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Designing long life pavements including eco-friendly ACs by means of the Mechanistic-Empirical approach

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Abstract

Two eco-compatible bituminous materials were analyzed as surface layers in two different structures under varying conditions. The pavement performances were simulated using the CalME design software with parameters obtained from Repeated Simple Shear Test and 4 Point Bending tests. The primary purposes of this study are to demonstrate the value of the eco-compatible mixes with regard to their mechanical performances and to examine the relations between their fatigue and rutting performances and the pavement structures. It was verified that the suggested asphalt thickness should correspond to a reliable pavement foundation when surface layers may suffer of stiffness and/or rutting deterioration.

Keywords: CalME; 4PB; Simple Shear Test; eco-compatible asphalt concretes

1. Introduction

Appropriate asphalt concrete characterization is essential for a realistic performance prediction of asphalt concrete pavements. Volumetric (mix design) and mechanical (rutting and fatigue) properties are important factors to evaluate. Rutting reduces the useful service of life of the pavement and, by affecting vehicle handling characteristics, creates serious hazards for highway users. This phenomenon in the asphalt concrete layer is caused by a combination of densification and shear deformation, each resulting from the repetitive application of traffic loads. Fatigue is the process by which the pavement deteriorates through cracking because of small built-up irrecoverable strains induced by repeated loading over time [1]. An ideal design method to integrate the laboratory characterization consists of a structural model capable of predicting the state of stresses and strains within the pavement structure under the action of traffic and environment.

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To carry out such analysis effectively, the design tool should be equipped with material models capable of capturing the mechanistic response of the various materials used to construct the road structure. Advances in computational mechanics have greatly improved the ability to predict pavement response to external actions, mainly because improved material characterization and constitutive models make it possible to incorporate nonlinearities, rate effects, and other realistic features of material behavior [2, 3].

The primary purpose of this research is to demonstrate, using the CalME design software, the dual value of the eco-compatible mix with regard to their environmental and mechanical performance. At the same time it is verified how the pavement structure influences the performance of these mixes in terms of stiffness deterioration and rutting resistance and how the surface layer choice can influence the weakening of mechanical properties of the pavement structure under varying traffic and weather conditions.

2. CalME Software description

In order to verify the mechanical validity of the two eco-compatible mixes and the reciprocal relationship between surface layer and pavement structure in terms of fatigue and rutting damage with defined traffic and environmental conditions, CalME was the application of choice (Mechanistic Empirical design program).

The University of California Pavement Research Center (UCPRC) has been supporting the effort of Caltrans to develop CalME and implement ME pavement design by working on a series of tasks since year 2000. The software includes three approaches to flexible pavement design, including the current Caltrans procedures based on the Hveem R-value, a “classical” ME method based on the Asphalt Institute method, and an Incremental-Recursive Mechanistic-Empirical (IRME) method in which the material properties for the pavement are updated in terms of damage as the pavement life simulation progresses.

The IRME design method, used in this study and based on the layered elastic theory, incorporates various mathematical models to describe and predict material and pavement performances. This procedure works with increments of time and uses the output from one increment, recursively, as input for the next increment. The procedure predicts the pavement conditions, in terms of layer moduli, crack propagation, permanent deformation and roughness, as a function of time, however it does not carry out an automatic design where the needed layer thicknesses to meet certain distress criteria at the end of the design life are determined. Inputs required for running CalME IRME design can be classified into the following groups: environment, structure and traffic (Fig. 1).

Environmental inputs include pavement temperature and effects of moisture variation and freeze-thawing on unbound layer stiffness. The temperatures at different depths of the pavement structure, over the simulation period, are first calculated. The temperature at the surface is read from the EICM database (with 30 years of data) and the temperatures at different depths are calculated using the surface temperature, a constant deep soil temperature and the prior temperatures. This is done using a 1-D Galerkin Finite Element formulation with a finite difference time step. Structural inputs include layer thickness and mechanical properties. Layer thicknesses are standard inputs for pavement design, while mechanical properties can be quite different for different types of materials. Note that Poisson’s ratio is assumed to be 0.35 for all materials unless otherwise specified. Mechanical properties of each AC layer are determined in CalME from: the stiffness master curve, the fatigue resistance, and the rutting resistance.

In this study a specific laboratory characterization, summarized in Table 1, was followed to define the model parameters of the materials. For the unbound materials instead, the mechanical properties typically include only stiffness and rutting resistance. In CalME unbound layers like aggregate base or subgrade are assumed to be nonlinear. Specifically, unbound layer stiffness decreases with weakening confinement from the layers above, which can be caused by damage in those layers and may either increase or decrease with increasing of load level. The permanent deformation (rutting), for the unbound layers, is based on the vertical resilient strain at the top of the layer and on the modulus of the material.

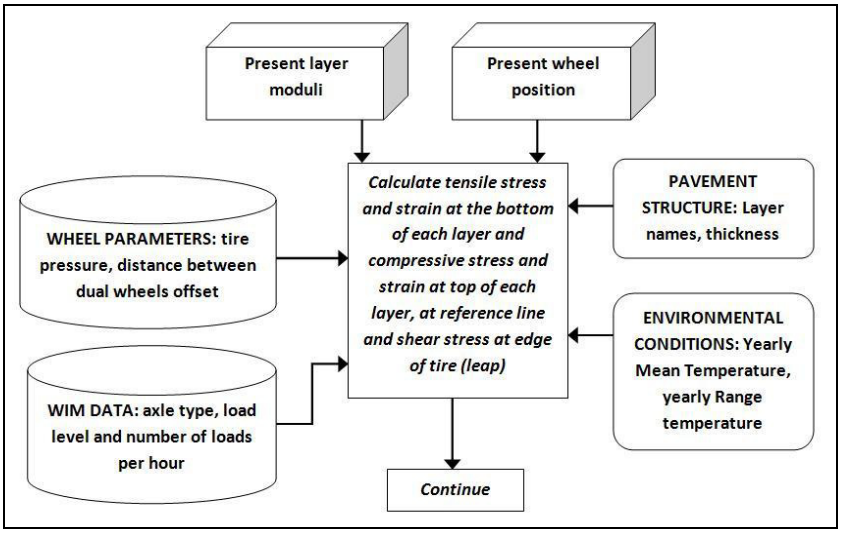

Fig. 1. Flow Chart of the Incremental Recursive procedure of CalME

Traffic inputs are defined by two components: traffic pattern and traffic volume. Traffic pattern defines the percentage of axle counts for any given axle type (steering, single, tandem and tridem), axle load (from 10 kN up to 250 kN), and hour of the day. Traffic volume defines the total number of axle counts for any given year, following exponential growth. Note that no seasonal or daily variation of traffic volume is considered by default, but it is possible to apply traffic volume adjustments for any given period.

Table 1. Standard set of laboratory tests to obtain the mechanical properties for each AC.

AC Property	Test Type	# of Specimens
Stiffness Master Curve	Beam Bending Frequency Sweep [4]	3Temps. x2 Replicates=6
Fatigue Resistance	Beam Bending Fatigue [4]	3Temps. x2 Strains x3 Replicates=18
Rutting Resistance	RSST-CH [5]	2Temps. x2 Stresses x3 Replicates=18

3. Models: pavements, traffic and environmental inputs

The pavement structures, to evaluate the structural performance as a function of different surface materials, are flexible with the same layers' thicknesses and two different subbase classes. The surface materials object of this study are a Gap Graded Rubber Asphalt Concrete (GGRAC), a Dense Graded Warm Mix Asphalt (DGWMA) and a Dense Graded Asphalt Concrete (DGAC) used as a comparison one. All of these mixes were characterized in the Pavement Research Center of the University of Berkeley and the modulus were modeled through a specific master curve [6].

The respective Fatigue Damage and Rutting models were extrapolated following the AC characterization suggested in Table 1. The base layer is a traditional Asphalt Concrete appropriately modeled like the previous asphalt mixes. The base is kept constant for all the studied pavement structures and its behavior was evaluated with CalME, varying the surface layers (GGRAC, DGWMA, DGAC). A stiff aggregate subbase with a resilient modulus of 500 MPa and a relatively weak one with 160 MPa were selected. The subgrade is also an unbound material modeled as a standard clay. The two pavement structures are listed below; according to Rolt [7] as the thickness of asphalt material is more than 180 mm, they can be expected to behave as LLP:

1. Surface course (60 mm), Base course (140 mm), Subbase 160 MPa (200 mm) and Subgrade 80 MPa,
2. Surface course (60 mm), Base course (140 mm), Subbase 500 MPa (200 mm) and Subgrade 80 MPa.

Three million of 80 kN ESALs per year and a 0% growth rate were selected as traffic inputs. Environmental conditions were selected as two climate zones: the San Francisco Bay Area and the California Central Valley. The yearly mean surface temperature for both areas are similar, but they differ in the yearly range. Consequently, the Bay Area is a colder area compared to the Central Valley during the summer and warmer during the winter (Tab. 2)

Table 2. Temperature characteristics of the two selected regions.

Climate Zone	Representative Site	Pavement Surface Temperature (°C)		
		Yearly Mean	Yearly Range	Daily Range
Central Valley	Sacramento	21	23	24
Bay Area	San Francisco	19	14	20

4. Simulations'results

4.1. Bay Area conditions

Based on all the defined inputs and the considered variables, it was proposed to run, for each surface layer type, one simulation for each pavement structure. The objective of the simulations was to compare fatigue damage and rut depth of the bituminous bound courses, as well as the total surface cracking and the total rutting depth. The failure criteria for total cracking and rutting were set, as acceptable limit values, to 0.5 m/m^2 and -10 mm respectively. Referring to the first pavement structure the results (Fig. 2), obtained with the three different course layers, show that DGAC is the first mix to exhibit cracking at the surface, followed by DGWMA, while GGRAC does not undergo this kind of damage. On the contrary, in terms of rutting performance, the latter has a lower resistance and fails at 2.58E+07 ESALs whereas the best performance is shown by DGAC that fails approximately at 5.80E+07 ESALs.

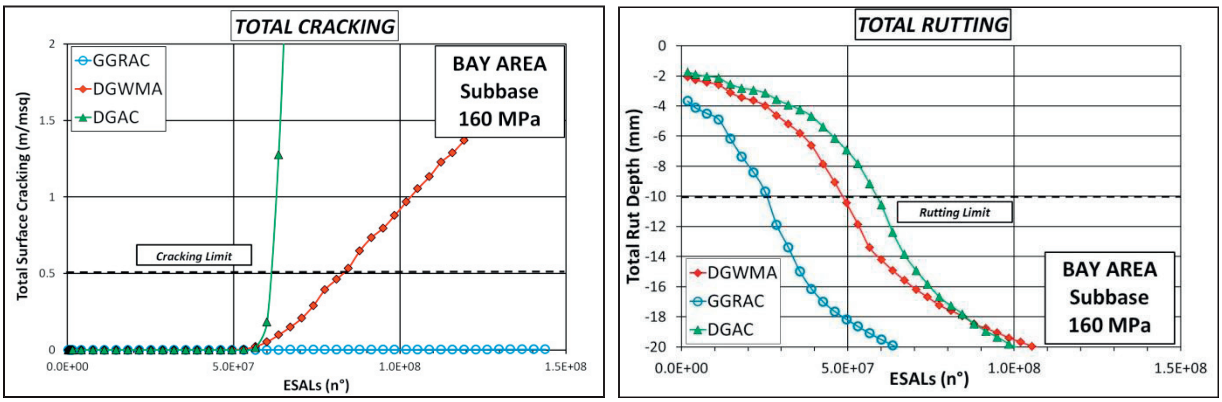

Fig. 1. Total Cracking (a) and Total Rutting depth (b) in Bay Area with softer Subbase.

Upon analyzing the behavior of the asphalt bound layers, it can be seen (Fig. 3 and 4) that the fatigue damage starts in the base layer and it then propagates to the wearing course layer. The GGRAC, being the softest material, exposes the base to higher stress and strain levels compared to the DGWMA and DGAC.

With the increasing of fatigue damage in the base layer, the pavement structure becomes weaker also in terms of rutting resistance as the material modulus drops. Here, the rut depth growth for each mix in both layers is evidently the concurrent appearance of both the actual material tensile and shear resistances decrease. It should also be noticed how, when the fatigue damage model for layer 2 reaches the maximum value of 0.9, the corresponding rutting depth model suddenly stops the rut evolution and the pavement is considered failed. The surface cracking line – dotted line at 0.4 in figure 3 – defines the magnitude of fatigue damage generated in the surface layer, that corresponds to the pavement surface cracking limit of 0.5 m/m^2 (dotted line in figure 2).

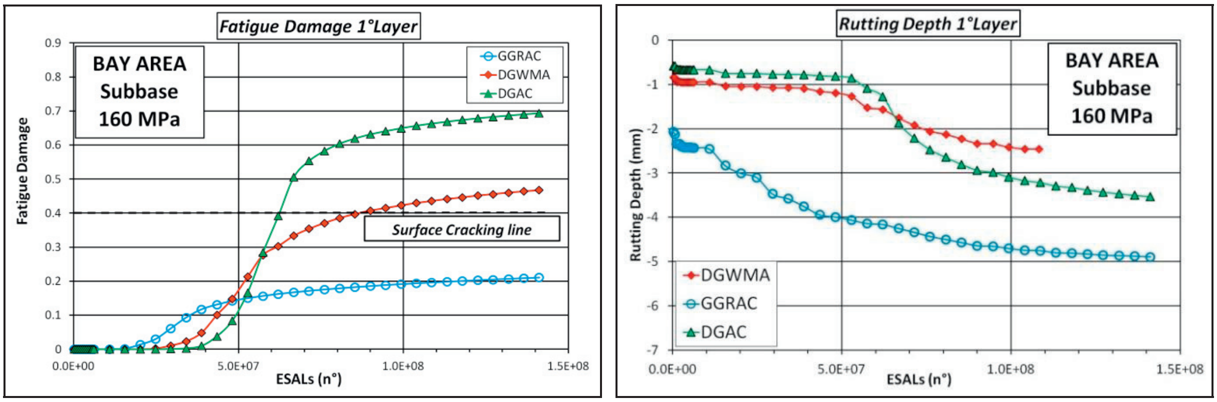

Fig. 3. Fatigue damage (a) and Rut depth (b) in the first layer with the first pavement structure.

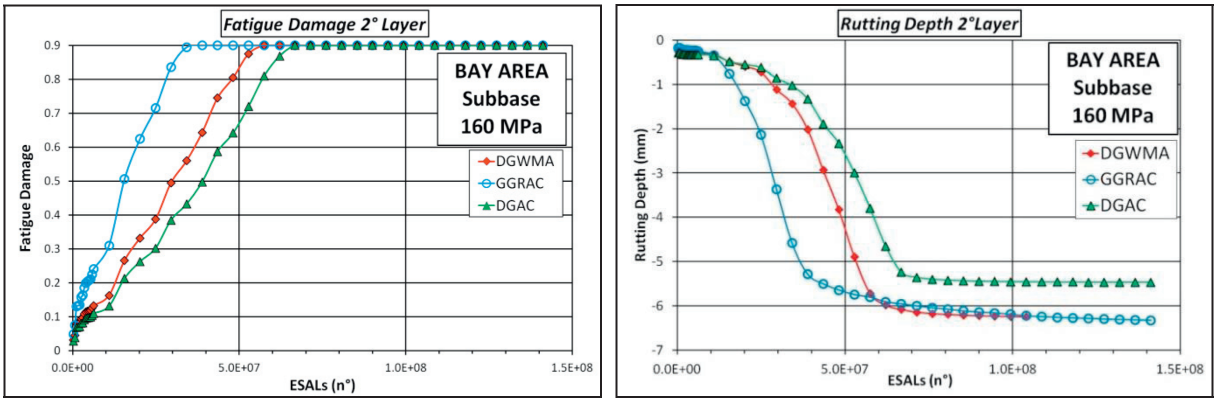

Fig. 4. Fatigue damage (a) and Rut depth (b) in the second layer with the first pavement structure.

The performance of the second pavement structure is different from the first one and the fatigue and rutting behavior of each layer is improved. The stiffer subbase reduces the strain level at the bottom of the AC base layer decreasing the damage rate and, consequently, increasing the expected life. Furthermore, there is no development of surface cracking, while rutting is under the limit criteria (Fig. 5). With a 500 MPa subbase, the pavement with GGRAC still exhibits more rutting than the other structures. Upon checking the fatigue damage for each bound layer, it is possible to justify the following: the damage in the first layer is close to zero for all the studied pavements; this is mainly verified because the fatigue damage in the base layer does not exceed 0.4-0.5 (Fig. 5).

As for the permanent deformations, approximately 50% of the total rut depth comes from the unbound materials of the subbase and subgrade, while the total rut depths for the only AC layers is mainly due to the first layer. In fact, the base layer for the three surface layers structures shows the same rut depth trend with a maximum of 1 mm at the end of the simulations.

Therefore, the largest amount (around 65%) of the difference in the total rut depth comes from the surface layer. DGAC and DGWMA exhibit the same behavior with a larger resistance to rutting damage if compared to GGRAC that, because of its reduced stiffness, evidently weakens the overall structural performance of the modeled pavement (Fig. 6).

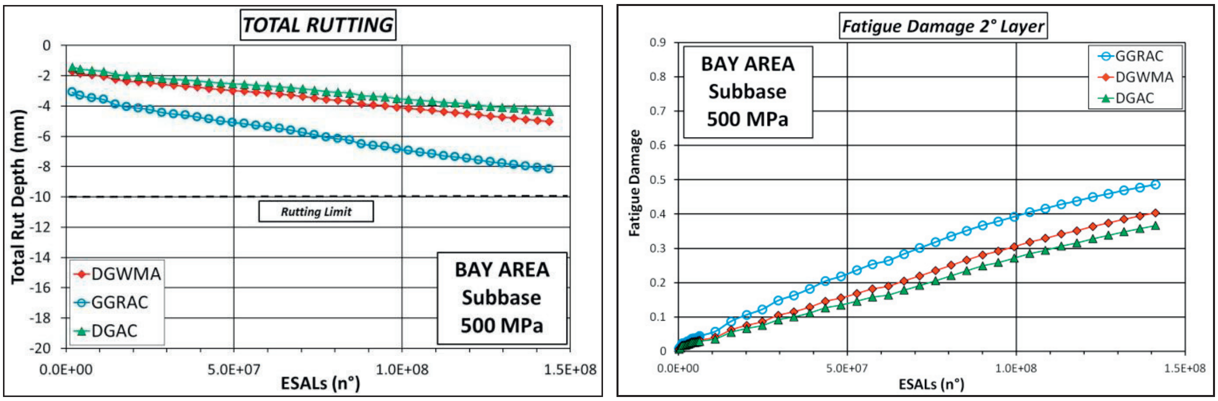

Fig. 5. Total Rut depth, no surface cracking (a); Fatigue damage in the second layer, no fatigue damage in the first (b).

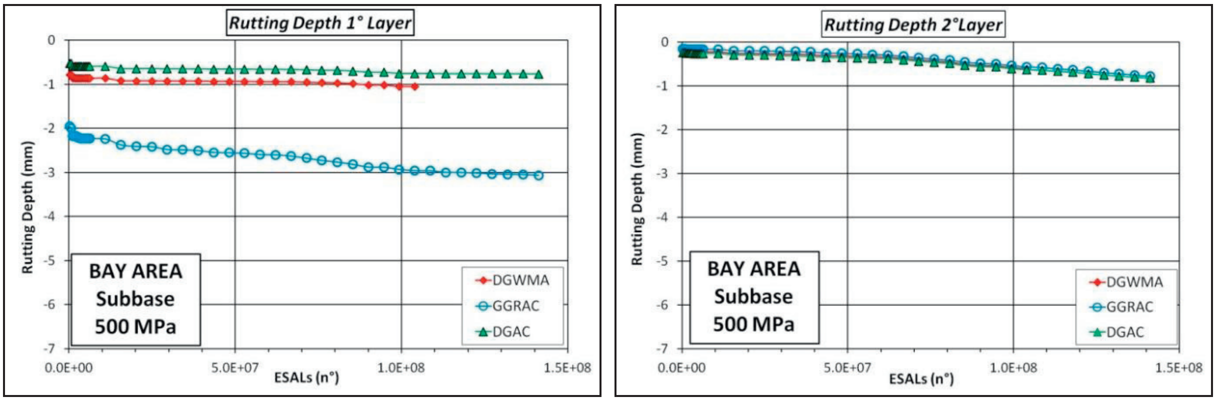

Fig. 6. Rut depth in the first (a) and second layer (b) with the second pavement structure.

4.2. Central Valley conditions

The Central Valley environment, with its higher yearly temperature ranges, tends to significantly affect the pavement behavior. Considering the first pavement structure, the combination of a weaker subbase and higher temperatures contributes to an increase of strains in the asphalt bound layers for all the simulations.

Figure 7 reports the evolution curves of total cracking and rutting for each pavement with different surface layers.

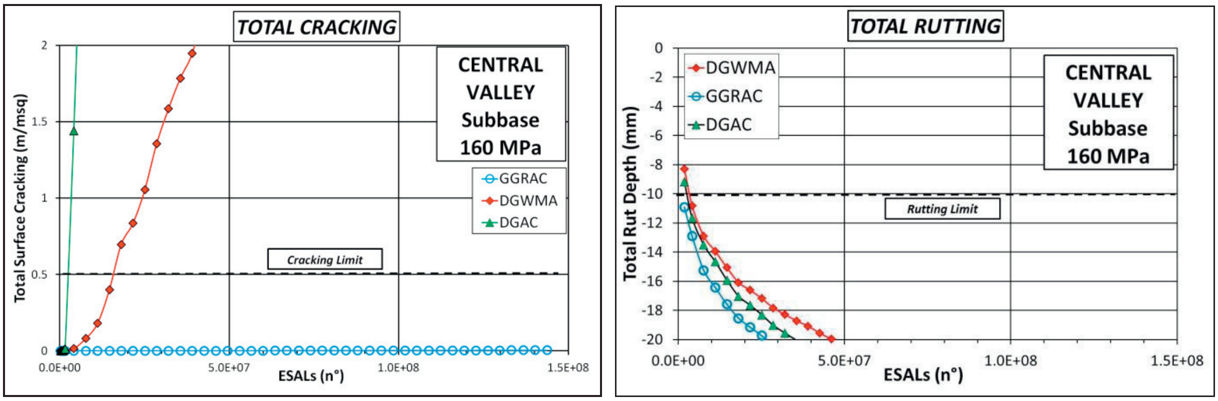

Fig. 7. Total Cracking (a) and Rutting (b) in Central Valley with softer Subbase.

The cracking performances of the pavements with the three mixes are completely different. In particular, for the given pavement structure, the DGAC seems to suffer more the stronger climate conditions. The DGWMA resists longer, while the GGRAC is the only mix without evident surface cracking. The higher flexibility of GGRAC enables the mix to have better fatigue resistance, but it compromises its permanent deformations performance.

Figure 8 represents the fatigue damage and rutting depth curves of the wearing course. According to the global pavements behaviour, in the structures with DGAC and DGWMA damage develops quickly in the first layer, while the GGRAC layer slowly approaches a damage of 0.2. Rutting of this layer follows the total rutting trend with the DGWMA course showing the best performance.

The second layer of each pavement (Fig. 9) reveals the reasons of the total cracking and total rutting failures: the base layer is damaged within 2 million ESALs and, consequently, the layer modulus is abated and the rutting curve drops, following the full fatigue damage of the layer. The approximately constant value of rut depth after failure is due to the rutting modelling within CalME. The surface total cracking of the GGRAC pavement describes that the first layer is not cracked, while the second is fully damaged.

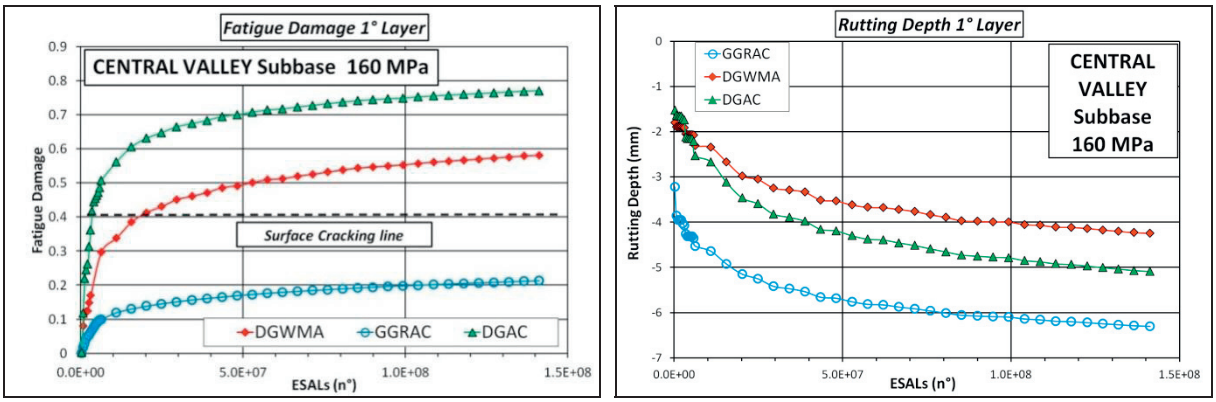

Fig. 8. Fatigue damage (a) and Rut depth (b) in the first layer with the first pavement structure in Central Valley.

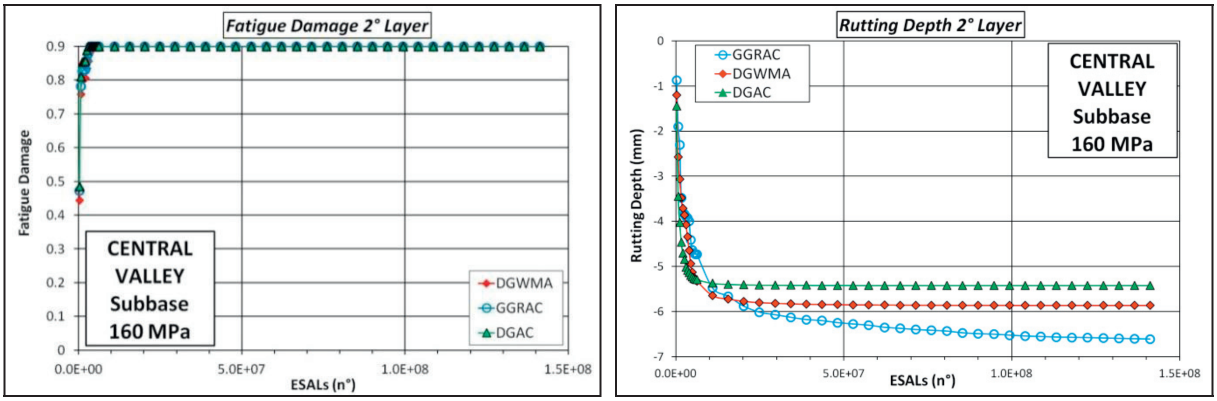

Fig. 9. Fatigue damage (a) and Rut depth (b) in the second layer with the first pavement structure in Central Valley.

The situation is completely different considering the second pavement structure. Comparing the results obtained for the first, the presence of a stiffer subbase contributes to the conspicuous increase in the cracking and rutting performance of all the pavement solutions. After 1.10E+08 ESALs, cracking is seen with DGAC on the surface, while both DGWMA and GGRAC succeed to contain the effect of the fatigue damage (Figure 10). As in the first simulations, the total rutting trend is similar for all the pavements, but the GGRAC structure reaches the limit before the other pavements.

The fatigue damage in the first layers (for all three mixes) increases slowly during the first 3.00E+07 ESALs until the base fatigue damage is kept under the limit value of 0.4. When the damage of the second layer exceeds this point, the strain level at the bottom of the surface layer increases and, with that, the damage in the layer itself.

The DGAC layer is more damaged than other surface layers, being the only one with final surface cracking due to the fatigue damage in the first layer. DGWMA reaches a fatigue damage value of 0.2, while GGRAC stays below 0.1. With this pavement and climate configurations the less fatigue and rutting damaged base is the one of the pavement structure with GGRAC at the surface (Fig. 12).

The rut depth results confirm that rutting comes mainly from the unbound subbase and subgrade and that the pavement structure with a GGRAC wearing course is more prone to accumulate permanent deformations in the top layer itself (Fig. 11).

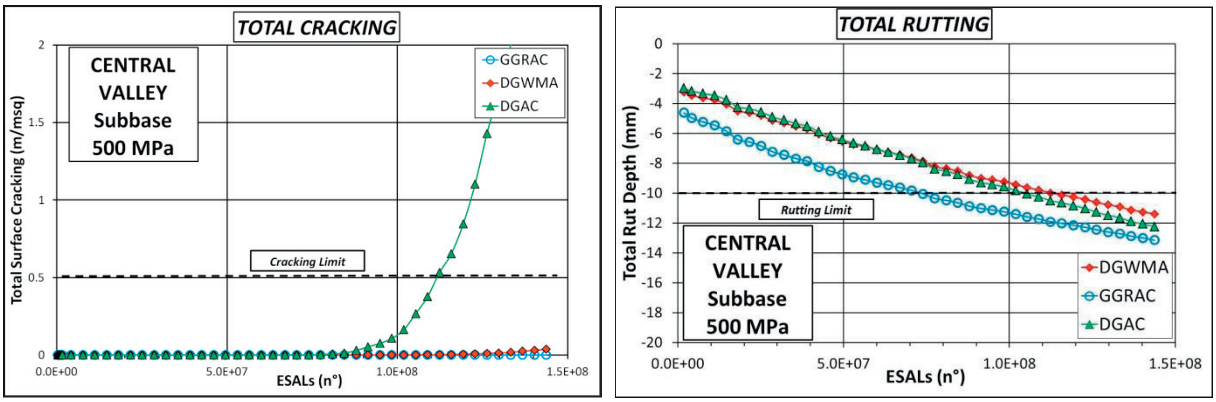

Fig. 2. Total Cracking (a) and Rutting (b) in Central Valley with stiffer Subbase.

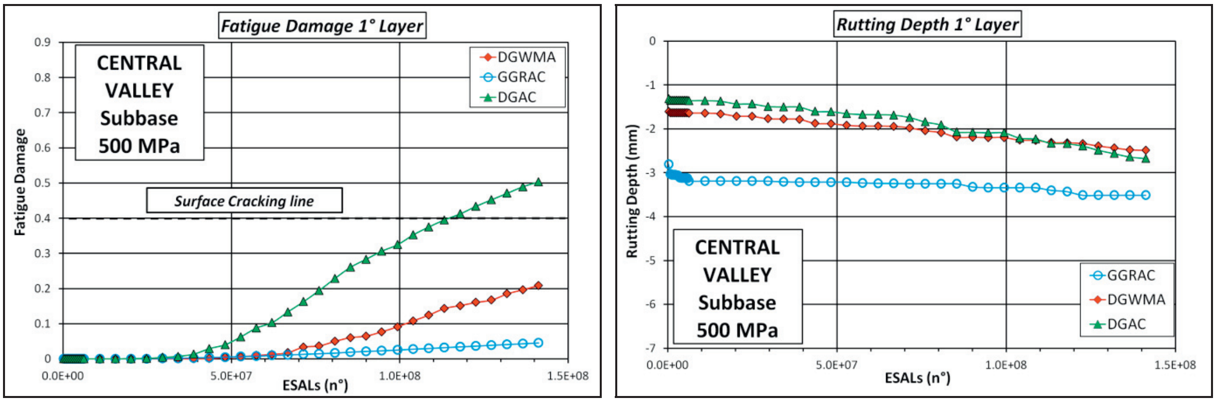

Fig. 11. Fatigue damage (a) and Rut depth (b) in the first layer with the first pavement structure in Central Valley.

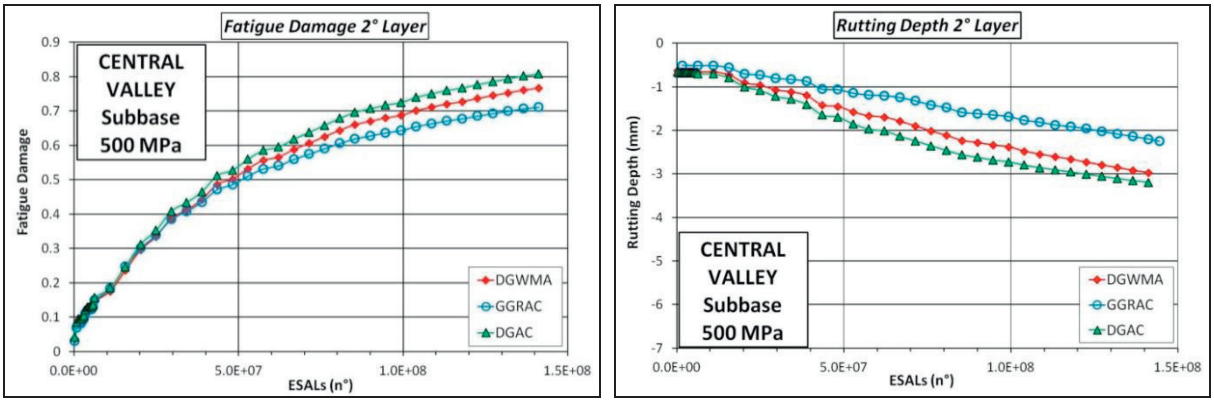

Fig. 12. Fatigue damage (a) and Rut depth (b) in the second layer with the second pavement structure in Central Valley.

5. Results' summary

Table 3 and Figure 13 summarize the simulation results both for the studied pavement structures and environmental conditions. The cracking and rutting performances were normalized to provide an easier interpretation of the behavior in each different scenario. The normalization criteria is based on the attainment of the end of simulations (1.44E+08 ESALs), without failures in terms of total cracking and rutting. The overall view of the simulation results helps into state that the subbase stiffness and climate conditions are highly influencing the calculations. The best performance for all the materials is in the Bay Area models with the stiffer subbase. In this case the pavements with the considered surface layers demonstrate satisfactory performance without reaching neither rutting, nor fatigue limit.

Focusing on the Central Valley with the same pavement structure the broader temperature ranges modify the performance of all the studied mixes reducing their rutting resistance. However, in terms of fatigue performance, there is no reduction for GGRAC and DGWMA pavements, as opposed to the traditional mix one.

With regard to the weaker subbase, the overall performance in the Bay Area is drastically decreased. The DGAC pavement has the best resistance in terms of permanent deformations, while the GGRAC one confirms the limited surface cracking of the top layer, even if the base suffers in damage most likely because of its insufficient thickness.

In the Central Valley simulations, the weaker subbase reduces rutting resistance independently from the kind of surface layer, whereas with regard to crack propagation the model of the GGRAC layer confirms its strength in limiting the surface emersion of damage.

The CalME modeling considers the development of surface cracking when the surface layer undergoes a certain amount of bulk fatigue damage and does not fully consider the propagation of bottom up cracks from a failed base course.

Table 3 Cracking and rutting results in ESALs and normalized

	Environment	Subbase Stiffness	Fatigue	Rutting				
			DGAC	GGRAC	DGWMA	DGAC	GGRAC	DGWMA
ESALs	Bay Area	160	6.21E+07	1.44E+08	8.30E+07	5.86E+07	2.58E+07	4.90E+07
		500	1.44E+08	1.44E+08	1.44E+08	1.44E+08	1.44E+08	1.44E+08
	Central Valley	160	3.30E+06	1.44E+08	1.70E+07	2.80E+06	1.60E+06	3.50E+06
		500	1.10E+08	1.44E+08	1.44E+08	1.04E+08	7.40E+07	1.14E+08
Normalized by 1.44E+08	Bay Area	160	0.431	1.000	0.576	0.407	0.179	0.340
		500	1.000	1.000	1.000	1.000	1.000	1.000
	Central Valley	160	0.023	1.000	0.118	0.019	0.011	0.024
		500	0.764	1.000	1.000	0.722	0.514	0.792

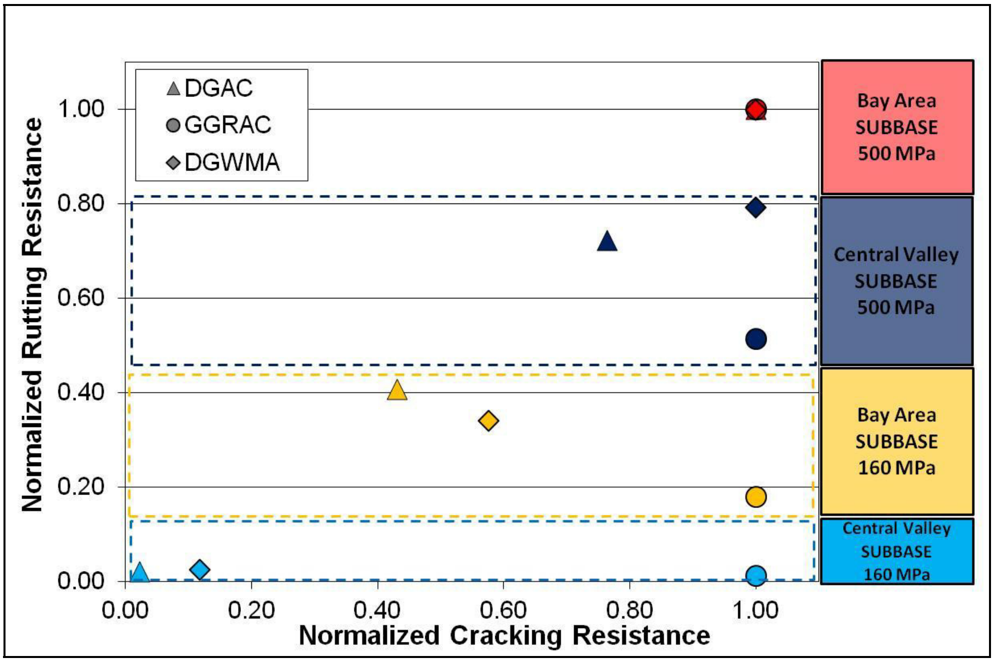

Fig. 13. Normalized cracking and rutting resistance in both environmental conditions and pavement structures.

6. Conclusions

The combination between the laboratory characterization of bituminous materials and the Mechanistic Empirical design method provides the opportunity to analyze the asphalt concrete performances under two different perspectives. With the laboratory characterization the distinct resistance of materials to fatigue damage and rutting is assessed by means of established test procedures that directly provide the calibration of the modeling parameters [8].

On the other hand, the CalME Recursive method combines the material models joining the effects of climate and traffic to the structural properties of the pavement and iteratively adjusts the damage conditions of each layer superimposing the effects of each damage model. In this sense the use of CalME could be considered part of the preliminary material characterization for design purposes.

It has been shown that with a proper laboratory characterization, the behavior of eco-friendly bituminous materials can be successfully modeled with CalME. It is also evident that CalME is able to represent the reciprocal interaction between the selected surface layer and the pavement structure itself. The pavement design is refined adjusting layer thicknesses and required stiffness in order to minimize and balance the fatigue damage and rutting resistance of each layer. In order to achieve a durable structure, for instance a Long Life Pavement, the sufficient bearing capacity of foundation and base layers is as important as the correct modeling of climate sensitivity of materials through all the years of service. In fact, the simple variation of the daily and yearly temperature ranges and of the subbase stiffness drastically changes the simulations' results of the modeled pavements and forces the resistance characteristics of the wearing course materials to emerge. It is also interesting to see how fatigue and rutting damages are correctly associated and represented in the simulations, as well as the same damages are consistently modeled for the correspondent first and second layers of each pavement.

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References

[1] Sousa, J. B., Craus, J. & Monismith C. L. (1991). Summary Report on Permanent Deformation in Asphalt Concrete, Report SHRP-A/IR-91-104, SHRP, National Research Council. Washington, D.C.

[2] Carvalho L. & Schwartz C.W. (2007). Comparisons of Flexible Pavement Designs AASHTO Empirical Versus NCHRP Project 1-37A Mechanistic–Empirical, TRR: Journal of the Transportation Research Board s, Vol. 1947/2006, Washington, D.C., p.167-174.

[3] Dondi, G., Simone, A., Vignali, V., & Manganelli, G. (2012). Numerical and experimental study of granular mixes for asphalts. Powder Technology, 232, pp. 31–40.

[4] AASHTO T320. (2007). "Standard Method of Test for Determining the Permanent Shear Strain and Stiffness of Asphalt Mix using the Superpave Shear Tester (SST)", AASHTO, US.

[5] AASHTO T321-1. (2007). "Standard Method of Test for Determining the Fatigue Life of Compacted Hot-Mix Asphalt (HMA) Subjected to Repeated Flexural Bending", AASHTO, US.

[6] Pettinari, M., Sangiorgi, C. & Dondi, G. (2012). Fatigue resistance of Warm Mix Asphalt and Rubber Asphalt Concrete with the Dissipated Energy Approach, accepted for MAIREPAV7 Proceedings, Auckland, New Zealand.

[7] Rolt, J. (2001). Long-life pavements. The World Bank Regional Seminar on Innovative Road Rehabilitation and Recycling Technologies, Amman, Jordan, 24 - 26 October 2000, PA3736/01.

[8] Cocurullo A., Airey G.D., Collop A.C., Sangiorgi C. (2008). Indirect Tensile versus Two Point Bending Fatigue Testing. ICE Transport, 161, pp. 207-220.