Calibration of Mechanistic-Empirical Fatigue Models Using the PaveLab Heavy Vehicle Simulator

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ABSTRACT

In Costa Rica, pavement design has been traditionally based on empirical methods such as AASHTO 93, which was originally developed several decades earlier and is based on the AASHO road test. It is important to note that the method was calibrated for conditions that significantly differ from tropical climates. For this reason, the National Laboratory of Materials and Structural Models of the University of Costa Rica (LanammeUCR) has actively worked on research projects with the objective of incorporating the fundamental principles of engineering to pavement design. To achieve this goal, an Accelerated Pavement Testing (APT) program was established in 2012: PaveLab. The program relies on a Heavy Vehicle Simulator (HVS) as a tool to assess full scale performance of pavement structures. Four full-scale test pavement structures with different configurations (materials and thicknesses) have been constructed in the PaveLab, for a total of 8 test sections that will allow the analysis of the behavior of materials under different structural and humidity conditions. All the test tracks were instrumented and are continuously monitored. The analysis and correlation between the laboratory results and the performance observed in the different test section will allow the calibration of fatigue damage models for different kinds of pavements.

Keywords: HVS, Accelerated, Pavement, LanammeUCR, APT

1. INTRODUCTION

Important progress in pavement engineering have been traditionally achieved through real time load (RTL) testing since the technique does not require large specialized equipment for carrying out the test. However, significant time is required (more than 10 years of continuous monitoring for a given experimental section). In Central America, there is a great need to characterize the performance of pavement structures as the only means of developing and calibrating design methodologies. For this purpose, the implementation of an Accelerated Pavement Testing (APT) program was considered a better alternative (1).

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 (2, 3, 4). 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 analysed. Currently, PaveLab aims to generate a series of products that have already been obtained under similar studies but for different conditions (5, 6, 7):

- Mechanistic-empirical pavement design methodology and software based on material conditions, weather, traffic and actual construction practices.

- Development of new material specifications 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 structures or identify possible deficiencies.

2. PAVELAB TEST SECTIONS

The initial set of experiments performed at PaveLab corresponds to four structures shown in Figure 1 and detailed in Table 1. The test tracks AC4 and AC3 are under investigation, for this reason, are excluded to this analysis.

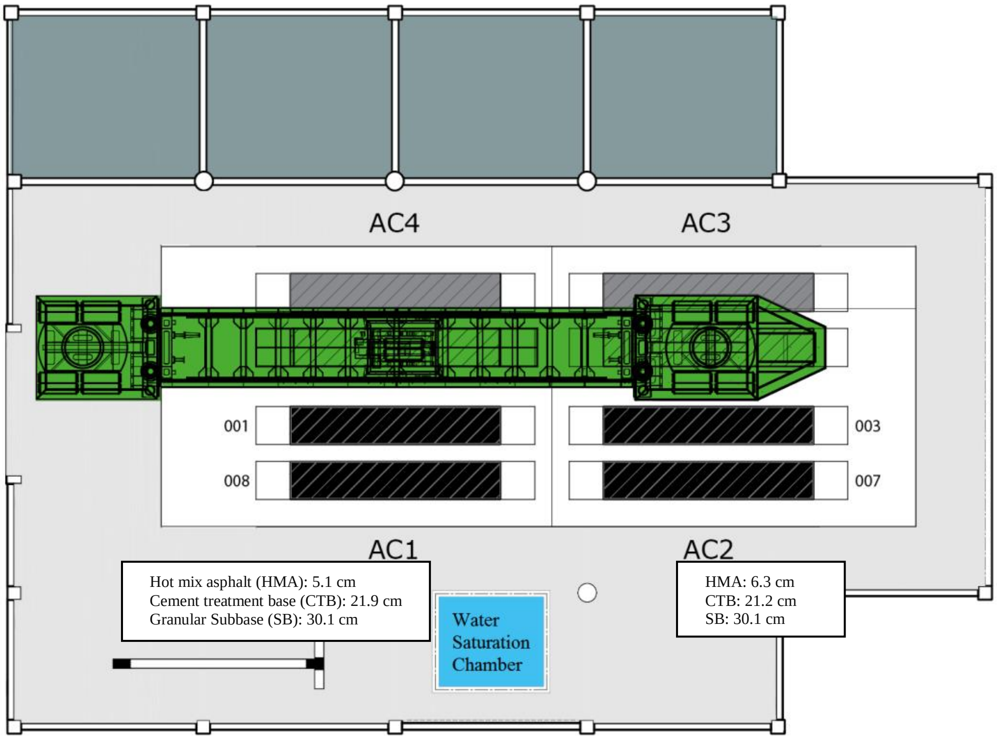

FIGURE 1 Test track distribution

TABLE 1 Test tracks in-place properties after 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), MPa [@ 25 °C, 1.5 Hz]	3500	3500	3500	3500
Base Modulus (E2), MPa	1200	115	1750	300
Subbase Modulus (E3), MPa	142	75	500	100

The CTB layer has a 3MPa of compressive strength at 7 days. The HMA has a 5 % of asphalt content as percent of the mass of the oven-dry total aggregate. The granular base and subbase is river coarse material, crushed and well graded. The subgrade is a cohesive soil, with high plasticity.

3. INSTRUMENTATION

The measurements were performed using the HVS integrated instrumentation and embedded sensors in all four test sections. HVS onboard instrumentation records 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) was used to obtain deflection basins at any location along the test section. Figure 2 shows the typical instrumentation array used for the experiments.

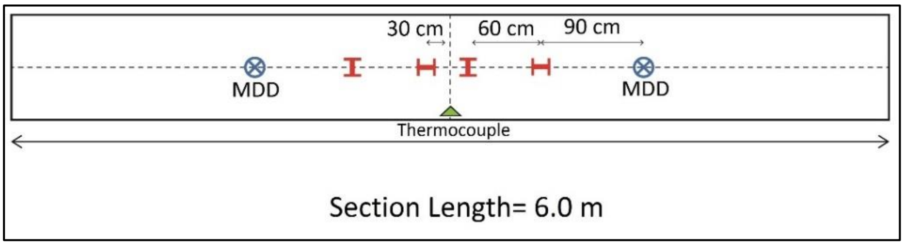

FIGURE 2 Sensor array used for each test track

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, International Roughness 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.

4. SATURATION OF THE TEST TRACKS

The humidity levels were strictly controlled to maintain a constant water table at 70 cm from the pavement surface, which allows to maintain saturation levels in the subgrade at approximately 87% (the optimum dry density of this soil is achieved at 80% saturation, equivalent to an optimum humidity of 55%). For base and subbase layers, the saturation level was controlled at approximately 43%. To regulate the water table, the saturation chamber has an automated system to ensure the optimal flow of water to maintain stable humidity conditions.

5. PROPOSED FATIGUE MODEL

Damage functions can be used for modelling cracking of bound materials, permanent deformation and roughness for all layers. A general damage function can be expressed as follows (8).

$$Damage = A \times MN^{\alpha} x \left(\frac{resp}{resp_{ref}} \right)^{\beta} x \left(\frac{E}{E_{ref}} \right)^{\gamma} x e^{\delta T} \qquad (1)$$

Where MN = the number of load repetitions (ESAL) 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 are model constants.

For bound materials, structural damage may be defined as the relative decrease in modulus (the decrease in modulus -dE- relative to the initial modulus -Ei-). During early stages in the service life of a layer, the decrease in modulus will primarily be due to micro cracking that will later evolve into macro cracking. The process is complex and using the average modulus of the layer is not considered adequate.

6. RESULTS

6.1 Four Point Bending Beam (4PBB) Fatigue Tests

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

Damage of the asphalt mixture was defined as the relative decrease in modulus dE relative to the initial modulus Ei for each sample; this was used to calibrate the model shown in Eq.(2). Equation parameters were determined from 4PBB strain controlled samples, by minimizing Root Mean Square (RMS) of the difference between measured and calculated damage from Eq. (1).

$$\omega = 0.189 \times (MN)^{0.271} \times \left(\frac{\varepsilon}{200} \right)^{1.07} \times \left(\frac{E}{3000} \right)^{0.535} \times e^{(0.035 \times T)} \qquad (2)$$

Where MN= the number of load repetitions in millions, ε= tensile micro strain, E= material modulus, T= temperature.

The initial calibration corresponds to apply a 1.4 adjustment factor to Eq.(2). This factor was generated with preliminary HVS data analyzes of thick layers sections and dry conditions, from a previous work (9).

6.2 Backcalculated Layer Moduli

RSD deflection data was used to determine the progression of the pavement layer moduli through backcalculation. 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, which is based on Odemark's methodology. Stress, strains and deflections calculation was realized using Boussinesq theory (10).

Damage was determined for the laboratory tests as well as for each individual test section at five different locations. Three deflection measurements were performed at each location. Therefore, it was possible to determine strain responses based on Layered-Elastic Theory and verified these with strain gauges embedded in each track. In addition to estimation of damage, temperature records at mid depth of the asphalt layer were also recorded to correct the modulus of the temperature-susceptible layers.

Damage to asphalt concrete was estimated to evaluate how the laboratory model relates to the APT results. This correction was performed using factors to shift the damage between laboratory and field conditions. The different conditions for each test track indicate that a single adjustment factor might not be adequate for predicting fatigue damage. Consequently, independent calibration factors for each test were developed: granular base, CTB, optimal humidity or high degree of saturation in subgrade.

Differences from 100% to 150% in damage were observed between the four point bending beam (4PBB) laboratory model and the 003AC2-Dry APT test section (based on measured values of maximum strain at the bottom of the HMA layer). On the other hand, there is a 6% difference between the damage values predicted from 4PBB data and real damage measured in section 007AC2-Wet. However it has to be considered that the section failed early at 450,000 equivalent axles.

For pavements with CTB layer, the predicted damage with the 4PBB regression considerably underestimates the damage, the CTB layer causes initial strains at the bottom of HMA layer to be low. These pavement structures show significantly less damage when the experiment was completed.

Equation 3 is obtained by transforming equation 2 into a classical fatigue function. The models were calibrated for the strain level measured at the bottom of the HMA for each section, at three damage levels between 60% and 90%.

$$MN = k_1 * \left(\frac{\varepsilon}{200}\right)^{-k_2} * \left(\frac{E}{3000}\right)^{-k_3} \tag{3}$$

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

If equation 2 is transformed in a classical fatigue function, the model defined in equation 3 is obtained, and the respective calibration coefficients are shown in Tables 2 and 3. The coefficients were calibrated for three damage levels, since loading for the four test tracks was stopped when damage levels reached the range 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 15 με and in the pavement with granular base was 353 με.

TABLE 2 Calibration parameters for thin 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 3 Calibration parameters for thin HMA layer 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		

Three levels of damage are calculated in the models because these levels of damage were shown during the test, it's very important clarification that the failure criteria and the criteria to stop the test are two conditions very different, associated directly to the type of structure.

7. CONCLUSIONS

The generated fatigue models account for different conditions in terms of materials and humidity for pavements with a thin HMA layer. Throughout the present project, it was verified that the 4PBB regression equation does not adequately match with the f full-scale accelerated pavement test performed on HMA thin layer sections. For this reason is very important a field calibration, under different humidity conditions and different pavements structures. Furthermore, in the future other conditions must be considered to validate the results obtained in this tests.

The calibration of the fatigue model coefficients between 4PBB and APT sections shown in Tables 2 and 3 are satisfactory for each of the test tracks. Different calibration parameters were required for each section since the behaviour for each test condition was different, mainly for the test tracks with CTB layer under higher humidity levels.

The currently undergoing tests will allow the analysis of the behaviour of thick HMA layers under different humidity conditions.

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.

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