CREEP-FATIGUE INTERACTIONS DURING CRACK GROWTH IN A FINE-SAND ASPHALT CONCRETE MIXTURE

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Fatigue and creep crack growth experiments were performed on centre-cracked tensile specimens of fine-sand asphalt materials. Frequency and R values were varied. Most of the tests were cyclic and non-cyclic constant load experiments, but constant ΔK experiments were also performed. The relative importance of fatigue and creep crack growth was investigated by performing crack growth tests at different frequencies. It is found that under cyclic load the crack growth mechanism is pure creep for $R>0$, while for $R<0$ a fatigue mechanism also contributes to the crack growth. The fatigue part of the total crack growth increases when R is made more negative and/or when the test frequency is raised. A simple calculation is presented to calculate the relative contribution of fatigue and creep to the crack growth.

INTRODUCTION

Traffic loading is one of the main causes of deterioration of asphalt concrete pavements. In this research we compare the crack growth which occurs due to long-term repetitive traffic loading (*i.e.* fatigue) with crack growth due to constant loading (*i.e.* creep).

Asphalt mixes, which consist of a graded mineral aggregate bound by bitumen, are inhomogeneous viscous-elastic materials; defects are always present. When the stresses are high enough, defects act as crack initiators. Both repetitive and constant loading may result in crack initiation and growth.

In reference 1, Kleemans et al., it was shown that although the material studied is not linear elastic, the stress field near the crack tip can be described by the linear elastic fracture mechanics parameter K, the stress intensity factor, since use of this factor yields reasonable results.

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It was shown that for positive values of the load ratio R (i.e. tensile stresses) it was possible to fit the results for different frequencies into one scatter band when the frequency f times the crack growth rate da/dN was plotted against ΔK. The crack growth mechanism is creep, as in this case the effect of R on the results of the fatigue tests can be predicted from the results of slow stable crack growth (creep) under constant loading.

However, for negative R values (i.e. also compressive stresses) this was found to be not possible. Fatigue becomes an important crack growth mechanism in such cases.

In order to further investigate the fatigue and creep crack growth rate behaviour in asphalt mixes, a new series of experiments was conducted on centre-cracked tensile specimens.

EXPERIMENTS

Crack growth tests were performed on centre-cracked tensile specimens 390 mm long, 230 mm wide and 30 mm thick under fatigue and creep loading conditions.
The material of the test specimens was a sand asphalt with a maximum aggregate size of 2 mm. The asphalt mix contained 8.5% bitumen 45/60; the mineral aggregate consisted of 20% Wigro filler, 75% crushed sand and 5% river sand. The test temperature for all tests was 0 °C.
The linear elastic K factor for the specimens is:

$$K = \frac{P}{t \cdot w}\sqrt{\pi a \sec\left(\frac{\pi a}{w}\right)}\,, \qquad (1)$$

the accuracy is < 1% for $2a/w \leq 0.8$.
Fatigue and creep crack growth tests were performed. Various frequencies and R values were used for the fatigue crack growth tests. Fatigue tests were performed either with a constant load amplitude or with constant ΔK. In both cases this was achieved by controlling the (sinusoidal) load.
The crack length was measured by an automated measurement device using digital image processing. The main components of the image processing system are a video camera and a personal computer with software for image processing. The procedure is described in detail by Riemslag (2).
In figure 1 the measured crack length versus the number of cycles is shown for a constant ΔK test. The result in figure 1 is the basis for the use of K as a crack growth controlling parameter.

THEORY

If the crack growth under constant amplitude fatigue loading conditions is due to a pure creep mechanism, then the crack growth rate ${}^{da}/_{dt} = f\,{}^{da}/_{dN}$ is not frequency-dependent. If we compare two situations with different fatigue loading frequencies f_1 and f_2 we obtain in this pure creep case:

$$f_1 \cdot (da/dN)_{f_1} = f_2 \cdot (da/dN)_{f_2} \tag{2}$$

where $(da/dN)_f$ is the increase in crack length per cycle for frequency f.
However, if we have a pure fatigue crack growth mechanism, there is no frequency dependence of da/dN. In this case:

$$(da/dN)_{f_1} = (da/dN)_{f_2} \tag{3}$$

Thus when we perform tests at different frequencies, we will obtain overlapping results in the case of a pure creep crack growth mechanism when we plot f da/dN versus ΔK. This was found in (1) for fine sand asphalt for positive R values, but not for negative R - values.

Suppose that tests are carried out at two frequencies f_1 and f_2 and that da/dN is measured at the same ΔK. The ratio x of both f da/dN will lie between 1 and f_1/f_2 ; x = 1 is for pure creep and x= f_1/f_2 for pure fatigue. The ratio x is:

$$x = \frac{f_1 \dfrac{da}{dN_{f_1}}}{f_2 \dfrac{da}{dN_{f_2}}} = \frac{f_1(\dfrac{da}{dN})_{creep,f_1} + f_1(\dfrac{da}{dN})_{fatigue}}{f_2(\dfrac{da}{dN})_{creep,f_2} + f_2(\dfrac{da}{dN})_{fatigue}} \tag{4}$$

where $(da/dN)_{creep,f_1}$ is the pure creep contribution to the da/dN measured at frequency f_1 , etc. The pure fatigue da/dN can be found by measuring x and calculating da/dN for pure creep, using a creep crack growth relation. In equation (4) it is assumed that a simple superposition of both fatigue and creep parts is permitted.

RESULTS

In figure 2 creep crack growth results are shown. Two tests were performed under constant load conditions. A number of tests under constant K loading were also performed. There are no large differences between the results of the two kinds of tests. A type of "Paris relation" can be found for da/dt versus K:

$$\frac{da}{dt} = 330K^4 \tag{5}$$

This equation forms the basis for the prediction of da/dN (or f da/dN) versus ΔK, when a pure creep crack growth mechanism is present. The sinusoidally varying K fatigue loading signal is divided into 100 steps per cycle. For every step the crack growth increase is calculated using equation (5). The calculation is performed for two R values and the result of f da/dN versus ΔK, which is thus a pure creep result, is compared with actual measurement results in figure 3,

A very good result is obtained for a positive R = 0.5 value with only tensile stresses. For the negative R = -1 value the prediction does not fit the actual results. It is assumed that a fatigue contribution to da/dN is present in this situation .

We can use the measurement result to find the pure fatigue contribution. The real f $^{da}/_{dN}$ at ΔK = 0.7 MPa$\sqrt{m}$ and R = -1 is assumed to consist of a superposition of pure creep and pure fatigue parts. The real f $^{da}/_{dN}$ value = 3 µm/s. The creep part = 1 µm/s, as calculated using equation (5). This leads to a pure fatigue f $^{da}/_{dN}$ of 2 µm/s.

PREDICTION OF da/dN AT A DIFFERENT FREQUENCY

The foregoing result offers the possibility of predicting the $^{da}/_{dN}$ at a different frequency. We have found that f $^{da}/_{dN}$ (and $^{da}/_{dN}$) at ΔK = 0.7 MPa$\sqrt{m}$ is $^{1}/_{3}$ due to creep and $^{2}/_{3}$ due to fatigue (for R = -1 and f = 29.3 Hz). What will $^{da}/_{dN}$ be at f = 2.93 Hz ?

When the frequency is lowered by a factor of 10, from 29.3 to 2.93 Hz, only the pure creep part of the real $^{da}/_{dN}$ ($^{1}/_{3}$ of the total value) will be affected. This part will increase by a factor of 10, see equation 2. This leads to:

$$(^{da}/_{dN})_{2.93} = 10\ ^{1}/_{3}\ (^{da}/_{dN})_{29.3} + ^{2}/_{3}\ (^{da}/_{dN})_{29.3} = 4\ (^{da}/_{dN})_{29.3} \qquad (6)$$

Of course we can also use equation 4. For the ratio of f $^{da}/_{dN}$ we obtain x = 0.4. Since f_1/f_2 = 10 we predict a ratio value of 4 for $^{da}/_{dN}$ for ΔK = 0.7 MPa$\sqrt{m}$, which is the same result. In figure 4 $^{da}/_{dN}$ - ΔK results are shown for 2.93 and 29.3 Hz. The ratio of $^{da}/_{dN}$ is indeed approximately 4 for ΔK = 0.7 MPa$\sqrt{m}$. It should be noted that for a higher frequency the pure creep part is smaller than for a lower frequency, meaning that the reverse is true for the pure fatigue part of the total crack growth rate.

CONCLUSIONS

We conclude that it seems justified to divide the crack growth rate at negative R values into pure fatigue and creep parts. The total crack growth rate $^{da}/_{dN}$ can be found by simple addition of the pure fatigue and creep crack growth rate parts.

SYMBOLS USED

a = length of a single crack (in mm)
f = frequency
K = stress intensity factor (MPa$\sqrt{m}$)
N = number of cycles
P = load (in kN)
R = load ratio = P_{min}/P_{max} = K_{min}/K_{max}
t = specimen thickness
w = specimen width

REFERENCES

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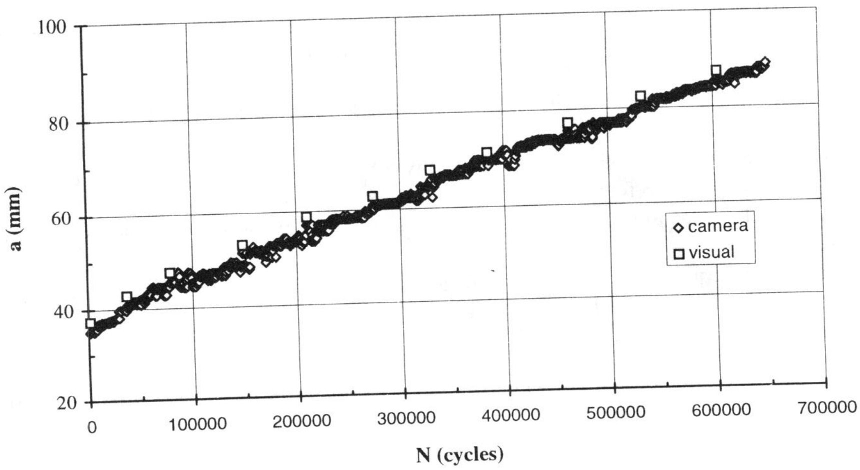

Figure 1 Crack length versus number of cycles for a constant ΔK test, $\Delta K = 0.33$ Mpa $\sqrt{m}$, $R = 0.1$, $f = 10$ Hz

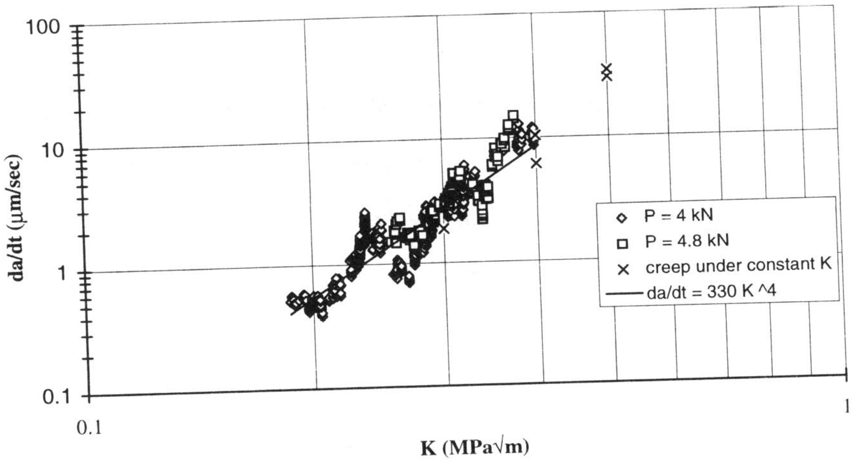

Figure 2 Creep crack growth data under constant load and constant K loading situations

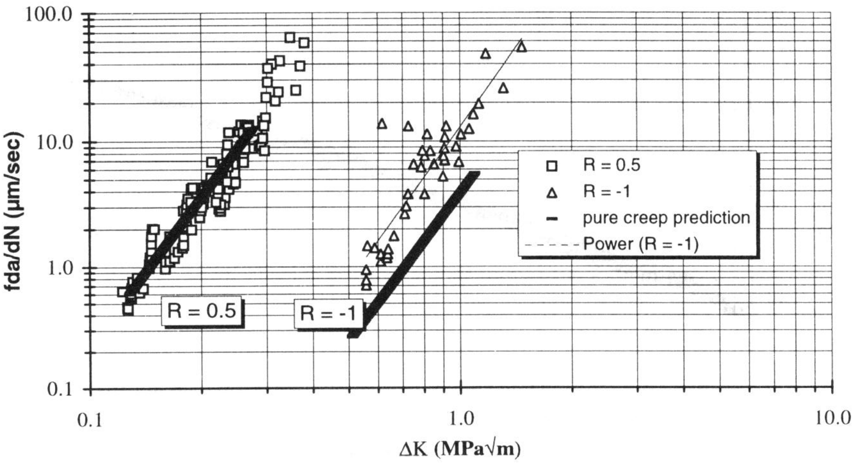

Figure 3 R dependence of f da/dN versus ΔK. Prediction lines based on integration of creep crack growth curve (eq.(5)) are shown for R = 0.5 and R = -1, f = 29.3 Hz

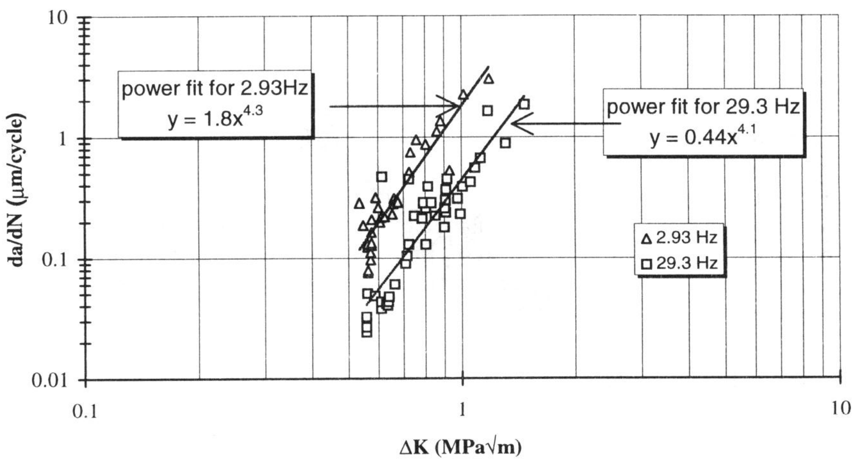

Figure 4 Frequency effect on da/dN using a decade difference in frequency, R = -1 and ΔP = 10 kN