Calibration of Reflection Cracking and Permanent Deformation Models for Overlays Using Heavy Vehicle Simulator Tests

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ABSTRACT

The main objective of the study described in this paper was to evaluate different conventional and modified overlay materials for use in California. Twelve Heavy Vehicle Simulator (HVS) experiments were carried out and all were simulated using the computer program CalME. The purpose of the simulations was to enable “virtual” experiments to be conducted under exactly uniform conditions, and to enable extrapolation to other loading and climatic conditions. Six HVS experiments were done on sections where the overlays were placed on a two year old pavement which had had only light trafficking. This rutting experiment had uni-directional loading at elevated temperatures. For six other sections the overlays were placed on sections that had already been loaded to cracking in a previous HVS experiment. Reflection of cracks, in an existing pavement, through a new overlay is difficult to predict using Mechanistic-Empirical models. A simple model for calculating the strain at the tip of a crack was developed based on a large number of 2D and 3D finite element calculations. This response model was used in CalME, to determine damage to the overlay and to predict the appearance and propagation of visible cracks. Other models in CalME were from calibration studies on new pavements.

The overlay materials were dense graded asphalt concrete, gap graded asphalt rubber hot-mix, and several asphalt concrete materials with modified binders. The overlays were placed in thicknesses of 38 mm to 95 mm. The master curves of the asphalt materials were determined from frequency sweep tests in the laboratory and layer moduli were also backcalculated from Falling Weight Deflectometer (FWD) tests. The parameters of the fatigue damage models (for modulus reduction) were determined from beam fatigue tests at constant strain in the laboratory and the permanent deformation parameters from Repeated Simple Shear Tests at Constant Height (RSST-CH). The model parameters from the laboratory tests were used in CalME for simulation of the HVS experiments and calibration factors were determined from these simulations.

During the HVS tests temperatures were measured at different depths, the applied loads were recorded, and the resilient and permanent deformations were measured at several depths in the pavement, using Multi Depth Deflectometers (MDDs). A Road Surface Deflectometer (RSD) and a laser profilometer were used to record the resilient surface deflections and the permanent deformation profiles, respectively. Any surface cracking was also recorded. The results were imported into the CalME database and the experiments were simulated, hour by hour, using the incremental-recursive procedure. Care was taking to ensure that the calculated resilient deflections matched the measured deflections reasonably well during the full experiment.

For the empirical model of permanent deformation a calibration factor was determined to relate the laboratory deformation to the in situ down rut. A relationship for prediction of reflection cracking was also developed. Values measured periodically during the full experiment were used in the calibration, not only the start and end points of the tests.

Keywords: HVS, Reflection Cracking, Mechanistic-Empirical, Overlay, Rutting

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Introduction

The goal of the study described in this paper was to evaluate the reflection cracking and rutting performance of asphalt mixes used in overlays for rehabilitating cracked asphalt concrete pavement in California. The main objective was to compare the performance of three overlays with mixes containing binders using California Department of Transportation's (Caltrans') MB specification (binders including recycled tire rubber and polymers blended at the refinery) against two control overlay mixes [dense-graded asphalt concrete (DGAC) and gap-graded rubberized asphalt concrete (RAC-G)]. These control overlays represent typical pavement structures currently used throughout California.

The project was divided into two phases. In the first phase six test sections were trafficked with the HVS to induce fatigue cracking on the asphalt concrete layer. The original pavement consisted of 77 to 88 mm of DGAC on a design thickness of 410 mm of aggregate base (AB) on a clay subgrade. The AB consisted of 100% recycled building waste material with a high percentage of crushed concrete. Reactive cement was found in the AB. In the second phase, selected overlay mixes were placed both on the trafficked and on the untrafficked sections, to evaluate:

- Reflection cracking (expected failure mode) under HVS trafficking at moderate temperatures (≈ 20 ˚C), and
- Rutting performance under HVS loading at high temperature (45-50 ˚C).

A laboratory study, primarily investigating the shear and fatigue properties of the mixes, was undertaken in parallel with the HVS study.

Both the reflection cracking experiment and the rutting experiment had one of each of the following overlays:

1. Half-thickness (45 mm) MB4 gap-graded overlay with minimum 15 percent recycled tire rubber (referred to as "MB15" in this paper)
2. Half-thickness rubberized asphalt concrete gap-graded (RAC-G) overlay
3. Full-thickness (90 mm) DGAC overlay (split into two subsections in the analysis)
4. Half-thickness MB4 gap-graded overlay
5. Full-thickness MB4 gap-graded overlay
6. Half-thickness MAC15TR gap-graded overlay with minimum 15 percent recycled tire rubber.

The test sections were instrumented with Multi Depth Deflectometers (MDDs) and thermocouples. At regular intervals during the HVS tests the resilient deflections were recorded at several depths using the MDDs and at the pavement surface using a Road Surface Deflectometer (RSD, similar to a Benkelman beam). The permanent deformations were also recorded by the MDDs and the pavement profile was measured using a laser profilometer. Any distress at the surface of the pavement was recorded. During HVS testing the temperature was controlled using a climate chamber. Falling Weight Deflectometer (FWD) tests were carried out before and after the HVS tests. Details on the HVS and the instrumentation can be found in Harvey et al., 1998 and on the overall study in Jones et al, 2007.

Simulation of HVS Tests using CalME

The HVS tests were simulated using an incremental-recursive program known as *CalME* (Ullidtz et al., 2007). Data from each HVS test were imported into a *CalME* database. The data comprised information on loads (time of application and load level), temperatures at different levels, RSD results, MDD resilient and permanent deformations and pavement profiles.

The backcalculated layer moduli from the last FWD test before commencement of the HVS loading were used as the initial layer moduli (for asphalt layers at the reference temperature of 20 ºC). Layer moduli were backcalculated using *CalBack*. For asphalt layers the master curve was obtained from frequency sweep tests on beams in the laboratory, with the exception of the original DGAC layer where the master curve was based on FWD backcalculated moduli. For the subgrade the change in stiffness with changing stiffness of the pavement layers and with changing load level was obtained from FWD backcalculated values. These parameters were used with the response model (*LEAP*, Symplectic Engineering Corporation, 2004) to calculate stresses, strains and deflections in the pavement structure. The strain in the overlay over an existing cracked asphalt layer was calculated using the reflection cracking model described below.

To predict the pavement performance, in terms of cracking and permanent deformation, a number of models were used. Parameters for prediction of asphalt fatigue damage were obtained from controlled strain fatigue tests on beams. Repeated Simple Shear Tests at Constant Height (RSST-CH) were used to determine the parameters for predicting permanent deformation in the asphalt layers. A crushing model was developed for the self-cementing base layer, consisting of recycled building waste material with a high content of crushed concrete. Cracking at the pavement surface was calculated from the reflection damage to the surface layer, using a model developed based on previous simulations of HVS tests and the WesTrack experiment, with coefficients modified based on the results of the present experiment. For the details of these and other models used in CalME see Ullidtz, et al. 2008a and 2008b.

An incremental-recursive process was used to simulate the performance of the test sections. The time increment used was one hour. For the first hour of the simulation the program would read the temperatures from the database and calculate the moduli, for a constant wheel speed of 9.6 km/h, the approximate speed of the HVS wheel. The number of loads during the first hour, as well as the load level and the tire pressure, were also read from the database. The modulus of the subgrade would be adjusted to the stiffness of the pavement layers and to the load level. If the test had wheel wander, five different positions of the wheel would be considered. For the first wheel position the stresses and strains at the center line of the test section were calculated and used to determine the decrease in moduli and the increase in permanent deformation of each of the pavement layers. The output from these calculations were used, recursively, as input to the calculation for the next wheel position. Because of the changes to moduli, response, damage, and permanent deformation the "time hardening" procedure was used (Deacon et al. 2002).

The first step in the simulation is to make sure that the calculated pavement response is reasonably close to the actual pavement response during the test. The calculated pavement response is used to predict the pavement performance (damage and permanent deformation). Therefore, if the calculated response is not reasonably correct it would be futile to try to use it for calibration of the performance models. For the HVS tests used for this paper, response measurements were available in the form of resilient MDD deflections and/or RSD deflections.

Once the resilient deflections are predicted reasonably well during the simulations, it is possible to calibrate the performance models so that the permanent deformation of each layer, the decrease in layer moduli and the observed surface cracking, are reasonably well predicted.

Reflection Cracking Model

Reflection cracking damage was calculated using the method developed by Wu (2005). In this method the tensile strain at the bottom of the overlay is estimated using a regression equation. The calculated tensile strain at the bottom of the overlay is used with the fatigue equation to calculate damage in the asphalt layers.

The regression equation for tensile strain at the bottom of the overlay is based on many 2D and 3D finite element calculations, and assumes a dual wheel on a single axle:

$$\varepsilon = \alpha \times E_{an}^{\beta 1} \times E_{bn}^{\beta 2} \times \left(a1 + b1 \times \ln\left(LS_n\right)\right) \times \exp\left(b2 \times H_{an}\right) \times \left(1 + b3 \times H_{un}\right) \times \left(1 + b4 \times E_{un}\right) \times \sigma_n$$

$$E_{an} = E_a / E_s,\ E_{bn} = E_b / E_s,\ E_{un} = E_u / E_s,\ \sigma_n = \sigma_o / E_s,$$

$$LS_n = LS / a,\ H_{an} = H_a / a,\ H_{un} = H_u / a$$

Equation 1 Strain, in µstrain, over existing crack

where E_a is the modulus of the overlay,
H_a is the thickness of the overlay,
E_u is the modulus of the underlayer,
H_u is the thickness of the underlayer,
E_b is the modulus of the base/sub-base,
E_s is the modulus of the subgrade,
LS is the crack spacing,
σ_o is the tire pressure, and
a is the radius of the loaded area for one wheel.

The following constants were used:

α = 342650, $\beta 1$ = -0.73722, $\beta 2$ = -0.2645, $\beta 3$ = -1.16472, $a1$ = 0.88432, $b1$ = 0.15272, $b2$ = -0.21632, $b3$ = -0.061, $b4$ = 0.018752.

To predict reflection cracking, the resulting strain was used with the model for the master curve of the damaged asphalt, which has the format:

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

Equation 2 Modulus of damaged asphalt.

where δ, α, β, and γ are constants, tr is reduced time in sec and the damage, ω, is calculated from:

$$\omega = \left(\frac{MN}{MNp}\right)^{\alpha}$$

$$MNp = A \times \left(\frac{\mu\varepsilon}{\mu\varepsilon_{ref}}\right)^{\beta} \times \left(\frac{E}{E_{ref}}\right)^{\beta/2} = A' \times \left(\frac{SE}{SE_{ref}}\right)^{\beta/2}$$

Equation 3 Damage as a function of number of loads, strain, and modulus.

where E is the modulus of damaged material,
E_i is the modulus of intact material,
MN is the number of load repetitions in millions ($N/10^6$),
$\mu\varepsilon$ is the strain at the bottom of the asphalt layer in µstrain,
SE is the strain energy, and
A, A', α, β, $\mu\varepsilon_{ref}$, E_{ref}, and SE_{ref} are constants

The initial (intact) modulus, E_i, corresponds to a damage, ω, of 0 and the minimum modulus, $E_{min}=10^{\delta}$, to a damage of 1.

Simulation of Pavement Response

The deflections normally increase considerable during an HVS test, as a result of damage to the bound layers (asphalt and self-cementing AB in this case). This means that the stresses and strains in the pavement layers, which are used in calculation of the pavement performance, also change during the test. To ensure that the pavement response calculated by *CalME* was reasonably correct for the duration of the test, the surface deflections and the deflections at the depths of the MDD modules were calculated by *CalME* and compared to the RSD and MDD measurements.

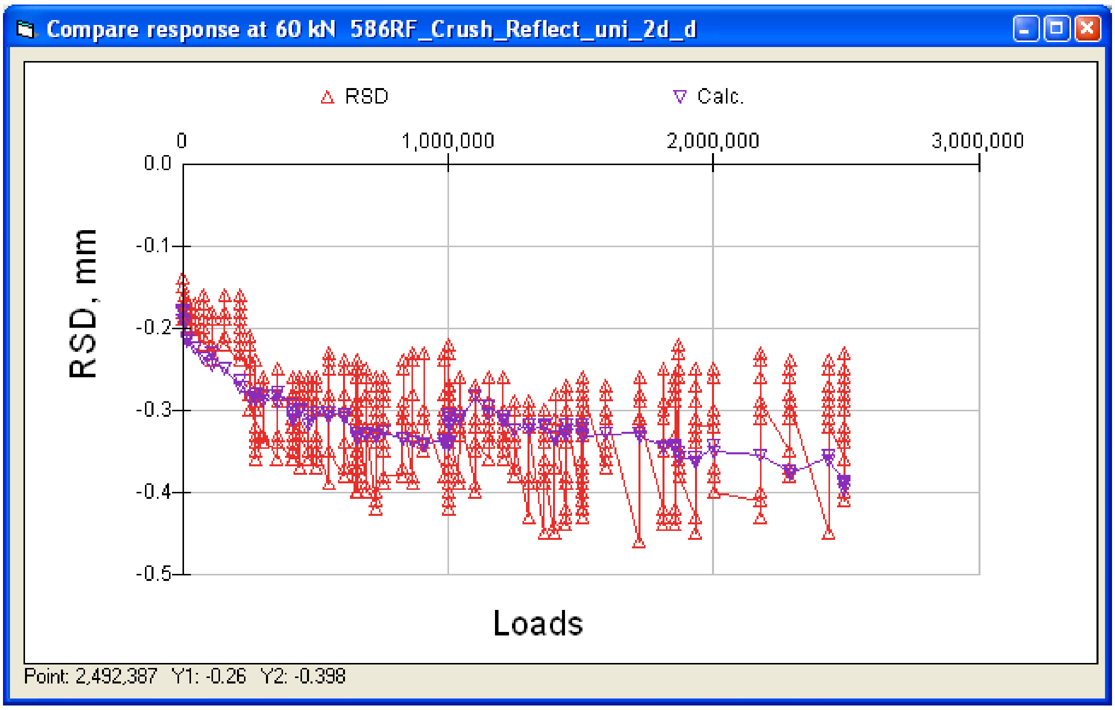

Figure 1 Measured (RSD) and calculated (Calc) surface deflection versus load applications.

Figure 1 shows a comparison of surface deflection under a 60 kN wheel load, for the test section with a 45 mm MB15 overlay. Even though the test section is only 6 m long the measured surface deflections vary considerably over the area of the test section, sometimes by as much as a factor of 2. The coefficient of variation on the RSD measurements varies from less than 10% to more than 20%. It may be noticed that the deflection increases by more than 50% within the first one million load applications. The drop in deflection after one million load applications is due to the temperature being reduced from 20 ºC to 15 ºC. The deflections calculated by CalME are seen to be in reasonably good agreement with the average of the RSD deflections. The three MDDs shown in Figure 2 measured the deflection at (approximately) the top of the aggregate base. They also indicate a considerable variation within the test section, and show the same trend as the RSD deflections. The deflections calculated by *CalME* are seen to be in good agreement with the measured deflections.

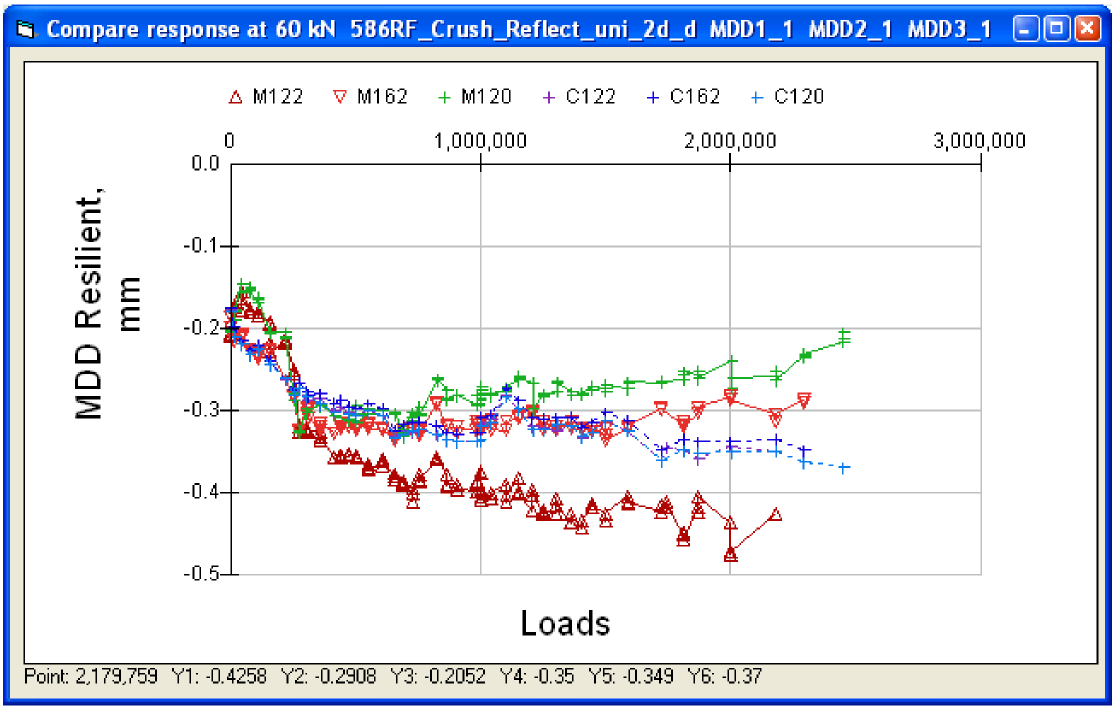

Figure 2 Measured (M, by MDD) and calculated (C) deflections, approximately on top of base.

Permanent Deformation

Permanent deformations were measured both during the rutting experiment and during the reflection cracking experiment. The permanent deformation in the asphalt layers was calculated from:

$$dp = K \times \sum h_i \times \gamma_i^i$$

Equation 4 Permanent deformation (down rut) of asphalt.

where K is a calibration factor determined from HVS testing,
h_i is the thickness of layer i, and
γ^i_i is the inelastic (permanent) shear strain in layer i, determined from:

$$\gamma^i = \exp\left(A + \alpha \times \left[1 - \exp\left(-\ln(N)/\gamma\right) \times \left(1 + \ln(N)/\gamma\right)\right]\right) \times \exp\left(\beta \times \tau/\tau_{ref}\right) \times \gamma^e$$

Equation 5 Gamma function for inelastic shear strain.

where γ^e is the elastic (resilient) shear strain,
τ is the shear stress,
N is the number of load repetitions,
τ_{ref} is a reference shear stress (0.1 MPa), and
A, α, β, and γ are constants determined from the RSST-CH.

The summation in Equation 4 is done for the top 100 mm of the asphalt. Permanent deformation due to post compaction was not calculated. Permanent deformations of

the unbound layers were calculated using the model given in Ullidtz, et al. (2008a). They were quite small for all tests.
The same calibration factor (K = 1.4) was used for all of the tests, even though the rutting experiment was done using uni-directional loading and the reflection cracking experiment was with bi-directional loading.

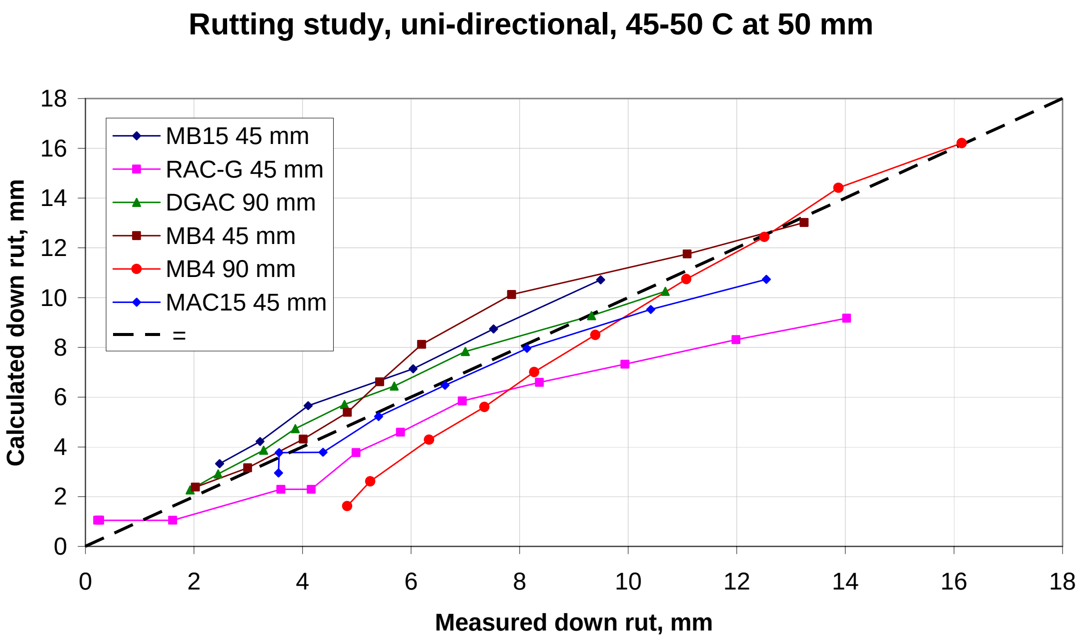

Figure 3 Measured and calculated down rut during rutting study.

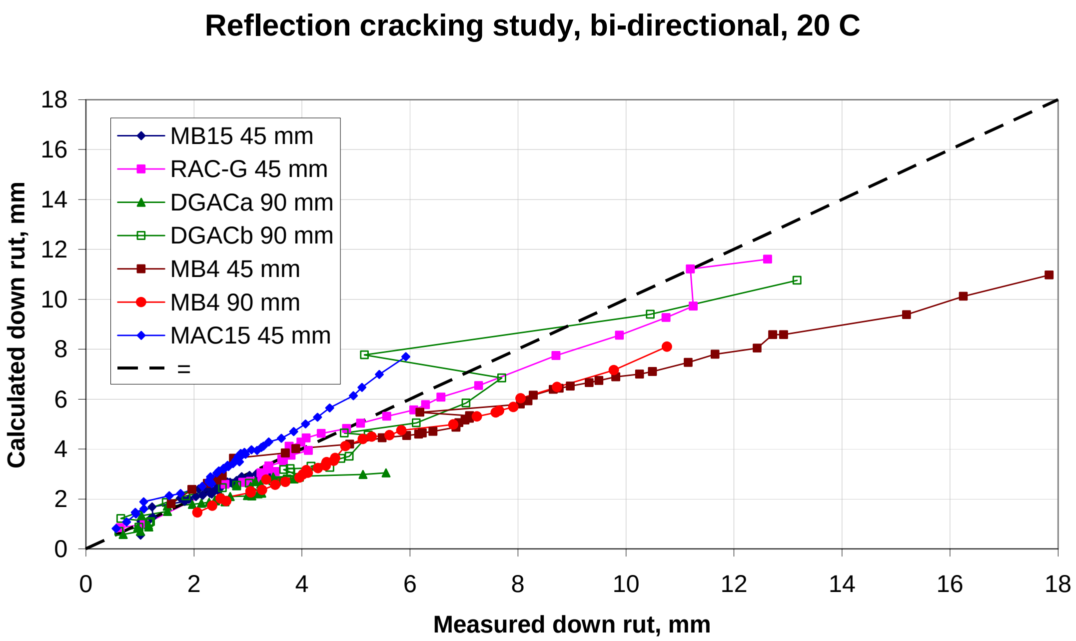

Figure 4 Measured and calculated down rut during reflection cracking study.

The measured and the simulated down rut during the rutting study are shown in Figure 3. For all of the tests the calculated down rut is 6% lower than the measured values, with an R^2 of 0.86 and a standard error of estimate of 1.3 mm. For the reflection cracking study (Figure 4) the calculated down rut is 19% below the measured values, the R^2 is 0.83 and the standard error of estimate is 0.9 mm.

Cracking

Based on previous HVS experiments on new pavement and on simulation of the WesTrack experiment the following equations were found to be capable of estimating the severity, or density, of surface cracking, in m/m^2, reasonably well:

$$\omega_i = \frac{1}{1+\left(\frac{h_{AC}}{250\,mm}\right)^{-2}}$$

Equation 6 Model for estimating damage at crack initiation.

where ω_i is the damage at crack initiation, and
h_{AC} is the combined thickness of the asphalt layers.

$$Cr = \frac{10\,m/m^2}{1+\left(\frac{\omega}{\omega_o}\right)^{-8}}$$

Equation 7 Model for estimating crack density (severity)

where Cr is the crack density (severity in m/m^2),
ω is the damage to the surface layer, and
ω_o is a constant.

ω_o was determined based on the assumption that crack initiation corresponds to a severity of 0.5 m/m^2.

Figure 5 shows the crack severity, in m/m^2 of the wheel track, as a function of the fatigue damage determined from the strain at the bottom of the original asphalt layer. This damage is used to reduce the average modulus of both the original asphalt layer and of the overlay. In Figure 5 the original pavement sections, before overlay, are designated by their test numbers. The overlayed sections are given by the type and thickness of the overlay. The heavy curves indicated by a thickness value are the crack severities calculated using Equation 6 and Equation 7. The approximate thickness of the asphalt layer before overlay was 80 mm, and the thicknesses of the combined asphalt layers after overlay were either about 125 mm or 170 mm.

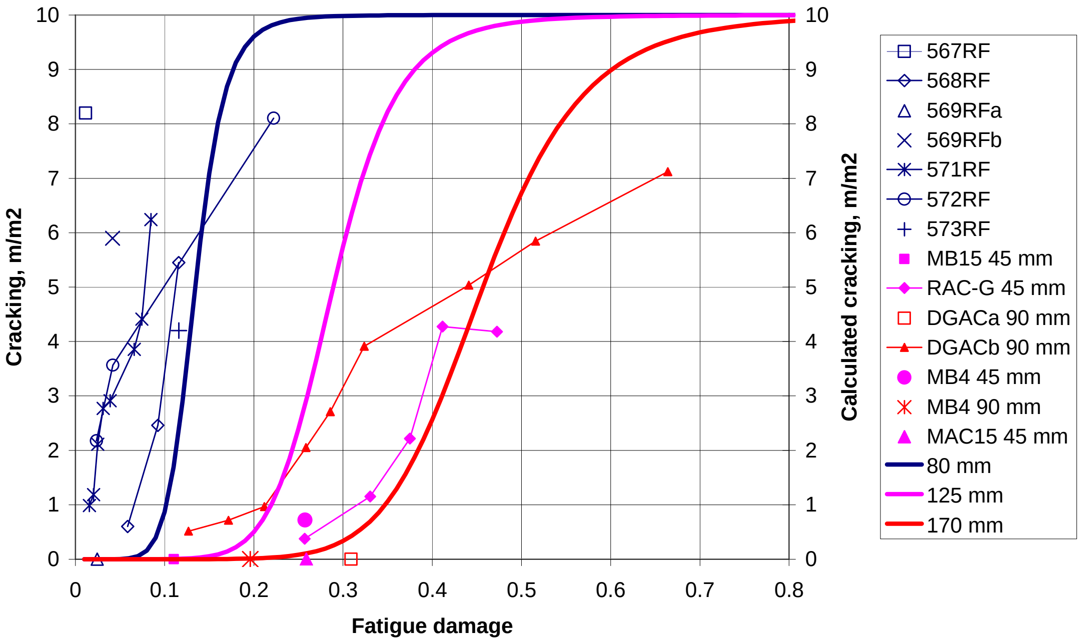

Figure 5 Surface cracking as a function of fatigue damage.

The original sections, before overlay, are seen to crack more rapidly than predicted from the equations. FWD tests showed that the modulus of the asphalt layer before HVS testing was considerably below the modulus from frequency sweep tests in the laboratory, whereas the moduli of the overlays from FWD tests were in good agreement with the frequency sweep data. It is possible that the low in situ modulus of the original asphalt layer was due to some initial damage to the material. If that were the case, this initial damage should be added to the fatigue damage in Figure 5. This would shift the curves to the right.

For the overlay sections the observed cracking does not correspond to the respective thickness curves. A better fit can be obtained if the reflection damage calculated from the strain over the existing cracks (Equation 1) is used with the following equations:

$$\omega_i = \frac{1}{1+\left(\dfrac{h_{AC}}{390\,mm}\right)^{-1}}$$

Equation 8 Model for reflection damage at initiation of reflection cracking.

$$Cr = \frac{10\,m/m^2}{1+\left(\dfrac{\omega}{\omega_o}\right)^{-3.5}}$$

Equation 9 Model for estimating reflection crack density, as a function of reflection damage.

Reflection crack initiation was assumed to correspond to a density of 0.5 m/m^2.

Figure 6 compares the observe reflection cracking on the overlay sections to the reflection damage predicted using Equation 8 and Equation 9, as a function of the reflection damage calculated from Equation 1 and Equation 3.

Figure 7 shows the predicted reflection cracking severity as a function of the observed severity.

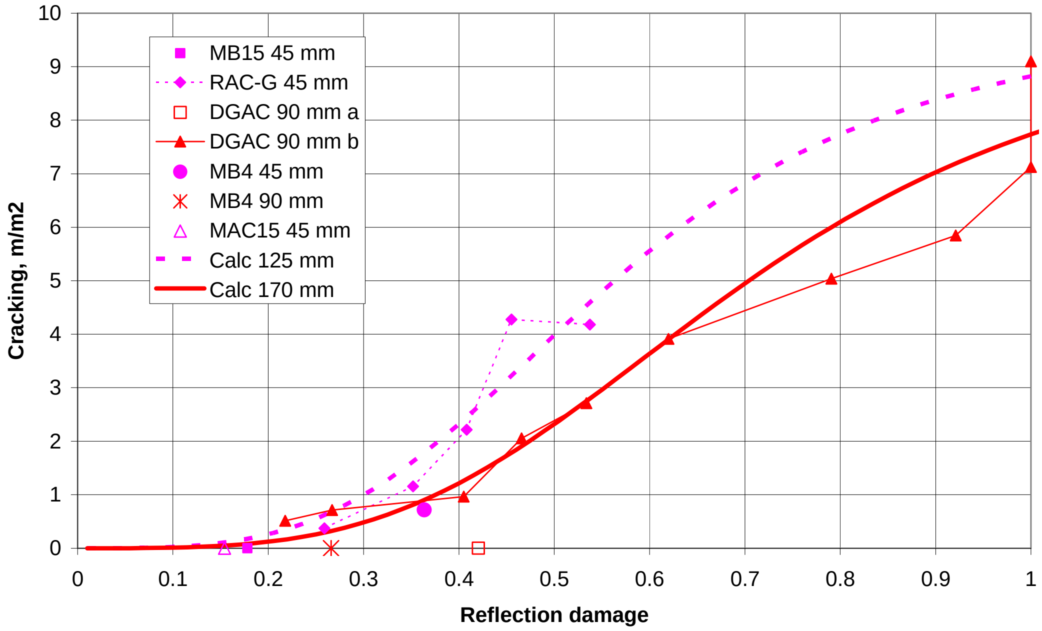

Figure 6 Surface cracking as a function of reflection damage.

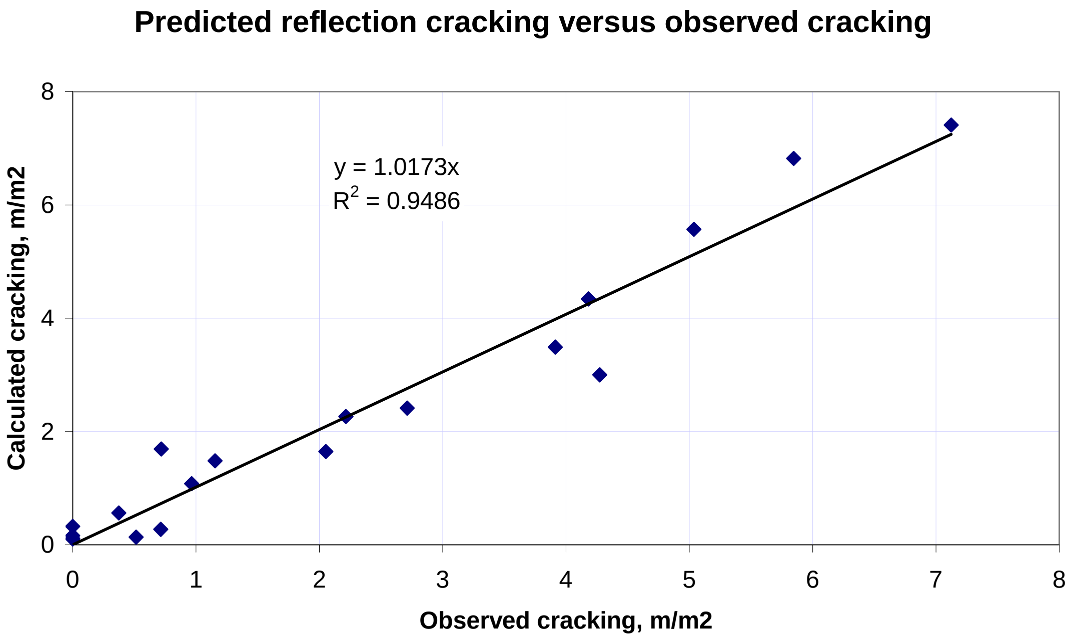

Figure 7 Predicted reflection cracking severity as a function of observed severity.

Conclusion

Although the original pavement was built to provide a uniform support for the rutting and the reflection cracking studies, the FWD tests and the forensic investigation showed that there were large variations over the length of the structure. The conditions of underlying structure, wheel loads and climate should be identical when ranking the different overlays. Because it was found that the permanent deformations

and reflection cracking were predicted reasonably well with CalME it was possible to carry out a number of "virtual" HVS tests with identical conditions.
The rutting study was simulated using the rutting experiment with the highest number of load applications. The results are shown in Figure 8.

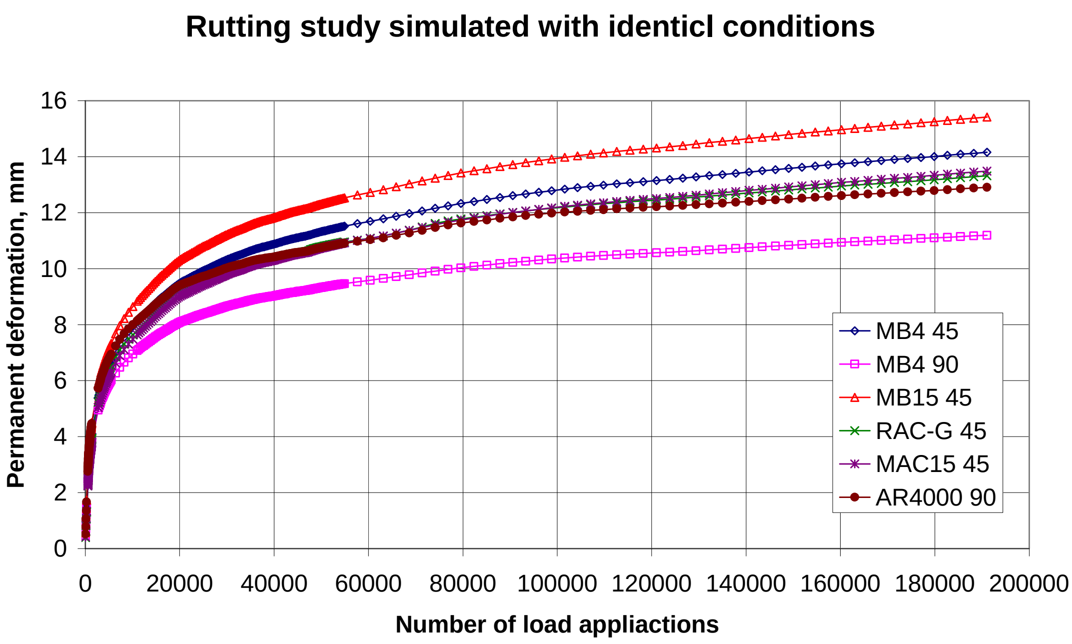

Figure 8 Rutting study simulated with identical underlying structure, loads and temperatures.

Several of the reflection cracking sections did not get any cracking during the "real" experiments, even though the traffic loading corresponded to up to about 100 MESAL (million ESAL) and lasted from 150 to 230 days. The "virtual" experiments were, therefore, done with about 500 MESAL.

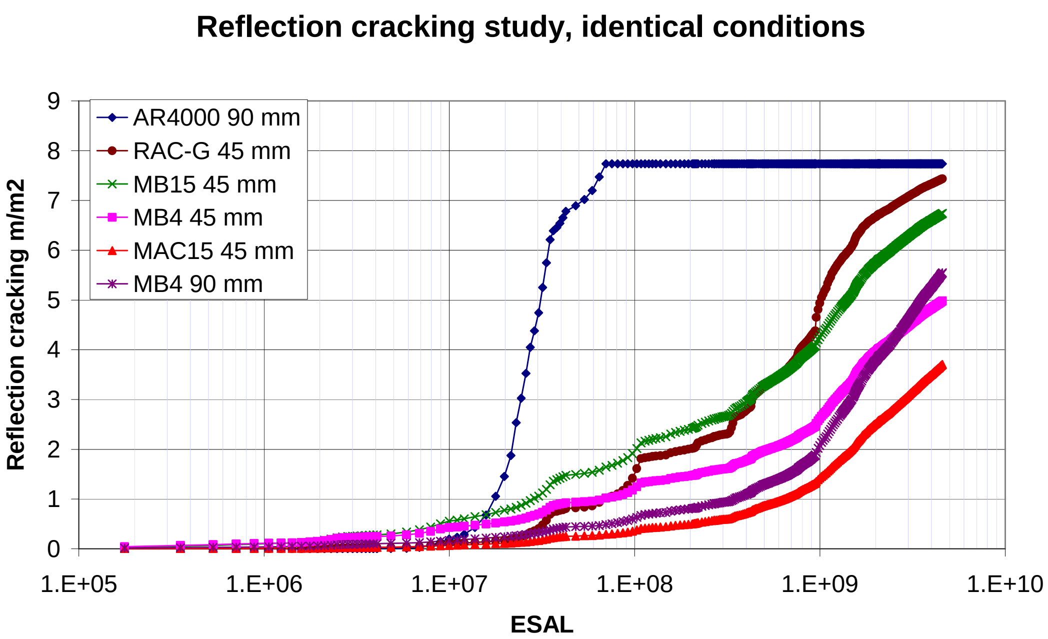

Figure 9 Reflection cracking study with identical underlying structure, loads and temperatures.

If the overlay materials are ranked (1 being the best) according to the final condition from the "virtual" rutting and reflection cracking studies the results of Table 1 are obtained.

Table 1 Ranking according to "virtual" experiments

		Final rut depth, mm	Rut rank	Final cracking, m/m2	Crack rank
AR4000	90 mm	12.9	2	7.7	6
RAC-G	45 mm	13.3	3	7.4	5
MB4 G	45 mm	14.2	5	5.0	2
MB4 G	90 mm	11.2	1	5.5	3
MB15 G	45 mm	15.4	6	6.4	4
MAC15 G	45 mm	13.5	4	3.1	1

Before the models can be applied to the design of rehabilitation overlays a number of issues need to be addressed such as the influence of aging, seasonal variations, wheel speeds and rest periods, and variability of materials, structure, loads and climate, but the calibration using the HVS data reported in this paper is believed to provide a solid foundation for the ongoing calibration effort.

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