Loading Frequency and Fatigue: In situ conditions & Impact on Test Results

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ABSTRACT: 4PB test according EN 12697-24 are used for evaluating the fatigue resistance of asphalt. For type testing of asphalt concrete (EN 13108-20) these tests have to be performed at a temperature of 20°C and a frequency of 30 Hz which demands extensive test machinery. Results gained on uniaxial cyclic tensile stress tests indicate that the impact of test frequency could be neglected if the interpretation techniques of fatigue test results are changed. The variation of traffic speed induces various loading rates in different types of asphalt pavements. Asphalt strain measurements in a full scale test track under real heavy vehicle loading are used to derive realistic frequencies for the application in laboratory tests. In order to elaborate the impact of frequency on results of 4PB tests fatigue tests these parameters are varied in an ongoing research study. The results of these tests are presented in the proposed paper.

1 INTRODUCTION

The European standard EN 13108-0 prescribes the loading frequency to be used in fatigue bending tests to \( f = 30 \) Hz. This paper discusses the influence of this test parameter in terms of meeting real loading conditions, technical problems in laboratory tests as well as its impact on test results.

In chapter 2, strain measured in a test road is used to evaluate the real loading conditions asphalt concrete layers are subjected under traffic loading. In chapter 3 the impact of loading frequency on laboratory fatigue tests are discussed. The problems related to moving masses are illustrated. Further, the fatigue lives measured at varied loading frequencies are discussed. By applying alternative test evaluation principles it is tried to diminish the impact of loading frequency on the fatigue test result. Conclusively, a proposal for the conducting of future fatigue tests is drawn.

2 IN-SITU LOADING CONDITION

2.1 Full scale pavement test facility at Bundesanstalt fuer Strassenwesen (BASSt)

The full scale indoor pavement test facility at BASSt consists of a 38 m long, 7.5 m wide and 3.5 m deep concrete trough. For the current project, eight different asphalt pavement constructions according to the German pavement design guideline RStO 01 were built in. The test track under construction and after completion is shown in Figure 1.
Figure 1. Test track at BASt under construction and after completion

The pavement surface is at the same level as the surrounding floor so that truck overruns can be conducted over two lanes, each with four different sections. The pavement constructions represent three different construction classes (SV, III, V) which are designed for certain amount of equivalent 10t-axle loads for a design period of 30 years. Following ranges of 10t-ESALs are assigned to the construction classes chosen for the test track:

- SV: > 32 mio. 10t-ESALs
- III: > 3 mio. < 10 mio. 10t-ESALs
- V: > 0.1 mio. < 0.3 mio. 10t-ESALs

The layout and geometry of the test track with all eight sections and construction classes is shown in figure 2.

![Figure 2. Layout and geometry of the test track with sections and construction classes](image)

Subgrade, granular layers and asphalt base course were built in and compacted manually with light compaction machinery. Due to the confined conditions the use of paver and rollers was not possible for building these layers. Asphalt binder and wearing course were laid with a paver and compacted with vibration rollers. Material test and control checks according to German technical standards were conducted for each layer.

Figure 3 shows the cross sections of the two lanes, each with four pavement constructions. Static plate load test were conducted on top of each granular course. The $E_{22}$ values (mean value of five tests per section) for all granular layers are also shown in figure 3.

On the granular layers all required $E_{22}$ moduli were met. The asphalt base course compaction values in two sections were slightly lower than the required ones, mainly due to the manual compaction. With regard the confined boundary conditions these values were accepted for the test track.
Each test section was equipped with asphalt strain gauges, soil pressure cells and temperature sensors. The principal location of the sensors (example: section 3) is shown in Figure 4.

**2.2 Measured pavement response**

**2.2.1 Boundary situations for high and low stress level**

Four different truck/trailer and truck/semitrailer combinations were selected for the overruns. The gross weight was varied for each vehicle from empty vehicle (~15 t) up to 52 t for a 6 axle truck/semitrailer combination. The speed was varied in four steps from 2, 7.5, 15 and 30 km/h.
2500 overruns were conducted with variation of gross weight, speed, lateral wander and tyre pressure.

Due to the amount of varied parameters and the number of different pavement test sections the following selected parameter combinations shown in Figure 5 and Figure 6 give an overview of the possible range of mechanical stress levels which occurred within the boundary conditions of the test series.

- Low stress situation: low asphalt-temperature (7 °C), high speed (30.5 km/h) and low gross weight (18.1 t) (Figure 5).
- High stress/strain situation: high asphalt-temperature (16.7 °C), low speed (2.7 km/h) and high gross weight (40.1 t) (Figure 6).

Each figure compares asphalt strain induced by truck overruns measured in two comparable pavement construction types of the strongest construction class SV (34 cm asphalt on 0/32 sand/gravel) and the weakest construction class V (12 cm asphalt on 0/32 sand/gravel).

Following observations can be verified and derived from the measured data within the range of parameters of the entire test program:
Asphalt strains between 10 µm/m and 220 µm/m were measured in the test sections. Higher strains are expected to occur in real service pavement constructions, especially due to higher temperatures.

- Temperature and vehicle speed are decisive factors for the influence on stress and strain level in both, asphalt and granular layer.
- Superposition of stress in asphalt and in granular layers occur under wheel bases of 1.30 m or less.
- Due to the alternating compression and tension zones in the asphalt base course superposition of adjacent wheels of a triple axle aggregate results in a lower maximum of strain under the mid-wheel of a triple axle aggregate (Figure 6).
- The influence interval of a wheel is determined by the flexural stiffness of the asphalt layer-package.
- Absolute compression/tension strain peak ratios of 0.7 at the bottom of thin asphalt packages (12 cm) were observed.
- Tension/compression strain ratios at the bottom of the asphalt layers vary. Most decisive factors are temperature, axle configuration, speed and layer thickness.

2.2.2 Influence of the static wheel load

To describe the influence of the static wheel load on the pavement response, the peak values of longitudinal asphalt strain and vertical granular stress under the wheel of the 1st trailer single-tired axle of a 2-axle articulated truck with 3-axle trailer were examined. The overruns with four different load stages were all conducted within a range of average asphalt temperatures from 11.0 °C to 14.0 °C. To describe the function using a linear regression analysis, the peak values (average of peak values of three vehicle passes) of each load stage were shifted linear to a reference temperature of 12.5 °C.

Due to the low vehicle speed between 2.4 km/h and 3.0 km/h and the good evenness of the pavement surface the dynamic vertical wheel forces were considered negligible.

The regression functions validate section 8 as the weakest (14 cm asphalt on granular base) and section 1 as the strongest (30 cm asphalt on 20 cm cement stabilized layer). A precise distinction line can be drawn between sections of the weakest construction class V (section 4 and 8), sections of class III (section 5, 6 and 7) and sections of the strongest class SV (section 1, 2 and 3).

Considering the slope of each function as indicator for the stiffness of the construction, the stiffness of the strongest section 1 (slope = 0.008) is 7 times higher than the stiffness of section 8 (slope = 0.0558) for the asphalt strain.

Figure 7 shows the influence of static wheel load on the longitudinal asphalt strain.

![Figure 7. Longitudinal asphalt strain versus static wheel load - all sections](image)
2.2.3 Frequency in asphalt layers of sections with different layer thickness

Full friction between the asphalt layers result in a transformation of shear forces. Thus, the asphalt package acts like a slab under bending with additional vertical stress induces by the transient wheel. The stiffness and therefore the deformation shape of a slab under bending are determined by the material stiffness and the overall thickness of the entire package.

A comparison of the longitudinal strains at the bottom of the asphalt base course in three different sections (section 3: 34 cm asphalt, section 7: 22 cm asphalt and section 8: 14 cm asphalt) reveals the influence of the asphalt package thickness on the time and length of the compression and tension zones of the asphalt fibres. The geometrical length of the tension zone at the bottom of the asphalt base course is calculated from the sampling rate (1000 Hz) and the average measured vehicle speed. Figure 8 shows the compression and tension zones under a transient steering axle wheel in three different pavement constructions. It can be seen, that the influence area of a wheel and the length of tension and compression zones increase with increasing asphalt thickness which means higher flexural stiffness.

![Figure 8. Length of asphalt base course tension zone depending on layer thickness](image)

Table 1 shows examples of calculated tension/compression ratios observed in three different pavement constructions.

<table>
<thead>
<tr>
<th>test road section</th>
<th>asphalt thickness [cm]</th>
<th>min. compression strain [µm/m]</th>
<th>max. tension strain [µm/m]</th>
<th>tension / compression ratio [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>34</td>
<td>7,8</td>
<td>46,4</td>
<td>5,9</td>
</tr>
<tr>
<td>7</td>
<td>22</td>
<td>14,1</td>
<td>67,3</td>
<td>4,8</td>
</tr>
<tr>
<td>8</td>
<td>14</td>
<td>26,5</td>
<td>93,0</td>
<td>3,5</td>
</tr>
</tbody>
</table>

2.2.4 Vehicle speed and corresponding frequency in asphalt layers

The analysis of the strain peak values due to vehicle passes at various speeds confirm the decreasing of asphalt strain with increasing speed due to the increase of dynamic stiffness. The evaluation also reveals the decrease of tension and compression periods under the transient wheel with increasing speed. The frequency of an equivalent sinusoidal function can be derived from the length of the tension and compression periods.

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Figure 9 shows the measured longitudinal strain shapes at the bottom of an 18 cm asphalt layer and the length of the tension periods. It can also clearly be seen that the peak values decrease with increasing speed.

Table 2 shows the length of the tension periods and the calculated frequencies for the measured vehicle speeds up to 31.4 km/h. An extrapolation for 60 km/h and 80 km/h was done by using a regression analysis.

Figure 10 shows the functions of vehicle speed on the asphalt tension zone and the derived frequency.

In laboratory cyclic tests a sinusoidal load signal is applied. To show the difference between cyclic loading in standard bending tests and in-situ-loading, the strain signal applied in cyclic tests at 2 frequencies are added to the measured strain signals of the test sections (Figure 11). Whereas the actual measured bending strain in the test roads show tension This shows the difference between real measured strains under real loading compared to the induced force shape in the four point bending test where the tension/compression ratio is 1. The time-dependent
course of horizontal flexural strain in a four point bending specimen corresponds with the applied vertical force and the measured vertical displacement in the middle of the beam. Focussing on the shape, the frequency and the tension and compression periods Figure 11 compares the asphalt strain from in-situ measurements with the applied vertical force measured in a four point bending test of asphalt concrete 0/11 with bitumen 50/70 and with frequencies of 1.0 Hz and 2.0 Hz. The corresponding length of the tension (or the corresponding compression zone) is also shown. It can be seen that the loading frequency of 1.0 Hz corresponds to a frequency of asphalt strain induced by a passing wheel at ~7.6 km/h at the bottom of a 34 cm asphalt layer. The loading frequency of 2.0 Hz corresponds to an asphalt strain frequency at the bottom of a 14 cm asphalt layer.

Figure 11. Comparison between in situ strain shape and four point bending force shape

To compare the tension/compression periods depending on time in a four point bending test specimen applying a frequency sweep for stiffness determination the relation between the tension zone/tension period and the corresponding frequency the relationships were evaluated and shown in table 3.

| Table 3. Frequency and corresponding tension zone period in four point bending test |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Sinusoidal force/displacement function: 4 point bending tests | frequency [Hz] | 0.1 | 0.2 | 0.5 | 1 | 2 | 5 | 10 | 20 | 30 |
| tension zone [ms] | 5000 | 2500 | 1000 | 500 | 250 | 100 | 50 | 25 | 16.7 |

To summarize the results found before, it can be stated from the full scale in-situ measurements of longitudinal strain that vehicle speed and asphalt thickness have a decisive influence on the shape and the frequency of asphalt strain. Extrapolated to a realistic travelling speed on in-service pavements asphalt strain frequencies may vary from 4 Hz to up to more that 20 Hz, depending on the tension/compression function. This means that the corresponding dynamic stiffness may also vary due to the wide range of observed frequencies.
Figure 12 shows the asphalt strain periods and corresponding frequencies in different pavement structures depending on vehicle speed.

These results lead to lower loading frequencies than calculated from test road measurements in Chenevière et al. (2005). If the shape of the strain peak is used for fitting a sinusoidal strain function as shown in Figure 13, the frequency - traffic speed relationship gained at temperatures of 20°C and 30 °C results in similar correlation (Chenevière et al. 2005).

2.3 Conclusions of in-situ measurements for asphalt laboratory tests

The analysis of measured asphalt strain response in various pavement constructions induced by real vehicles with a wide range of vehicle parameters show the wide range of stress level and strain frequency that occurs at the bottom of asphalt pavement constructions. The analysis of the peak values and tension and compression zones induced by vehicle specific axle configurations provide important information for the boundary conditions and the assessment of asphalt laboratory tests for stiffness and fatigue. Following principles with regard to the boundary conditions for four point bending tests have been found:
At temperatures between 7 °C and 17 °C horizontal strain levels between 11 µm/m and 220 µm/m could be measured in the various pavements constructions and varied loading vehicles.

The full scale tests confirm the decreasing of asphalt strain level with increasing speed. Higher loading speeds result in higher frequencies of as well as lower strain reaction which results in an increase in the stiffness modulus.

The ratio between the maximum observed tension and compression strain varies depending on asphalt stiffness, layer thickness and loading conditions. The ratio rises with the thickness of the asphalt pavement. Especially for pavements of high thickness as used in motorways in Germany, the maximum tension strain reaches a value 6 times the value of the maximum compression strain. For this reason, loading conditions for dynamic asphalt tests should be thought over.

The loading speed occurring of asphalt strain depends on layer thickness and varies along the cross-section. At the bottom of thin asphalt layers higher loading speeds occur than at the bottom of thick asphalt structures. For a traffic speed of 80 km/h and depending of the structure thickness, the derived frequencies vary between 8 Hz and 22 Hz if the tension zone duration is applied for fitting the sinusoidal function and between 4 Hz and 9 Hz if the duration between the maximum compression peaks is applied. These values are smaller than frequencies earlier evaluated at test roads subjected to higher temperatures.

A more detailed analysis of all observed in-situ measurements may serve as a basis to adapt loading conditions to archive more realistic stiffness and fatigue determination in four point bending tests.

3 LOADING FREQUENCY IN LABORATORY FATIGUE TESTS

3.1 Impact of loading frequency on fatigue resistance

Due to various traffic speeds, the loading speed of in situ loading of asphalt courses varies considerably. In cyclic tests the loading speed is simulated by the test frequency.

Saal & Pell (1960) analysed the influence of frequency by varying the loading speed in cyclic of force-controlled bending tests. The fatigue live (number of load cycles) at a test frequency of 13 Hz was found significantly lower than at a frequency of 50 Hz.

Neifar et al. (2003) used uniaxial tests to analyse the permanent deformation in cyclic tests by applying compressive and tensile haversine force-controlled loading. At tensile loading with rest periods at a temperature of +25°C and varied loading frequencies they found that the permanent deformation after a number of applied load cycles at 1 Hz exceeds the deformation at 10 Hz. If the deformation courses are plotted versus the testing time the slow loading of 1 Hz still results in higher permanent strain than the faster loading at 10 Hz.

Using a viscoelastic continuum damage model for interpretation of fatigue tests on asphalt material, Daniel & Kim (2002) found unique pseudo stiffness failure functions for cyclic tests at varied frequencies and even monotonic tests. The used interpretation procedure is based on the implementation of testing time into the failure model.

In Mollenhauer (2008) the influence of varied testing frequencies on force-controlled Uniaxial Cyclic Tensile Stress Tests (UCTST) was analysed. As also shown in Mollenhauer & Lorenzl (2008) the number of load cycles until specimen cracking increased with increasing frequency (Figure 14). But if the test duration until the cracking is used as fatigue criterion, the fatigue lives obtained at varied test frequencies result in the same Wöhler function. This observation could also been made for further fatigue criterions, e.g. stiffness reduction as shown in Figure 15. The left side shows the stiffness moduli measured during UCTST at three varied frequencies versus the number of load cycles. On the left side the figure shows the same values drawn versus the test duration. To consider the frequency-dependent stiffness modulus the measured values are referred to their initial values at the beginning of the test. By this analysis the stiffness measurements result in similar courses which inhibit on their quasi-linear section the same slope $d(S_{mix}/S_{mix,0})/dt$. 

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Figure 14. Results of UCTST at varied loading frequencies (Mollenhauer & Lorenzl 2008)

Figure 15. Course of the stiffness modulus $|E|$ versus the number of load cycles $N$ (left) and course of the relative stiffness modulus $|E|/|E_0|$ versus test duration $t$ [s] (right)

3.2 4PB-test program

3.2.1 Tested material

In the framework of this study a hot mix asphalt material AC 11, as often used as a wearing course material in Europe, was subjected to uniaxial cyclic tensile stress tests (UCTST). Main compositional characteristics of this material are summarised in Table 4.
3.2.2 Test device

The 4PB tests were conducted in a hydraulic test device capable to induce cyclic loads of up to ±50 kN with a frequency of maximum 30 Hz. A test frame was constructed to enable 4PB tests at specimens of various sizes from 40 x 40 x 240 mm³ up to 100 x 100 x mm³. The frame inhibits bearings which allow the rotation of the inner and outer clamps. Slide bearings allow the translation at the outer clamps. To reduce the moving masses sliding bearings were avoided at the inner clamps. Furthermore, the upper load frame was constructed using aluminum whereas the bottom (fixed) part of the load frame is made of stainless steel.

The force is measured using a load cell which is located outside of the temperature chamber. The deflection is recorded using a LVDT (± 5 mm) positioned in the centre of the asphalt beam (x = 0,5·L).

Before conducting the tests the device was calibrated against three aluminium reference beams of the nominal size 40 x 40 x 280 mm³ with nominal stiffness moduli of 94430, 90880 and 83070 MPa. To reach these values the deflection value was corrected using Equation 1 to consider the bearing play as well as the stiffness of the bending frame elements. Further the calibration measurements showed a device-induced time lag between the measured force and deflection signal which could not be explained by the moving masses only. As shown in Figure 17 the measured time lag is dependent of the applied test frequency and rises from 3 ° at slow loading with f = 1 Hz up to values of 20° at high frequencies of f = 20 Hz. When calculating the effective time lag which produces this phase angle by Equation 2 it can be observed that it reaches a constant value of about 2.8 ms at frequencies higher than 5 Hz (Figure 17, right). At lower frequencies the impact of the device time lag is decreasing as the duration of the loading cycles

### Table 4. Material properties of the hot mix asphalt AC 11 investigated in this study

<table>
<thead>
<tr>
<th>Maximum aggregate density [kg/m³]</th>
<th>2,698</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grading</td>
<td></td>
</tr>
<tr>
<td>&lt; 0.09 mm</td>
<td>9.5 %</td>
</tr>
<tr>
<td>&gt; 0.09 mm &amp; &lt; 2.0 mm</td>
<td>37.5 %</td>
</tr>
<tr>
<td>&gt; 2.0 mm</td>
<td>53.0 %</td>
</tr>
<tr>
<td>Content of crushed aggregate C₉₀/₁</td>
<td></td>
</tr>
<tr>
<td>Binder type</td>
<td>50/70</td>
</tr>
<tr>
<td>Binder content [mass-%]</td>
<td>6.0</td>
</tr>
<tr>
<td>Maximum density [kg/m³]</td>
<td>2,476</td>
</tr>
<tr>
<td>Mean void content of specimens [vol-%]</td>
<td>2.8</td>
</tr>
</tbody>
</table>
is much higher. Because of this the effective resulting time lag which reaches values of 14 ms at very low frequencies can be neglected.

Consequently, in the following study, the measured time lags were corrected by using Equation 3.

\[
Z(X)_{\text{korr}} = Z(X) - (4.53241 \cdot 10^{-8} + F0 \cdot 2.0616 \cdot 10^{-5})
\]

\[
t_{\varphi} = \frac{\varphi}{360 \cdot f}
\]

\[
\varphi_{\text{corr}} = \varphi_{\text{measured}} - f \cdot 360 \cdot 0.0028 \text{ s}
\]

Figure 17. Device-Induced Phase lag

3.2.3 Moving masses

In cyclic tests a specimen is loaded sinusoidally. In 4-Point-Bending tests a comparatively long prismatic specimen is clamped in supports near of its edges whereas two inner clamps are moved sinusoidally in vertical direction. By this loading, horizontal bending strain \( \varepsilon \) is induced, which is constant between the inner clamps according to bending theory. The bending strain \( \varepsilon \) can be calculated by using Equation 4 from the vertical deflection \( z(t) \) and the geometrical constant \( K(x_S) \). In the following tests are evaluated which were conducted on asphalt specimens with an effective length \( L_0 \) of 240 mm and a cross section \( B \times H = 40 \text{ mm} \times 40 \text{ mm} \). The distance between inner and outer clamps \( A \) is 80 mm. The deflection is measured in the middle of the asphalt beam directly \( (x_S = 120 \text{ mm}) \) by means of a LVDT. Thus the geometrical constant \( K(x_S) \) reaches a value of 0.033 1/mm.

Cyclic test to derive stiffness modulus \( S_{\text{Mix}} \) are usually conducted using a strain amplitude \( \varepsilon_a \) of 50 \( \mu \text{m/m} \). According Equation 1 this implies a deflection amplitude of \( z_a = 15.3 \mu \text{m} \). Typical strain values applied during cyclic fatigue tests are \( \varepsilon_a = 200 \mu \text{m/m} \) which is provoked by a deflection amplitude of \( z_a = 61.3 \mu \text{m} \). Equation 2 represents the function of the deflection versus time.

\[
\varepsilon = K(x_s) \cdot Z(x_s) \cdot 10^6
\]

\[
z(t) = z_m + z_a \cdot \sin(2 \cdot \pi \cdot f \cdot t + \varphi_z)
\]

Besides the two inner clamps, also the upper load frame as well as the loading bar moves according Equation 5. The used bending device results in an equivalent mass \( M_{\text{aq}} \) of 15 kg. This moving mass induces a cyclic force function according Equation 6.

\[
F_m(t) = M_{\text{aq}} \cdot a(t) = M_{\text{aq}} \cdot \ddot{z}(t) = -M_{\text{aq}} \cdot z_a \cdot \omega^2 \cdot \sin(\omega t)
\]
For evaluating the impact of this force, the forces during 4-Point-Bending tests are calculated from the stiffness modulus of an AC 11 for the two deflection amplitudes representing loading conditions during a stiffness and a fatigue test. Further, the left figure contains the resulting forces due to moving masses. As seen on the right figure, the force ratio rises at high test frequencies (60 Hz) up to a value of 20%.

The reduction of the test frequency would limit the described impact of moving masses on the measured forces. To limit this influences suppliers of bending devices introduced an acceleration measurement system to correct the measured force during the test. Only by these means force-controlled bending tests at frequencies higher than 10 Hz are possible.

![Figure 18 Exemplar calculation of the impact of moving masses on the force measured during 4PB: Left: Bending force resulting from beam stiffness modulus & force induced by moving masses; Right: Force ratio versus frequency and stiffness modulus](image)

### 3.2.4 Test results 4PB

The 4-point-bending tests were analysed according EN 12697-24 by plotting the applied strain amplitude $\varepsilon_a$ versus the number of load cycles $N_{F/50}$ until the traditional failure criterion is reached (Figure 19). It can be observed that the asphalt endures more loading cycles when loaded by a frequency of 10 Hz rather than 30 Hz. This contradicts the observation made with uniaxial cyclic tensile stress test as shown in Figure 14 where a lower loading frequency results in a decrease of endured load cycle number. This discrepancy can be explained by the differently applied mode of loading. Whereas the UCTST were conducted in force-controlled mode, the 4PB tests were conducted deflection controlled. Due to the frequency-dependent stiffness modulus and phase angle raising the frequency results in higher stiffness and thus for same strain amplitudes in higher induces bending stresses.

![Figure 19. Results of 4PB tests at varied frequency](image)
By applying the approach introduced by van Dijk (1975) according Equation 7 this observation can be explained by the differences in energy dissipation per load cycle. Due to the higher stress level, the value of dissipated energy per load cycle is higher for the high frequency loading compared to the lower frequency. In terms of force-controlled loading as applied at UCTST, the higher stiffness modulus at high loading frequency result for a given applied stress in lower strain amplitudes and thus in lower dissipated energy compared with slower loading.

\[
W_{\text{dis}}(N) = \sigma_x(N) \cdot \varepsilon_x(N) \cdot \pi \cdot \sin \phi
\]  

(7)

To validate this assumption, the dissipated energy was calculated for each load cycle during the 4PB tests and summarized. In Figure 20 this accumulated energy dissipation is plotted with the course of stiffness modulus during a fatigue test. From the beginning of the test the stiffness modulus decreases whereas the phase angle rises. Both changes result in a nearly constant energy dissipation during each load cycle and a quasi-linear rising accumulated energy curve. This observation that the changes of stiffness modulus and phase angle result in a nearly constant dissipation rate can be observed during all tests.

At the end of the test, characterized by an accelerating decrease of stiffness modulus, the energy dissipated during each load cycle decreases and the accumulated energy reaches an asymptote-like plateau. This plateau value can be interpreted as the total energy dissipated \( \Sigma W_{\text{dis, tot}} \) during the fatigue test until failure of the specimen.

Following an approach of Spiegl (2008) \( \Sigma W_{\text{dis, tot}} \) is plotted versus the number of load cycles until conventional failure criterion \( N_{f/50} \) in Figure 21. Compared to Figure 19 the resulting curves are moved closer to each other.

![Figure 20. Course of stiffness decrease \( S_{\text{mix}} \), phase angle \( \phi \) and dissipated energy \( \Sigma W_{\text{dis}} \) during 4PB fatigue test (\( T = 20^\circ C, f = 30 \) Hz)](image)

![Figure 21. Total accumulated dissipated energy \( \Sigma W_{\text{dis, tot}} \) versus number of load cycles until conventional failure criterion \( N_{f/50} \)](image)
4 CONCLUSION

The structure of an asphalt pavement and the traffic speed result in varying loading conditions. In cyclic laboratory tests this impact can be analysed by varying the loading frequency.

The horizontal bending strain at the bottom of asphalt structures of varied thickness by varied loading conditions could be measured for deriving loading rates occurring in real pavements. These results show that the loading conditions as applied in cyclic fatigue tests don’t meet real loading conditions necessarily. According to these results especially the loading frequency as applied in fatigue tests should be reduced to a value considerably lower than the prescribed frequency of 30 Hz.

The application of a lower loading frequency would simplify the demands on the test equipment as high loading frequencies result in high inertia-induced forces by moving masses. In deflection-controlled tests the results of 4-point bending tests can be corrected by the known equations. But as the force value induced by mass can reach at high loading frequencies considerable proportions of the total force applied, the conduction of force-controlled 4-point-bending tests demands high efforts to the test equipment as further acceleration measurement devices.

The varying of the loading frequency has an important impact on the results of fatigue tests. According to results gained at UCTST as well as 4PB there is a distinction between the loading mode. While higher loading frequencies lead to higher load cycles numbers in controlled-force loading, the life time is reduced considerably in controlled deflection tests. In both cases the dissipated energy can be used for the interpretation of this phenomenon.

5 REFERENCES


Van Dijk, W. 1075; Practical fatigue characterization of bituminous mixes; Annual meeting of the Association of Asphalt Paving Technologists; Phoenix, 1975