# LESSONS LEARNED FROM THE APPLICATION OF CalME ASPHALT FATIGUE MODEL TO EXPERIMENTAL DATA FROM CEDEX TEST TRACK

*Prepared for the 4th International Conference of Accelerated Pavement Testing*

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## ABSTRACT

Predicting asphalt fatigue evolution in the field represents a problem of the utmost difficulty. There are very few models that can tackle this complex process, and even less where actual damage levels, determined from structural evaluations, can be efficiently incorporated in order to improve previous performance predictions. One of these models is CalME "California Mechanistic-Empirical Software for Structural Design of Flexible Pavements", which incorporates an incremental-recursive procedure based on mechanistic-empirical principles.

Experimental data for this research come from four full-depth pavements that were tested at the CEDEX Test Track over 28 months. Pavements were periodically evaluated in terms of bearing capacity, and surface cracking was measured as well. This provided detailed information regarding asphalt layer deterioration under changing environmental conditions.

CalME asphalt fatigue model has been used in order to study and reproduce the deterioration process in the test track. Special attention has been paid to the accumulation of damage as a function of loads and temperature and how this damage, together with aging and post-compaction under traffic, determine the stiffness of the asphalt layer. This paper shows experimental evidence that supports the ability of CalME model to reproduce the main aspects of asphalt performance in flexible pavements.

The ability of the model to predict future asphalt mixture performance, after recalibration from field data, is also presented in this paper. The model was initially calibrated from laboratory fatigue tests, and it was later recalibrated based on FWD tests conducted at an early stage of the deterioration process. After this early recalibration, the model was able to predict future asphalt layer deterioration until an ultimate damage level was reached.

# INTRODUCTION

Predicting asphalt fatigue evolution in the field represents a problem of the utmost difficulty. The large number of variables that take part in the deterioration process, the complexity of the process itself or the interaction with other distress mechanisms are some of the reasons behind such difficulty. It should be borne in mind that preventing pavements to fail from asphalt fatigue requires significant efforts in economic, social and environmental terms, not only at the initial construction but also throughout the complete service life. As a consequence, an accurate prediction of asphalt fatigue will result in significant benefits, since pavement structures could be optimized in order to minimize the overall cost.

Figure 1 represents the typical evolution of asphalt layer modulus in a flexible pavement during its service life. The reduction of this modulus is reflecting damage accumulation up to a point where cracking process begins. This cracking process will continue until a "failure" condition is reached after $N_f$ load applications. Prediction of $N_f$ has been the goal of classical analytical design methods for at least two decades. But the ultimate goal of an asphalt fatigue model should go further if it is deemed to be efficient in order to minimize the significant costs of pavements construction and rehabilitation. At this point, as reflected in Figure 1, more advanced goals can be stated as follows:

1. Being able to predict asphalt modulus evolution.
2. Being able to determine asphalt damage from actual modulus.
3. Being able to determine asphalt cracking from damage.

Even in theory, there are very few models that can achieve the goals here stated. One of the most widely recognized is CalME "California Mechanistic-Empirical Software for Structural Design of Flexible Pavements"*(1)*. This program incorporates three design levels of growing complexity, the most advanced being an incremental-recursive procedure based on mechanistic-empirical principles. CalME incorporates specific models for different distress mechanisms, including permanent deformation of asphalt, granular and soil layers, longitudinal unevenness, stabilized soils fatigue and bottom-up asphalt fatigue.

A research effort has been conducted at CEDEX Transport Research Center, in cooperation with the University of California Pavement Research Center, in order to evaluate the potential of CalME asphalt fatigue model to predict actual performance observed from four flexible sections tested at the CEDEX Test Track. Important lessons have been learned from this research effort, that help to understand the complex process of asphalt mixture deterioration in the field. Main lessons are described and analyzed in the present paper, where special emphasis has been placed on the application of CalME model to in-service pavements. The reason for this is the increasing importance that the structural evaluation is gaining in Spain and also in other countries with a consolidated road network, where most investments are dedicated to maintenance and rehabilitation rather than new pavements construction. Under these circumstances, the assessment of actual pavement structural condition and the prediction of its future evolution become priorities, which are typically accomplished by conducting periodic structural evaluations. These evaluations provide large amount of data that, conveniently processed, can be incorporated into the fatigue model, thus improving previous performance predictions.

## Objective

The objective of the research here presented is the evaluation of the applicability of CalME asphalt fatigue model as a tool for the correct interpretation of deflection testing data of an in-service pavement and, based on this, for the prediction of future asphalt fatigue performance.

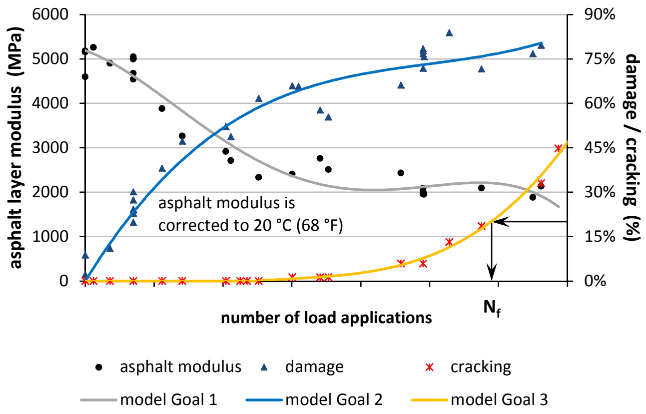


**Figure 1.- Evolution of asphalt fatigue along the service life of a flexible pavement**

## Research Approach

CEDEX Test Track is a linear-circular combined accelerated pavement testing (APT) facility located outdoors *(2)*. Traffic is simulated by two automatic vehicles that continuously move along a closed circuit, which is provided with a test pit. Six flexible sections (15-19 meters long) were tested within a research project that was focused on subgrades performance (Figure 2). Sections consisted of a 120-150 mm (4.7-5.9") asphalt layer placed directly on top of medium-high quality subgrades, as presented in Figure 2. The two sections with cement-stabilized soil were not included in this particular research, since the critical distress mechanism was not conventional (bottom-up) fatigue cracking. Additional information about the test is presented below:

- Beginning and end: 2007-August-29 to 2009-December-31
- Total number of passes: 1,323,600
- Vehicles loading: 65 kN (14.6-kip) dual wheel (corresponding to 130 kN axle)
- Transverse distribution: ± 195 mm (± 7.7")
- Vehicle speed: 30-40 km/h (19-25 mph)
- Environmental conditions: Open air; Water table generated by rainfall

Actual structural performance of the sections was periodically evaluated throughout the test. Bearing capacity was evaluated from falling weight deflectometer (FWD) testing and surface cracking was measured by means of visual inspection. FWD testing was conducted at 15-20 points along each section, and the average deflection bowl was used in order to back-calculate asphalt layer modulus by using Evercalc. The asphalt temperature assigned to asphalt modulus was the mean value from two thermocouples embedded in the asphalt layer (one at the top and one at the bottom).

The pattern of the evolution of the stiffness of the asphalt layer, determined from FWD testing, was studied as a function of three main factors: damage, aging and densification under traffic loads. The hypotheses of the CalME model concerning the effects of these three factors have been evaluated by comparing the actual pattern with the pattern expected according to the model.

The CalME asphalt fatigue model was initially calibrated in laboratory, by conducting 4-point bending fatigue tests at three different temperatures: 10 / 20 / 30 °C. Fatigue tests were conducted in controlled-deflection mode following European Standard EN 12697-24 Annex D “Four-point bending test on prismatic shaped specimens”. A shift factor was then introduced, according to CalME approach, that takes into account the beneficial effects of rest periods between loads. The unknown part of the shift factor was determined on the basis of field data for cycle 140,000. The ability of the model to predict future performance has been evaluated by comparing actual asphalt layer modulus evaluated from FWD testing to model predictions after this cycle.

The CalME transfer function for asphalt cracking was evaluated by comparing measured cracking to model predictions. Actual damage estimated from FWD testing was used as input, which means that the transfer function was specifically evaluated.

Finally, an application example is presented where the model is used to analyze the structural response of the sections in terms of deflections. Research is now under way to study other response variables that were measured by means of embedded sensors, in particular horizontal strain in asphalt and vertical stress and strain in soils.

Actual CalME software has not been used for this research, whereas its model for consideration of damage was indeed followed. This allowed some flexibility in order to work with available data, but it also meant an important additional effort as well as missing part of the potential of CalME. Apart from other distress models than asphalt fatigue, CalBack back-calculation program could not be used. This program incorporates specific features that make it unique in order to get the most out of FWD testing, apart from modulus strictly speaking *(3)*.

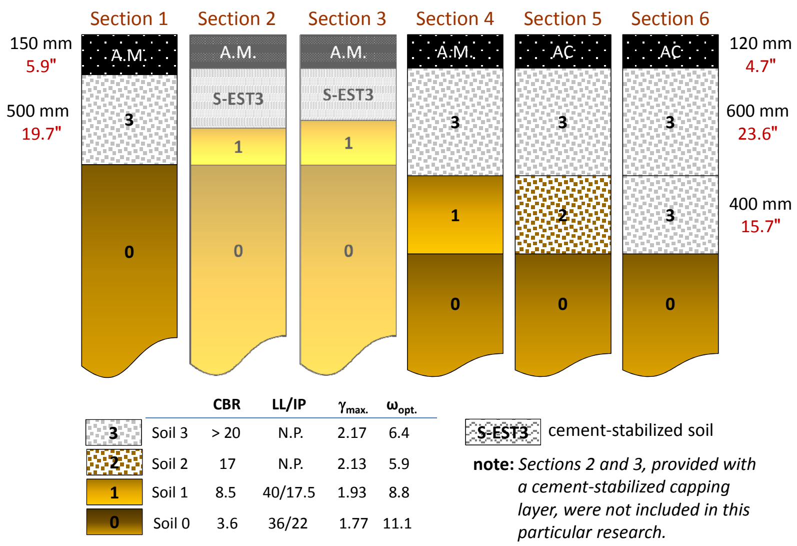


**Figure 2.- Flexible sections included in the subgrade test**

## DETERMINATION OF ASPHALT DAMAGE FROM STRUCTURAL EVALUATIONS

The ratio of the actual modulus of the asphalt layer to the original value represents an indicator of the damage in the material. Nonetheless, the quantification of damage from this ratio is not straightforward, because of two main reasons:

1. The evolution of asphalt modulus in the field is not only related to damage. It is widely accepted that aging and post-compaction under traffic are two main factors that must be considered as well.

2. For a particular level of damage, the ratio $E_{actual}/E_{undamaged}$ is not independent of the temperature and frequency content of the FWD loading pulse.

CalME uses the MEPDG sigmoidal curve for the asphalt mixture dynamic modulus, according to equation [1]. Parameters of this equation are determined in laboratory by conducting temperature and frequency sweep dynamic modulus tests.

$$\log(E) = \delta + \frac{\alpha}{1+e^{\beta+\gamma\cdot\log(fr)}} \quad [1]$$

Original asphalt layer moduli can be also obtained by means of back-calculation from FWD tests conducted after construction, before traffic begins. These values are representative of the undamaged asphalt mixture. A good correlation is typically found when these moduli are compared to master curve values, as soon as a correct frequency is chosen that is representative of the FWD loading pulse. Such frequency was 15 Hz for the particular load and buffer configuration of the Kuab device used for this particular study. Figure 3 shows the good agreement achieved for the four sections included in this study. It can be concluded that the original master curve constitutes a reliable reference to which compare FWD back-calculated moduli during the service life of the pavements.

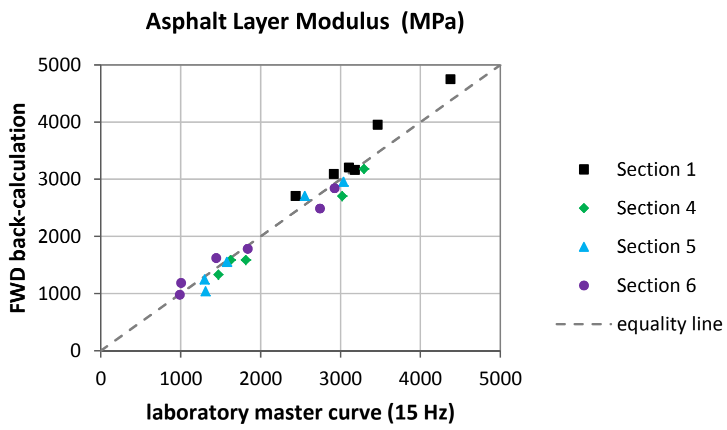


**Figure 3.- Comparison between laboratory and FWD back-calculated moduli**

Figure 4.a shows the asphalt layer modulus values that were obtained by back-calculation from FWD testing throughout the test. Only Section 5 is here presented due to limited space, but similar results were found for the rest of the sections *(4)*. Three issues in Figure 4.a deserve special consideration:

1. When temperatures below 15 °C (59 °F) are considered, modulus reduction is clear during the test. In particular, modulus decreases consecutively throughout the following intervals:

   0 / 140,000 / 200,000 / 275,000 / 920,000 / 1,323,000 cycles

2. When temperatures over 30 °C (86 °F) are considered, modulus tends to converge to original (undamaged) values.
3. No clear evolution can be observed for intermediate temperatures, unless for the highly damaged material after 1 million cycles. In fact, asphalt layer modulus tends to increase between cycles 500,000 and 730,000. For this last cycle, the "apparent damage" seems to be even smaller than for cycles 200,000-275,000.

It is evident that this particular pattern is directly related to the specific sections that were tested and to the specific loading and environmental conditions under which the test was performed. But CalME approach actually shows that the pattern just reflects different phenomena that take place to a greater or lesser extent in every flexible pavement during its service life. In particular, it reflects the combined effects of damage, aging and densification under traffic, as shown below.

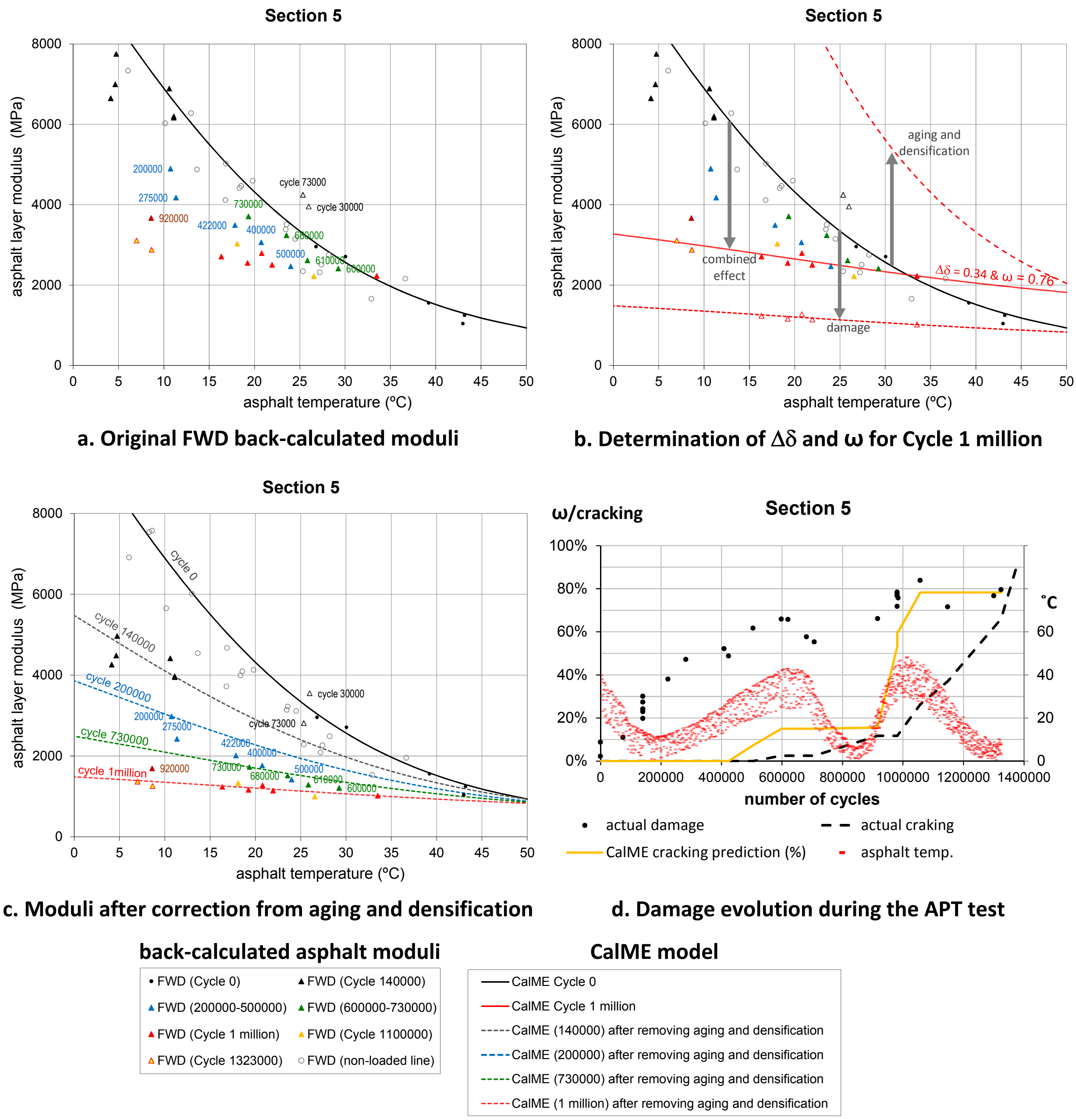


**Figure 4.- Asphalt layer modulus evolution throughout the test**

CalME introduces aging and densification under traffic by increasing the $\delta$ parameter in the master curve, as shown in equation [2]. This is equivalent to multiplying the modulus by the factor $10^{\Delta\delta}$ for any combination of temperature and frequency. Damage is introduced by multiplying the $\alpha$ parameter by (1-ω). As damage (ω) increases, the viscous part in equation [2] decreases, and for the maximum level of deterioration (ω = 1) the modulus will be a constant value, $10^{\delta+\Delta\delta}$, as in any linear elastic material.

$$\log(E) = \delta + \Delta\delta + \frac{\alpha \cdot (1-\omega)}{1+e^{\beta+\gamma\cdot\log(fr)}} \qquad [2]$$

According to equation [2], the evolution of the asphalt mixture master curve follows the pattern reflected in Figure 5. Aging and densification shifts vertically the master curve in the logarithmic scale, while damage effects are higher, in absolute and relative terms, for increasing reduced frequencies. As a result, structural evaluations conducted at high temperatures will mainly reflect aging and densification, thus hiding the real magnitude of the damage; the opposite will happen for low temperatures. This is the pattern that was observed in Figure 4.a, in particular for what concerns to issues 1 and 2 listed above. It should be noted that each “CalME model” curve in Figure 4 comes from a particular “actual master curve” as presented in Figure 5, by assuming the frequency corresponding to the FWD pulse (15 Hz for the configuration of the KUAB deflectometer used in this particular study).

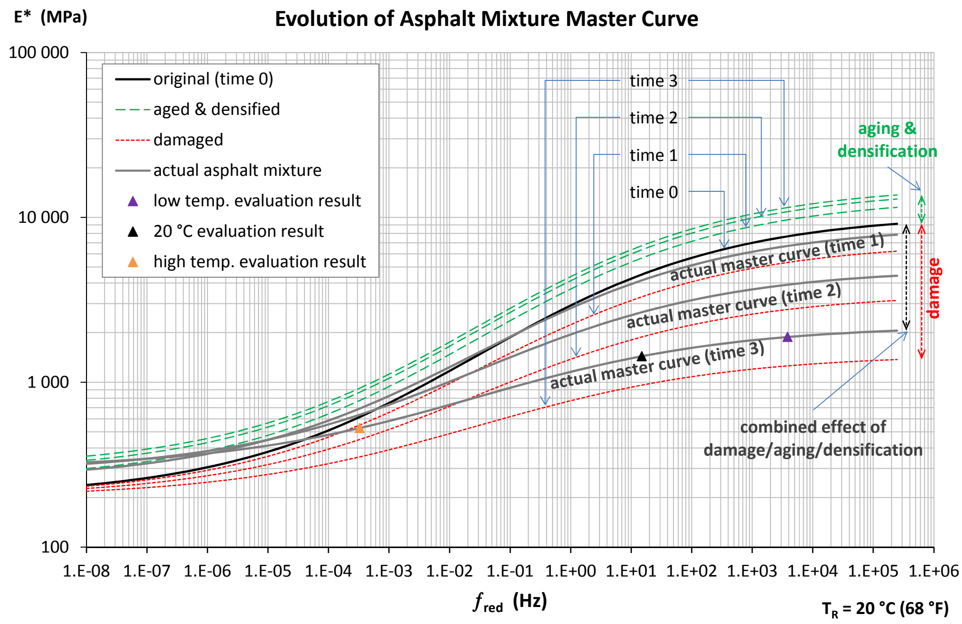


**Figure 5.- Asphalt master curve evolution according to CalME**

It should be indicated that the prediction of $\Delta\delta$ during the service life of a flexible pavement constitutes a quite complicated problem. CalME software incorporates different aging and densification models, including sets of recommended parameters depending on the particular conditions of the pavement under consideration. These parameters can be lately readjusted on the basis of actual performance evaluated from deflection testing.

In practice, $\Delta\delta$ can be estimated for an in-service pavement as soon as deflection testing is conducted for a wide temperature interval. Tests must be conducted throughout a relatively short period of time, where both $\Delta\delta$ and $\omega$ can be regarded as constant. For this particular research, the estimation was possible for cycle 1 million, since five FWD tests were carried out at different temperatures between 15 and 35 °C (59-95 °F). An iterative process was followed by changing $\Delta\delta$ and $\omega$ in equation [2] in order to fit actual back-calculated moduli. Excel’s Solver tool was used, and results for Section 5 are presented in Figure 4.b. An attempt was also tried for cycle 140,000, but the resulting temperature range was relatively short and too far from the highest temperatures to be used for the estimation of the increase in $\delta$.

Once $\Delta\delta$ values were estimated for the four flexible sections, aging and densification models parameters were readjusted. This provided a reliable evolution of $\Delta\delta$ during the previous cycles as well as a reliable prediction of its future evolution. A detailed description of the approach can be found in reference *(4)*. Results for Section 5, after removing both effects, are presented in Figure 4.c, where damage evolution is now clear for the whole temperature range.

One of the main problems when the described approach is applied to outdoors APT facilities is the difficulty in conducting FWD tests for a relatively wide temperature interval where both $\Delta\delta$ and $\omega$ remain relatively constant. For an in-service pavement, the low rate of damage accumulation entails a clear advantage, since it will be possible to perform the FWD tests throughout a relatively wide time period, thus resulting in a wider temperature interval, as required for a reliable determination of $\Delta\delta$. Another problem when the approach is applied to APT is that the time required for stabilization of densification effects is of the same order of magnitude of the test duration. This means that the effects of this factor will confound with asphalt fatigue, making more difficult its discrimination. For an in-service pavement, densification will mostly take place during the first years, while fatigue will continue until the end of its service life.

It is difficult to give a figure concerning the period of time required for densification to get stable in an in-service pavement, since it will depend on numerous factors: traffic, environment and asphalt mixture related. Nonetheless, several studies show that mechanical properties of asphalt mixture remain fairly constant after the first two years *(5) (6)*. The figure of two years is also supported by observations from this research, where 87% of the permanent deformation of the wearing layer at the end of the test had taken place during the first year, as presented in Figure 6. Permanent deformation from the base course was negligible in this test.

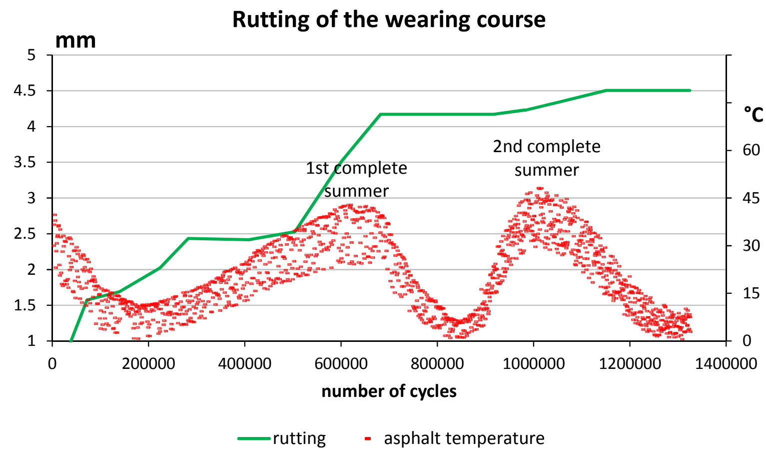


**Figure 6.- Evolution of permanent deformation of the wearing layer during the test**

It can be observed in Figure 6 that post-compaction effects concentrated at the beginning of the test and also throughout the first summer, between cycles 500,000 and 700,000 approximately. This is believed to be the main reason behind the third issue that was previously observed in Figure 4.a, i. e., the increase in back-calculated asphalt layer modulus during that interval. Still, a slight increase in asphalt modulus is observed in Figure 9, even after removing aging and densification effects, which might indicate asphalt healing during this warm period.

Once FWD back-calculated moduli were corrected from aging and post-compaction effects, they could be compared to the original (undamaged) values in order to determine damage ($\omega$), by applying equation [3]. Results obtained for Section 5 are included in Figure 4.d.

$$\frac{E}{E_{original}} = \left( \frac{10^{\delta}}{E_{original}} \right)^{\omega} \qquad [3]$$

Equation [3] can be deduced from equations [1] and [2], and represents an assumption of CalME asphalt fatigue model. This assumption, as well as those corresponding to aging and densification effects on asphalt mixture stiffness, have been validated for CEDEX sections within this research effort *(4) (7)*.

It should be indicated that aging, damage and densification are here considered as "overall" asphalt layer properties, but this is just a simplification, since they vary across the pavement thickness. This simplification is required when actual asphalt layer back-calculated moduli are used for the calibration, since present back-calculation techniques cannot distinguish between wearing and base asphalt courses.

## FATIGUE OF THE ASPHALT MIXTURE: MOVING FROM LABORATORY TO FIELD

CalME asphalt fatigue model presents an important advantage versus the classical fatigue laws employed in most mechanistic-empirical design procedures. This advantage is the ability to reproduce actual modulus reduction of the asphalt mixture due to damage. In fact, the model is calibrated in laboratory by using the complete records "modulus vs cycles" obtained in fatigue tests, as can be appreciated in Figure 7. Once the model is calibrated in laboratory, it could be used to predict asphalt modulus reduction throughout a fatigue test with changing load and temperature, as presented in the example of Figure 8. As a consequence, the model can also be used to predict asphalt layer modulus reduction in the field, under changing temperature and traffic loads, as soon as horizontal strain at the bottom of the asphalt layer is known. CalME estimates this strain by taking into account pavement structure and axle configuration, but also temperature and actual damage as well as vehicle speed and levels of aging and densification. Additional information concerning CalME asphalt fatigue model can be found in the program help file *(8)*.

It is very desirable to conduct laboratory calibration for a wide temperature interval, as close as possible to the expected temperature range in the field. For the research here presented, fatigue tests were conducted at 10, 20 and 30 °C (50 / 68 / 86 °F), which still represents less than 50% of the actual temperature range that took place in the sections during the test. A considerable good agreement was found between model and laboratory data for the three temperatures, with an overall error of 5.1% of the initial modulus. Details concerning this laboratory calibration can be found in reference *(7)*.

The application of the model to in-service pavements is not straightforward, since numerous experimental studies show that asphalt fatigue life predicted from laboratory tests will systematically underestimate field performance *(9)*. Nowadays, it is widely accepted that a shift factor must be introduced that divides actual number of load applications in the field, as presented in Figure 7. There are different reasons that explain the existence of the shift factor, like time required for cracking initiated at the bottom of the asphalt layer to reach the surface, traffic wandering across the wheels paths or mixture densification. But probably the main reason is the existence of rest periods between traffic loads, where asphalt healing takes place. This point has been hypothesized by different authors *(9)*, and is fully supported by experimental evidence from this research, which shows that around 90% of the total shift factor was directly related to the beneficial effects of rest periods *(7)*. It should be indicated that this quantification was possible due to the approach used by CalME.

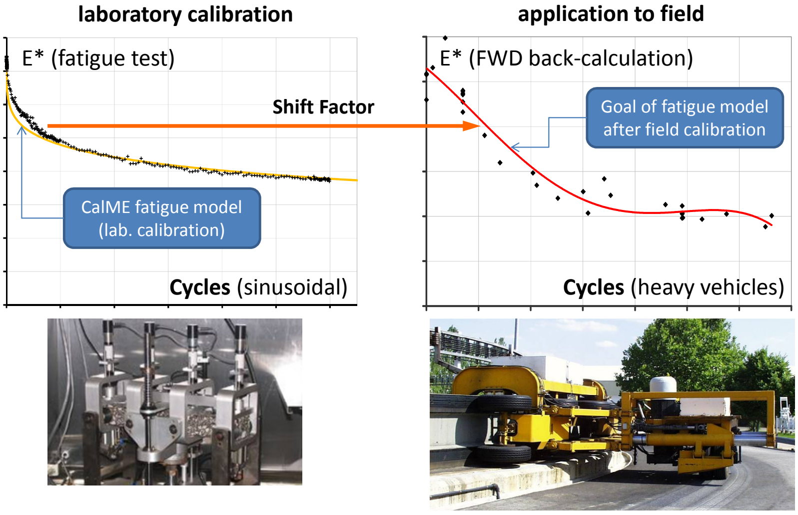


**Figure 7.- Application of laboratory data to field**

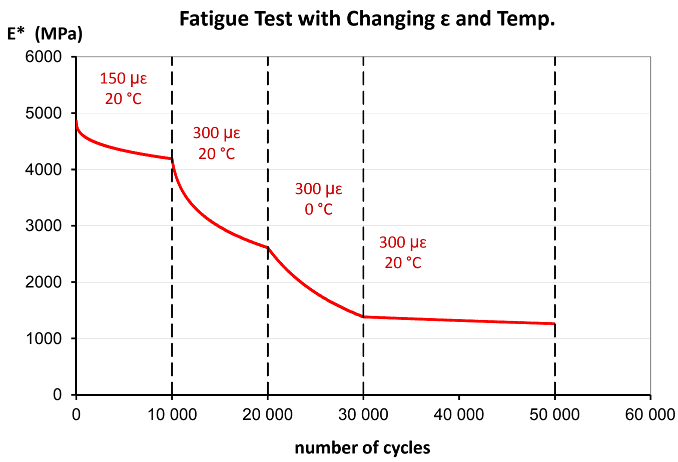


**Figure 8.- Example of application of CalME asphalt fatigue model to laboratory**

CalME incorporates the beneficial effects of rest periods into the shift factor, by using the concept of reduced rest period, as developed in the frame of NCHRP 9-44 project *(10)*. This reduced period results from the application of time-temperature correspondence principle to actual rest periods between traffic loads, as defined by equation [4].

$$\log(\mathrm{RPr}) = \log(\mathrm{RP}) - \log(a_T) \quad [4]$$

where, RP is actual rest period between traffic loads

$a_T$ is time-temperature shift factor for the temperature corresponding to the rest period

According to this approach, the beneficial effect of a rest period will be larger for higher temperatures, which recognizes the well-known fact that healing potential increases for increasing temperatures. This assumption entails important consequences concerning the rate of damage accumulation as a function of temperature. In particular, the critical periods with the highest rate of damage accumulation will not be the warmest periods anymore, but the periods with the lowest temperatures. This pattern was observed for the flexible sections included in this research, as presented below.

Time-temperature relationship was determined for the asphalt mixture on the basis of dynamic modulus testing in laboratory, and a shift factor was introduced according to equation [5]. Actual rest periods between loads of the two automatic vehicles were known, as well as asphalt temperature measured from thermocouples embedded in the asphalt layer. Strain was estimated at the bottom of this layer by using Bisar, the well-known multilayer linear elastic program developed by Shell. Damage was calculated in increments of 10 cycles, assuming constant temperature, speed and pavement conditions. Asphalt layer modulus was calculated for each 10-cycle interval by applying equation [2].

$$SF = k \cdot (1 + RPr)^{\alpha} \quad [5]$$

where, k is unknown part of the shift factor (to be determined from field calibration)
RPr is reduced rest period
$\alpha$ is parameter that takes into account the nonlinear evolution of healing versus time

It should be noted that the unique unknown of the approach described above is the k parameter in equation [5]. This parameter was back-calculated, through a manual iterative process, in order to fit actual field performance. Values obtained for the four sections ranged from 0.5 to 1.7, when asphalt strain in fatigue tests was interpreted according to normative AASHTO T 321. Details of this approach can be found elsewhere *(7)*.

The ability of CalME model to predict asphalt performance in the field is presented in the example of Figure 9. The k parameter was determined by fitting actual modulus in cycle 140,000 with the model. It can be observed in this figure that the model reproduces almost exactly the reduction of asphalt layer modulus that takes place during the following cycles. It can also be observed from the figure that the rate of damage accumulation was clearly higher for medium and low temperatures rather than for high temperatures; in fact, FWD back-calculated modulus, after aging and densification correction, remained almost constant during the summer. The model was also applied by considering a constant shift factor ($\alpha$=0 in equation [5]), but in this case a wrong pattern of damage accumulation versus temperature results, even though the fatigue model was calibrated in laboratory for different temperatures. Still, some limitations of the model can be deduced from Figure 9, like the rapid decrease in modulus during the first cycles, that is not supported by experimental results. Actually the model is just reproducing the pattern of the laboratory fatigue tests that were used for its initial calibration. But it is widely known that the initial reduction of the specimen modulus in these tests is mainly related to heating and thixotropy rather than actual damage *(11)*, which explains the deviation observed. Problems were also found in order to reproduce asphalt performance during the second half of the test, probably due to the high level of damage and the presence of discrete cracking, which makes unrealistic the hypothesis of continuity upon which CalME asphalt fatigue model is based. As a consequence, a second calibration was required after cycle 800,000.

It must be indicated that in order to estimate asphalt strain under the heavy vehicles, the moduli of the subgrade layers that were introduced in Bisar were the actual values obtained from FWD back-calculation. So no prediction was carried out. The same can be stated for the asphalt temperature, that was indeed measured throughout the test. CalME incorporates models in order to predict these variables, but the use of them was not attempted in this research, since the objective was the specific evaluation of the asphalt fatigue model. It is obvious that achieving a satisfactory prediction in a real in-service pavement will be considerably more difficult, due to the uncertainties in the different variables that represent the inputs to the problem.

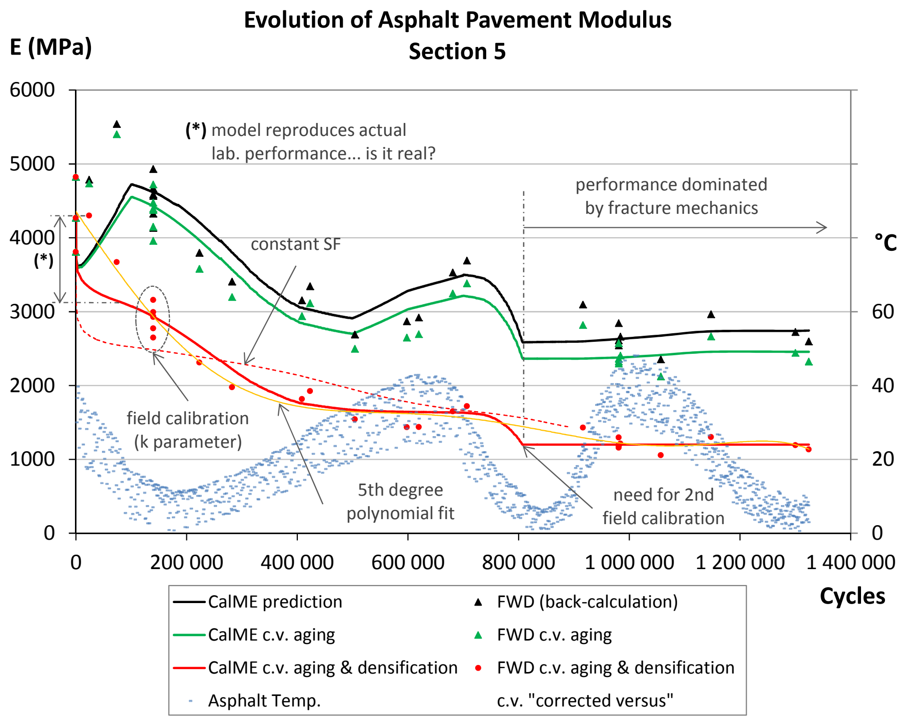


**Figure 9.- Application of CalME model to predict field performance**

The third "model goal" included in Figure 1 is the ability to determine asphalt cracking from damage. CalME incorporates a transfer function that relates ω parameter to cracking; a detailed description of this function is included in the program help file *(8)*. Results for Section 5 are included in Figure 4.d, where a quite good agreement can be observed between measured and predicted cracking. Similar results were obtained for the rest of the sections *(4)*. It should be indicated that the damage values used for this calculation were the values determined from FWD testing, so the transfer function was here specifically evaluated. The good agreement observed for the different sections was, to some extended, unexpected, due to the inherent difficulty in predicting a variable like cracking from a variable like damage; the first one is dominated by fracture mechanics while the second one is based on continuum mechanics.

CalME transfer function includes the variable $h_{AC}$, the combined thickness of the asphalt layers, in order to predict damage at cracking initiation. The introduction of this variable recognizes that time required for bottom-up cracks to reach the surface increases with layer thickness. As expected, the contribution of each layer to this combined thickness will depend on the characteristics of the asphalt mixture. For this particular test, the asphalt mixture that was employed in the base course was an asphalt concrete with a plain bitumen content of 4.0% by mass of aggregates, while the wearing course was a gap-graded mixture with 5.3% content of a highly modified bitumen. This wearing course, 30 mm (1.2") thick, was expected to result in a significant cracking delay, although the challenge was how to quantify such delay. In order to do it, actual damage values were determined when cracking first appeared in the sections. Then, the equivalent thickness of the wearing course was obtained through an iterative analysis, where experimental values were fitted with CalME transfer function. As a result, it was determined that the equivalent thickness of the wearing course mixture was around 6 times its real thickness. This figure must be understood in comparison to the mixture of the base course.

## APPLICATION EXAMPLE: STRUCTURAL RESPONSE IN TERMS OF DEFLECTIONS

Deflections measured under the FWD loading plate throughout the test are presented in Figure 10 (each point in Figure 10 is the average of 16-20 points along each section). Predictions according to CalME approach are also included in this figure. Actual back-calculated moduli for the subgrade layers were used with CalME asphalt fatigue, aging and densification models. As expected, a direct link exists between the pattern of deflections in this figure and the performance observed in Figure 4.a in terms of asphalt layer modulus. An additional factor is here introduced, which is the moisture content of the subgrade soils. The test was conducted without shed, so a water table was generated inside the test pit by natural rainfall. The water table level was allowed to rise up to 1 m (3.3 ft) below the top of the subgrades, which happened around cycle 350,000. Then, the level was kept constant by either pumping or water supply.

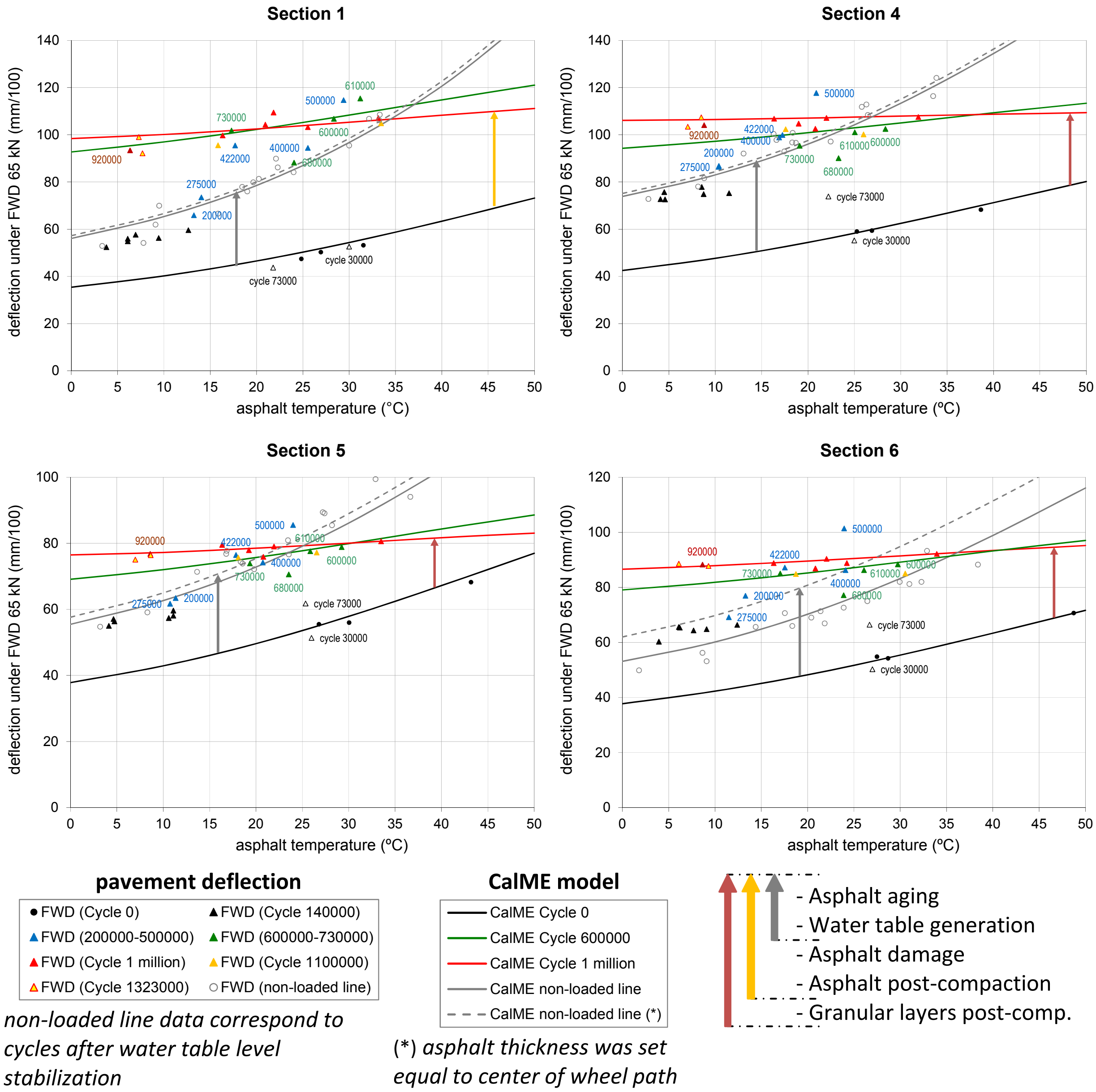


**Figure 10.- FWD deflection evolution throughout the test**

The effect of the water table can be appreciated in Figure 10, by comparing experimental data for cycle 0 to data for the non-loaded line. The non-loaded line is situated 2,5 m (8.2 ft) far from the center of the wheel path, so traffic effects are negligible. FWD deflections for the non-loaded line correspond to cycles after 350,000, so water table level was constant. It can be observed in Figure 10 that the generation of a water table produced, as expected, a significant increment in deflection as well as an increment of temperature sensitivity. Additional aging took place from cycle 0 to cycles after 350,000, whose effects are present in this comparison. But these effects are very reduced when compared to water table effect, due to the relatively short period of time. It should be noted that CalME model for the non-loaded line was applied by considering two asphalt thicknesses: the mean asphalt layer thickness along this line and the mean thickness along the center of the wheel path (dashed line in Figure 10). This dashed line should be considered in order to compare to CalME model predictions corresponding to the center of the wheel path, especially for Section 6 where a significant difference between both thicknesses existed.

Asphalt damage is clear for the low temperature range in Figure 10. This is the same issue that was previously observed in Figure 4.a in terms of asphalt layer modulus. Damage effects can be appreciated by comparing deflections for 920,000 and subsequent cycles to those corresponding to the non-loaded line. Cycles 200,000 and 275,000, conducted at asphalt temperatures below 15 °C (59 °F), cannot be included in this comparison since the water table had not reached its final level.

For the high temperature range, over 30 °C (86 °F), damage evolution is not evident at all, as can be appreciated by comparing deflections along the wheel path for 1 million cycles to values along the non-loaded line (Figure 10). This is in part related to asphalt layer modulus convergence to original values for high temperatures, as observed in Figure 4.a; this pattern was explained by aging and densification of the asphalt mixture. But an additional factor is here present, which is the densification that took place in the capping layer under the pass of the vehicles. This densification was verified in terms of back-calculated modulus for Sections 4, 5 and 6, and also by means of penetrometer testing, which indicated that resistance to penetration was multiplied by a factor around 2. As a consequence, the deflections measured at high temperatures for these three sections are below those obtained along the non-loaded line, where no damage had taken place.

The main conclusion that can be extracted from this application example is that the interpretation of FWD data, even if it is only in terms of the central deflection, represents a very complex process. This process will be more efficient and reliable if the different factors affecting asphalt mixture stiffness in the field are fully understood and properly modeled.

**CONCLUSIONS**

The evaluation of four flexible sections at CEDEX Test Track has provided detailed information concerning asphalt mixture deterioration in the field. The complexity of asphalt deterioration process itself, together with its interaction with aging and densification as well as changing environmental conditions, have been the main obstacles, as well as challenges, of the research presented in this paper.

Experimental results from this test indicate that the rate of damage accumulation is strongly dependent on asphalt temperature. Most damage took place for medium to low temperatures, while very little damage took place during summer, even though strain at the bottom of the asphalt layer reached maximum values. This pattern was fully explained by CalME, as a consequence of the beneficial effects of rest periods, that are higher for increasing temperatures. This program incorporates a variable shift factor based on the concept of “reduced rest period”. It should be indicated that the pattern of damage accumulation that was observed in this test could not be explained by only the increase in asphalt fatigue life that results when temperature increases in laboratory fatigue tests conducted in controlled deformation. This entails that the introduction of a constant shift factor, as in most existing mechanistic-empirical procedures, will not be enough to bridge the gap between laboratory and field.

Important conclusions could be also extracted from this test concerning how damage, in combination with asphalt aging and densification under traffic, affect the modulus of the asphalt layer. Damage produced a reduction of mixture modulus that was higher, in absolute and relative terms, for decreasing asphalt temperatures, while aging and densification effects reflected as a factor that seemed to multiply asphalt layer modulus for any combination of temperature and frequency. This pattern was expected according to CalME model, that employs a master curve format that incorporates the effects of the three factors: damage is introduced by decreasing the $\alpha$ parameter of the master curve (viscous term) and aging and densification by increasing $\delta$ (elastic term).

CalME model was successfully used in this research as a tool for the interpretation of deflections from FWD testing. This interpretation was not straightforward, since aging as well as densification effects had to be removed from FWD backcalculated asphalt layer modulus. After removing the effects of both factors, modulus values could be compared to the original (undamaged) master curve in order to determine actual damage. These damage values were also used in order to predict asphalt cracking by using the corresponding CalME transfer function; the agreement between measured and predicted cracking was excellent.

The ability of the model to predict future performance, after recalibration from FWD testing results, has also been shown in this paper. The unknown part of the shift factor was determined on the basis of FWD results for cycle 140,000. After this recalibration, the model was able to reproduce field performance up to cycle 800,000, when an ultimate deterioration level was reached.

As a general conclusion, the CalME asphalt fatigue model was an indispensable tool in order to understand the performance of the four flexible sections tested in CEDEX Test Track. The validity of the assumptions of the model, together with the flexibility to incorporate results from FWD testing, make it a unique tool in order to get the most out of structural evaluations.

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