Simulation of Full Scale Accelerated Pavement Test from CEDEX Using the Californian Predictive Pavement Design System (*CalME*)

P. Ullidtz
Dynatest International, Denmark

A. Mateos and J. Ayuso
CEDEX, Madrid, Spain

J. Harvey
University of California Pavement Research Center, Davis, California, USA

I. Basheer
California Department of Transportation, California, USA

ABSTRACT: This paper describes our major findings from the use of the California asphalt pavement mechanistic-empirical design and analysis system (known as *CalME*) to simulate full scale accelerated tests conducted at CEDEX, Spain. The CEDEX accelerated testing included fully instrumented test sections which were monitored regularly throughout the experiment for primary responses, moisture content, deflection, pavement temperature, and pavement performance in terms of asphalt surface cracking and permanent deformation. Various laboratory tests were also conducted on asphalt and unbound materials at both the CEDEX and the University of California Pavement Research Center (UCPRC) laboratories to complement the accelerated test data. This paper illustrates the two-step approach that was used in conducting the simulations; namely verification of the mechanistic pavement response models against the measured responses during the experiment, followed by calibration of the distress models. The full scale tests were simulated, hour by hour, using *CalME*. Although *CalME* was developed for design of new pavements and for rehabilitation design, it has facilities for simulation of full scale accelerated pavement tests. For each hour of the experiment the number and magnitude of the load applications were imported into the *CalME* database. Measured temperatures at different locations and different depths were also imported into the database, again for each hour of the experiment, and used in the simulation process. *CalME* was found to predict the response and the performance of the analyzed pavement system reasonably well in both fatigue cracking of the asphalt layer and permanent deformation of the pavement layers..

KEY WORDS: Full scale testing, mechanistic-empirical analysis, instrumentation

1 INTRODUCTION

The computer program *CalME* was developed by Caltrans for design of flexible pavements and for asphalt rehabilitation in California (Ullidtz et al., 2006). The program incorporates the existing Caltrans empirical design methods, a “classical” mechanistic-empirical method, and an incremental-recursive damage prediction based on mechanistic-empirical principles (Ullidtz et al., 2007). For each time increment the stresses and strains caused by the loads are calculated using the mechanistic model based on multilayer linear elastic theory, and from this response the damage is determined using a set of empirical relationships. The output from the increment is then used, recursively, as input for the next increment. To facilitate calibration of the mechanistic and the empirical models, the program has a facility for importing the results of Accelerated Pavement Tests (APT) into the program database, and for simulating the experiment on the computer. As part of *CalME* verification, a vast number of simulation studies have been conducted on approximately 40 Heavy Vehicle Simulator (HVS) tests carried out in California as well as on the 26 original sections of the WesTrack experiment (Ullidtz et al., 2007).

The full scale testing done at CEDEX in Spain supplements the experiments from the USA by having additional instrumentation, fully controlled loading, like the HVS, but with longer test sections and climatic variations, and by including different materials. For these reasons it was decided to attempt a simulation of the CEDEX experiment. This paper describes the considerations made with respect to simulation of the first test section.

2 FULL SCALE TEST

The testing was carried out in the full scale testing facility of CEDEX (see Figure 1). Six different test sections were tested simultaneously, but this paper only deals with Section 1. The length of the test section, without the transition zones, was 15 m. A wheel load of 63.8 kN was applied to a dual wheel, with a tire pressure of 785 kPa and a centerline distance between the tires of 350 mm. A total of 770 000 loads (corresponding to 5.5 million 18-kip ESALs) were applied between August 2007 and November 2008, with 24 hours of loading per day. The wheel velocity was 35 km/hour for most of the experiment. The lateral distribution of the wheel was within ± 195 mm of the center line.

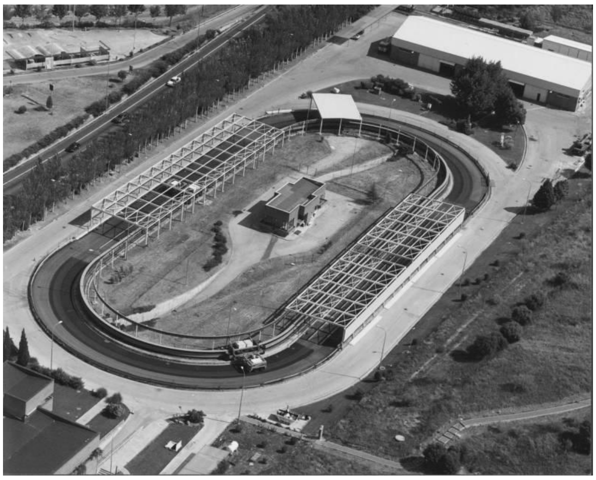
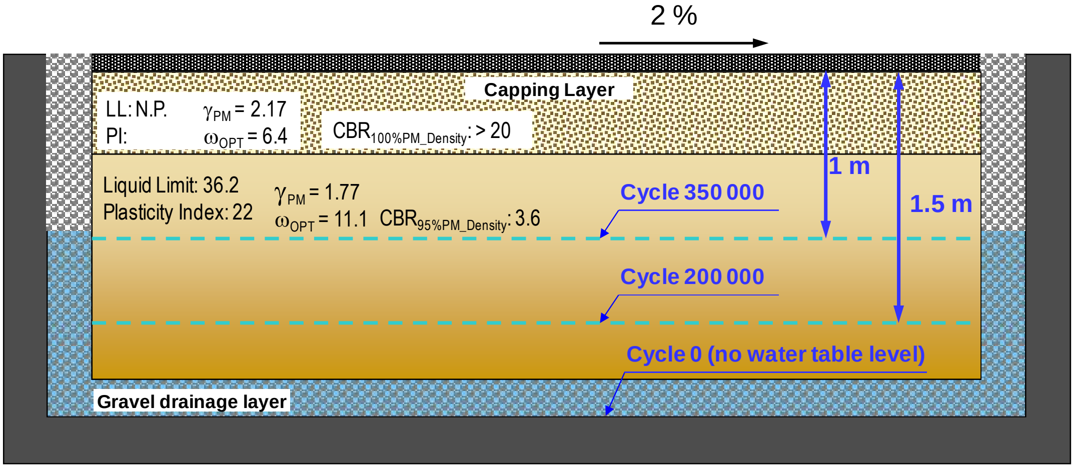


Figure 1 CEDEX full scale testing facility.

The pavement of Section 1 was a full depth asphalt pavement, with a thickness of 155 mm (coefficient of variation 0.05), on a 500 mm thick non-plastic capping layer with 16% passing the 0.08 mm sieve and a minimum CBR of 20%, on a subgrade (CBR ≥ 3%) with a thickness of 1300 mm above the rigid bottom of the test pit (see Figure 2). The asphalt consisted of two layers: a 30 mm thick open graded mix, BBTM11B surface (M10), with SBS modified bitumen, bitumen content 5.3%, air voids 17.1%, on top of 125 mm of asphalt concrete, AC22 base (G20), 60/70 pen bitumen, bitumen content 4.0% and air voids 6.8 %. Both asphalt layers were in accordance with the European standards EN 13108 “Bituminous mixtures – Material specifications”.

The air temperature and the asphalt temperature at depths of 30 mm and 120 mm were recorded, as well as the rainfall. As a consequence of the rainfall, a water table was generated. In early February 2008 (after 200 000 loads) the water level reached 1.5 m below the top of the capping layer and early April 2008 (350 000 loads) it reached 1 m, at which level it was kept constant by pumping for the remainder of the test. Soil moisture was measured at several depth in the capping layer and in the subgrade using Time Domain Reflectometer (TDR) sensors.

In addition, the section was instrumented with deflection sensors, longitudinal and transversal strain gauges at the bottom of the asphalt, vertical pressure gauges and strain cells [based on LVDTs (Linear Variable Differential Transformer)] at different levels of the capping layer and the subgrade soil. Additional information for CEDEX test track and its data collection system can be found in Cadavid et al. (2008).



** Water table level was kept constant (by pumping) from Cycle 350 000, during the complete APT test*

Figure 2 Water table levels.

3 ELASTIC PARAMETERS

The most important inputs to the mechanistic response model are the elastic parameters of the materials. These were determined both by laboratory tests and by in-situ tests.

For the asphalt materials the master curve format from the MEPDG (NCHRP, 2004) was used:

$$\log(E_i) = \delta + \frac{\alpha}{1 + \exp(\beta + \gamma \log(tr))} \qquad (1)$$

where E_i is the intact modulus in MPa,
tr is reduced time in seconds and
α, β, γ, and δ are constants determined from frequency sweep tests or FWD.

The parameters of Equation 1 were determined from tests on cylindrical specimens 100 mm in diameter and 200 mm high. The moduli were also backcalculated from Falling Weight Deflectometer (FWD) tests done at different intervals during the experiment. The backcalculated values from the non-loaded line of Section 1 are compared to the laboratory master curves in Figure 3.

The moduli of the capping layer and subgrade soil were determined from FWD tests. The initial modulus of the capping layer was about 120 MPa decreasing to about half that value, as the moisture content increased from a little less than 4% to 7.7%. For the subgrade soil the modulus decreased from 30-35 MPa to 20-25 MPa as the moisture content increase from 10% to almost 30%.

Triaxial tests gave resilient moduli of 60-120 MPa for the capping layer, depending on stress conditions and moisture content. For the subgrade, the triaxial moduli were in the range of 30-40 MPa.

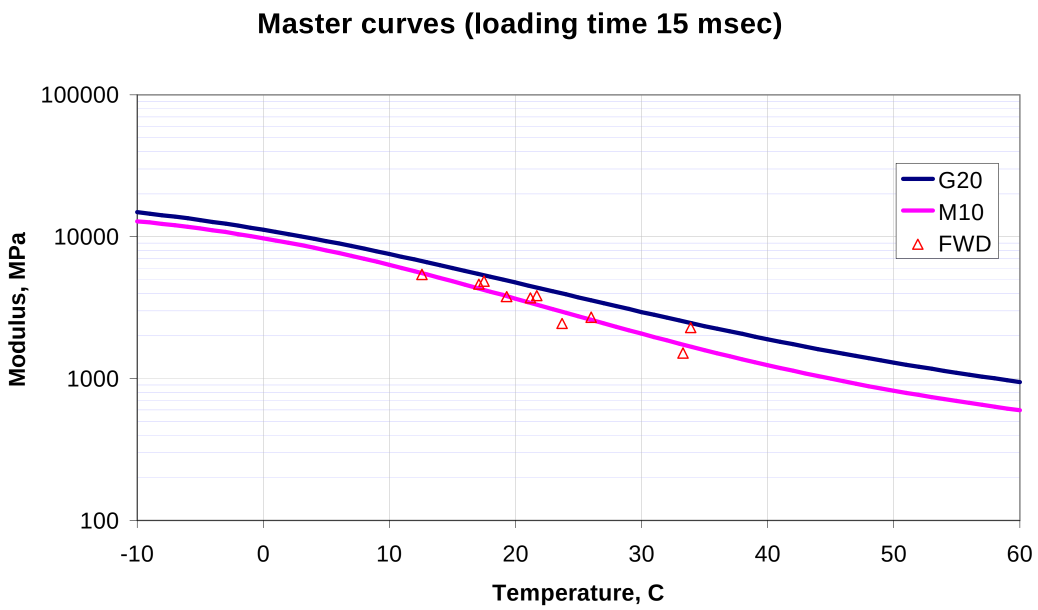


Figure 3 Master curves of the M10 and G20 asphalt layers obtained from laboratory testing and backcalculated moduli.

4 EMPIRICAL RELATIONSHIPS

The pavement response determined from the mechanistic model is used with empirical relationships to predict the decrease in modulus of bound materials, caused by fatigue, and the permanent deformation of each layer. In addition, empirical relationships are used to determine the hardening effects of time and temperature and to relate visible cracking to fatigue damage.

4.1 Fatigue Damage of Asphalt Concrete

For damaged asphalt concrete the modulus is determined from:

$$\log(E) = \delta + \frac{\alpha \times (1-\omega)}{1+\exp(\beta + \gamma \log(tr))} \tag{2}$$

where the damage, ω, is calculated from:

$$\omega = \left(\frac{MN/SF}{MN_p} \right)^{\alpha}, \qquad MN_p = A \times \left(\frac{\mu\varepsilon}{\mu\varepsilon_{ref}} \right)^{\beta} \times \left(\frac{E}{E_{ref}} \right)^{\gamma} \times \left(\frac{E_i}{E_{ref}} \right)^{\delta} \tag{3}$$

where *MN* is the number of load applications in millions,

SF is the shift factor from laboratory to in situ loading,
$\mu\varepsilon$ is the tensile strain at the bottom of the asphalt layer,
E is the current modulus of asphalt layer,
E_i is the intact (initial) modulus of the asphalt layer,
$\mu\varepsilon_{ref}$ and E_{ref} are reference constants, and
A, α, β, γ, and δ are constants (not related to the constants of Equation (1)).

The model parameter δ was set at 0 (zero) and γ as ½×β, making damage a function of strain energy. The remaining parameters A, α, β were determined from laboratory 4-point bending fatigue tests, conducted at a frequency of 10 Hz and a temperature of 20 °C on 10 specimens. A least squares method was used to fit the complete function of modulus versus number of loads applications for the 10 specimens. A quite good agreement was obtained as presented in the Figure 4 example.

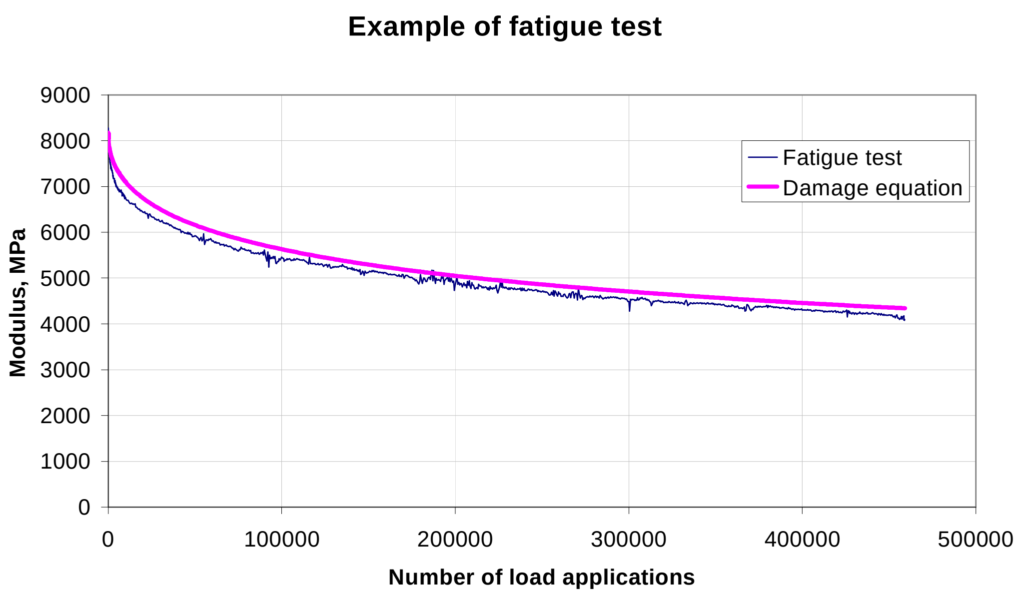


Figure 4 Example of fatigue test and fitted damage equation.

Previous experiments by the authors have shown visible cracking to be related to damage through:

$$\omega_i = \frac{1}{1+\left(\frac{h_{AC}}{250\,mm}\right)^{-2}}, \quad C_r\% = \frac{100\%}{1+19\times\left(\frac{\omega}{\omega_o}\right)^{-8}} \tag{4}$$

where ω_i is the damage at crack initiation,
h_{AC} is the thickness of the asphalt layers,
$C_r\%$ is visible cracking in percent of area, and
ω is the damage, and
ω_o is a constant.

4.2 Permanent Deformation of Asphalt Materials

Permanent deformation of the asphalt may be caused by post compaction of the material or by shearing. The post compaction is normally small and is assumed to be proportional to the reduction in air voids. In *CalME* it may be imposed during the initial loading phase. The shear deformation is more important and is determined using a shear-based approach, developed by Deacon et al. (2002).

The permanent, or inelastic, shear strain, γ_i, will depend on the shear stress, τ, the elastic shear strain, γ_e, and the number of load repetitions. The relationship is determined from Repeated Simple Shear Tests at Constant Height (RSST-CH) in the laboratory. The best fitting relationship for the materials used was found to be a gamma function:

$$\gamma_i = \exp\left(A + \alpha \times \left[1 - \exp\left(-\ln(N)/\gamma\right) \times \left(1 + \ln(N)/\gamma\right)\right]\right) \times \exp\left(\beta \times \tau / \tau_{ref}\right) \times \gamma_e \quad (5)$$

where γ_e is the elastic shear strain,
τ is the shear stress,
N is the number of load repetitions,
τ_{ref} is a reference shear stress, and
A, α, β, and γ are constants determined from the RSST-CH

The permanent deformation of the asphalt is calculated from:

$$dp = K \times \sum h_i \times \gamma_i^i \quad (6)$$

where K is a calibration factor determined from HVS testing,
h_i is the thickness of layer i, and
γ^i_i is the permanent (inelastic) shear strain in layer i.
The summation is done for the top 100 mm of the asphalt.

4.3 Permanent Deformation of Unbound Materials

The model for permanent deformation of the unbound layers, *dp*, is given in Equation 7. The relationship was derived from tests in the Danish Road Testing Machine during the International Pavement Subgrade Performance Study (Ullidtz 2005):

$$dp,\ mm = A \times MN^{\alpha} \times \left(\frac{\mu\varepsilon}{\mu\varepsilon_{ref}}\right)^{\beta} \times \left(\frac{E}{E_{ref}}\right)^{\gamma} \quad (7)$$

where MN is the number of load applications in millions,
$\mu\varepsilon$ is the vertical strain at the top of the layer,
E is the modulus of the layer, and
A, α, β, γ, $\mu\varepsilon_{ref}$ and E_{ref} are constants.

The constants normally used are A = 0.8 for granular layers and A = 1.1 for subgrades, α = 0.333, β = 1.333, γ = 0.333, $\mu\varepsilon_{ref}$ = 1000 µstrain and E_{ref} = *40* MPa.

Because of the changes in moisture content during the experiment it was found necessary to decrease the reference strain, $\mu\varepsilon_{ref}$, from the normal value of 1000 µstrain to 140 µstrain as the water level increased to within 1 m of the pavement surface. Triaxial tests showed very high permanent strains at the high moisture content, but it was not possible to deduce a model for permanent deformation based on the triaxial tests.

5. PAVEMENT RESPONSE

At the start of the experiment the pavement response was measured at a range of asphalt temperatures. The response was also calculated for the initial layer moduli, from frequency sweep testing for the asphalt and from FWD testing for the unbound layers, using *CalME*.

In Figure 5the measured surface deflections (two sensors) at different asphalt temperatures are compared to the values calculated using *CalME*. There is a tendency for the theoretical values to increase more with temperature than the measured values. This tendency is even more pronounced for the horizontal strains at the bottom of the asphalt layer, where the measured longitudinal strains are also smaller than the theoretical values. For the capping layer the vertical stress was underestimated. The vertical strain in the capping layer was predicted reasonably well. For the subgrade the vertical stress was predicted well whereas the vertical strain was overestimated compared to the measured values (opposite to what happened in the capping layer).

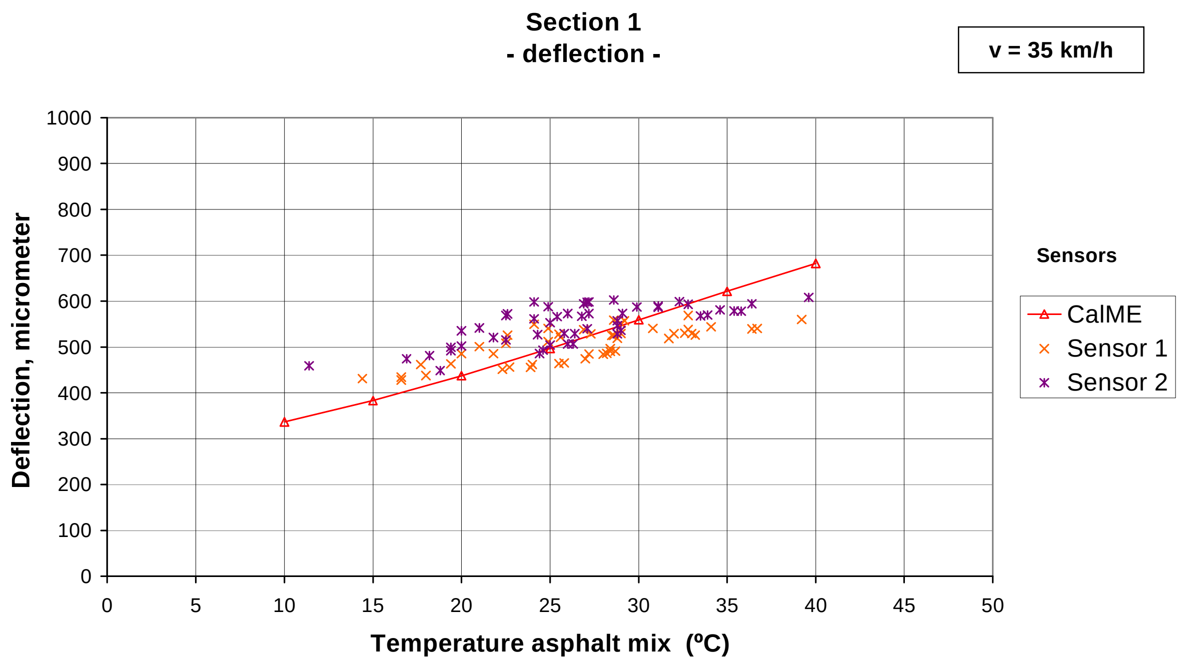


Figure 5 Measured surface deflection compared to theoretical values.

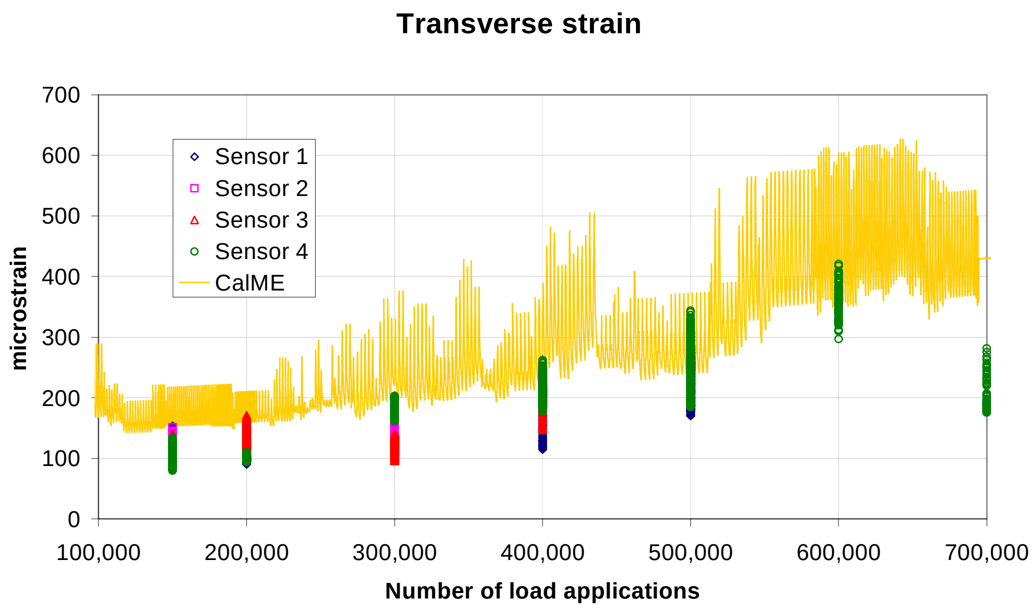


Figure 6 Measured and calculated transverse strains at bottom of asphalt layer.

The response was measured at regular intervals during the experiment. The deflections predicted from *CalME* were in reasonably good agreement with the measured deflections (as seen in Figure 5), but the *CalME*-computed horizontal strains at the bottom of the asphalt layer continued to be larger than the measured values for most of the experiment, as seen in Figure 6. Simultaneously the vertical stress and the vertical strain at the top of the capping layer tended to be underpredicted. With layered elastic theory it would not be possible to get agreement for all of the measured response values simultaneously. During the experiment there was an increase in the measured response by roughly 100-200%. These changes in response with the number of load applications were predicted reasonably well.

6. FATIGUE DAMAGE AND CRACKING

The damage to the asphalt, ω in Equation (3), may be calculated from the FWD tests using:

$$\omega = 1 - \frac{\log\left(E / Af / E_{\min}\right)}{\log\left(E_i / E_{\min}\right)} \qquad (8)$$

where E is the modulus determined from FWD testing,
E_i is the intact modulus,
E_{min} is the minimum modulus, and
Af is an ageing factor.

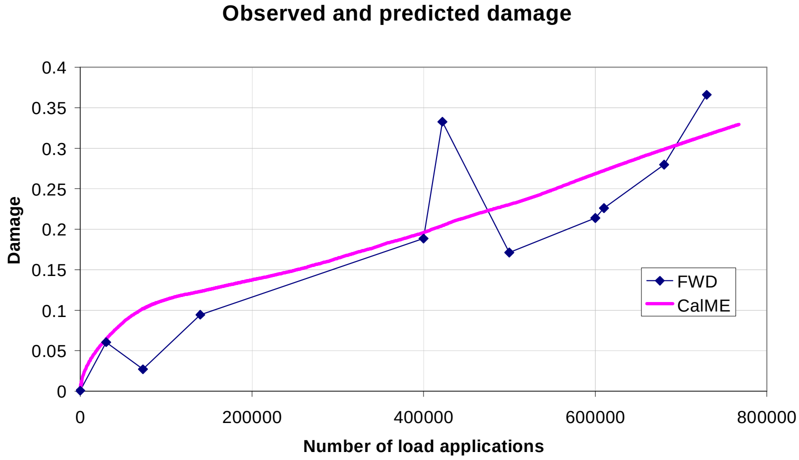


Figure 7 Comparison of damage determined from FWD testing and predicted by *CalME*.

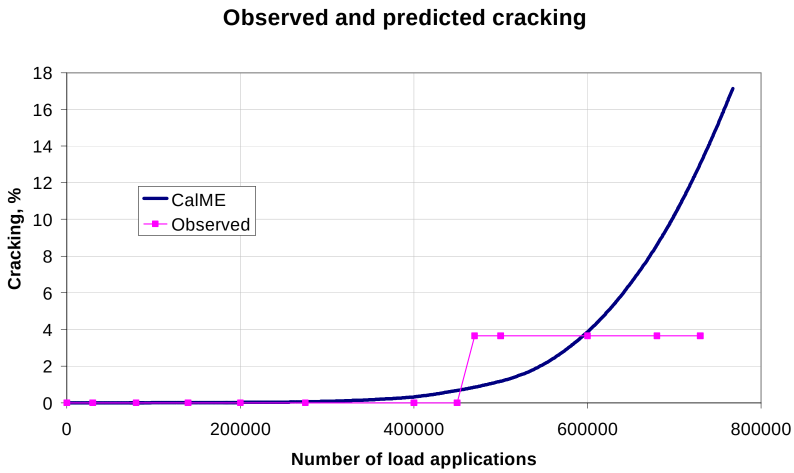


Figure 8 Observed and predicted visible cracking.

Figure 7 shows the damage calculated from Equation (8) with an ageing factor *Af* = 1.0, compared to the damage predicted by *CalME* (Equation 3) using a shift factor *SF* = 1.0. Observed and predicted cracking, from Equation (4), are shown in Figure

7. PERMANENT DEFORMATION

Most of the permanent deformation took place in the capping layer. Figure 9 shows the permanent deformation of the top 120 mm of the capping layer, as measured by an LVDT. For comparison, half of the permanent deformation in the capping layer, as predicted by *CalME*, is also shown. The total permanent deformation at the pavement surface is shown in Figure 10. Within the test section the permanent deformation varied from 20 mm to 38 mm.

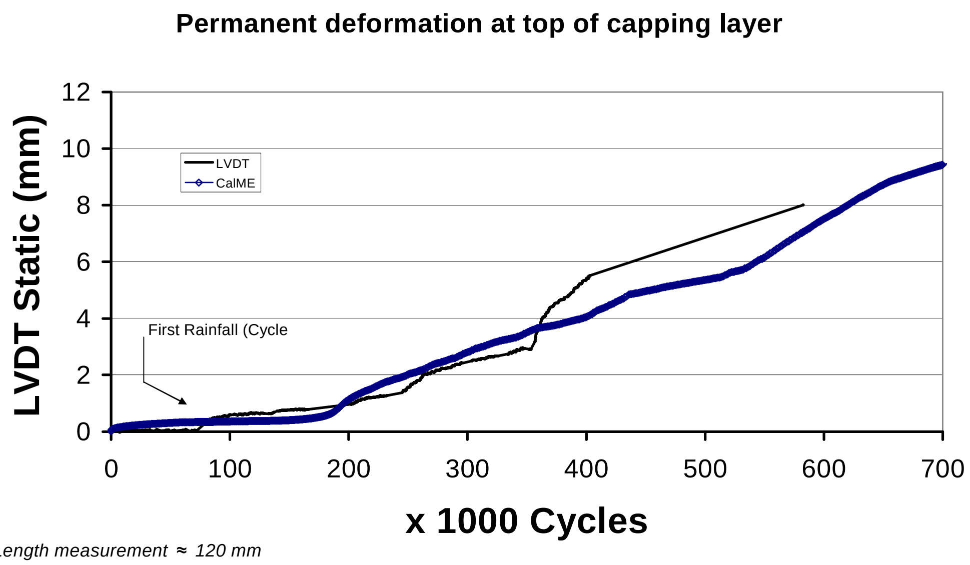


Figure 9 Permanent deformation at top of capping layer.

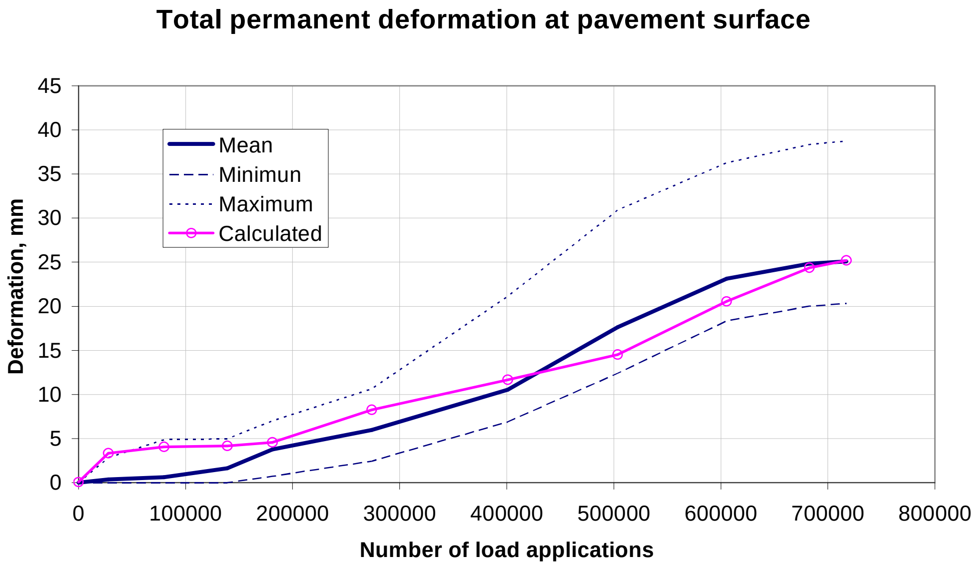


Figure 10 Measured and predicted permanent deformation at pavement surface.

The calculated permanent deformation of the asphalt layers was 5 mm.

8. CONCLUSIONS

The master curves determined for the asphalt materials from frequency sweep testing in the laboratory and derived from Falling Weight Deflectometer testing on the pavement structure were in good agreement. This was also the case for resilient moduli from triaxial testing and backcalculated moduli for the capping layer and the subgrade. It was not possible to get agreement for all of the measured response values using layered elastic theory, possibly due partly to shortcomings of this theory.

The empirical fatigue damage model determined from flexural beam testing in the laboratory gave a reasonably good prediction of the fatigue of the asphalt layer, as determined from FWD backcalculation. The relationship between cracking and fatigue damage tended to overpredict the actual cracking.

Permanent deformation was dominated by the compression of the capping layer. The default empirical model in *CalME* for unbound materials would have predicted much less permanent deformation than observed in this layer. To obtain the actual permanent deformation of the capping layer it was necessary to reduce the reference strain to 14% of the default value, once the ground water level had reached its maximum value.

The permanent deformation model determined from Repeated Simple Shear Tests at Constant Height predicted approximately the permanent deformation due to the asphalt layer.

REFERENCES

Cadavid Jáuregui, B., J. Perez Ayuso and A. Mateos, 2008 *Managing Data from Instrumentation in the CEDEX Test Track*, Third International Conference on Accelerated Pavement Testing, Madrid.

Deacon, J.A, Harvey, J.T., Guada, I., Popescu, L. & Monismith, C.L., 2002 *Analytically Based Approach to Rutting Prediction*, Transportation Research Record 1806, Washington D.C..

NCHRP, 2004 *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures*. National Cooperative Highway Research Program, Report 1-37A

Ullidtz, P., 2005 *A Simple Model for Pavement Damage*, Transportation Research Record 1905, Transportation Research Board, Washington D.C.

Ullidtz, P, Harvey, J., Kanekanti, V., Tsai, B-w. & Monismith, C., 2006 *Calibration of Mechanistic-Empirical Models Using the California Heavy Vehicle Simulators.* Proceedings, The 10th International Conference on Asphalt Pavements, Québec, Canada.

Ullidtz, P., Harvey, J. Tsai, B.W. and Monismith, C.L. 2007. *Calibration of Incremental-Recursive Flexible Damage Models in CalME Using HVS Experiments.* Report prepared for the California Department of Transportation. UCPRC-RR-2005-06. Available for download from www.its.berkeley.edu/pavementresearch/.