

# Estimation of fatigue characteristics of asphaltic mixes using simple tests

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A simplified procedure for estimation of fatigue characteristics of asphaltic mixes is presented. The procedure requires the determination of the so-called master curve (i.e. the relationship between the mix stiffness, the loading time and the temperature), the asphalt properties and the mix composition. It is shown that the master curve does not only give information about the variation of the mix stiffness, the loading time and the temperature, but also on the fatigue behaviour of asphaltic mixes. This information can reliably be obtained from rather simple tests, which can be performed in any road-engineering laboratory. Procedures of the determination of the fatigue characteristics of asphaltic mixes from simple tests are of special interest in mix design procedures where the quality of various mixes with respect to fatigue and crack resistance has to be evaluated. It is obvious that such a procedure is also extremely attractive for specification and pavement evaluation purposes. An insight is provided as to how the fatigue parameters for an asphaltic mix can be estimated using the Wöhler approach.

*Keywords:* fatigue, master curve, Wöhler approach, simple tests

## 1 Introduction

Transport vehicles are increasing in number as well as magnitude, and the use of super single tyres and different axle configurations is increasing too. The effects of these factors tend towards increased pavement deterioration, including fatigue, resulting in increased costs to maintain road networks to an adequate standard. Furthermore, the need to predict the remaining life of asphalt pavements and the design of new pavements to withstand heavier traffic loading with new axle and suspension configurations requires knowledge of the critical asphalt strain levels. This necessitates knowledge of the mechanical properties of the materials and the fatigue characteristics of asphalt mixtures.

Cracking, or fatigue, of the asphalt layer arises from repeated tensile strains due to traffic loading, the maximum of which, according to structural analysis, is found at the bottom of the bituminous layer. The crack, once initiated, propagates up-wards causing gradual weakening of the structure. The assessment of fatigue characteristics is normally done through fatigue tests, but these tests are not possible in many cases, either they are not available because they are too costly, or time consuming. The only alternative till now is the use of nomographs [e.g. Cooper and Pell [1975], Bonnaure *et al* [1980]]. However, these nomographs have been developed from results obtained out of tests per-

formed under specific conditions. For that reason it seems extremely useful if the estimation of the fatigue characteristics can be made from results of relatively simple and inexpensive tests which can be performed in any road-testing laboratory. This is especially of interest in mix design procedures where the quality of various mixes with respect to fatigue and crack resistance has to be evaluated.

## 2 Fatigue characterisation using the Wöhler approach

In the Wöhler relationship the number of strain applications to failure is related to the tensile strain, which occurs at the bottom of the asphalt layer as:

$$N_f = k_1 \left( \frac{1}{\epsilon} \right)^n \quad (1)$$

where:

- $N_f$  : number of strain applications to failure,
- $\epsilon$  : strain at the bottom of the asphalt layer and
- $k_1, n$  : factors, depending on the composition and properties of the asphalt mix.

The Wöhler fatigue relationship is shown in Figure 1.

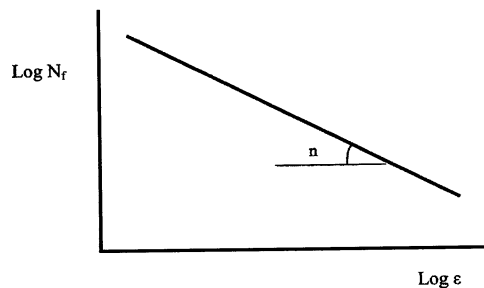


Fig. 1. The Wöhler fatigue relationship

Using the Wöhler relationship (Equation 1) as base for the description of fatigue results, several researchers found material depending characteristics for the parameters  $k_1$  and  $n$ . Some of the relationships, determined by regression analysis, are:

- SPDM [1978]:

$$N_{f,SPDM} = (0.856V_b + 1.08)^5 (S_m \cdot 10^6)^{-1.8} \left( \frac{1}{\epsilon} \right)^5 \quad (2)$$

- Bonnaure *et al.* [1980]:

$$N_{f,Bon} = (4.402PI - 0.205PIV_b - 2.707)^5 (S_m \cdot 10^6)^{-1.8} \left(\frac{1}{\epsilon}\right)^5 \quad (3)$$

- SHRP [1994]:

$$N_{f,SHRP} = 2.738 * 10^5 \exp^{0.077VFB} \epsilon^{-3.624} (S_m \sin \delta)^{2.720} \quad (4)$$

where:

$N_f$	:load cycles to failure,
$\epsilon$	:strain at the bottom of the asphalt layer,
$V_b$	:volume percentage of binder in the mix,
$V_a$	:volume percentage of air in the mix,
$V_g$	:volume percentage of aggregate in the mix,
$PI$	:Penetration Index
$S_m$	:stiffness modulus (in MPa)
$pen$	:penetration of the bitumen (in 0.10 mm)
$VFB$	:voids in the aggregate skeleton filled with bitumen = $V_v / (V_b + V_a)$
$\delta$	:phase angle

It appeared that the phase angle  $\delta$  is highly correlated with the stiffness of the mixture [MPa] following:

$$\delta = 174.644 - 17.172 \ln(S_m) \quad (5)$$

It can be noted that in equations (2), (3) and (4) the value of the slope of the fatigue relation,  $n$ , has a constant value of 5 in equations (2) and (3), and of 3.624 in equation (4). This assumption of a constant value of  $n$  is not completely correct. That's because it means that at low temperatures and short loading times (high vehicle speeds), when the material is brittle, a same value would be valid as at high temperatures and long loading times (low vehicle speeds), when the material is more flexible. The brittle behaviour should be represented by a high  $n$  value, while a flexible behaviour should be represented with a low  $n$  value [Molenaar and Medani, 2000].

### 3 Estimation of fatigue and crack growth characteristics of asphaltic mixes using simple tests

Fatigue tests are costly and time consuming. Therefore a methodology was developed at the Delft University of Technology by Jacobs [1995], extending the work of others, to derive the fatigue characteristics of asphaltic concrete (AC) materials from simple, relatively fast and inexpensive tests. This methodology is based on fracture mechanics and uses Paris' law which describes the crack growth process as:

$$\frac{dc}{dN} = AK^n \quad (6)$$

where:

- $A, n$  : parameters, depending on the material and on the experimental conditions (waveform, temperature, frequency)  
 $c$  : crack length (mm)  
 $N$  : number of load repetitions  
 $K$  : stress intensity factor.

The methodology to derive the fatigue characteristics of AC materials consists of two main steps: the first step is the derivation of the crack growth characteristics of the material (i.e., the parameters  $A$  and  $n$  of Paris' law). The second step is the application of these crack growth characteristics in modeling of the fatigue process as the growth of one 'equivalent' crack. The latter step requires the input of the actual geometry of the fatigue process being modeled (four-point bending test, or actual pavements, etc). In short, in its present form, the methodology requires three main inputs:

- The relationship between the AC mix stiffness and the loading time for a given temperature (master curve),
- The relationship between the tensile strength of the AC mix and the bitumen stiffness,
- The relationship between the fracture energy of the AC mix and the bitumen stiffness.

The Jacobs methodology [1995] still requires conducting uniaxial static tensile tests to determine the relationships between the tensile strength, the fracture energy and the bitumen stiffness and also back-calculation of the bitumen stiffness from the mix stiffness. Furthermore, he uses some regression constants developed for certain mixes, which were tested in his program. This means that if the fatigue characterisation is desired for a mix that is different from the mixes tested by Jacobs, then the average regression constants for all the tested mixes might be used. These constants will be used in the determination of many variables required as input for his procedure. This might lead to accumulation of errors. Therefore it is believed that a procedure which is based on less testing and regression constants which were developed for several mixes will be extremely useful for the estimation of fatigue characteristics.

#### 4 A proposed simplified procedure for estimation of fatigue parameters for asphaltic mixes

The proposed modified procedure is simpler than Jacobs' methodology and can be used for practical purposes for the characterisation of the fatigue parameters. The procedure uses the famous phenomenological Wöhler formula. This approach requires the determination of the  $n$ -parameter from the relationship between the mix stiffness and the loading time, which can be established by repeated load indirect tensile tests. This test can be performed easily and at relatively low costs with servo-pneumatic testing equipment, which is readily available nowadays. IPC'S UTM-5P system is an example of such a system. The dimensions of the specimen should be chosen such that the

assumption of plane stress conditions holds. According to Lytton *et al.* [1993] the thickness of the specimen should not be over 30 mm for a 102-mm diameter specimen. Then the  $k_1$ -parameter in the Wöhler fatigue formula can be estimated using regression equations.

#### 4.1 Estimation of $n$

Work carried at the Road and Railroad Research Laboratory (RRRL) of the Delft University of Technology (Molenaar [1983]; Jacobs [1995]; Sabha *et al.* [1995] and Medani [1999]) have shown that the slope,  $n$ , of the fatigue relation is dependent on the slope,  $m$ , of the relationship between log of the mix stiffness and log of loading time. An example of the relationship between log of the mix stiffness and log of loading time is shown in Figure 2.

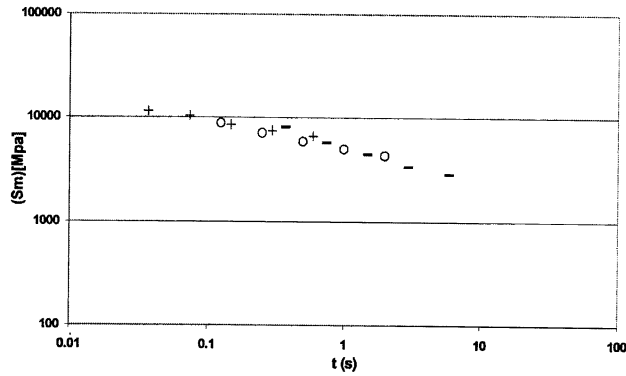


Fig. 2. Example of the relationship between log mix stiffness and log loading time

The relationship between the mix stiffness  $S_m$  and the loading time  $t$  at a certain reference temperature (the master curve) can be represented by the log-log equation:

$$\log S_m = f(\log t) \quad (7)$$

The slope of the master curve  $m$  at a certain loading time can be determined as:

$$m = \frac{d(\log S_m)}{d(\log t)} \quad (8)$$

Schapery [1973, 1975] derived the following theoretical relationship between  $n$  and  $m$  (strain-controlled condition):

$$n_{mas} = \frac{2}{m} \quad (9)$$

where:

$n_{mas}$  :  $n$ -value determined from the master curve

However, differences between the  $n$ -values as estimated from the master curve ( $n_{mas}$ ) and those determined from the four-point bending test ( $n_{exp}$ ) were reported by Molenaar [1983], Jacobs [1995] and Medani [1999]. This difference can be attributed to the limitations of the model as Schapery's theory is developed for ideal visco-elastic material. This assumption is not fully applicable to asphaltic mixes since they contain voids and aggregate particles which influence the crack growth. A correction factor (CF) is then defined as:

$$CF = \frac{n_{mas}}{n} \quad (10)$$

The regression equation (with  $R^2$  equals to 0.92 and a standard error of the estimate of 0.25) found for the correction factor is:

$$CF = 0.541 + 0.173n_{mas} - 0.03524V_a \quad (11)$$

where:  $V_a$  = air content (%)

In Figure 3 it is shown how the  $n$  values that were determined experimentally for 38 mixtures ( $n_{exp}$ ) agreed with the estimated  $n$  values ( $n_{est}$ ). It can be concluded that a very good agreement is obtained between ( $n_{exp}$ ) and ( $n_{est}$ ).

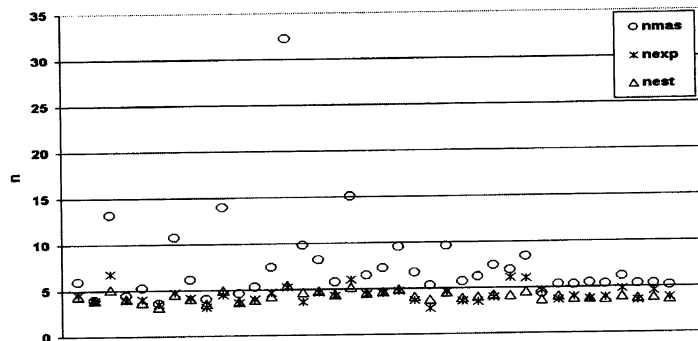


Fig. 3. Comparison of  $n$  values obtained from experiments ( $n_{exp}$ ), master curves ( $n_{mas}$ ) and estimated by means of the correction procedure ( $n_{est}$ )

In Table 1 an overview is given of the range in volumetric composition of the mixtures that were involved to obtain the relationship to estimate the exponent  $n$  of the displacement controlled fatigue test.

Slightly higher values for  $R^2$  could be obtained if some mixtures were excluded but equation 11 is preferred. That is because 10 different types of mixes including modified (SBS modification) and non-modified mixes were included in the derivation of the equation, and hence it is preferred for practical reasons and the more comprehensive nature of its applicability.

Table 1. Range of mix compositions involved

$V_b$ [%]	$V_a$ [%]	$V_g$ [%]
11.0-20.7	1.0-8.3	71.0-89.6

Note:  $V_g$  = volume percentage of aggregates

After the determination of the  $n_{mas}$  from the master curve the  $n$ -value can be directly estimated. In order to characterise the fatigue behaviour of the asphaltic mix the parameter  $k_1$  of the Wöhler approach is needed.

#### 4.1.1 Estimation of the Wöhler parameter $\log k_1$

Regression analysis performed on the results of 108 displacement controlled fatigue tests to derive a relationship between the constant  $k_1$  and the composition of the asphalt mixtures resulted in the following equation:

$$\log k_1 = 6.589 - 3.762n + \frac{3209}{S_m} + 2.332 \log V_b + 0.149 \frac{V_b}{V_a} + 0.928PI - 0.0721T_{R\&B} \quad (12)$$

with  $R^2 = 0.985$  and a standard error of the estimate of 0.595.

where:

- $n, \log k_1$  : the Wöhler equation parameters
- $V_b$  : volume percentage of bitumen
- $V_a$  : volume percentage of voids
- $PI$  : Penetration Index
- $S_m$  : mix stiffness (MPa)
- $T_{R\&B}$  : ring and ball temperature (°C) of bitumen

The data used to derive this relationship were taken from fatigue tests performed by SHELL, the Road and Hydraulics Engineering Division of the Dutch Ministry of Transport, and the Road and Railways Research Laboratory of the Delft University of Technology. The tests were either 3 point or 4 point bending fatigue tests. The mix composition, bitumen properties, test conditions and fatigue parameters for the data set used is shown in Table 2.

Table 2. Composition of the mixtures involved in development of the equation for  $k_1$

$V_b$ [%]	$V_a$ [%]	$V_g$ [%]	$f$ [Hz]	$T$ [°C]	$T_{R\&B}$ [°C]	$PI$
6.1-19.3	1.9-30.9	69-88.10	10-50	-10- +35	43-78	-1.5-+2.0

Figure 4 shows the agreement between the estimated and the experimentally determined  $\log k_1$  values. It is believed that the proposed equation is capable of providing very good estimates for  $\log k_1$  as only 3 out of 108 points lie outside the range of  $\pm 10\%$  and all the points are predicted within the range of  $-10$  to  $14\%$ .

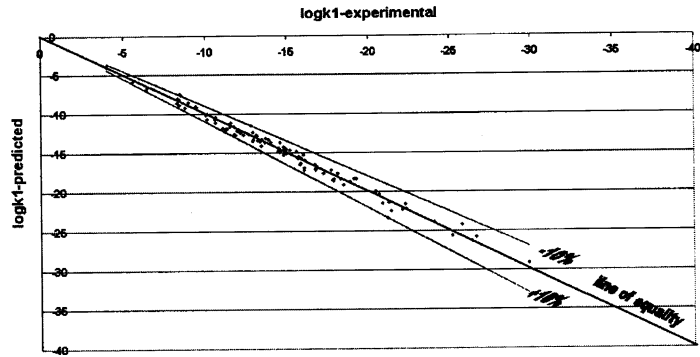


Fig. 4. Comparison between the experimentally determined and predicted  $\log k_1$

The quality of the proposed relationship was tested by predicting the  $\log k_1$  values of 10 mixtures that were tested in the SHRP-A-404 Project [1994]. It appeared that the difference between the predicted and experimentally determined  $\log k_1$  values remained between  $-6\%$  and  $+9\%$ , which is the same range as found for the data from which the equation was developed.

## 5 Stepwise description of estimation of the fatigue parameters for an asphaltic mix

In order to determine the fatigue relationship for a specific mix for a given temperature and a particular loading time the following stepwise procedure is described:

### ➤ Step 1

Prepare specimens for the determination of the master curve for the stiffness modulus by means of e.g. the repeated load indirect tensile test.

### ➤ Step 2

Determine the relationship between the stiffness modulus and the loading time at the temperature of interest (master curve). After constructing the master curve, regression analysis is used to define the relation:

$$\log(S_m) = f(\log(t)) \tag{13}$$

where:

$S_m$  : stiffness modulus at the temperature of interest

$t$  : loading time



► **Step 3**

Calculate  $n_{mas}$  using:

$$n_{mas} = \frac{2}{m} = \frac{2}{\frac{d(\log S_m)}{d(\log t)}} \quad (14)$$

where:

$m$  : slope of the stiffness master curve

► **Step 4**

Estimate  $n_{est}$  from:

$$n_{est} = \frac{n_{mas}}{CF} \quad (15)$$

and

$$CF = 0.541 + 0.173n_{mas} - 0.0352V_a \quad (16)$$

► **Step 5**

Estimate the  $k_1$ -value from the mix composition and the bitumen properties from:

$$\log k_1 = 6.589 - 3.762n + \frac{3209}{S_m} + 2.332 \log V_b + 0.149 \frac{V_b}{V_a} + 0.928PI - 0.0721 T_{R\&B} \quad (17)$$

where all symbols are as defined before.

## 6 Conclusions

Based on the material presented in this paper, the following conclusions can be drawn:

- It has been shown that the relationship (the so-called master curve) between the loading time and the stiffness modulus can be established by repeated load indirect tensile tests which can be performed easily at relatively low costs with pneumatic servo-system testing equipment which is readily available nowadays.
- A simplified procedure for fatigue characterisation of asphaltic mixes is proposed. The procedure requires the determination of the master curve as the only input.
- The equation to predict the slope of the fatigue line  $n$  has been developed on 38 fatigue tests including tests on polymer modified mixtures.
- A relationship between the parameter  $k_1$  of the Wöhler approach and  $n$  (which can be estimated from the master curve), volumetric composition and bitumen characteristics was proposed. This equation allows the characterisation of the fatigue behaviour of asphaltic mixes using the Wöhler equation.

- The equation to predict  $k_1$  has been developed using the results of 108 fatigue tests. The equation has successfully been used to predict the  $k_1$  values of 10 asphalt mixtures that were tested in the Strategic Highway Research Program. The mixtures included polymer modified binders.
- The proposed procedure is of special interest in mix design procedures where the quality of various mixes with respect to fatigue has to be evaluated. It obvious that such a procedure is also extremely attractive for specification and pavement evaluation purposes.

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