Asphalt Stiffness and Fatigue Parameters from Fast Falling Weight Deflectometer (FastFWD) Tests

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Abstract

With the occurrence of the Falling Weight Deflectometer (FWD) in the 1980’s it became possible to quickly determine the most important input parameters for the ‘mechanistic’ part of the mechanistic-empirical (M-E) pavement design method—the in-situ modulus and critical stress/strains in pavement. However, the ‘empirical’ part which predicts the future pavement deterioration is still primarily based on costly and extensive full scale Accelerated Pavement Testing (APT). Therefore, engineers have had to mainly rely on small-scale laboratory test methods for evaluation of existing pavement structures or a particular pavement design. Given the limitations of the laboratory test methods, there is a wide gap between the critical response and prediction of the future pavement deterioration or “residual life”.

To bridge this gap, the Fast Falling Weight Deflectometer (FastFWD)—an electrically powered FWD with faster loading rates—was evaluated to assess its suitability to rapidly predict the fatigue performance of asphalt pavements. In this experiment, the FastFWD was used to apply 700,000 load applications on a pavement test section over 8 days, later supplemented by additional loads up to over 1.6 million load cycles. The dynamic modulus master curve was first backcalculated from in-situ FastFWD testing and was used to filter out the viscoelastic response of the asphalt layer due to temperature changes from the damage of the material due to repeated loading. An Incremental-Recursive fatigue model accurately predicted the damage in asphalt modulus.

With the FastFWD it is now possible to perform in-situ performance testing of pavements to provide input parameter for the ‘empirical’ part of the M-E methods.

Key words

1. Introduction

With the occurrence of the Falling Weight Deflectometer (FWD) in the 1980’s it became possible to determine the most important input parameters for the ‘mechanistic’ part of the mechanistic-empirical (M-E) pavement design method—in-situ modulus and stress/strain distribution in existing pavement structures and materials. This still left a gap between the critical response and prediction of the future pavement deterioration or “residual life”. Currently, the ‘empirical’ part of the methods relies on models calibrated based on Long Term Pavement Performance (LTPP) studies and full scale accelerated pavement tests (APT)—e.g. the AASHO Road Test and Heavy Vehicle Simulator (HVS) systems. However, due to the limited accessibility of full scale APT methods, engineers have had to mainly rely on small-scale laboratory test methods specified by the European and US standards for evaluation of an existing pavement structure or a particular pavement design. Yet, the inherent limitations of small-scale laboratory test methods have led to a significant discrepancy between the predictions from different laboratory test methods and hampered their ability to adequately predict the pavement fatigue performance.

To pave this gap, the suitability of Fast Falling Weight Deflectometer (FastFWD)—an electrically powered FWD with faster loading rates—was evaluated as an intermediate accelerated pavement testing (iAPT) technology to predict the fatigue performance of a flexible pavement structure.

1.1. Background on Stiffness and Fatigue Testing

American Association of State Highway and Transportation Officials (AASHTO) and European Committee for Standardization (Comité Européen de Normalisation—CEN) have developed standards for determining the stiffness and the fatigue characteristics of asphalt mixtures. These standards comprise a wide range of different laboratory test equipment and test procedures, including different bending tests and direct and indirect tensile tests, on specimens of different shapes and sizes, prepared by various methods.
The European standards for laboratory testing of stiffness of bituminous materials and resistance to fatigue are described in EN 12697-26 (1) and EN 12697-24 (2), respectively. Both standards allow a wide range of testing methods: 2-point bending tests on trapezoidal specimens, 2-, 3-, or 4-point bending tests on prismatic specimens, and indirect tensile tests on cylindrical specimens. In addition, stiffness may be determined from direct tension-compression on cylindrical specimens or from direct tension to either cylindrical or prismatic specimens.

CEN does not specify a method for the fabrication of specimens. Specimens can be compacted in the laboratory by suitable devices or cut from in-situ pavement slabs. It is noticed that laboratory compacted specimens are likely to produce different results than the specimens cut from pavement slabs (2).

Depending on the test method, the load may be sinusoidal (at varying frequencies), repeated load pulses with rest periods (haversine waveform), or applied at a constant strain rate (for direct tension tests). An example of repeated load pulses with rest periods is shown Figure 1 (2). This load form is quite similar to the loads applied by the FastFWD.

Figure 1: Example of repeated load pulses with rest periods (2).
Similarly, AASHTO has specified several standard test methods for determination of the modulus and fatigue resistance of asphalt mixtures. The modulus can be determined in indirect tension or direct compression mode as specified in AASHTO TP 31 and AASHTO TP 62, respectively. To determine the fatigue life, AASHTO T 321 specifies repeated flexural bending test (3,4,5).

As part of the Strategic Highway Research Program (SHRP) the axial, diametral and flexural stiffness of different aggregate-asphalt mixes were measured (6). Some of the conclusions derived from this comprehensive study were that in general the axial, diametral, and flexural testing of asphalt-aggregate mixes will yield different estimates for the resilient modulus with differences up to 50%. The effect of mix variables such as aggregate type, bitumen type, bitumen content and degree of compaction, could be different in different test methods (i.e. the ranking of the mixes could be dependent on the test method).

In a companion SHRP study of asphalt concrete fatigue response (7), the fatigue failure criterion was set in terms of the number of load repetitions required to reduce the initial modulus by 50%. Some of the proposed test methods—uniaxial tension-compression, fracture mechanics and tensile strength testing—were eliminated from the study for various reasons. For the remaining three test methods (flexural beam, flexural cantilever and diametral testing), the diametral and flexural beam tests generated the lowest and highest fatigue life expectancy for the same mixture. On average, the beam test led to 34.2 times as many load repetitions as the diametral test, while the cantilever test resulted in 2.3 times as many load repetitions.

Laboratory tests in connection with full scale testing in the French circular test track in Nantes (8) and in the Dutch Lintrack facility (9) have confirmed the differences between different laboratory tests. De la Roche et al. (8) reported the well-known difference between controlled strain and controlled stress testing, and found a large effect of rest periods on laboratory fatigue lives. The paper also reported that the laboratory ranking of different asphalt materials was different from the ranking resulting from the full scale tests. Molenaar (9) even concluded that “Laboratory fatigue tests are only providing specimen
properties rather than mixture properties” and that “Shift factors of significant magnitude need to be applied on laboratory fatigue relations to be able to use them for field fatigue performance prediction”.

Past researches clearly convey the limitations of the small scale laboratory test methods in evaluating the stiffness and fatigue performance of asphalt concrete pavements indicating the need for a more accessible full scale APT.

While the common purpose of FWD testing has been to evaluate the pavement layer moduli for input to the ‘mechanistic’ (or analytical) part of the M-E pavement design, the higher loading rate of the FastFWD makes it possible to also provide input for the ‘empirical’ relationships, through in-situ testing of the actual pavement structure and materials.

1.2. Material and Test Method

A 5 × 5 m² flexible pavement section was constructed with 120 mm (4.7”) of asphalt concrete over 400 mm (15.7”) of granular base on a cohesive subgrade (moraine till). The asphalt concrete included aggregate with maximum size of 16 mm (0.63”), 5.3% by weight of binder (12.3% by volume) with penetration of 70/100, and 3.5% air void content. Test points were placed 1.5 m (5 ft) from the edge of the section to avoid any boundary conditions. The FastFWD was configured with a 300 mm (11.8 in) loading plate with eight deflection sensors positioned at -300, 0, 200, 300, 450, 600, 900 and 1200 mm (-11.81, 0.00, 7.87, 11.81, 17.71, 23.62, 35.43, 47.24”) from the center of the loading plate.

To determine the dynamic modulus master curve of the asphalt concrete, testing was performed at a low load level of 38 to 40 kN (8.5 to 9.0 kip) to keep the pavement response in the linear viscoelastic region and avoid any potential damage to the pavement. Three drops were applied every 20 minutes for periods of minimum 24 hours with temperatures ranging from 5 to 30 ºC (41 to 86 ºF). Temperatures were measured at several depths in the asphalt layer, to establish the approximate depth at which the temperature was representative of the layer. The layer moduli were backcalculated using Elmod (www.dynatest.com) and the results were fitted to the dynamic modulus master curve format (10) used in the Mechanistic Empirical Pavement Design Guide (MEPDG).
To determine the fatigue parameters, a single test point was subjected to 700,000 load cycles over 8 days, later supplemented by additional loads, up to 1,650,000 load cycles within 36 days. The number of load applications and the target load levels are presented in Table 1.

Table 1 The FastFWD experiment Target Load Levels

<table>
<thead>
<tr>
<th>Target Load Level kN (kips)</th>
<th>Number of Load Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>44 (10)</td>
<td>0—1,319,999</td>
</tr>
<tr>
<td>55 (12)</td>
<td>1,320,000—1,419,999</td>
</tr>
<tr>
<td>65 (15)</td>
<td>1,420,000—1,529,999</td>
</tr>
<tr>
<td>75 (17)</td>
<td>1,530,000—1,650,000</td>
</tr>
</tbody>
</table>

The moduli were backcalculated for every 50 drops. An incremental-recursive model, developed for the CalME program—used by Caltrans for design and evaluation of flexible pavements—was used to model the damage and recovery in the asphalt modulus (11). The details of the dynamic modulus and fatigue modeling analysis and results are followed next.

2. Dynamic Modulus Master Curve

In the experiment described in this paper, the MEPDG (10) equation below was used to generate the dynamic modulus master curve for the intact asphalt:

\[
\log(E_i) = \log(E_{min}) + \log(E_{max}/E_{min})/(1 + \exp(\beta + \gamma \times \log(tr)))
\]

\[
tr = lt \times (visc_{ref}/visc)^\text{jT}
\]

\[
\log(\log(visc \text{ cpoise})) = A + VT \times \log(T_k)
\]

(1)

where \( E_i \) is the initial, intact modulus in MPa,

\( E_{min} \) is the minimum modulus in MPa,

\( E_{max} \) is the maximum modulus in MPa,

\( tr \) is reduced time in seconds,
\( \text{lt} \) is loading time in seconds (constant for the FastFWD),

\( \text{visc} \) is the viscosity of the bitumen,

\( \text{visc}_{\text{ref}} \) is the viscosity at a reference temperature,

\( T_{K} \) is the temperature in °K, and

\( \beta, \gamma, aT, A \) and \( VTS \) are constants.

Equation (1) may be simplified to:

\[
\log(E_i) = \log(E_{\text{min}}) + \log(E_{\text{max}}/E_{\text{min}})/(1+\exp(A + B \times (1 - (T_{K}/T_{K_{\text{ref}}})^{VTS}))),
\]

\[
A = \beta + \gamma \times \log(\text{lt}), \quad B = \gamma \times aT \times 10^A \times T_{K_{\text{ref}}}^{VTS} \quad (2)
\]

To characterize the master curve for FastFWD use, 5 parameters need to be determined: \( E_{\text{min}}, E_{\text{max}}, A, B \) and \( VTS \). The reference temperature \( (T_{K_{\text{ref}}}) \) can be arbitrarily chosen. The \( T_{K_{\text{ref}}} \) equal to 293 °K (20 °C, 68 °F) was selected in this study.

FastFWD tests were carried out on the test point every 20 minutes for a minimum of 24 hours, on different days. The asphalt temperature was measured at different depths, and the layer moduli were backcalculated using Elmod.

Damage to the asphalt during fatigue testing, is calculated from the difference between the backcalculated modulus and the master curve (see equation 3). It is, therefore, important that the master curve is known for the range of temperatures encountered during the fatigue experiment.
The tests shown in Figure 2 were done in two sequences. During the first sequence temperature was measured at depths of 45 mm (1.8”) and 93 mm (3.7”) over a 43-hour period. The temperature decreased from about 30 °C (86 °F) to 17 °C (63 °F), increased again to 22 °C (72 °F) and finally decreasing to about 13 °C (55 °F). During the second sequence, temperature was only measured at the depth of 50 mm (2”) for a little over 24 hours. The temperature decreased from about 13 °C (55 °F) to 7 °C (45 °F) and increased again to about 11 °C (52 °F) during this run.

From Figure 2 it appears that the representative temperature of the asphalt layer would be at about mid depth, 60 mm (2.4”).

For the test point where fatigue testing was carried out, the following master curve parameters were obtained: $E_{min} = 900$ MPa, $E_{max} = 16,000$ MPa, $A = -0.151$, $B = 8.688$ and $VTS = -3.505$. 
### 3. Fatigue Modeling

For damaged asphalt the master curve is modified to:

\[
\log(E_i) = \log(E_{\text{min}}) + \log\left(\frac{E_{\text{max}}}{E_{\text{min}}}\right) \times (1 - \omega)/(1 + \exp(A + B \times \left(1 - \left(\frac{T_k}{T_{Kref}}\right)^{VTS}\right)))
\]  

(3)

where \(\omega\) is the damage, \(\omega = 0\) for intact asphalt and \(\omega = 1\) for asphalt where the modulus has decreased to the minimum value, \(E_{\text{min}}\).

For the first part of the experiment, the test point was loaded by an approximate haversine load pulse of about 25 msec duration and a peak load of 45 kN (10 kip), at a rate of 3,650 loads/hour. For each 50 load applications the layer moduli were backcalculated using Elmod. During this part of the experiment the asphalt temperature, at approximately mid depth, varied between 10 and 25 ºC (50 and 77 ºF), and the asphalt modulus decreased from 9,000 to 1,700 MPa (1300 to 250 ksi) as presented in **Figure 3**. The decrease in the asphalt modulus is attributed to both the increase in temperature and increasing damage. It should be noticed that the asphalt modulus represents a mean value for the layer, whereas in reality, the damage is largest in the vicinity of the loading plate.
Figure 3 Asphalt temperature and modulus versus time, first part of the experiment.

The damage was modelled assuming a non-linear Miner’s law, as used in the Californian system for design of flexible pavements, CalME (11, 12).

\[ \omega = (MN/MN_p)^\alpha, \quad MN_p = (\varepsilon/\varepsilon_r)^\beta \times (E/E_r)^\gamma \]  

(4)

where \( MN \) is the number of load applications in millions,

\( \varepsilon \) is the tensile strain at the bottom of the asphalt layer,

\( \varepsilon_r \) is a reference strain,

\( E \) is the (damaged) modulus,

\( \alpha, \beta, \gamma, \) and \( E_r \) are constants.
In CalME, $\gamma$ is assumed to be equal to $\beta/2$, which implies that damage is a function of strain energy. The same assumption was made for this study which allowed the number of parameters to be determined to be reduced to three, $\alpha$, $\varepsilon_r$, and $\beta$, as $E_r$ can be freely chosen. In this case $E_r$ of 3,000 MPa (435 ksi) was used. The tensile strain at the bottom of the asphalt was calculated from the modelled value of the asphalt modulus and the back-calculated modulus of the base.

As noticed by Briggs et al. (13) resting time, with no load, reduces the damage. The following format was used for calculating the damage after a rest period:

$$\omega = 1 - (t/t_r)^\delta \quad (5)$$

where $t$ is time at rest,

$t_r$ is a reference time, and

$\delta$ is a constant.

Both damage caused by the load and recovery with time were calculated using an incremental-recursive approach, with the time hardening procedure, as described in Briggs et al. (13).
Figure 4: Modelled asphalt modulus, superimposed on measured values.

In Figure 4 the modelled asphalt modulus has been superimposed on the measured values. The model parameters for equation (4) were: \( \alpha = 1, \epsilon_r = 367 \, \mu\text{strain (tensile)} \) and \( \beta = -3.55 \), and for equation (5): \( t_r = 48.5 \, \text{days} \) and \( \delta = 1 \). The calculated tensile strain at the bottom of the asphalt layer varied between 200 and 470 \( \mu\text{strain} \), for this first part of the experiment. At the end of the first part of the experiment, the maximum permanent deformation at the asphalt surface was about 8 mm.
Figure 5: Moduli adjusted to 20 °C, versus number of load applications—first part of the experiment

The back-calculated and modelled asphalt moduli were adjusted to the reference temperature of 20 °C (68 °F) in Figure 5.

With ‘fatigue life’ being defined as the number of load applications to cause the modulus to decrease to half the initial value, the FastFWD test point had a fatigue life of about 570,000 load applications where the modulus dropped from the initial value of 4230 MPa to half. It is important to note that this number would have been different, had the length of the rest periods been different.
Figure 6: Moduli adjusted to 20 °C, versus number of load applications.
The moduli adjusted to 20 ºC are shown in Figure 6 and Figure 7, versus number of load applications and versus time, respectively. As it is observed from Figure 6 and Figure 7, the model predicting the damage and recovery in the asphalt layer follows the measured moduli quite well for the full duration of the experiment. At the highest load level there was no further decrease in the asphalt modulus. The modulus approached 900 MPa (130 ksi) towards the end of the experiment providing a reliable determination of $E_{\text{min}}$. During the latter part of the experiment the temperature ranged from 10 to 27 ºC (50 to 81 ºF) and the strain at the bottom of the asphalt eventually increased to 1,400 μstrain.

At the end of the experiment the maximum permanent deformation at the asphalt surface was 36 mm.
4. Conclusion

With the occurrence of the FWD in the 1980’s it became possible to determine the most important input parameters for the ‘mechanistic’ part of the mechanistic-empirical method—in-situ modulus and stress/strain distribution in existing pavement structures and materials. The backcalculated layer moduli determined from the surface deflections through an inverse process, can be used with the mechanistic (or analytical) model, to calculate the critical stresses or strains in the pavement layers.

This still leaves a wide gap between the critical response and prediction of the future pavement deterioration or “residual life”. Presently, the ‘empirical’ part of the method mainly relies on models calibrated based on LTPP studies and manual and automated full scale accelerated pavement testing (e.g. the AASHO Road Test and HVS). While HVS and other full scale testing are helping to close the gap, for the evaluation of a particular pavement design or of an existing pavement structure, engineers have mostly had to rely on laboratory testing of material samples, as specified in the European and US standards. With the FastFWD it is now possible, within a limited space and time, to carry out intermediate accelerated pavement tests (iAPT) directly on the proposed design or on an existing pavement structure. FastFWD application as an iAPT can significantly reduce the gap by providing pavement and materials specific input parameter for the ‘empirical’ part of the Mechanistic Empirical method.

In this study, the FastFWD was used to apply 1,650,000 load cycles on a $5 \times 5 \text{m}^2$ pavement test section in 36 days. The dynamic modulus master curve was first obtained through testing at low load levels and in a wide range of temperatures to provide the basis to differentiate the damage and recovery of asphalt layer from the viscoelastic response due to variation in the asphalt temperature. The fatigue parameters where obtained through fitting the Incremental-Recursive fatigue model used in CalME (11). The predicted damage and recovery in the asphalt layer followed the measured moduli quite well for the full duration of the experiment.

The FastFWD does not apply a rolling wheel load and the testing is of a relatively short duration compared to the normal design life of a pavement. FastFWD testing must be supplemented by past
experience—especially the valuable experience from LTPP and full scale APT studies. But meanwhile, it shows promise as an iAPT tool to directly evaluate the stiffness and fatigue parameters of full scale pavement structures and materials, under full scale loads and actual climatic conditions.

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