Calibration of a Mechanistic-Empirical Fatigue Model under Different Moisture Conditions

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Word count: 3690 words text + 10 tables/figures x 250 words (each) = 6190 words

Tuesday, August 01, 2017

ABSTRACT

Traditionally, the design of pavements in Central America has been made using the AASHTO 93 design method, which is based on empirical correlations from results obtained several decades ago in the AASHO road test. To return to the use of more fundamental engineering principles, the necessity of a transition from this empirical state to a mechanistic-empirical one has been recognized. The National Laboratory of Materials and Structural Models of the University of Costa Rica (LanammeUCR) has implemented an Accelerated Pavement Testing (APT) program, and; a Heavy Vehicle Simulator (HVS) provides a first step in the validation/calibration process of fatigue and deformation models.

In addition, the effect of moisture is fundamental in determining pavement responses. The effect becomes more important when high levels of moisture and precipitation are present thatis the case of tropical regions such as Central America where high precipitation rates, high variability in water table levels, and materials highly susceptible to the previous are common.

Consequently, to capture the effect of moisture on pavement performance, 4 APT tests have been conducted to compare how a pavement section deteriorates in the presence of water: pavement sections were initially evaluated under optimum moisture conditions and replicas of the sections were later evaluated under high water table conditions and surface precipitation.These sections are used to calibrate 4 differents fatigue damage models.

Keywords: Damage, Fatigue, Pavement performance, Moisture

INTRODUCTION

Important progress in pavement engineering have been traditionally achieved through real time load (RTL) testing because the technique does not require large specialized equipment for carrying out the tests (*1, 2*). However, the time required to perform the RLT tests (more than 10 years of continuous monitoring of an experimental section) is associated with many difficulties since most of the experimental sections are located along roadways in operation.

In the case of Central America, the big variability in materials, traffic, climatic conditions, and the cost of developing a suitable RTL test program covering all these conditions is prohivitive. Due to local conditions, there is a great need to characterize the performance of local pavement structures as the only means of developing and calibrating design methodologies. For this purpose, it was considered that the implementation of an Accelerated Pavement Testing (APT) program was a better alternative (*3*).

High loads traveling at low speeds, expansive soils and drainage systems that are insufficient or non-existent to meet the demand of the rainy season are common in the region. All the previous factors combine to generate high moisture damage probability that can range from stripping of the asphalt film,batches and cracking that allow water to enter the pavement structure, and changes in material response due to moisture dependent behavior of the unbound layers; all leading to an overall structural and functional failure of the pavement structure.

The effect of moisture on the different materials used in pavement construction has been analyzed by several authors, but the calibration of pavement response models that consider this effect are highly dependent on the material and climatic conditions for each region.

To attend this need, a Costa Rican APT program was implemented (PaveLab), relying on a Heavy Vehicle Simulator (HVS) since it was considered the best option for the local and regional needs. Specifically, the PaveLab had to meet the following requirements: mobility, accelerated pavement evaluation, application of real loads and comparable results to similar equipment (*4, 5, 6*). To evaluate the effect of moisture on pavement performance, pavement structures with different types of base and under different humidity conditions in the lower layers have been analyzed. With the current project, PaveLab aims to generate a series of products that have already been obtained under similar studies but for different conditions (*7, 8, 9*):

- Mechanistic-empirical pavement design methodology and software based on material conditions, weather, traffic and actual construction practices.
- Development of new material specifications that are based on actual performance and contribution of structural materials in the field.
- Optimization of pavement structures in use at the national level, based on structural, materials, traffic, and climatic conditions specific to the area where the structure is planned to be built.
- Potential for an improved evaluation methodology of new materials or materials currently in use.
- Capacity to evaluate pavement structures of high importance prior to opening to traffic to ensure the required performance of the structure or identify possible deficiencies.

PAVELAB TEST SECTIONS

The test sections used in the analysis are part of the initial set of experiments performed at PaveLab in Costa Rica, and correspond to 4 structures (AC1 to AC4) that were constructed in March 2012 (Figure 1) (*3*). HVS trafficking on the sections began in July 2013 using a dual 11R22-5 tire, with 90 psi inflation pressure, applying a standardized load between 40 kN and 80 kN. The objective of this set of experiments consisted in the structural comparison of typical conditions in the Central American region: use of granular vs cement-treated bases (CTB), and thin vs thick HMA layers. Table 1 summarizes the thickness and material properties of the analyzed sections. Layer thicknesses were verified by means of Ground Penetrating Radar (GPR) and coring. Initial layer moduli were determined by means of backcalculation based on Falling Weight Deflectometer (FWD), Road Surface Deflectometer (RSD) and Multi-depth Deflectometer (MDD) results (*10*).

One of the advantages of the Pavelab test track is the ability to change the moisture in the pavement layers. to this end; a water saturation chamber was built (Figure 1), which allows to generate and control the water table in the test section and therefore, modifying the moisture in the pavement layers. In this experiment, the test track numbers 001AC1 and 003AC2 are the dry test sections and the 008AC1 and 007AC2 are the saturated ones.

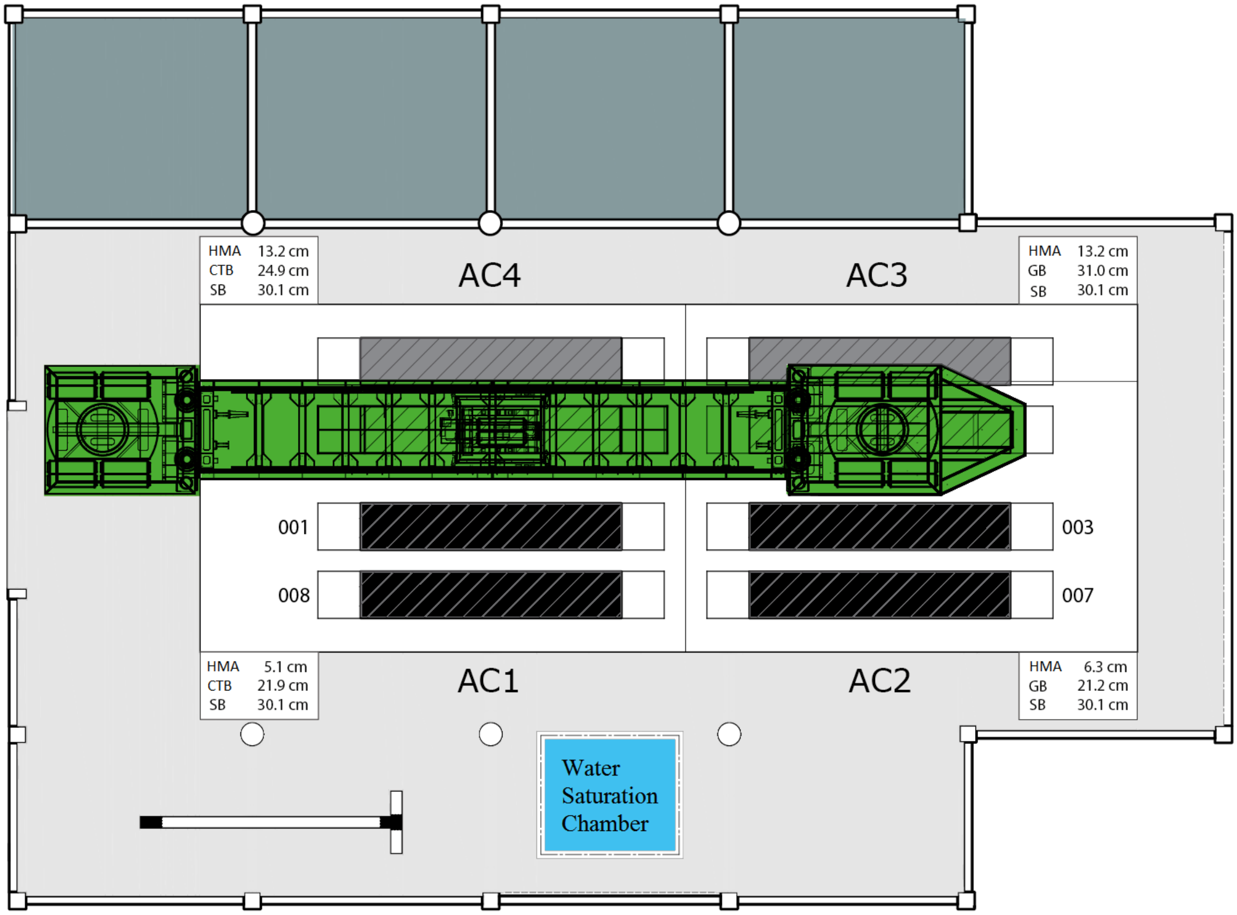

FIGURE 1 Test track distribution.

TABLE 1 Test tracks in-place propertiesafter construction.

Section Properties	001AC1	003AC2	008AC1	007AC2
AC Thickness (H1), cm	6.1	6.3	6.1	6.3
Base Thickness (H2), cm	21.9	21.2	21.9	21.2
Subbase Thickness (H3), cm	30.1	30.1	30.1	30.1
AC Modulus (E1)@25 °C& 1.5 Hz, MPa	3500	3500	3500	3500
Base Modulus (E2), MPa	1200	115	1750	300
Subbase Modulus (E3), MPa	142	75	500	100
Subgrade Modulus (E4), MPa	104	75	60	30

INSTRUMENTATION

The measurements were performed using the HVS integrated instrumentation and embedded sensors in all four test sections. HVS onboard instrumentation record different signals: the applied load, tire pressure and temperature, position and velocity of the load carriage. Embedded sensors included asphalt strain gauges, pressure cells, multi-depth deflectometers (MDDs), and moisture and temperature probes. The HVS was equipped with a laser profiler that can be used to recreate a three-dimensional profile of the section. Additionally, a road surface deflectometer (RSD) to obtain deflection basins at any location along the test section.

Figure 2 shows the instrumentation array used for the experiments. The asphalt strain gauges were placed at the base/HMA layer interface in the longitudinal and transverse directions. Pressure cells were placed at the subbase/subgrade interface. MDDs were installed at 4 different depths to cover all 4 structural layers.

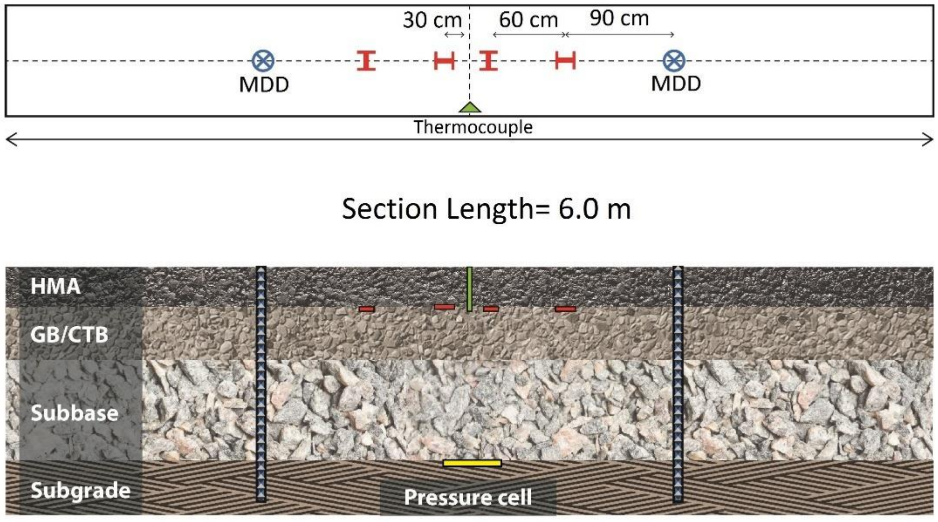

FIGURE 2 Sensor array used for each test track.

Data collection of the 3D profile, strain, pressure, temperature, and deflection was performed based on load repetitions. At the beginning of each test, data was obtained at short intervals: 1,000, 2,000, 5,000, and 10,000 loads repetitions. After 20,000 load repetitions, data is collected on daily basis. Inspection of fatigue and reflective cracking, friction loss, loss of aggregate-asphalt bond, and any other surface deterioration is performed on daily basis during the HVS maintenance check.

Finally, Intenartional Roghness Index (IRI) was calculated by means of a quarter-car vehicle math model for each of the longitudinal data lines: the transverse measurements are independent. A limitation associated to the IRI estimation is that the length of the section is 6 m, and within this distance the effective measuring distance of the lasers is 5.1 m. Therefore, the IRI corresponds to an average property within the defined distance.

SATURATION OF THE TEST TRACKS

The humidity levels were strictly controlled, to maintain the constant water table at 70 cm from the pavement surface.This water table allows to maintain saturation levels in the subgrade around 87% (Figure 3), and the optimum dry density of this soil is reached at 80% of saturation (equivalent to an optimum humidity of 55%). For the base and subbase layers, the saturation level was established around 43% (equivalent to an optimum humidity of 4%) to obtain the optimum density.

To control the water table, the saturation chamber has an automated system to ensure the optimal flow of water to maintain stable humidity conditions.

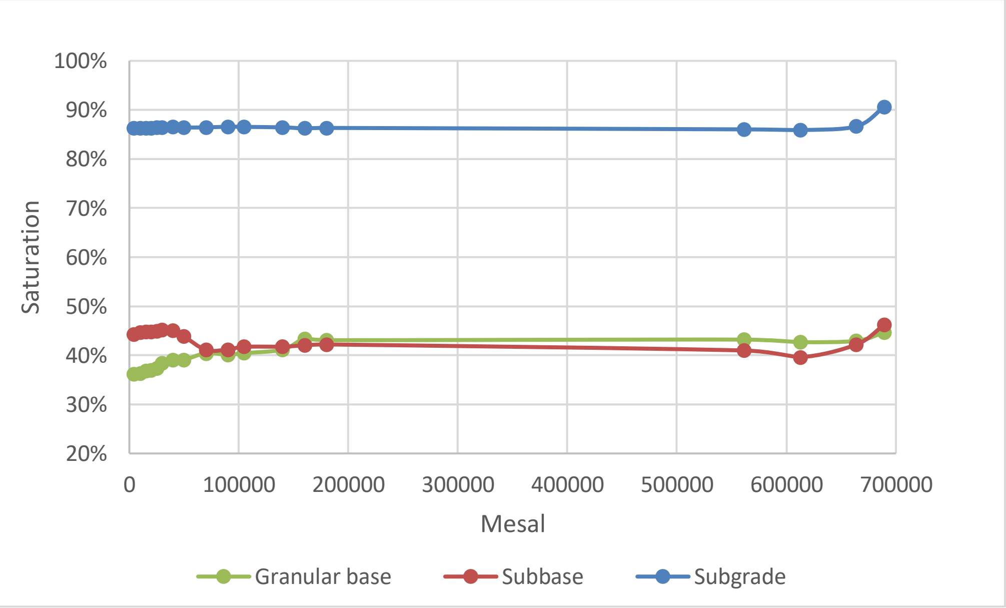

FIGURE 3 Example of controlled moisture conditions on 007AC2 test section.

FATIGUE CRACKING

Fatigue cracking is one of the most important distresses in flexible pavements.The cracks in pavement structures can start from top or at the bottom of the asphalt layer (*11*). In the Pavelab was observed tha the cracks start at the bottom of the asphalt mixture layer due to the large stresses produced by the traffic loads and these propagate as damage increases. Fatigue resistance of the asphalt layers depends on the properties of the material and the structural capacity of the pavement. In the laboratory, one of the most popular test procedures used to determine susceptibility to fatigue cracking is the four point bending beam (4PBB) test, in accordance with AASHTO T 321.

This test is considered to simulate the flexural stresses that an HMA layer experiences in a pavement structure. The results are interpreted in terms of a relationship between applied strain or applied stress and the number of cycles to failure. There are several mathematical models used to predict the fatigue life of asphalt mixtures, the simplest being the model proposed by Pell (12). For a controlled strain test, the fatigue model is described by Equation 1:

$$N_f = k_1 \left(\frac{1}{\varepsilon}\right)^{k_2} \tag{1}$$

Where N_f = number of cycles to failure, ε = tensile microstrain, and k_1, k_2 = mix-dependent regression coefficients.

The previous approach is a simplified method to analyze the fatigue performance of HMA pavements. It is mainly an empirical approach and does not provide a relation between the actual load and any form of damage accumulation in the asphalt mixture (13). The obtained results are material dependent, loading mode dependent, or both, and consequently this approach can not be applied directly to real loading scenarios of in service pavements structures (14). In addition, the relationship between fatigue life and stress level is assumed linear, which previous research has shown to be inadequate for low strain conditions (15).

PROPOSED MODEL

Damage functions can beused for modeling cracking of bound materials, permanent deformation, and roughness for all layers. The general format of a damage function can be expressed as (16).

$$Damage = A \times MN^{\alpha} x \left(\frac{resp}{resp_{ref}}\right)^{\beta} x \left(\frac{E}{E_{ref}}\right)^{\gamma} x e^{\delta T} \tag{2}$$

Where MN = the number of load repetitions in millions, $resp$ = the response (stress or strain), $resp_{ref}$ = a reference response (can be related to strength), E = the modulus of the material (adjusted for climate and damage), E_{ref} = a reference modulus, and A, α, β, and γ = model constants.

For bound materials, structural damage may be defined as the relative decrease in modulus, i.e. the decrease in modulus (*dE*) relative to the initial modulus (*Ei*).During the early stages in the life of the layer, the decrease in modulus will primarily be due to microcracking which, will later develop into macro-cracking. The process is complex and using the average modulus of the layer is a simplification.

RESULTS

Four Point Bending Beam (4PBB) Fatigue Tests

Tests were performed for laboratory produced and plant asphalt mixes to the number of load repetitions required to reach 50% stiffness reduction as function of the tensile strain at different temperatures.Tests were conducted in accordance with AASHTO T 321 under constant strain loading at three strain levels 400, 600 and 800 microstrain and three test temperatures (10, 20 and 30 °C) (17).

Table 2 shows all the regression coefficients computed for both laboratory and plant mixes. In both cases, it was determined that the modulus of the mixture was not statistically significant for a 95% confidence level. This could be due to the high correlation (R-value = 0.91) between temperature and modulus (collinearity) and the limited number of observations used to develop each model.

TABLE 2 Regression estimates for laboratory fatigue models.

Mix	Coefficient	Value	Std. Error	T-stat.	P-value
Laboratory	A	0.189	0.0079	65.85	<0.05
	α	0.271	0.0014	162.82	<0.05
	β	1.070	0.0084	117.12	<0.05
	γ	0.535	0.0081	19.23	<0.05
	δ	0.035	0.0005	32.29	<0.05
	Residual Standard Error	0.04897 for 25,172 degrees of freedom			

Damage of the asphalt mixture was defined as the relative decrease in modulus *dE* relative to the initial modulus, *Ei* for each sample and this was used to calibrate the model shown in Equation 3. The parameters on this equation were determined from 4PBB strain controlled samples, by minimizing the Root Mean Square (RMS) of the difference between the measured and the calculated damage from Equation 2 with the incorporation of the temperature variable (*17*).

$$\omega = A \times (MN)^{\alpha} \times \left(\frac{\varepsilon}{200}\right)^{\beta} \times \left(\frac{E}{3000}\right)^{\lambda} \times e^{(\delta \times T)} \qquad (3)$$

Where

MN = the number of load repetitions in millions

ε= tensile micro strain

E = the modulus of the material, MPa

T = Temperature °C, and,

$\alpha, \beta, \lambda, \delta$ = confficients from table 2

The initial calibration corresponds to apply an adjustment factor of 1.4, to the equation 3. This factor was generated with preliminary HVS data analyzes of sections with thick layers and dry conditions and this work was presented in a previous work (*17*)

Backcalculated Layer Moduli

RSD deflection data was used to determine the progression of the pavement layer moduli through backcalculation. Figure 4 shows the RSD with the HVS tire. By means of the mentioned equipment, monitoring the pavement performance under different humidity conditions was possible. The backcalculation was based on the method of equivalent thickness (MET) where the thickness of the different layers is transformed into an equivalent single layer. This conversion is based on Odemark's methodology and the calculation of stresses, strains and deflections was performed using the Boussinesq theory (*18*).

Damage was determined for the laboratory testing as well as for each individual test section at five different locations.Three deflection measurements at each location were performed. Hence, it was possible to determine strain responses based on Layered-Elastic Theory, and these responses were verified with the strain gauges placed in each track. Also, to determinate the damage the investigation used temperature records at mid depth of the asphalt layer, thicknesses, and correspondent load repetitions.

Damage on the asphalt concrete was estimated in order to asses how the laboratory model relates to the APT results. Such estimation was performed using the various coefficients obtained from laboratory samples (Table 2), The different conditions for each test track indicate that a single adjustment factor might not be adequate in the prediction of fatigue damage. Consequently, initially independent calibration factors for each test section were developed: granular base, CTB, optimal humidity or high degree of saturation in the subgrade.

FIGURE 4 Measurements with RSD equipment and HVS tire.

Figure 5 shows the models calibrated in function of the damage (equation 3) for the AC2 tests tracks (granular base with thin HMA). The calibrated models tend to adequately describe damage as a function of load repetitions, tensile strain and stiffness, using the parameters initially determined from 4PBB testing (Table 2).

The differences between the laboratory model and the APT test section 003AC2 dry range between 100% and 150% (Figure 5), respect to the damage observed. This behavior is mainly due to the measured values of maximum strain at the bottom of the HMA layer used to calibrate the initial model. For the section 007AC2 wet, the difference between the damage values predicted from the 4PBB regresión and the real measured damage is 6%, however, it has to be considered that this section fails at 450,000 equivalent axles.

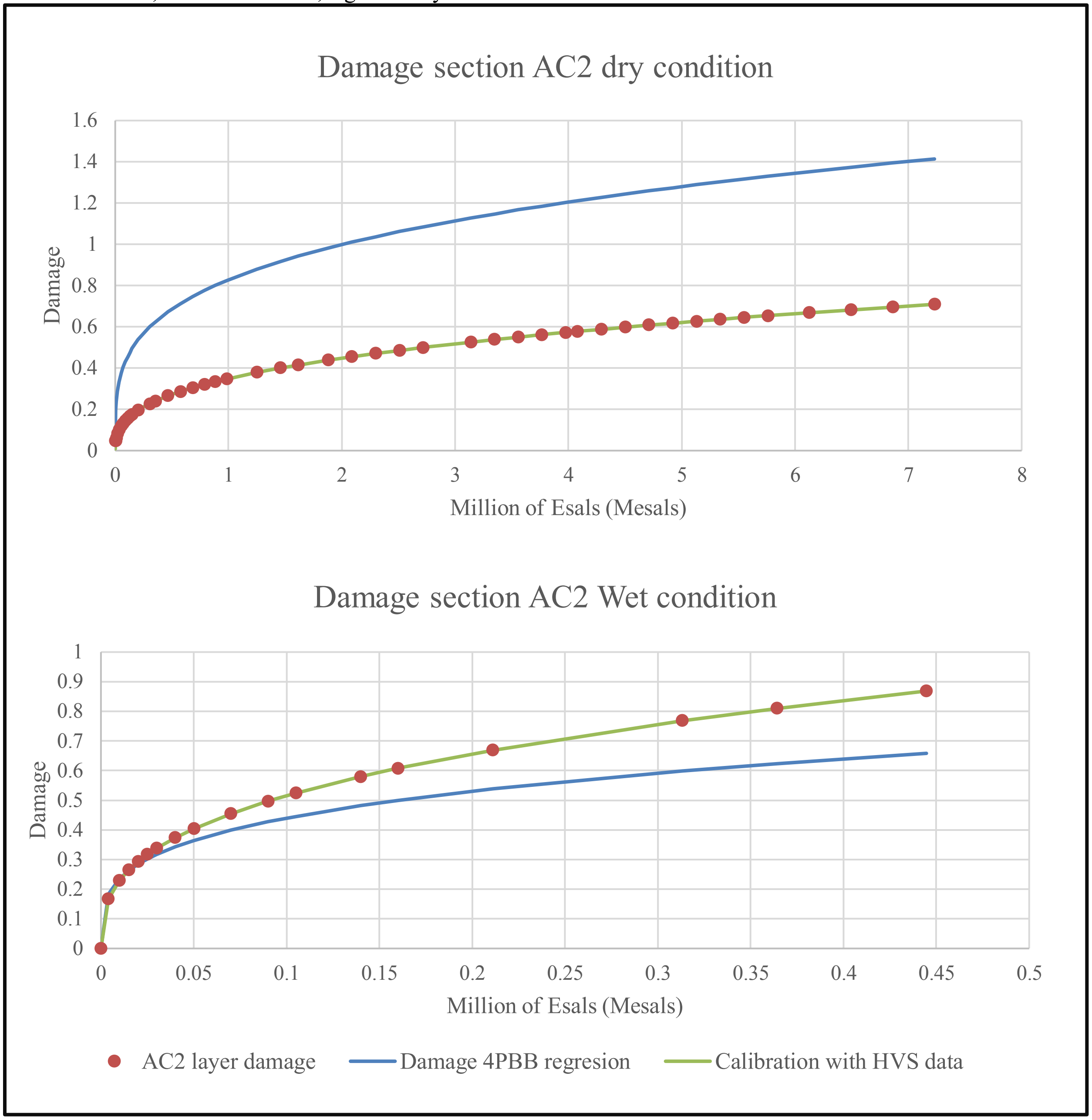

FIGURE 5 Predicted damage with HVS data calibration on 003AC2 and 007AC2 sections.

For the pavements with a CTB layer, the damage predicted with 4PBB regression considerably under-estimates the damage (Figure 6). In this section, the CTB layer causes that the initial strains at the bottom of the HMA layer were very low. These pavement structures had considerably less damage when the experiment was finalized (70% of real damage vs 8% of damage in the 4PBB regression equation).

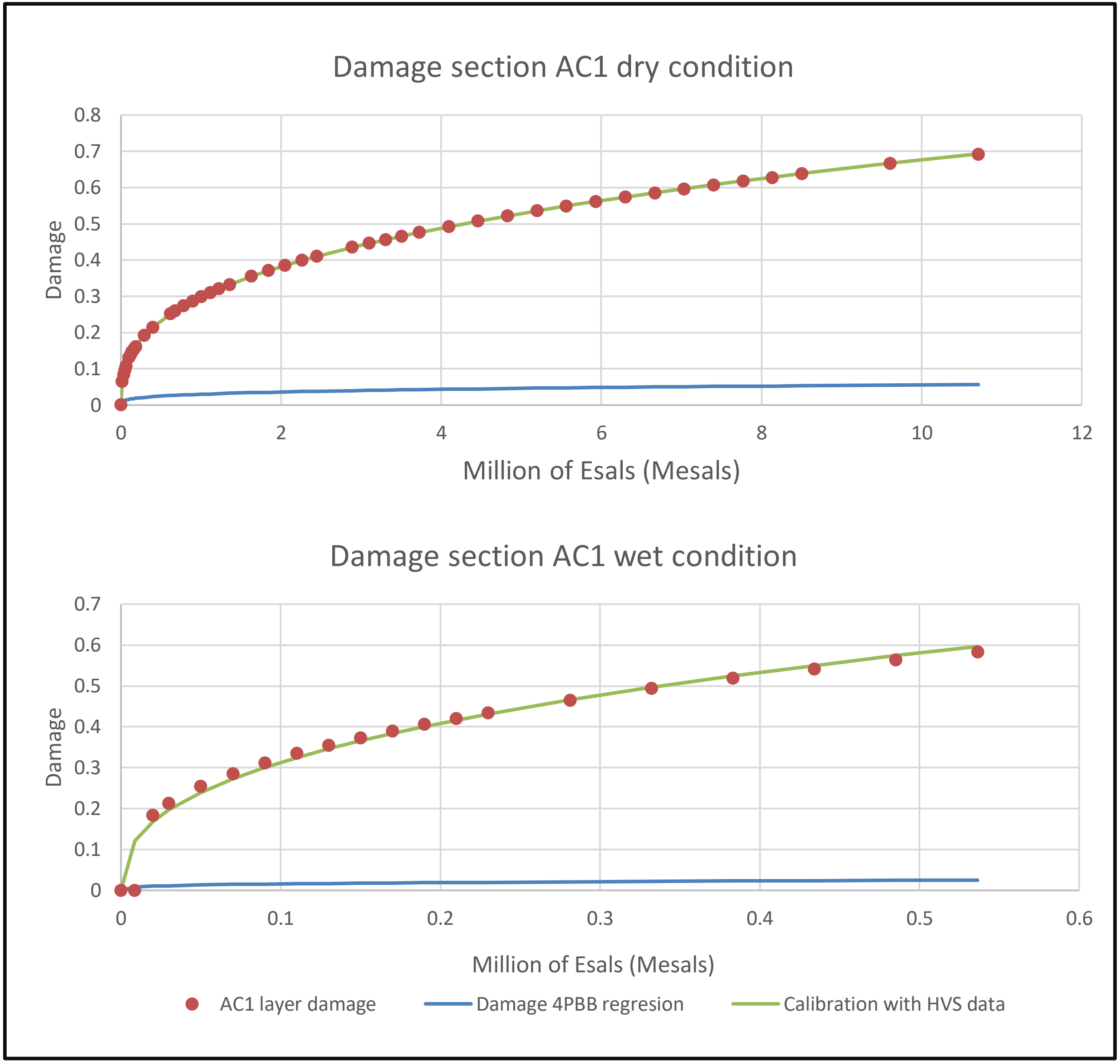

FIGURE 6 Predicted damage with HVS data calibration on 001AC1 and 007AC1 sections.

If the equation 3 is transformed in a classical fatigue function, the model defined in equation 4 is obtained, and the respective calibration coefficients are shown in Tables 3 and 4. The coefficients were calibrated for three damage levels, since for the four test tracks werre stopped for damage levels between 60% and 90%. In addition, the models were calibrated for the strain level measured at the bottom of the HMA for each section. In the case of the pavement with CTB the strain was 15με and in the pavement with granular base was 353 με. It is expected that other test conditions will generate a different model that contemplates other levels of deformation.

$$MN = k_1 * \left(\frac{\varepsilon}{200}\right)^{-k_2} * \left(\frac{E}{3000}\right)^{-k_3} \tag{4}$$

Where

k_1, k_2, k_3 and k_4= regression coefficients, corrected with HVS data

TABLE 3 Calibration parameters forthin HMA layer over CTB.

Section AC1 Dry conditions				**Section AC1 Wet conditions**			
Coefficients	**Damage level**			**Coefficients**	**Damage level**		
	60%	**70%**	**90%**		**60%**	**70%**	**90%**
k_1	0.040	0.061	0.124	K_1	0.004	0.006	0.012
k_2	-3.006			K_2	-2.784		
k_3	-1.503			K_3	-1.392		
k_4	-0.099			K_4	-0.092		

TABLE 4 Calibration parameters for thin HMA over granular base.

Section AC2 Dry conditions				**SectionAC2 Wet conditions**			
Coefficients	**Damage level**			**Coefficients**	**Damage level**		
	60%	**70%**	**90%**		**60%**	**70%**	**90%**
K_1	276.892	425.623	857.887	K_1	10.161	15.784	32.365
K_2	-2.983			K_2	-3.056		
K_3	-1.492			K_3	-1.528		
K_4	-0.098			K_4	-0.100		

CONCLUSIONS AND RECOMMENDATIONS

The generated fatigue models account for different conditions in terms of materials and humidity for pavements with a thin HMA layer. Through the present expetiment it was verified that the 4PBB regression equation does not fit adequately with the full-accelerated pavement test performed on HMA thin layer sections.

The calibration of the fatigue modelcoefficients between 4PBB and APT sections showed in Tables 3 4 are staticsally satisfactory for each of the test tracks. Different calibration parameters were required for each section since the behavior for each test condition was different, mainly for the test tracks with CTB layer under higher humidity levels.

The fatigue models were calibrated for strain levels corresponding to the pavements shown in Table 1 (AC1 and AC2). Future tests sections will expand the strain level range.

Tests currently underway will allow the analysis of the effect of thick HMA layers under different humidity conditions. The previous will allow for the calibration of a more robust model based on additional data that consider:

- Universal asphalt concrete fatigue model that predict damage as a function of load applications, tensile strain and stiffness.
- Type of base layer (CTB and unbound layers) using parameters from flexural beam testing (4PBB).
- Thin and thick HMA layer and humidity on interlayers.

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