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Performance evaluation of eco-friendly asphalt concretes using the simple shear and 4p bending tests

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Abstract

A Warm Mix Asphalt (WMA) and a Rubberized Asphalt Concrete (RAC) have been compared with a traditional Hot Mix Asphalt Concrete through the use of a specific software called *CalME*, developed for Caltrans. The required performance models' parameters have been inferred from the laboratory characterization of those materials through the use of the Superpave Simple Shear Constant Height Test (SST) and the 4 Point Bending Fatigue Test (4PB). The difference between these two materials flatly arises from their simulated rutting and fatigue behaviours. This research was partially undertaken at the Pavement Research Center of Berkeley (California).

Keywords: 4PB, Simple Shear Test, Warm Mix Asphalt, *CalME*.

1. Introduction

The "sustainability" concept is relatively new and has already proved useful. Sustainability relates to the prolonging of human economic systems with as little detrimental impact on ecological systems as possible. One such method of sustainability in the pavement design and asphalt industry is using eco-compatible materials and design processes able to guarantee the quality of the final product with minimal environmental costs and low pollution levels. An environmental design method cannot be solely based on eco-compatible materials, but must be supported from an appropriate characterization of these materials and from design methods able to estimate the long term behavior with different external conditions. Warm Mix Asphalt (WMA) and Rubberized Asphalt Concrete (RAC), belonging to that materials' class, are the central topics of discussion in this study.

Warm asphalt has gained increasing popularity in the recent years for its versatile properties. The benefits of using this eco-compatible material are mainly the reduction in energy consumption and emissions during production and placement. There are also several other advantages of using warm asphalt, for instance, longer

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paving 'seasons', longer hauling distances, reduced wear and tear of the plants, reduced ageing and oxidative hardening of binders, and thus reduced cracking in the pavement and ability of opening the site to traffic sooner. With the availability of several proprietary chemicals and processes to produce warm asphalt, it is now possible to produce it without affecting the mechanical properties of the mix [1].

On the other hand, the use of crumb-rubber modifier (CRM) in hot-mix asphalt (HMA) can be traced back to the 1840s when natural rubber was first introduced into bitumen to increase its engineering performance. Since the 1960s, researchers and engineers have used shredded automobile scrap tires in HMA mix for pavements. This has been in use in the United States since the mid 1980s and has proven to be an environmentally friendly alternative to conventional asphalt pavements. The use of waste tires is not only relevant in an environmental aspect, but also for the engineering properties of the new asphalt [2]. Based on various research reports, the addition of crumb rubber from tires has improved the flexibility, durability, temperature susceptibility and road noise attenuation.

The use of WMA and RAC is the first phase towards an eco-compatible design, but cannot be the only step. The eco-compatible approach should be extended also to the design method and to the material characterization because only with these phases is it possible to exploit the maximum potential properties of the used materials.

The Simple Shear and Flexural Fatigue Beam Tests are used to characterize respectively, the permanent deformation and fatigue response of each mix.

2. Laboratory Characterization

2.1. Mixtures and Tests

Three kinds of asphalt concrete were studied in this research:

- Dense-Graded Warm Mix Asphalt (DGWMA);
- Gap-Graded Rubberized Asphalt Concrete (GGRAC);
- Dense-Graded Asphalt Concrete (DGAC).

DGWMA and GGRAC are considered eco-compatible mixes, designed with modified binder, and are the main focus of this study, while DGAC, a mix with unmodified asphalt, was used as reference.

The aggregate source of the DGAC and GGRAC was Franciscan Greywacke, a variety of sand stone, with a blend of sand, while the aggregate for the DGWMA was mainly Granite. The gradations were developed following the Caltrans Standard Specifications 2006, Section 39, and are graphically represented in Figure 1.

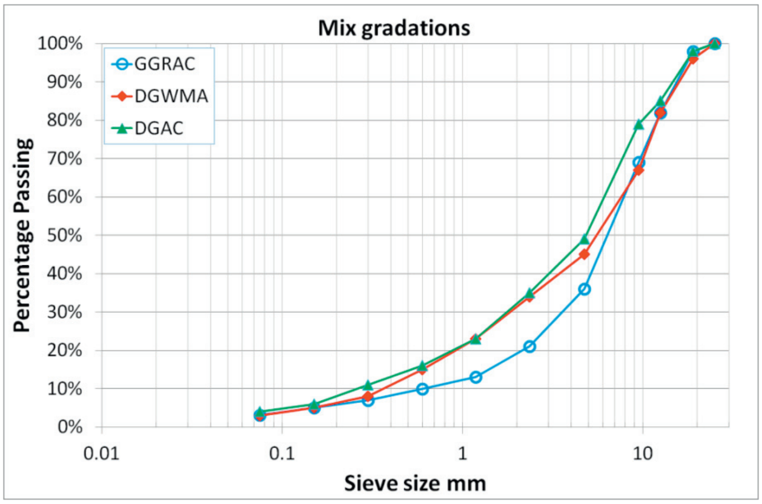


Fig. 1. Gradation curves of DGWMA, GGRAC and DGAC

Both DGWMA and DGAC were dense graded mixes, while GGRAC was gap graded for the reason that this gradation generally performed better than dense graded mixes if used as surface layers thinner than 60 mm [3]. With regard to the bound phase in Table 1, the asphalt characteristics were described as follows:

Table 1. Binder characteristics

Material	Asphalt Specific Grade	Additive (2)	Asphalt design content (3)	Production Temperature
DGWMA	PG 64-10 (1)	Warm Modify 1.5%	5.2%	135°C
GGRAC	PG 64-16	Rubber Modify 7.0%	7.2%	180°C
DGAC	PG 64-16	Unmodified	5.0%	165°C

(1)PG 64-16 binder supplied as PG 64-10 (2) directly blended with binder, percent referred by mass of binder (3)Percent referred by mass of aggregates

Cores and specimens for the mechanical characterization were laboratory mixed and compacted. The volumetric properties in terms of target and average air voids content are summarized in Table 2.

Table 2. Target air voids content compared to effective air voids content for the 3 mixes.

Material	Target Air Voids%	Average Air Voids Content %	
		Shear cores	Fatigue&Frequency Beams
DGWMA	6.5	8.1±0.6%	6.9±0.6%
GGRAC	6.0	6.0±0.4%	5.8±0.3%
DGAC	6.0	6.0±0.3%	6.2±0.3%

A total of 42 specimens, consisting of 24 beams and 18 cores, for each mix, were produced for testing (Table 3). Regarding the beams, six were tested with the frequency sweep procedure to estimate the complex modulus master curve. In order to define the fatigue resistance of each asphalt mix, 18 beams were tested using the Fatigue Four Point Bending test. Evaluation of the applied strain and resulting fatigue life was made to fit regressions to predict the fatigue performance of each mix [4, 5, 6].

For the Repeated Simple Shear Test at Constant Height (RSST-CH) 18 cores were tested. The damage produced from shear stress induced rutting. Using this test, it is possible to specify the rutting performance parameters. The Master Curve together with the Fatigue and Rutting performance model parameters, obtained from a comprehensive laboratory characterization, represent the key input for the Mechanistic Empirical design method. On-going studies evaluate the effects of aggregate shape on rutting for the same materials [7].

Table 3. 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 (AASHTO TP 321)	3T(1) x2 Replicates=6
Fatigue Resistance	Beam Bending Fatigue (AASHTO TP 321)	3T(1) x2 Strains x3 Replicates=18
Rutting Resistance	RSST-CH (AASHTO TP 320)	2T(1) x2 Stresses x3 Replicates=18

(1)Temperature

3. Master Curve model using Mechanistic Empirical method

The complex modulus master curve is obtained from Flexural Controlled-Deformation Frequency Sweep Tests following the modified AASHTO T-321 (2007) [8]. To ensure that the specimen is tested in a non-destructive manner, the frequency sweep test is conducted at a small strain amplitude level (100 με). For each mix six specimens are analysed, two at each temperature (10, 20 and 30°C), and at the following loading frequencies: 15, 10, 5, 2, 1, 0.5, 0.2, 0.1, 0.05, 0.02 and 0.01 Hz. The upper limit of 15 Hz is a constraint imposed by the testing machine; the general principle for testing is to run the specimen from high to low loading frequencies.

The master curve describes the variation of modulus with temperature and loading time for intact asphalt materials. It is a critical input for flexible pavement design and it is modelled in *CalME* via equation (1) [9]:

$$\log(E) = \delta + \frac{\alpha}{1+exp(\beta+\gamma\cdot log(tr))} \tag{1}$$

where:
E is the modulus in MPa,
tr is the reduced time in seconds,
α, β, γ and δ are constants, and logarithms are to base 10.

The reduced time is:

$$tr = lt \cdot \left(\frac{visc_{ref}}{visc}\right)^{\alpha T} \tag{2}$$

where:
lt is the loading time (in seconds),
$visc_{ref}$ is the binder viscosity at the reference temperature,
$visc$ is the binder viscosity at the present temperature, and
αT is a constant.

It should be noted that δ in equation (1), is typically fixed at 2.30, indicating a single value for a minimum stiffness of 200 MPa. Moreover, in the calculations described, a fixed value of 0.35 for the Poisson's ratio has been used. To fit the *CalME* master curve model (1) to the flexural frequency test, it is necessary to identify the four parameters α, β, γ and aT by reducing the root mean square of the difference between the measured and the calculated data. All the remaining parameters are considered constant or indirectly determinable using the first four. The summary of the fitting results are provided in Table 4:

Table 4. Master curve parameters of the 3 asphalt concrete mixes

Material	δ	β	γ	αT	A	VTS	$E_{ref}(MPa)$	Tr_{ef}°C	α
DGWMA	2.3010	0.0261	0.7422	1.0086	9.6307	-3.5047	5319	20	1.8025
GGRAC	2.3010	1.5242	0.6307	1.4139	9.6307	-3.5047	1297	20	1.9923
DGAC	2.3010	-0.5442	0.7991	1.1985	9.6307	-3.5047	8592	20	1.8537

According to the existing literature, the parameters describing the viscosity of the binder were chosen as A=9.6307 and VTS=-3.5047, for all the master curves. Figure 2 compares the modulus versus reduced time for the asphalt concrete materials.

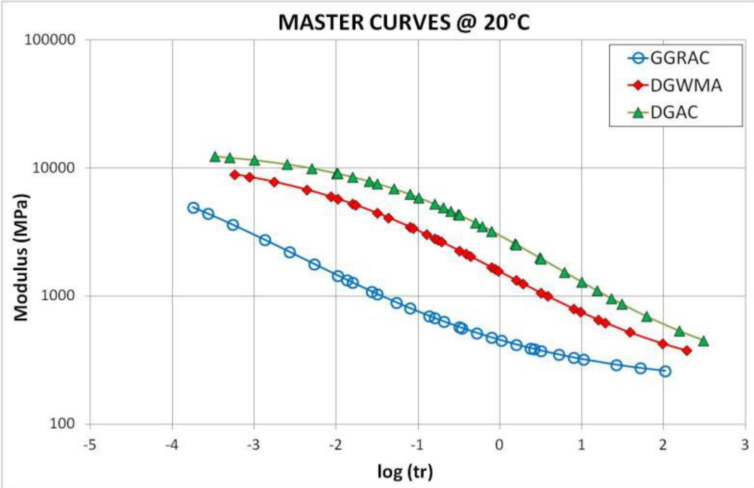


Fig. 2. Comparison of modulus versus reduced time for different asphalt concretes

Upon analyzing the results and the relative master curves the following observations can be made:

- For any value of frequency analyzed the DGAC mix has the highest modulus and the GGRAC the lowest.
- As reported in Table 4, considering the reference temperature of 20°C at -1.9 log(tr), the stiffness modulus of DGAC is 8591 MPa, DGWMA is 5319 MPa while GGRAC is 1297 MPa, one seventh of the DGAC modulus.
- The complex modulus of each master curve reduces as the log(tr) increases. The curve shapes are generally upwardly concave. The only exception is the master curve of the DGAC mix, which is "S" shaped as it happens with traditional asphalt mixes. The GGRAC curve is markedly insensitive to the variation of frequencies.
- For DGAC and DGWMA mixes, the master curves are well above the gap-graded master curve. This could imply that binders with dense gradations will have potentially improved resistance to rutting, but reduced fatigue-resistance.

4. Shear performance model using Mechanistic Empirical method

All The permanent deformation performances of the 3 mixes are determined with the Repeated Simple Shear Test at Constant Height (RSST-CH) developed by the Pavement Research Center (PRC) for the well-known Strategic Highway Research Program (SHRP). Each specimen, 150 mm in diameter and 50 mm in height, had cut surfaces on the top and bottom as well as on the vertical face. The RSST-CH was performed at two temperatures, 45°C and 55°C, and with three different shear stress levels, 70, 100 and 130 kPa. For calibrating the parameters of the performance model, 18 specimens were tested for each mix (three replicates for each temperature and stress level) [9]. The applied shear load is an haversine wave with a loading time of 0.1 seconds and a resting period of 0.6 seconds while the axial load is applied to prevent the specimen from changing height.

Rutting in asphalt is assumed to be controlled by the material shear deformation tendency [11]. The adopted rutting estimation uses the measured values of shear stress, τ, elastic shear strain, γ_e, and the number of load repetitions from RSST-CH in the laboratory. A shear-based approach, developed by Deacon [12] for predicting the rutting of the asphalt layer (3), was used as performance model in this research to foresee the permanent deformation behaviour.

According to that approach, the rutting in the asphalt concrete layer due to the shear deformation is determined from the following:

$$rd_{AC} = k \cdot \gamma_p \cdot h \tag{3}$$

where:
rd_{AC} is the vertical rut depth in the asphalt concrete (mm),
γ_p is the permanent (inelastic) shear strain at 50 mm depth,
k is a value relating permanent shear strain to the rut depth (mm), and
h is the thickness of asphalt concrete layer in millimeters.

The permanent shear strain may be calculated with equation (4) and (5):

$$\gamma_p = \exp\left(A + \alpha \cdot \left[1 - exp\left({-\ln(N)}/{\gamma}\right) \cdot \left(1 + {\ln(N)}/{\gamma}\right)\right]\right) \cdot exp\left({\beta \cdot \tau}/{\tau_{ref}}\right) \cdot \gamma_e \tag{4}$$

where:
τ is the shear stress (MPa) determined at a certain depth using the elastic analysis,
γ_e is the corresponding elastic shear strain (m/m),
N is the equivalent number of load repetitions, which is the number of load repetitions at the stress and strain level of the next time increment to reach the permanent shear strain calculated at the end of the current time increment, and
A, α, β, γ, and τ_{ref} are constants.

$$\gamma_e = \frac{\tau}{2 \cdot G_i} = \frac{\tau}{E_i/(1+\upsilon_i)} \tag{5}$$

where:
G_i is the shear modulus (MPa) of layer i,
E_i is the modulus (MPa) of layer i, and
v_i is the Poisson's ratio for layer i.

Similar to the master curve, the fitting of the RSST-CH data with the Permanent Deformation performance model (3) is obtained by resolving the parameters A, α, β, γ, k, and τ_{ref} minimizing the root mean square between the measured and calculated permanent deformations. The Rutting Performance Model parameters for the three materials are listed in Table 5.

Table 5. Rutting Performance Model parameters of the three mixes

Material	β	γ	A	k	τ_{ref} (MPa)	α
DGWMA	0.04759	2.54833	1.00874	1.4	0.10	2.94491
GGRAC	0.23406	2.78198	0.49967	1.4	0.10	3.12836
DGAC	0.19173	2.93973	0.82193	1.4	0.10	2.82332

CalME simple simulations were run to compare the three Rutting Performance models calibrated for the tested asphalt mixes. A single layer pavement structure with the load configuration shown in Table 6 was considered at 40°C and 50°C (Figure 3). The asphalt layer was conveniently modelled over an infinitely deep Aggregate Base foundation.

Table 6. Conditions used for the comparison of the Performance Models

Pavement Conditions			Load Conditions		
AC Thickness (mm)	AB Modulus (MPa)	Poisson's ratio	Load (kN)	Tire Pressure (MPa)	Wheel axis distance (mm)
150	300	0.35	60	0.7	350

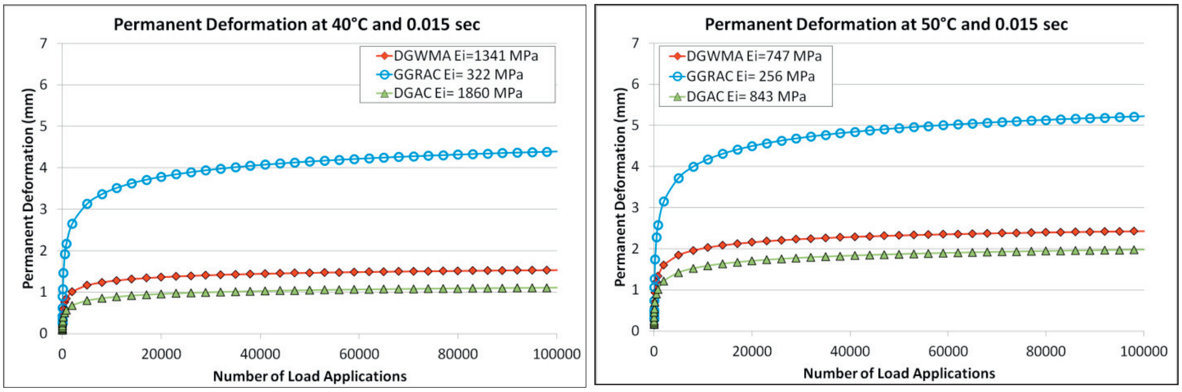


Fig. 3. Rutting Performance models of the three asphalt mixes at (a) 40°C and (b) 50°C (0.015 s = 10 Hz)

Figure 3 presents the simulations results of permanent deformations versus load applications for the 3 mixes compared in a simple loaded pavement; accordingly, the following observations were made:

- For all mixes, most of the total permanent deformation was accumulated before 5000 repetitions.
- The GGRAC is far more susceptible to shear stresses if compared to DGAC and DGWMA. Moreover, the permanent deformation of GGRAC is approximately twice as much as those of DGAC and DGWMA at both temperatures (40°C and 50°C). These effects could be imputed both to the gap gradation and quantity of binder.
- The temperature affected the permanent deformation of DGAC and DGWMA more than GGRAC.

In order to reference the reliability of the proposed rutting performance model with the related test results, Figure 4 presents the comparison of the measured and calculated γ_p for the GGRAC and DGWMA tests. Models are considered reliable within the shear deformation failure limit of 0.05.

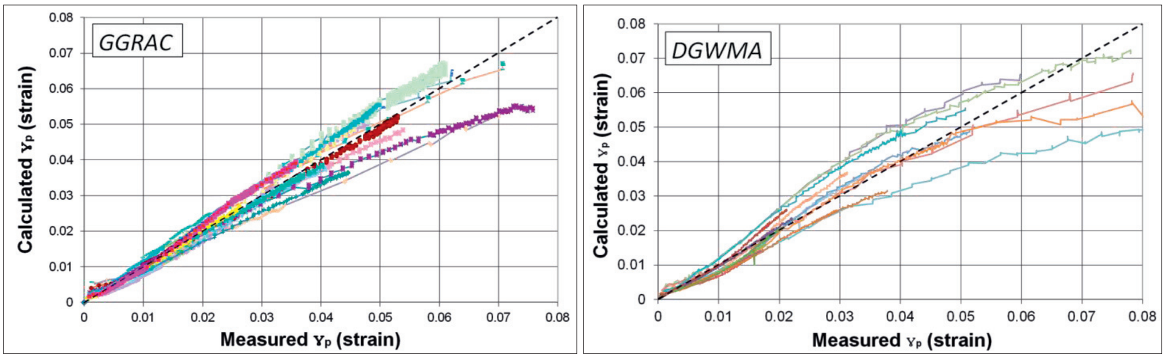


Fig. 4. Relationship between γ_p measured and calculated for (a) GGRAC and (b) DGWMA

5. Fatigue performance model using Mechanistic Empirical method

Damage to asphalt concretes caused by repetitive stresses and strains due to climatic and traffic-applied loading is considered fatigue, and is one of the primary distress mechanisms in bituminous pavements. Fatigue causes damage in the asphalt bound materials and in the field appears, mainly, as cracking. The stiffness deterioration process is the result of fatigue damage and was studied with the flexural controlled-deformation fatigue test following the AASHTO T-321 (2007) [8].

Beam specimens, nominally 50 mm thick, 63 mm wide and 380 mm long, are subjected to four-point bending using a haversine waveform at a loading frequency of 10 Hz. For each mix, a total of 18 fatigue tests were performed at three temperatures (10, 20 and 30°C) two strain levels (400 and 700 με for DGAC and GGRAC, while 200 and 400 με were used for DGWMA) and three replicates.

In *CalME*, the density of surface cracking caused only by fatigue is a function of the damage in the asphalt bound layer. The fatigue damage, in turn, is accumulated at a rate that is determined by the tensile strain caused by traffic loading in the asphalt concrete. Fatigue damage determines the residual stiffness of asphalt bound materials and the modulus changes consequently [13].

Specifically, the *CalME* model for the evolution of the complex modulus of the asphalt material with damage ω is:

$$\log(E) = \delta + \frac{\alpha \cdot (1-\omega)}{1+exp(\beta+\gamma \cdot log(tr))} \quad (6)$$

where the parameters are the same of equation (1) and the damage ω is calculated as:

$$\omega = A \cdot MN^{\alpha} \cdot \left(\frac{\mu\varepsilon}{200\mu strain}\right)^{\beta} \cdot \left(\frac{E}{3000MPa}\right)^{\gamma} \cdot exp(\delta \cdot t) \quad (7)$$

where:
MN is the number of load applications in millions of ESALs,
$\mu\varepsilon$ is the tensile strain at the bottom of modelled asphalt layer,
E is the input complex modulus (MPa),
t is the temperature (°C),
200 μstrain and 3000 MPa are reference constants, and
A, α, β, γ and *δ* are constants (not related with the constants of equation 1 and 6).

The constant γ in equation (7) was here assumed equal to β/2, making damage a function of the strain energy. The model parameters for equations (6) and (7) are determined from the four-point bending tests, at controlled strain levels, minimizing the root mean square of the difference between the measured modulus and the modulus calculated from equation (6). Moduli below 30% of the intact value were ignored, because the moduli are not representative of the asphalt layer field conditions. A summary of the fatigue performance model parameters are listed in Table 7.

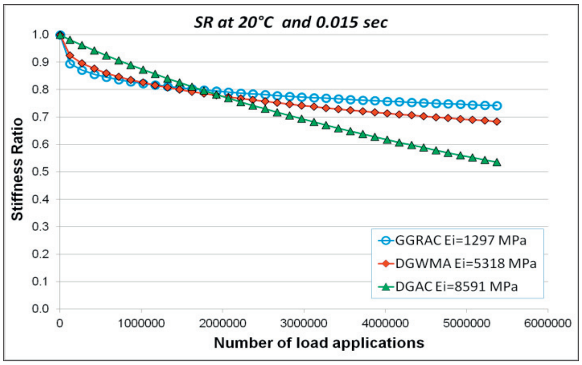
Table 7. Fatigue Performance Model parameters

Material	α	A	$\mu\varepsilon_{ref}$	β	$E_{ref}(MPa)$	γ	$\delta(Ei)$	$FSF^{(1)}$
DGWMA	0.420112	100.7936	200	-4.43972	3000	-2.21986	3.628643	1
GGRAC	0.264918	47321.1	200	-4.75210	3000	-2.37605	3.612244	1
DGAC	0.936303	2.885158	200	-4.31572	3000	-2.15786	2.389158	1

(1)Fatigue Shift Factor assumed as 1 for the direct comparison of material models.

Using these parameters, it was possible to compare the Fatigue Performance Models of the three mixes in terms of strain variation and SR decrease hypothesizing the same pavement and load conditions of Table 6.
Upon analysing the SR and strain at the bottom of AC (Figures 5, 6) it is possible to infer the following:

- The DGAC has the highest SR reduction rate and highest Initial Stiffness (Ei), at both temperatures (20 and 30°C). However the GGRAC, characterized from the smallest IS, exhibits the lowest SR reduction rate (Figure 5),
- The temperature influences the performance of the mixes. Specifically with DGWMA and DGAC the SR reduction rate increases with the temperature increase, while this is not evident for the GGRAC,
- The strains at the bottom of AC tend to increase with increasing damage. This increase is quicker for DGAC at 30°C than for GGRAC and DGWMA which show nearly the same slope of the strain curve (Figure 6),
- As expected strains increase with temperature for all the mixes,
- The minor temperature sensitivity of the GGRAC mix shown in the master curve models is confirmed with the *CalME* simulations where the strain increment is not producing further damage to the layer (Figure 5),
- According to Pettinari et al., (2012) [14], the GGRAC fatigue endurance limit measured with 4PB with haversine loading, is approximately 400 με. The simulation behaviour is consistent with lab results and the assumption that when loading strains are below the FEL condition, the layer exhibits an extraordinary long fatigue life.
- DGWMA behaves in between GGRAC and DGAC, in particular it is less prone to fatigue damage than the latter and its SR rate is similar to that of GGRAC at 20°C, but sensibly larger at 30°C,
- Both GGRAC and DGWMA show a quick evolution of SR that is initially larger than DGAC.



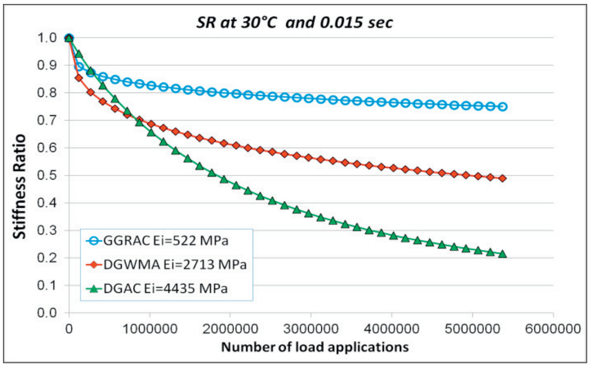
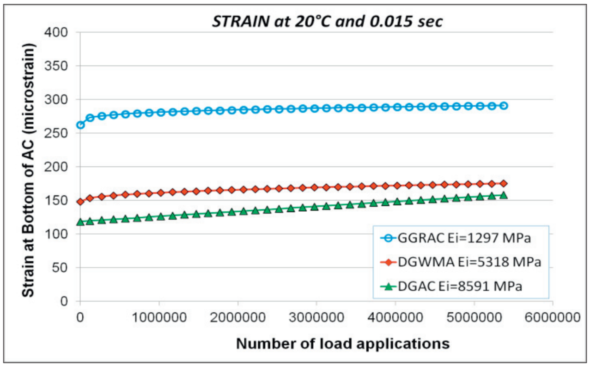


Fig. 5. Variation of the Stiffness Ratio at (a) 20°C and (b) 30°C (0.015 s = 10 Hz)



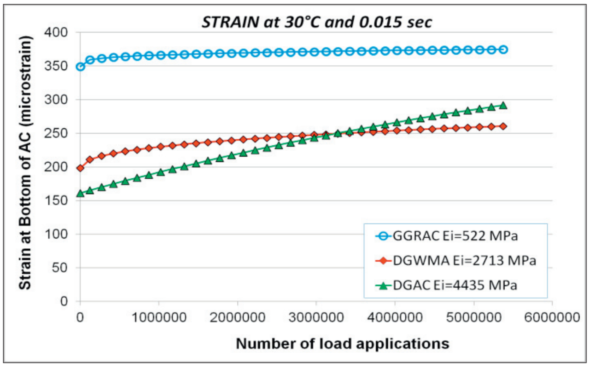


Fig. 6. Variation of the Strain at (a) 20°C and (b) 30°C (0.015 s = 10 Hz)

Figure 7 shows the validity of the fatigue performance model with the respective test results evidencing the relationship between measured and calculated Stiffness Ratios (SR) for the GGRAC and DGWMA tests.

Models are considered consistent within a modulus ratio of 0.5. At each test corresponds one of the different 18 curves.

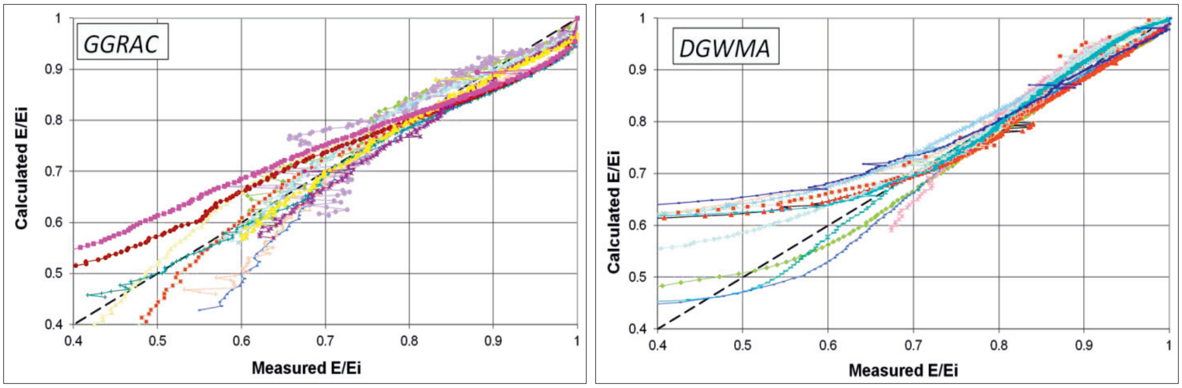


Fig. 7. Relationship between measured and calculated SR for (a) GGRAC and (b) DGWMA

6. Conclusions

This paper demonstrates how eco-friendly mixes, such as GGRAC and DGWMA, can be characterized by means of advanced mechanical testing, such as RSST-CH and 4PB tests, and of mechanistic-empirical models such those implemented in a proven and renowned design software like *CalME*.

The models' parameters for the eco-friendly materials have been calibrated by means of a set of laboratory tests and are compared to those obtained from a traditional bituminous mixture. The validity of each adopted model is confirmed through specific simulations that show separately the effects of rutting and fatigue on the materials. From the modelling of a single layered pavement subjected to fixed load and temperatures, their differences in terms of rutting and fatigue performances arise even more clearly than lab tests results. Nevertheless, a specific set of *CalME* simulations with consistent traffic and temperatures scenarios will help into merging the concurrent effects of rutting and fatigue over the pavement performance, thus finding, for design purposes, the best solution for each eco-friendly material application.

GGRAC appears to be more prone to rutting than DGWMA and DGAC both at 40 and 50°C, while its fatigue performance at 20 and 30°C is much better than the other two mixes, being DGAC the less resistant. These results are directly dependent from the mix proportion of each sample. GGRAC is a gap graded mix with a percentage of asphalt rubber of 7.2% by mass of aggregates. This high percentage of binder induces evident fatigue performance, but reduces rutting resistance. In particular, the evolution of damage represented by SR and strain curves denotes the singular behaviour of GGRAC that, also from the numerical simulations, appears to work in FEL conditions: from lab testing a value of 400 με was obtained as condition of fatigue endurance limit.

With regard to the Dense Graded mixes, the Warm one, being subject to a lower initial ageing if compared to the traditional one, presents lower permanent deformations resistance than DGAC, but better fatigue one. A balance of fatigue and rutting resistance of the material should be achieved with *CalME* full simulations, adjusting the pavement structure to make the most of the WMA potentialities for the best pavement performance.

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