Costa Rica´s Mechanical Empirical Design Software for Flexible Pavements, CRME

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By

Christopher Trejos-Castillo(Corresponding Author)
Researcher
National Laboratory of Materials and Structural Models (LanammeUCR)
University of Costa Rica, P.O. Box 11501-2060, UCR, San José, Costa Rica
Phone: + (506) 2511-2794
E-mail: christopher.trejoscastillo@ucr.ac.cr

Tania Ávila-Esquivel
Researcher
National Laboratory of Materials and Structural Models (LanammeUCR)
University of Costa Rica, P.O. Box 11501-2060, UCR, San José, Costa Rica
Phone: +(506) 2511-2794
E-mail: tania.avilaesquivel@ucr.ac.cr

JoséP. Aguiar-Moya, Ph.D.
Research Program Coordinator
National Laboratory of Materials and Structural Models (LanammeUCR)
University of Costa Rica, P.O. Box 11501-2060, UCR, San José, Costa Rica
Phone: + (506) 2511-2529
Fax: + (506) 2511-4442
E-mail: jose.aguiar@ucr.ac.cr

Luis G. Loría-Salazar, Ph.D.
Pavement Infrastructure Program Director
National Laboratory of Materials and Structural Models (LanammeUCR)
University of Costa Rica, P.O.Box 11501-2060, UCR, San José, Costa Rica
Phone: + (506) 2511-4122
Fax: + (506) 2511-4442
E-mail: luis.loriasalazar@ucr.ac.cr

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ABSTRACT

Traditionally, the design of flexible pavements in Costa Rica and countries in the region, has been performed with the empirical methodology defined by AASHTO in 1993. This methodology was developed for the climatic conditions and materials from Illinois, which are different from those found in tropical countries.

The new methodologies for flexible pavements design are based on the use of solid mechanics, which computes the responses of a pavement (stresses, strains and deflections) as a result of traffic loading, and with this, estimate the performance of the pavement through its service life by means of transfer functions.

To improve the local pavement design methodology University of Costa Rica has worked on several research lines (materials characterization, traffic, climate, software development, mathematical modeling, accelerated pavement testing and performance models) to develop its own mechanistic-empirical methodology (CRME). The research developed includes predictive models for determining the hot-mix asphalt dynamic modulus, unbound layers non-linear resilient modulus models, axle load spectra, lateral wander, moisture and temperature effect on the materials constituting the pavement structure.

A comparison was made between the CRME and two other design computational tools (MEPDG and AASHTOWare) to evaluate the results obtained with the software, also the mathematical background of some models differs from one application to the other. Differences were found between the outputs obtained, because of the way in which the climatic and traffic variables were considered. However, it was possible to note that the results obtained with the CRME are realistic and more representative of regional conditions.

INTRODUCTION

The mechanistic-empirical Pavement Design Guide (MEPDG) provides transfer functions to predict the performance of the pavement structure through its service life. These functions were calibrated for each country or region (*1-3*), reason why the results obtain from using them will not always apply for our own conditions.

Costa Rica has developed a computational tool to design flexible pavements using the mechanistic-empirical method, after a broad line of research, which includes the development of models to estimate the resilient modulus of the unbound layers, the dynamic modulus of the hot mix asphalt layer, and calibrated models using accelerated pavement testing to predict the distress after a determined quantity of load applications (*4,5*).

The software for mechanistic-empirical design of flexible pavement in Costa Rica, CRME, is a easy-to-use computational tool to predict the performance of the pavement structure, considering all the variables that will affect the behavior of the pavement.

To produce accurate designs, CRME includes models that consider the climate, the effect of traffic and the materials properties. The method is initially based on calibrated models to predict fatigue cracking and permanent deformation in the structure (*4-8*).

Besides the mentioned another important factor to develop CRME is due to the high cost of the software developed by AASHTO (AASHTOWare Pavement ME Design) and it's prohibition for local use.

OBJECTIVE

The aim of this research project is to create a computational tool to design flexible pavement structures by the mechanistic-empirical approach, able to predict the pavement performance through a period of time, to this end, an extensive effort was made to cluster all the efforts developed in Costa Rica for pavement design such as material characterization, climatic analysis, traffic data collection and performance determined using accelerated pavement testing.

SOFTWARE GENERAL DESCRIPTION

CRME is related to the design approach of the AASHTOWare Pavement ME Design (Pavement ME) software, by taking into consideration the climatic conditions, the traffic, and the material properties in the computation of pavement responses (stresses, strains and displacements) produced by traffic loads using MLET. With the responses, the software predicts the distress of the pavement with mechanic-based performance models based on the full-scale accelerated pavement testing (APT) experiment (9). The diagram in Figure 1, shows how the variables are used in the pavement design procedure.

The software result reports the rutting and cracking obtained on the pavement structure, product of the input variables and the level of knowledge selected for each variable. More accurate models are used for level 1 and simplified models for level 3. The software was developed with the Integrated Development Environment (IDE) Visual Basic 6.0. Further projects will migrate the software to a Java platform.

The designer should select the initial thicknesses for the layers of the pavement to be analyzed, and then establish the characteristics of the materials, which will be later affected by the climatic conditions, to compute the responses due to the traffic loading. Using the developed performance models, the designer should decide whether the design is approved (*9*).

Figure 2 shows the main window of the program, in which the user must include the project information. Every input requirement will be enabled after the user fills the information in the previous module. The “Run” button will generate the permanent deformation, the top-down and bottom-up fatigue damage, as well as the percentage of cracking area and longitudinal cracking.

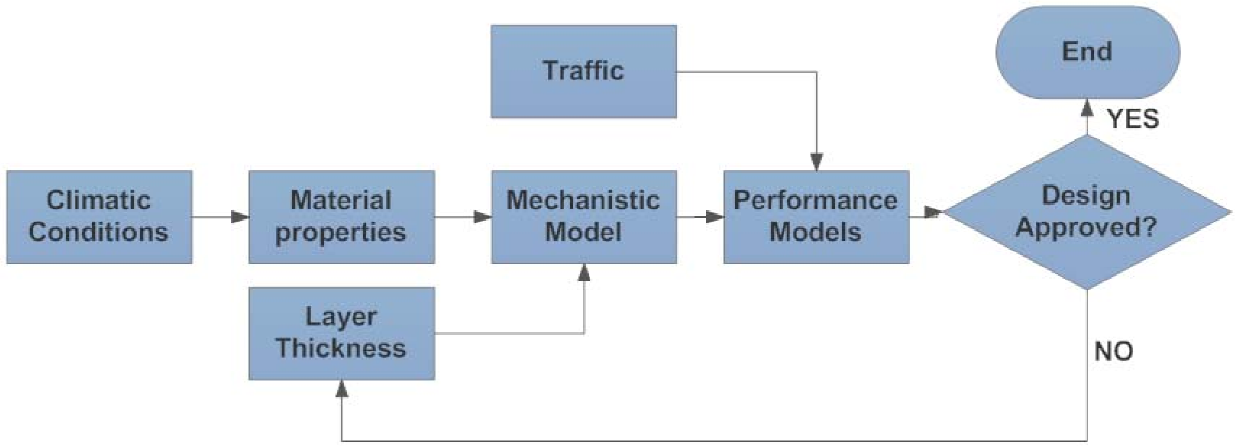

FIGURE 1 Conceptual design methodology.

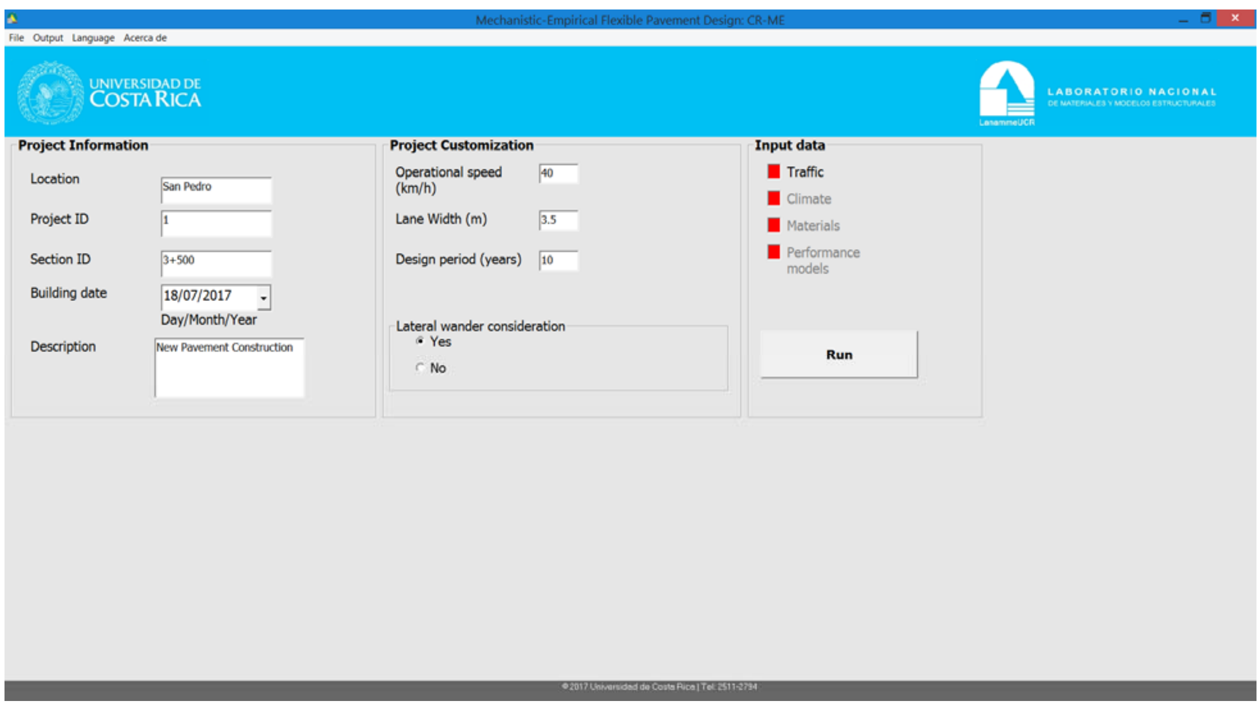

FIGURE 1 Main screen of the CRME software.

SOLUTION TO MULTILAYER ELASTIC THEORY (MLET)

MLET was used to compute the responses of the pavement due to the load since it does not require an excessive computational time to calculate the stresses, strains and deflections in the positions required for the design. A method to solve the MLET was developed and programmed into the software, with the aid of the equations specified by Huang (*10*).

The Hankel transformation method was used to determine the responses of a distributed load q on a circular area of radius a, as shown in equation 1. The numerical method based on the Gaussian quadrature rule was used to solve the integral, by means of the Bessel function; obtaining similar responses to the ones generated by tools such as 3D Move or Open Pave.

$$R = q\alpha \int_0^\infty \frac{R^*}{m} J_1(m\alpha)dm \quad [1]$$

where R^* is the response due to loading $=-mJ_0(m\rho)$, m is a model parameter, $J_0(x)$ is the first kind Bessel function of order 0, $\rho = r/H$, r is the cylindrical coordinate for radial direction, H is the depth to the subgrade layer, $J_1(x)$ is the first kind Bessel function of order one, $\alpha = a/H$, and R is the response due to load q.

TRAFFIC

The software allows two means to account for traffic. The typical Equivalent Axle Load method is used for the basic level. The second method that can be used to perform the analysis is by using the traffic load spectra, which can be obtained from field measurements or based on a load spectrum of similar roads(regional spectra). Within the tool the user must input the representative load for each of the load ranges given by the software and the total number of repetitions associated.

In Costa Rica, regular weight measurements are performed on the main national routes of the country, or by means of mobile load stations used where required, making it possible to obtain the axle load spectrum (*11).*

CLIMATE

The climatic factors are considered by means of the monthly minimum, average, and maximum temperature, and the Thornwaite Moisture Index (TMI). Both must be entered by the user. Resilient modulus models that take into consideration climatic conditions are included in CRME (*1*).

It is possible to include the degree of saturation as a function of the TMI or through the soil water characteristic curve (SWCC). Also, the software can estimate the monthly average dynamic modulus of the asphalt mix as a function of the monthly average temperature.

MATERIALS

Asphalt Layer

The software allows estimation of the dynamic modulus of the asphalt layer depending of the design level established by the designer.

Design Level 3 (Basic)

The software provides three options to estimate the dynamic modulus for the basic level. Figure 3 shows the asphalt layer data input window for this design level.

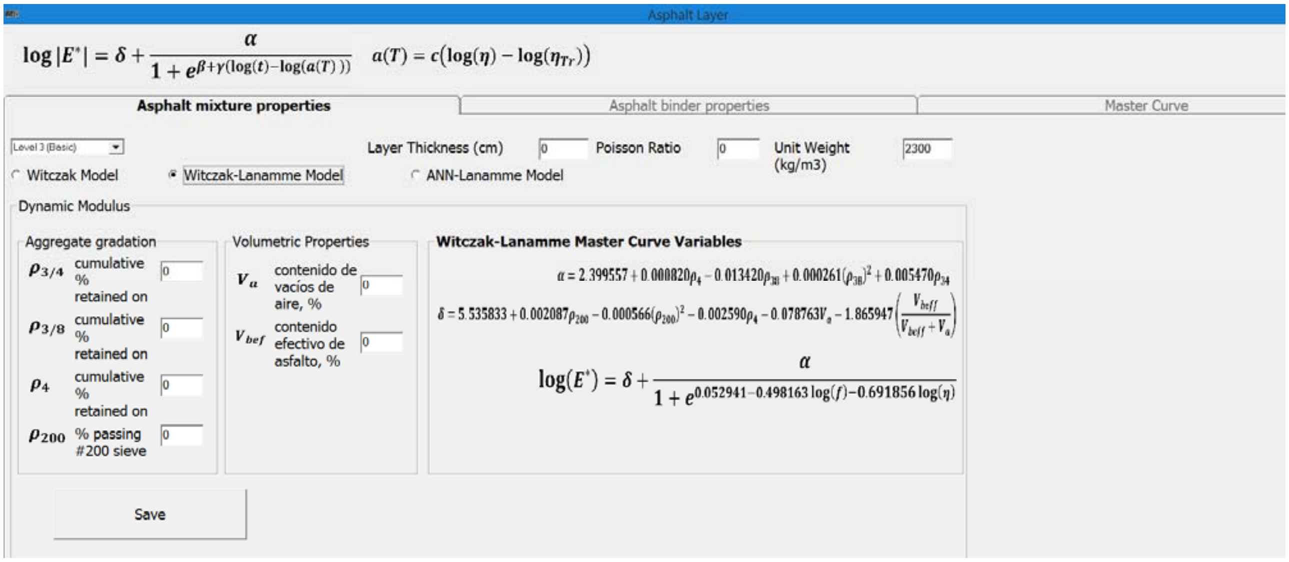

FIGURE 3 Asphalt layer data entry window.

First Option: Witczak Dynamic Prediction Model (*1*) This model predicts higher dynamic modulus than the ones found for typical asphalt mixtures in Costa Rica, because it was calibrated for modified asphalt mixtures. Therefore, it is preferable to use the calibrated model for Costa Rica.

Second Option: Witczak-LanammeDynamic Prediction Model (*12*) The model is a sigmoidal function, shown in equation 2. This model considers the type of binder and materials typically found in Costa Rica, making possible to predict in a more accurate way the dynamic modulus than the Witczak model.

$$\log E^* = 5.535833 + 0.002087\rho_{200} - 0.000566(\rho_{200})^2 - 0.002590\rho_4 - 0.078763V_a - 1.865947\left(\frac{V_{beff}}{V_{beff}+V_a}\right) + \frac{2.399557+0.000820\rho_4-0.013420\rho_{3/4}+0.000261(\rho_{3/8})^2+0.005470\rho_{3/4}}{1+e^{0.052941-0.498163\log f-0.691856\log\eta}} \quad [2]$$

where E^* is the dynamic modulus (psi), η the asphalt binder viscosity at the age and temperature of interest (10^6 Poise), f is the loading frequency (Hz), which is the reciprocal of the loading time t in seconds, V_a the air void content (%), V_{beff} the effective bitumen content (%), $\rho_{3/4}$ the cumulative % retained on the $3/4$ inches sieve, $\rho_{3/8}$ the cumulative % retained on the $3/8$ inches sieve, ρ_4 the cumulative % retained on the No. 4 sieve and ρ_{200} the % passing the No. 200 sieve.

Third Option: ANN-LanammeDynamic Prediction Model (*13*) Based on a recent project aimed to develop an Artificial Neural Networks (ANN) model, using a dynamic modulus database. The model is a feed-forward back propagation with the sigmoidal function shown in equations 3 through 5.

$$f(T) = \frac{2}{1+e^{-2T}} - 1 \quad [3]$$

$$H_k^1 = B_k^1 + \sum_{i=1}^{m} W_{ik}P_i \quad [4]$$

$$\text{Output} = \ln E^* = f\left(B_0 + \sum_{j=1}^{m} H_k^1 W_k\right) \quad [5]$$

where T is the placeholder variable, H_k^1 is the vector of transferred values of nodes at the hidden layer, P_i is the vector of input variables (ρ_{200}, ρ_4, $\rho_{3/4}$, V_a, V_{beff}, $\log\log\eta$, temperature and frequency) as defined previously for equation 2, W_{ik} is the matrix of weight factors for the hidden layer, W_k is the vector of weight factors for the output layer, B_k^1 is the vector of bias factors for the first layer, B_0 is the bias factor for outer layer and *m* is the number of nodes in hidden layer.

Design Level 2

At this level, the asphalt mixture master curve is used to compute the dynamic modulus. The shift factor of the master curve is estimated using the Arrhenius Equation (equation 6). The advantage of this model is that it allows the computation on the asphalt mixture dynamic modulus $E*$ without further binder testing.

The symmetrical sigmoidal function used to obtain the dynamic modulus at specific temperatures and frequencies is shown in equation 7 (*14*).

$$\log a_T = \frac{\Delta E_a}{2.303R}\left(\frac{1}{T} - \frac{1}{T_r}\right) \quad [6]$$

where ΔE_a is the apparent activation energy, typically 250 KJ/mol, *R* is the universal gas constant = 8.314 J/K-mol, *T* is the temperature in Kelvin, and T_r is the reference temperature in Kelvin.

$$\log E^* = \delta + \frac{Max - \delta}{1 + e^{\beta + \gamma(\log f + \log a_T)}} \quad [7]$$

where δ, β, γ, Max and ΔE_a are regression coefficients and *f* is the frequency (Hz).

Design Level 1

The most accurate method to estimate the dynamic modulus is described in level 1of the MEPDG guide (*1*). This methodology considers the binder viscosity to estimate the effect of temperature in the dynamic modulus, as shown in equation 8.

$$\log \log \eta = A + VTS \log T \quad [8]$$

where η is the viscosity in cPoise, *A* and *VTS* are regression parameters and *T* is the temperature of the asphalt mixture in Rankine. If the obtained viscosity values are higher than 2.7×10^{10} Poise, this value should be used instead. This often happens when evaluating low temperatures in the equation.

Asphalt Binder

The software offers the possibility of estimating *A* and *VTS* values using three different methods. For the basic level, the designer can input default values suggested depending on the Superpave Binder Performance Grade (PG), the Conventional AC Grade or the Conventional Penetration Grade. For intermediate level, these values can be determined from at least four points acquired from conventional binder testing, and for advanced level, the engineer can use at least three points obtained from SuperpavePG binder testing.

The shift factor in equation 9 depends on the viscosity calculated as function of the temperature. The symmetrical sigmoidal model is shown in equation 10.

$$\log a_T = c(\log \eta - \log \eta_{Tr}) \quad [9]$$

where η_{Tr} is the viscosity at the reference temperature in cPoise.

$$\log E^* = \delta + \frac{\alpha}{1+e^{\beta+\gamma(\log t - \log a_T)}} \quad [10]$$

where α, β, γ, δ and *c* are regression parameters and *t* is the loading time in seconds.

Equation 11 is used to estimate the loading time *t* (s) as a function of the speed *v* (km/h) and the depth *d* (m) (*15*).

$$\log(t) = 0.5d - 0.2 - 0.94\log(v) \quad [11]$$

Unbound Layers

The software allows two methods to estimate the resilient modulus of the unbound layers (base, subbase and subgrade); for the basic level (level 3) it is possible to use the California Bearing Ratio (CBR) to approximate the value or to input the resilient modulus directly. For level 1, the modulus will be calculated through the Universal Model (equation 12) (*16*), which considers the stress dependency of the granular and soil materials.

$$M_R = k_1 p_a \left(\frac{\theta}{p_a}\right)^{k_2} \left(\frac{\tau_{oct}}{p_a} + 1\right)^{k_3} \quad [12]$$

where θ is the bulk stress, τ_{oct} is the octahedral shear stress, and M_R is the resilient modulus.As previously mentioned, the software will account for an environmental factor which may vary the value of the resilient modulus.

As mentioned before, the climatic variable is considered computing an environmental factor which is calculated as shown in figure 4 (*17*).

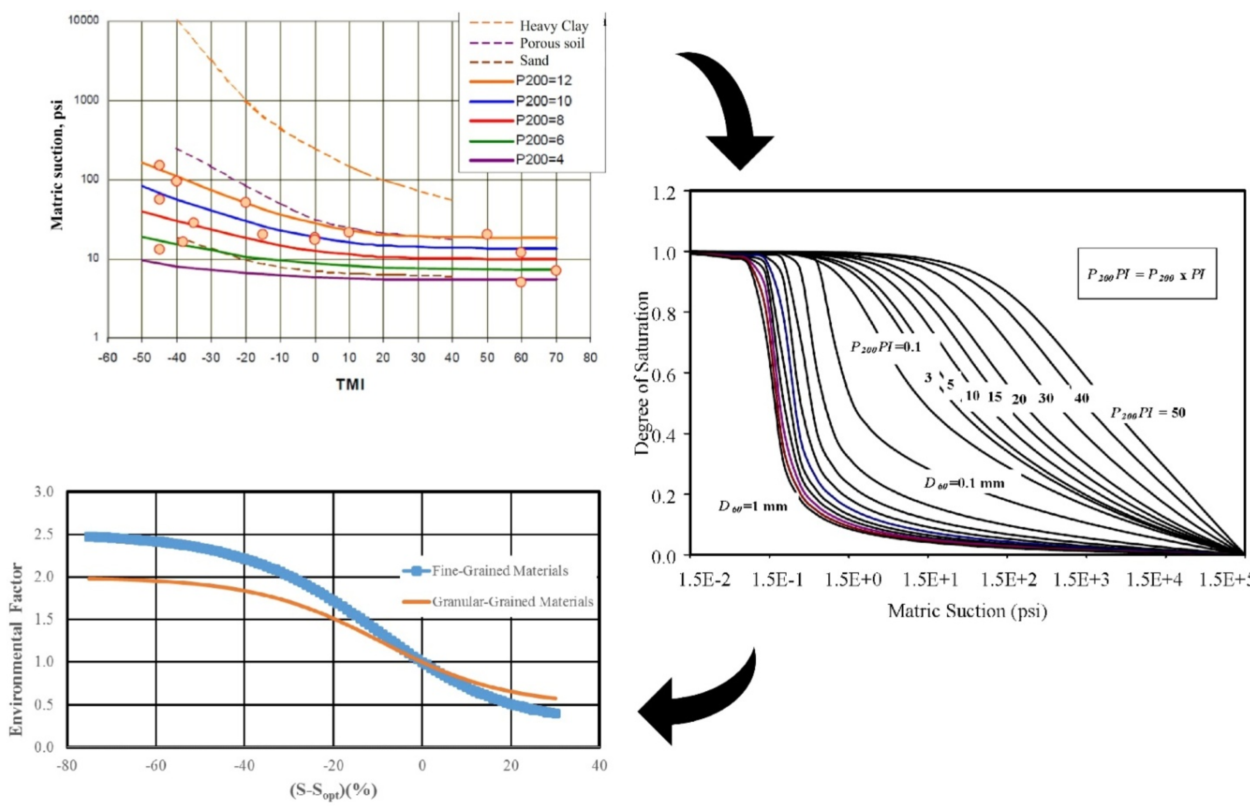

FIGURE 4 Environmental factor estimation using TMI

PERFORMANCE MODELS CALIBRATED WITH APT DATA

The way in which damage is predicted over the lifetime of a pavement structure, is of great importance within a design method based on a mechanistic-empirical approach. The performance models were calibrated using laboratory and full scale APT (PaveLab-University of Costa Rica) tests.

Fatigue models were determined with an incremental-recursive approach, considering the dynamic modulus decrease of the asphalt layer, as shown in equation 13; and with an approach like that of the MEPDG guide, as shown in equation 14 (*18*).

$$N_f = e^{37.352}(\varepsilon)^{-4.554}e^{T(0.094)} \quad [13]$$

$$\omega = 0.0925 \times MN^{0.31003} \times \left(\frac{\varepsilon}{200}\right)^{1.59529} \times \left(\frac{E}{3000}\right)^{0.79765} \times e^{0.04121\times T} \quad [14]$$

where ε is the tangential strain at the bottom of the asphalt layer, T is the temperature of the mix (°C), N_f is the allowed load repetitions, MN is the allowed load repetitions in millions, E is the dynamic modulus of the asphalt mixture in (MPa), and ω is the damage. These models were developed for plant mixtures and can be manually included in the CRME.

The development of the fatigue models has gone through several stages, starting with the formulation of laboratory data models, such as the one shown in equation 15 (*19*).

$$N_f = 4{,}345 \times 10^{16} \cdot \varepsilon^{-4{,}0651} \quad [15]$$

SOFTWARE COMPARISONS

To evaluate the results obtained with the CRME, a comparison has been done with other design computational tools: MEPDG and AASHTOWare Pavement Design ME. In this regard, to the end of covering a wide range of conditions, different input data were used for both examples.

To allow a direct comparison between the methods, it was necessary to process the data, due to the way in which the information is requested for each computational tool.

Table 1 shows the climatic conditions incorporated in both software for each one of the two comparisons. Table 2 shows the input data for traffic, the asphalt layer, asphalt binder, and for each of the unbound layers. Table 3 shows the gradation used for estimating the dynamic modulus of the asphalt layer with the Witczak model for the comparison done between the AASHTOWare Pavement software and the Costa Rican mechanistical empirical pavement design software, and Table 4 shows the input data of AASHTO T340 test for the master curve used to estimate the dynamic modulus of the hot mix asphalt layer (HMA) for the comparison between the previous MEPDG software version with the CRME software.

TABLE 1 Monthly Average Climatic Conditions

Rain, mm		Temperature, °C		TMI	
MEPDG	**AASHTOWare**	**MEPDG**	**AASHTOWare**	**MEPDG**	**AASHTOWare**
34	30	12	21.1	41.5	0
35	49	13.9	23.9	0	-28
56	88	17	25.3	0	-16.1
61	64	21.4	23.9	-14.9	-20.8
58	113	24.9	25.3	-31.1	-3.6
93	222	27.5	28.1	-22.2	12.2
85	141	28.1	28.1	-28.3	0
94	193	28.5	29.4	-26.1	0
88	180	26	25.3	-19.1	49.6
118	125	21.6	23.3	0	33.7
87	67	16.2	22.5	45.3	0
29	59	11.6	20	0	0

TABLE 2 Comparisons Input Data

Module	AASHTOWare Pavement	MEPDG
Climate	Climatic conditions used are shown in Table 1.	Climatic conditions used are shown in Table 1.
Traffic	17 500 000 Equivalent Load Axles.	103 326 000 Equivalent Load Axles
Asphaltlayer	Temperature 21°C, Effective asphalt 11.6%, Air voids 7%, Density 2403 kg/m3, Poisson 0.35, Layer thickness 15.24 cm.	Temperature 21°C, Effective asphalt 11%, Air voids 8.5%, Density 2370 kg/m3, Poisson 0.35, Layer thickness 25.4 cm.
Asphaltbinder	A=10.651 and VTS=-3.554, obtained through rheology	*A*=10.874 and *VTS*=-3.665, obtained through rheology
Granular base	Resilient modulus 275.8 MPa, Poisson 0.35, Plasticity index 6, Passing #200 sieve 8.7%, Specific gravity 2.70, Maximum dry density 2037.6 kg/m^3, Optimum water content 7.4%, Layer thickness 25.4 cm. For the SWCC, a_f=7.2555, b_f=1.3328, c_f=0.8242 and h_r=117.4	Resilient modulus 265 MPa, Poisson 0.35, Plasticity index 1, Liquid limit 6, Passing #200 sieve 8.7%, Specific gravity 2.70, Maximum dry density 2037.5 kg/m^3, Optimum water content 7.4%, Layer thickness 38 cm. For the SWCC, a_f=7.2555, b_f=1.3328, c_f=0.8242 and h_r=117.4
Granular subbase	Resilient modulus 193.05 MPa, Poisson 0.35, Plasticity index 6, Passing #200 sieve 30%, Specific gravity 2.70, Maximum dry density 1952.65 kg/m^3, Optimum water content 10.1%, Layer thickness 25.4 cm. For the SWCC, a_f=48.1615, b_f=1.0906, c_f=0.8869 and h_r=460	Resilient modulus 119 MPa, Poisson 0.35, Plasticity index 0, Liquid limit 11, Passing #200 sieve 5.2%, Specific gravity 2.70, Maximum dry density 1922 kg/m^3, Optimum water content 7.3%, Layer thickness 50 cm. For the SWCC, a_f=4.7572, b_f=2.8814, c_f=0.8694 and h_r=100
Subgrade	Resilient modulus 89.63 MPa, Poisson 0.35, Plasticity index 30, Passing #200 sieve 79.1%, Specific gravity 2.70, Maximum dry density 1565 kg/m^3, Optimum water content 22.2%. For the SWCC, a_f=136.42, b_f=0.5183, c_f=0.0324 and h_r=500	Resilient modulus 83 MPa, Poisson 0.35, Plasticity index 30, Liquid limit 51, Passing #200 sieve 79.1%, Specific gravity 2.70, Maximum dry density 1565 kg/m^3, Optimum water content 22.2%. For the SWCC, a_f=136.42, b_f=0.5183, c_f=0.0324 and h_r=500

TABLE 3 Dynamic Modulus Test Data (Witczak Model) for AASHTOWare Comparison

Gradation	Percent Passing
3/4 in	100
3/8 in	77
No. 4	60
No. 200	6

TABLE 4 Dynamic Modulus Test Data for MEPDG Comparison

Temperature	Dynamic Modulus E* (MPa)					
°C	25 Hz	10 Hz	5 Hz	1 Hz	0,5 Hz	0,1 Hz
-12.2	18834	17941	17626	16241	15626	14171
4.4	14102	13161	12471	10582	9817	8105
21.1	7905	7254	6370	4585	3946	2752
37.8	3718	2957	2417	1436	1158	730
54.4	1188	890	677	392	304	198

To make the comparison more accurate the transfer functions used in the CRME software were the same as those proposed in the MEPDG (*1*), which are the transfer functions placed default in the previous version of the software attached to this guide and the AASHTOWare Pavement computational interface.

Table 5 shows the results obtained with the CRME software and with the previous version of the software for the MEPDG and the AASHTOWare Pavement software.

There were used the two versions of software related with the MEPDG, since this methodology is the basis of the CRME software and, to evaluate the difference between the two computational tools of the MEPDG.

Differences between the values obtained may come from different considerations in the design, nevertheless the results obtained with the Costa Rican mechanistical empirical pavement design software, are among the expected values.

TABLE 5 Output Values

	Parameter	CRME	AASHTO Ware	Difference (%)
AASHTOWare	Cracking area (%)	14.27	5	185
	Longitudinal cracking (feet/mile)	2534	2000	27
	Asphalt layer rutting (mm)	15.75	22.35	30
	Total rutting (mm)	20.53	31.49	35
	Parameter	**CRME**	**MEPDG**	**Difference (%)**
MEPDG	Cracking area (%)	14.69	16.49	11
	Longitudinal cracking (feet/mile)	1415.9	1095.8	29
	Asphalt layer rutting (mm)	5.49	16.26	66
	Total rutting (mm)	7.73	24.89	69

As observed in Table 5, the major difference found correspond to 180%,in the comparison of the percentage of cracking area calculated with the AASHTOWare. Another high difference obtained (69%) are the asphalt layer rutting value associated with the MEPDG comparison. Lower rutting values observed in CRME can be associated to the consideration of the lateral wander.

The strain hardening approach was considered. This allows to account for the climatic variation and its effect on the pavement design. Seasonal variations in the design can be visualized due to the variation of unbound layers resilient modulus and the effect of the temperature on the dynamic modulus of the asphalt layer.

Figure 5 shows the monthly average dynamic modulus used within the CRME software and the MEPDG software. The last one has a big discrepancy with the Costa Rican computational tool, estimates a dynamic modulus at different depths of the asphalt layer for each month of the design period.

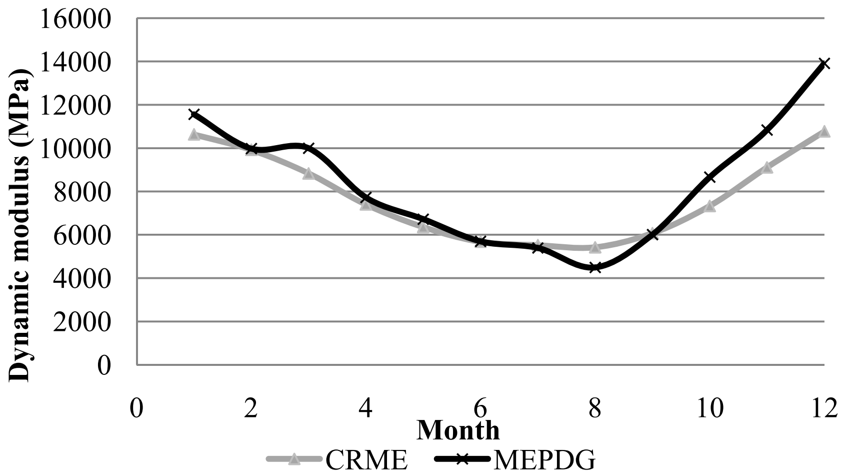

FIGURE 5 Monthly average dynamic modulus

The principal distresses predicted by the mechanistical empirical pavement design software are: HMA and total rutting, the cracking area and the longitudinal cracking. The difference between the models may be seen in the comparison graphs shown from Figure 6 to 9.

The comparison graphs between CRME and AASHTOWare Pavement software are not placed since the output of this software doesn't allow to produce them. Similarities between the two methodologies can be seen in the graphs when looking at the curve shapes.

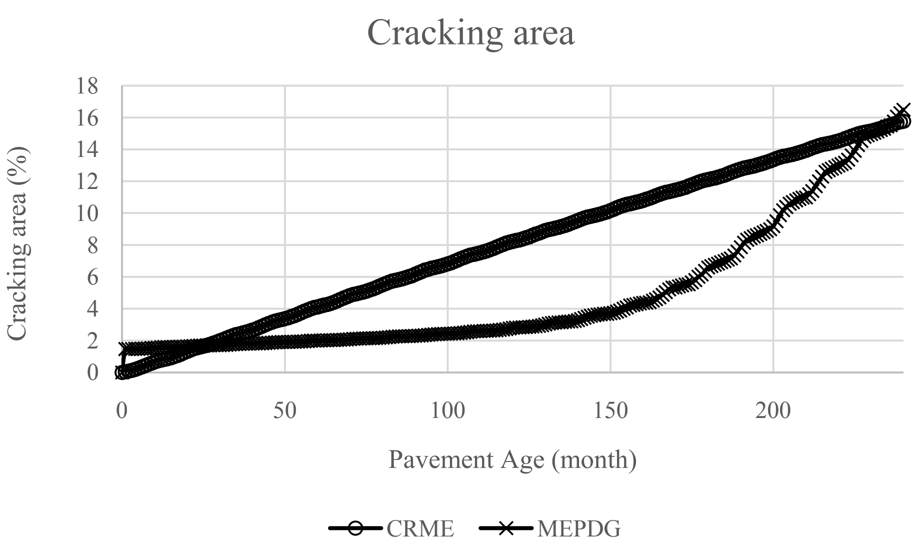

FIGURE 6 Predicted cracking area

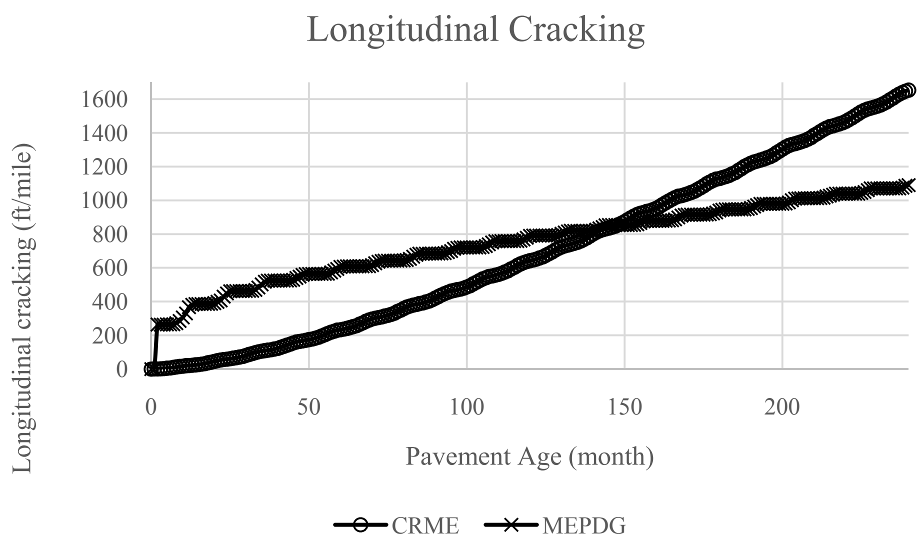

FIGURE 7 Predicted longitudinal cracking

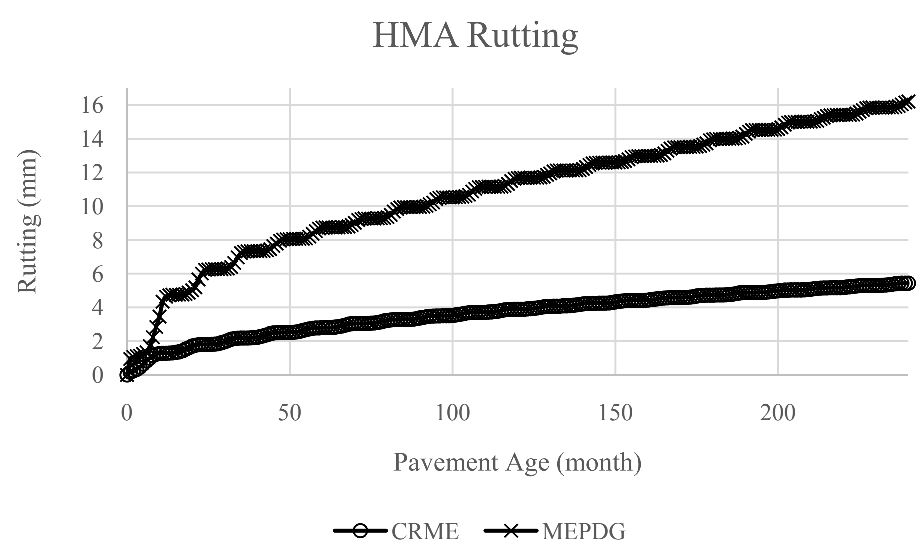

FIGURE 8 Predicted HMA rutting

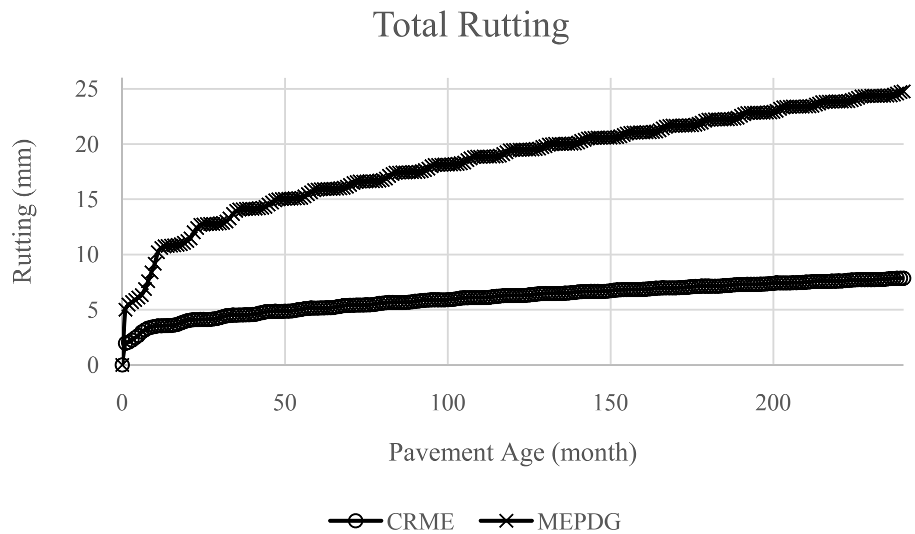

FIGURE 9 Predicted total rutting

CONCLUSIONS

With the implementation of the CRME design guide, Costa Rica looks to overcome the shortcomings of traditional empirical design methods. The possibility of performing detailed analysis considering mechanistic models will improve the use of resources, making it more efficient and at the same time more economical.

The development of the CRME implies a continuous improvement of the tool including more research. Further versions of the tool will be released to account for the results of different research related with material properties, damage development, and effect of moisture and aging.

CRME software includes mostly all the methodologies displayed in the AASHTO Mechanistical Empirical Pavement Design Guide (MEPDG), nevertheless, the Costa Rican Pavement Design Method bases its calculation on the monthly average, rather than the MEPDG, which computes for the predicted value for each month of the design life.

Differences found between the CRME and other methodologies were expected, since some models were calibrated for national conditions, and climate and traffic modules use different approaches. However, it is possible to conclude that the results obtained with the CRME are more representative of regional conditions.

REFERENCES

1. NCHRP 1-37A. *Guide for Mechanistic-Empirical Design of New and Rehabilitated Pavement Structures*. Final Report. Research Board of the National Academies, National Research Council, Washington, DC, 2004.
2. Zapata, C. E., Perera, Y. Y. andHouton, W. N. *Matric Suction Prediction Model used in the New AASTHO ME-PDG*. Transportation Research Record: Journal of the Transportation Research Board, Washington, DC, 2009.
3. Cary, C. E. and Zapata, C. E. *Enhancement of the model for resilient response of soils due to seasonal environmental changes implemented in the M-EPDG*. Transportation Research Record: Journal of the Transportation Research Board, Washington, DC, 2010.

4. Leiva-Villacorta, F., Aguiar-Moya, J. P. andLoría-Salazar, L. G. *Accelerated pavement testing first results at the LanammeUCR APT facility.* Transportation Research Board 94th Annual Meeting Proceedings, 2015.
5. Leiva-Villacorta, F., Vargas-Nordcbeck, A., Aguiar-Moya, J. P. andLoría-Salazar, L. G. *Development and Calibration of Permanent Deformation Models*.The Roles of Accelerated Pavement Testing in Pavement Sustainability. Engineering, Environment, and Economics, pp. 573-587.2016.
6. Leiva-Villacorta, F., Loría-Salazar, L. G. andCamacho-Garita, E. *Evaluating Nonlineartiy on Granular Materials and Soils Through the Use of Deflection Techniques.* The Roles of Accelerated Pavement Testing in Pavement Sustainability. Engineering, Environment, and Economics, pp. 111-129, 2016.
7. Loria, L. G., Badilla, G., Jimenez Acuna, M., Elizondo, F., and Aguiar-Moya, J. P. *Experiences in the Characterization of Materials Used in the Calibration of the AASHTO Mechanistic-Empirical Pavement Design Guide (MEPDG) for Flexible Pavement for Costa Rica*. Transportation Research Board 90th Annual Meeting,2011.
8. Aguiar-Moya, J. P., Corrales, J. P., Elizondo, F. andLoría-Salazar, L. G. *PaveLab and heavy vehicle simulator implementation at the National Laboratory of Materials and Testing Models of the University of Costa Rica*. Advances in pavement design through full-scale accelerated pavement testing, pp. 25-32, 2012.
9. Trejos-Castillo, C., Aguiar-Moya, J. P. and Loría-Salazar, L. G. *Desarrollo de software de análisis y diseño de pavimentos para Costa Rica.*Programa Infraestructura del Transporte (PITRA), LanammeUCR, 2016.
10. Huang, Y. H. *Pavement design and analysis*. Pearson/Prentice Hall, 2004.
11. Ulloa, Á., Badilla, G., Allen-Monge, J. and Sibaja-Obando, D. *Encuesta de Carga*. LanammeUCR, 2007.
12. Elizondo, F.; Ulloa, Á. and Badilla, G.*Predicción de módulos resilientes en mezclas asfálticas mediante el modelo de Witczak*. Infraestructura Vial, Vol. 10, no 3, 2007.
13. Leiva-Villacorta, F.; Loria-Salazar, L. G. and Aguiar-Moya, J. P. *Development of an Improved and More Effective Dynamic Modulus E* Model for Mixtures in Costa Rica by Means of Artificial Neural Networks*. Transportation Research Board 92nd Annual Meeting, 2013.
14. Zhao, Y. and Kim, Y. *Time-temperature superposition for asphalt mixtures with growing damage and permanent deformation in compression*. Transportation Research Record: Journal of the Transportation Research Board, no 1832, pp. 161-172, 2003.
15. Hu, X., Zhou, F., Hu, S., and Walubita, L. F. *Proposed loading waveforms and loading time equations for mechanistic-empirical pavement design and analysis*. Journal of Transportation Engineering, vol. 136, no 6, pp. 518-527, 2009.
16. Andrei, D., Witczak, M., Schwartz, C. and Uzan, J. *Harmonized resilient modulus test method for unbound pavement materials*. Transportation Research Record: Journal of the Transportation Research Board, 29-37, 2004.
17. Witczak, M. W., Zapata, C. E., & Houston, W. N. *Models incorporated into the current enhanced integrated climatic model: NCHRP 9-23 project findings and additional changes after version 0.7*. Final Report, Project NCHRP 9-23, 2006.
18. Leiva-Villacorta, F., Vargas-Nordcbeck, A., Aguiar-Moya, J. P. andLoria-Salazar, L. G. *Calibration of a Mechanistic-Empirical Fatigue Model Using the PaveLab Heavy Vehicle Simulator*.TransportationResearchBoard 95th Annual Meeting (No. 16-3509), 2016.
19. Aguiar-Moya, J. P. and Loria-Salazar, L. G. *Desarrollo de modelos de fatiga para capas asfálticas.* Revista de Infraestructura Vial, pp. 18-22. LanammeUCR, 2006.