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Estimation of the Fatigue Endurance Limit of HMAC for Perpetual Pavements

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Abstract: A simplified procedure was described to estimate the FEL of three kinds of hot-mix asphalt concrete (HMAC) without doing any fatigue tests. The procedure required two fundamental properties of HMAC, tensile strength under different temperatures and strain rates, and flexural stiffness under different stain levels. This information can reliably be obtained in simple tests, which are the monotonic uniaxial tensile test (MUTT) and the four-point bending test (FPBT). A new parameter, the initial stress ratio R_{initial}, was introduced to connect these two tests, which was defined as the ratio of applied initial stress and tensile strength of the specimen. At last the FEL can be expressed as a function of the initial flexural stiffness, frequency and temperature. Obviously, this procedure has the potential to be very useful in view of long-life pavement design and time consuming traditional fatigue tests.

Key words: fatigue endurance limit; hot-mix asphalt concrete; tensile strength; flexural stiffness; initial stress ratio

1 Introduction

Due to the high traffic volume, and the increase of the number of heavy vehicles, various types of distress such as fatigue cracking and rutting are getting worse and worse in asphalt pavements. These distresses are associated with the increase of maintenance cost and resource consumption. To improve this situation, perpetual (or long-life) pavements were introduced and studied by some researchers[1-3]. By repairing and rehabilitating surface distresses periodically, the perpetual pavement is capable of maintaining the pavement performance over 40 years without major structural reconstruction. In perpetual pavement design, the tensile strain ε_t at the bottom of asphalt concrete layer resulting in the fatigue cracking is a critical parameter. If the tensile strain ε_t is maintained at some level below the fatigue endurance limit (FEL) of asphalt concrete, the pavement will have infinite fatigue life in theory.

The principle of FEL has been proved[4, 5] and normally assessed through various fatigue tests in the lab. However, these fatigue tests are too costly and time consuming. This paper described a simplified procedure to evaluate the FEL of asphalt mixtures based on results of some relatively simple and inexpensive tests. Since the FEL depends on the temperature and frequency[6], this study just concerned the case at 20 ℃ and 8 Hz.

2 Experimental

The experiments and the test data came from the two previous research projects carried out at the Road and Railway Engineering Section of the Delft University of Technology[7, 8].

2.1 Materials

Three kinds of binders were used, denoted as binder 599-40, 602-42 and 604-41. The binder 599-40 were an unmodified binder and the other two binders were polymer modified binders. Crushed Norwegian granite is used for mixture. The fine aggregate was standard type river sand. Factory produced filler type, Wigro, was used. The type of mixture was a standard base course mixture in the Netherlands, called stone asphalt concrete (STAC) 0/22. Table 1 represents the mixture compositions.

2.2 Test methods

Monotonic uniaxial tension test (MUTT) and four-point bending test (FPBT) were performed on all mixtures. The MUTT was performed on the cylindrical specimens at three different temperatures (5, 20 and 40 ℃) and three strain rates. During each test the load-displacement curve was determined.

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Table 1 Mixture compositions

Sieve/mm	22.4-16	16-11.2	11.2-8	8-5.6	5.6-2	2-0(sand)	Filler	Binder	Total
wt%	5.1	11.6	11.3	12.91	13.68	34.42	6.6	4.4	100

FPBT were carried out in the deflection-controlled mode. 8 strain levels are selected in the range from 50 to 200 (μm/m). Fatigue life was defined as the number of load repetitions, $N_{f,\ 50}$, at which the stiffness of the specimen was reduced to half its initial value. All fatigue tests were performed at a temperature of 20 ℃ and a frequency of 8 Hz. Fig.1 shows the loading configuration as used in both tests.

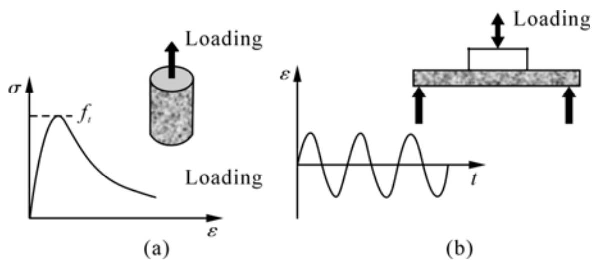

Fig.1 Loading configurations for MUTT (a) and FPBT (b)

3 Results and Discussion

3.1 Tensile strength in MUUT

Fig.2 shows an example of the relation between tensile strength and strain rate. According to the study of Erkens[9], the relation between the tensile strength (f_t [N/mm^2]), temperature (T [K]) and strain rate ([$\dot{\varepsilon}$ %/sec]) can be expressed using equation (1). Based on the results of the tensile tests, the regression constants were determined with the statistic package SPSS 9.0[10], and present in Table 2.

$$f_t = a\left[1 - \frac{1}{1+\left[\dot{\varepsilon}\, e^{\left(b+\frac{c}{T}\right)}\right]^d}\right] \tag{1}$$

where, a, b, c and d are the coefficients.

Table 2 Regression constants of three asphalt mixtures

Types of binder	Regression constants a	b	c	d	r^2	No. of data points
599-40	5.05	-87.02	26310	1.11	0.96	10
602-42	5.92	-64.15	19880	0.75	0.93	10
604-41	5.50	-70.99	21770	1.56	0.97	10

3.2 Fatigue life in FPBT

Fatigue results are shown in Fig.3. The value of fatigue endurance limit $\varepsilon_{\text{limit}}$ is not established in this project, because it would take too much time to find out these strain levels.

3.3 Initial stress ratio R_{initial}

For combining the results of the two tests, MUTT and FPBT, the initial stress ratio R_{initial} was introduced, which was defined as the ratio of applied initial stress and tensile strength of the specimen.

$$R_{\text{initial}} = \sigma_{\text{initial}} / f_t \tag{2}$$

where, σ_{initial} is the peak value of stress [MPa] at the 50th cycle in the four-point bending fatigue test; f_t the tensile strength [MPa] of the beam.

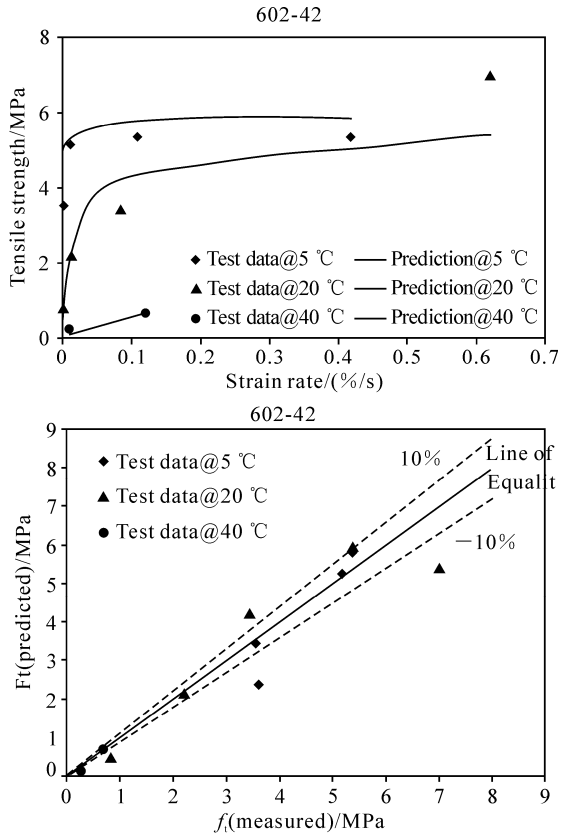

Fig.2 An example of the test results of MUUT

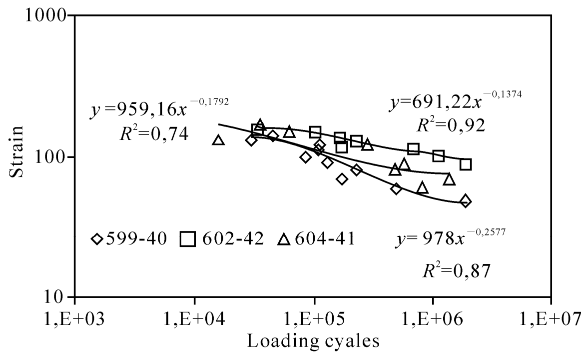

Fig.3 Fatigue relationships in FPBT

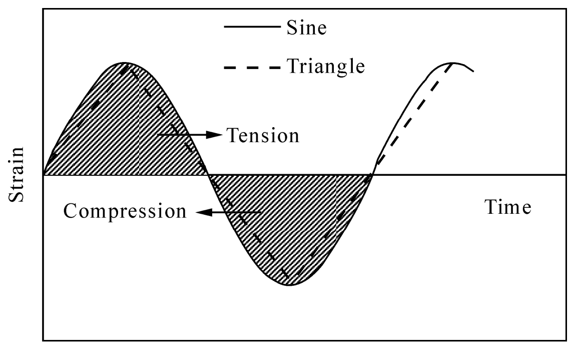

Fig.4 Conversion from a sine signal to a triangle signal

In MUTT, the strain rate is constant. However, during FPBT, the strain rate is not constant and follows a sine shape. Therefore the sine is converted into a triangle signal with the same maximum strain level and duration time, this is shown in Fig.4. In fact, the upper and lower semi-sections of beam are alternately loaded in tension and compression. Since the material is weaker in tension than in compression, the former loading case is the critical one. The strain rate of this alternating triangle signal is considered to be an acceptable approximation and can be computed as follows[9]:

$$\dot{\varepsilon} = 4(\varepsilon \cdot f) \tag{3}$$

where, $\varepsilon =$ strain amplitude m/m %, $f=$strain signal frequency, Hz.

Using this approximation for the strain rate, the tensile strength f_t at 20 ℃ is computed by using equation (1). Thus the initial stress ratio of applied stress and tensile strength in the FPBT can be calculated. As a result, each fatigue life corresponds to a different initial stress ratio, as shown in Fig.5. The relationships between R_{initial} and $N_{\text{f,50}}$ of these three asphalt mixture have a similar tendency. In general, $N_{\text{f,50}}$ increases when R_{initial} decreases. Taking into account the shape and the trend of the data points, the following regression equation can be used to simulate the R-N (initial stress ratio versus fatigue life) lines:

$$R_{\text{initial}} = R_0 - R_1\left(1-e^{-aN}\right)^b \tag{4}$$

where, a, b, R_0 and R_1 are regression constants, as shown in Table 3.

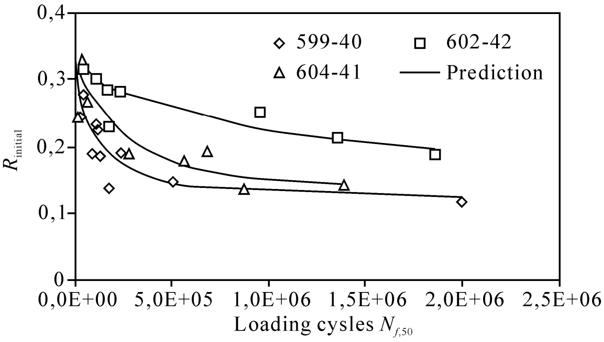

Fig.5 Initial stress ratio versus fatigue life $N_{\text{f,50}}$

The correlation coefficients R^2 of the equations for these three mixtures are all reasonable, as the average value of R^2 of the three asphalt mixes is around 0.75. Therefore it is believed that the equation (4) is capable of providing a fair prediction for the R-N lines.

Table 3 Regression constants and equations of three kinds of binder

Binder types	Regression constants				Regression equation	R^2
	R_0	R_1	a	b		
599-40	0.33	0.21	3.63E-06	0.51	$R_{\text{initial}}=0.33-0.21 \cdot (1-e^{-3.63E-06)N})^{0.51}$	0.739
602-42	0.34	0.17	7.94E-07	0.55	$R_{\text{initial}}=0.34-0.17 \cdot (1-e^{-7.94E-07)N})^{0.55}$	0.747
604-41	0.34	0.20	2.74E-06	0.67	$R_{\text{initial}}=0.34-0.20 \cdot (1-e^{-(2.74E-06)N})^{0.67}$	0.782

Furthermore, it is noteworthy for these three mixtures that the initial stress ratio, R_{initial}, tends to a limit value, R_{limit}, when the fatigue life, becomes infinite. In other words, the specimen will not have any fatigue damage under the loading condition $R_{\text{initial}}=R_{\text{limit}}$, which relates to the fatigue endurance limit, $\varepsilon_{\text{limit}}$.

3.4 Limit value of initial stress ratio R_{initial}

The value of R_{limit} can be calculated for three asphalt mixtures 599-40, 602-42 and 604-41 by using equation (4) with the assumption of $N \to \infty$. Table 4 presents the calculation of R_{limit} for the three mixtures.

Table 4 R_{limit} for the three mixtures

Types of binder	$R_{\text{limit}} = R_0 - R_1$
599-40	0,1196
602-42	0,1750
604-41	0,1455

According to the definition of R_{initial}, the expression of R_{limit} is given by:

$$R_{\text{limit}} = \frac{\sigma_{\text{limit}}}{f_{t,\text{limit}}} = \frac{\varepsilon_{\text{limit}} \cdot S_{\text{limit}}}{f_{t,\text{limit}}} \Rightarrow \varepsilon_{\text{limit}} = \frac{R_{\text{limit}} \cdot f_{t,\text{limit}}}{S_{\text{limit}}} \tag{5}$$

where, $\varepsilon_{\text{limit}}$ is the fatigue endurance limit [m/m], which is the amplitude of the strain level that can be applied to the material without causing fatigue failure; S_{limit}, σ_{limit} and $f_{t,\text{limit}}$ are the initial stiffness, the initial stress and the tensile strength, all in [MPa], of the specimen under the strain level of $\varepsilon_{\text{limit}}$, respectively.

From Fig.6, it can be seen that the initial stiffness is not affected too much by the strain level and fluctuates around its mean value. Therefore the mean value of the initial stiffness, $S_{m,\text{initial}}$, under the same condition, could be considered to be a rational approximation of S_{limit}.

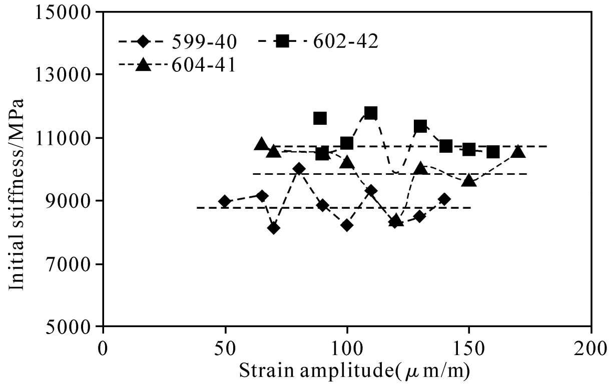

Fig.6 Initial stiffness *vs* strain amplitude in FPBT

Based on the calculation of the tensile strength f_t in FPBT discussed in section 3.1, the following equation can be obtained:

$$f_{t,\mathrm{limit}} = a\left[1-\frac{1}{1+\left[\dot{\varepsilon}e^{\left(b+\frac{c}{T}\right)}\right]^d}\right] = a\left[1-\frac{1}{1+\left[4\cdot f\cdot\varepsilon_{\mathrm{limit}}\cdot 100\cdot e^{\left(b+\frac{c}{T}\right)}\right]^d}\right] \tag{6}$$

where, a, b, c and d are the coefficients; T the temperature in the test, K; f the strain signal frequency, Hz.

The equation (6) is substituted into equation (5) and $S_{m,\mathrm{initial}}$ is used instead of S_{limit}:

$$\varepsilon_{\mathrm{limit}} = \frac{R_{\mathrm{limit}}}{S_{m,\mathrm{initial}}}\cdot a\left[1-\frac{1}{1+\left[4\cdot f\cdot\varepsilon_{\mathrm{limit}}\cdot 100\cdot e^{\left(b+\frac{c}{T}\right)}\right]^d}\right] \tag{7}$$

From the monotonic tests, the coefficients a, b, c and d can be obtained for a single mixture. The only remaining problem is to find out if a relationship between R_{limit} and $S_{m,limit}$ can be established.

In Fig.7, the limit value of the initial stress ratio R_{limit} is proportional to the mean value of the initial stiffness. Although three data points are not enough for regression, it seems that there is a linear correlation between R_{limit} and $S_{m,\mathrm{limit}}$. So the relation between R_{limit} and $S_{m,\mathrm{initial}}$ for the asphalt mixtures might possibly be described by:

$$\frac{R_{\mathrm{limit}}}{S_{m,\mathrm{initial}}} = (2.71\times10^{-5}) - \frac{0.1233}{S_{m,\mathrm{initial}}} \tag{8}$$

The equation (7) can be changed as follows:

$$\varepsilon_{\mathrm{limit}} = \left[\left(2.71\times10^{-5}\right)-\frac{0.1233}{S_{m,\mathrm{initial}}}\right]\cdot a\left[1-\frac{1}{1+\left[4\cdot f\cdot\varepsilon_{\mathrm{limit}}\cdot 100\cdot e^{\left(b+\frac{c}{T}\right)}\right]^d}\right] \tag{9}$$

If the mean value of initial stiffness of a mixture is known in the FPBT with the given frequency and temperature, $\varepsilon_{\mathrm{limit}}$ could be calculated by solving equation (9) based on the test results of monotonic tensile tests, as shown in Table 5.

Table 5 The values of $S_{m,\mathrm{initial}}$ and $\varepsilon_{\mathrm{limit}}$ for three asphalt mixtures

Types of mixtures	$S_{\mathrm{m,initial}}$/GPa	$\varepsilon_{\mathrm{limit}}$ (10^{-6} m/m)
599-40	8.9	50
602-42	10.8	80
604-41	10.1	75

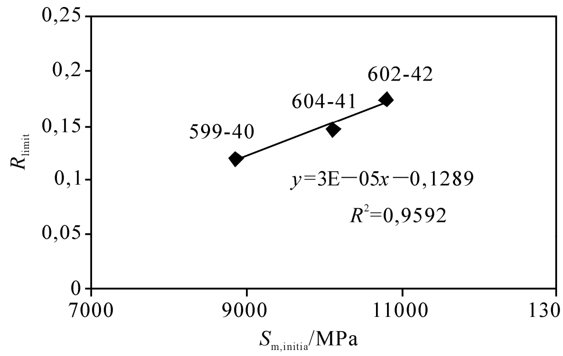

Fig.7 The relationship between R_{limit} and $S_{m,\mathrm{initial}}$

This finding presents a simple protocol for establishing a fatigue endurance limit $\varepsilon_{\mathrm{limit}}$, which can be expressed as a function of the temperature, frequency, the mean value of the initial stiffness and the tensile strength. Using monotonic test, the coefficients a, b, c and d can be calculated. The initial stiffness is measured in FPBT at different strain levels without running test to failure. Maybe it is possible that the initial stiffness S_{initial} can be estimated from different types of tests, however, more detailed research is need.

4 Conclusions

a) The initial stress ratio, R_{initial}, drops steeply for a short fatigue life $N_{\mathrm{f,50}}$ and its speed becomes slowly for long fatigue lives. When the fatigue life tends to infinity, R_{initial} remains constantly. The equation of $R_{\mathrm{initial}}=R_0-R_1(1-e^{-aN})^b$ could be used to describe the relation between R_{initial} and $N_{\mathrm{f,50}}$.

b) It seems that there is a linear correlation between initial stress ratio $R_{m,\mathrm{limit}}$ and the mean value of initial stiffness, $S_{m,\mathrm{initial}}$ with a high coefficient of R^2. However, the linear relationship between R_{limit} and $S_{m,\mathrm{initial}}$ is determined from only three kinds of asphalt mixtures, it is just an approximation and need to be proved by testing more different kinds of asphalt mixtures.

c) The fatigue endurance limit $\varepsilon_{\mathrm{limit}}$ can be expressed by the mean value of initial stiffness $S_{m,\mathrm{initial}}$, the frequency, the temperature and the coefficients of equation of tensile strength. This relationship allows the calculation of fatigue endurance limit without doing any fatigue tests to failure. In this study, the four-point bending tests are still needed for determination of initial stiffness. To simplify the procedure, it is proposed to determine the initial stiffness by using UPP test or Indirect Tension Test (ITT).

d) The procedure is simple and can be used for practical purposes after verified by additional experiments, especially in the long-life pavement design.

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