 \times \sigma^{-2.4239}$ $Log(N_p) = 3.3574 - 2.4239\ Log\ \sigma$	0.93
$N_{initial} = f(\sigma)$ $Log(N_i) = f\ Log(\sigma)$	$N_{initial} = 2.0210 \times 10^3 \times \sigma^{-2.0893}$ $Log(N_i) = 3.3056 - 2.0893\ Log\ \sigma$	0.89

Table 9 Values of Initial Strain and Stiffness, Ni, Np and Nfn for Asphalt Concrete without Geotextile (NGT) (Based on Regression Analysis)

Stress (MPa)	Initial Strain (10^{-4})	Initial Stiffness (MPa)	N initial (Ni) (Cycles)	N propagation (Np) (Cycles)	N failure (Nfn) (Cycles)
0.28	0.9928	2,738	7,655	1,149	8,675
0.40	1.4310	2,738	4,007	504	4,500
0.52	1.8693	2,738	2,489	275	2,777
0.64	2.3075	2,738	1,708	170	1,895
0.76	2.7457	2,738	1,250	114	1,381

Table 10 Values of Initial Strain and Stiffness, Ni, Np, Nfr and the Effectiveness Factor for Asphalt Concrete with Geotextile (GT) (Based on Regression Analysis)

Stress (MPa)	Initial Strain (10^{-4})	Initial Stiffness (MPa)	N initial (Ni) (Cycles)	N propagation (Np) (Cycles)	N failure (Nfr) (Cycles)	The Effectiveness Factor (EF=Nfr/Nfn)
0.28	0.9740	2,940	28,882	49,826	76,627	8.83
0.40	1.3822	2,940	13,708	20,989	34,649	7.70
0.52	1.7904	2,940	7,924	11,112	19,326	6.96
0.64	2.1985	2,940	5,135	6,718	12,175	6.42
0.76	2.6067	2,940	3,586	4,429	8,306	6.01

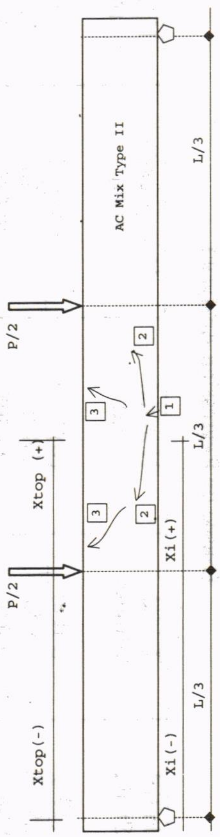


Figure 10 Cracking Mechanism of NGT Specimen

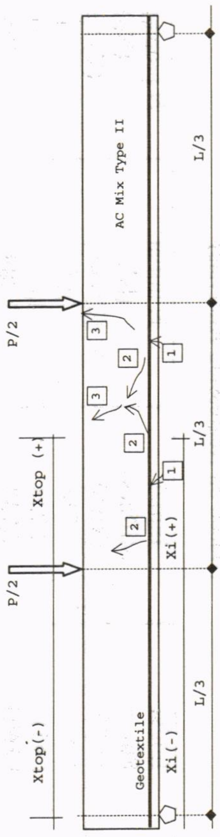


Figure 11 Cracking Mechanism of GT Specimen