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FIBRA

Fostering the implementation of fibre-reinforced asphalt mixtures by ensuring its safe, optimized and cost-efficient use

Deliverable 4.2

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1 Introduction

Bituminous mixtures have always been valued as the most relevant material for the construction of pavement infrastructures such as motorways, highways, streets, cycle paths, and parking lots, among others. The components that constitute this composite are mainly bitumen and mineral aggregates. Nevertheless, the higher demands in the automotive fleet and the constant climate change generated by the global warming have led to the development of modified mixtures with novel additives, with enhanced characteristics that guarantee an appropriate mechanical performance to extend the long service life.

The incorporation of fibers appears as an attractive solution to extend the resilience and durability of bituminous mixtures. According to a literature review carried out in work package two, it was observed that many types of fibers had been previously investigated in bituminous mixtures, especially in dense-graded asphalt mixtures. In general, it has been observed that fibers inclusion contributes to supporting the tensile stresses transmitted to the mix by the action of traffic loads.

In a previous task within the FIBRA project, the optimal design and mechanical characterization of fiber reinforced asphalt mixtures (FRAM) has been done (deliverable 4.1). Two standard and two FRAM were designed for the wearing course, a porous asphalt (PA) and an asphalt concrete (AC). Additionally, standard and FRAM dense mixes (AC) for being used in the binder and base course were designed. The results of task 4.1 showed that the use of fibres in porous asphalt mixtures (PA) results in a good performance strengthening the mixture at dry conditions, providing a better performance than the conventional penetration grade bitumen and close to polymer modified bitumen (PMB). Besides, they are also useful to increase the binder content, which is a requirement to improve the behaviour at wet conditions. Concerning asphalt concrete (AC) mixes, the use of fibres increases the tensile strength in both dry and wet conditions and the rutting performance. In relation to the fatigue resistance test, a higher dynamic modulus was achieved while keeping a similar fatigue resistance comparing to the control AC mixture with pen grade bitumen. For low temperatures, FRAM present similar behaviour than control AC mixes with pen grade bitumen and worse than PMB mixtures.

In this deliverable, the results from two different studies are presented. In the first study, the evaluation of the influence of the FRAM in the long-term deterioration of the pavement structure depending on the layer it is implemented was done. To carry out this study, the AC mixtures designed and characterized in task 4.1 were tested according to AASHTO standards in order to obtain the needed model parameters used in the pavement structural analysis program FlexPAVE^{TM}. This software can model fatigue cracking propagation (top-down and bottom-up) and permanent deformation. On the second study, the laboratory sized accelerated pavement testing machine (MMLS3) was used to evaluate the fatigue performance of FRAM. For this part of the project, the mixtures produced and implemented by the project partners (BAM and Veidekke) in the pilot sections in the Netherlands and Norway (Task 5.1) were sent to Empa for the accelerating test.

In the subsequent chapters, more information concerning the materials, experimental work, the discussion of results, and the most relevant conclusions are presented.

2 Numerical simulation with FlexPAVE^{TM}

Layered viscoelastic pavement analysis for critical distresses (FlexPAVE^{TM}) is a pavement response and performance prediction program developed by researchers at the North Carolina State University (NCSU). This tool combines the time-scale separation with the stress-strain analysis using Fourier transform-based layered structural analysis. This way, the tool is able to efficiently capture the effects of viscoelasticity of the pavement material, the temperature (thermal stress and changes in viscoelastic properties) and the moving nature of the traffic load [1-4]. The computed strain and stress are then used to calculate the fatigue damage and rut depth. To do so, researchers at NCSU have developed advanced material models to predict asphalt mixtures' behaviour. The Viscoelastic continuum damage (VECD) model [5,6] is employed to address fatigue cracking and the permanent strain shift model is used to address rutting [7,8].

The FlexPAVE program is able to differentiate the top-down and bottom-up cracking pattern due to viscoelastic material properties and boundary conditions of unbound layers under asphalt layers [9].

The models and test methods used in FlexPAVE^{TM} are described in following sections.

2.1 Introduction to FlexPAVE^{TM}

2.1.1 Linear viscoelastic properties (AASHTO T378)

Asphalt concrete is considered a mainly linear viscoelastic material at specific strain levels and is also known as being thermorheologicaly simple, being possible to combine the effects of loading frequency and temperature into a single parameter called reduced frequency. Thus, the dynamic modulus $|E^*|$ can be expressed in the form of a master-curve that exhibits frequency- and temperature- dependent behaviour. The sigmoidal model shown in Eq. 1 and the temperature shift factor relationship in Eq. 3 can be used to characterize$|E^*|$.

$$\log(|E^*|) = a + \frac{b}{1 + \frac{1}{e^{d+g(\log f_r)}}} \qquad \textit{Eq. 1}$$

Where $|E^*|$ is the absolute value of mixture's modulus and a, b, c, d, g are model parameters.

$$f_r = a_T f \qquad \textit{Eq. 2}$$

$$\log(a_T) = a_1 T^2 + a_2 T + a_3 \qquad \textit{Eq. 3}$$

Where a_1, a_2 and a_3 are model parameters.

Through the master-curve and shift factor relationship, the measured data can be extrapolated to include a broader range of loading frequency and temperature.

The asphalt mixture performance tester (AMPT) and the AASHTO T 378 test procedure are used to measure the dynamic modulus values and phase angles between 4.4ºC and 37.8ºC. In this test, a specimen is subjected to a controlled sinusoidal compressive stress at various frequencies and at a specific temperature. The applied stresses and resultant axial strains are measured and used to calculate the dynamic modulus and phase angle.

To transform a frequency-dependent property to a time-dependent property, the relaxation modulus, E(t), can be used as described in *Eq. 4*.

$$E(t) = E_\infty + \sum_{i=1}^{M} E_i \exp(-\frac{t}{\rho_i}) \qquad \text{Eq. 4}$$

Where E_∞. E_i and ρ_I are the parameters to be determined using the experimental data.

For a linear viscoelastic material, its mechanical response generally depends on the rate and history of the stress/strain input [10]. In the case of a strain input, the stress response is expressed as follow:

$$\sigma(t) = \int_{0^-}^{t} E(t-\tau)\frac{d\epsilon(\tau)}{d\tau}d\tau \qquad \text{Eq. 5}$$

Where σ is the stress response, ϵ is the strain input, τ the integration variable for time and $E(t-\tau)$ is the relaxation modulus. The relaxation modulus of the Prony series form are used as a unit response function in the relationship between strain and stress.

The test results are imported to an Excel based software tool called "FlexMAT™ cracking version 1.1.2" to develop the dynamic modulus mastercurve, time-temperature shift factors and the Prony series. All these coefficients are later directly exported to FlexPAVE™.

2.1.2 Fatigue performance

The S-VECD Material Model

In FlexPAVE™, the Simplified viscoelastic continuum damage (S-VECD) model is used to describe the fatigue behaviour of asphalt concrete under a wide range of loading and environmental conditions. This fatigue behaviour is characterized using the elastic-viscoelastic correspondence principle, continuum damage mechanics and time-temperature superposition principle [11, 12].

Damage Characteristic Curve (C-S curve)

The main output from S-VECD is a *damage characteristic curve* (C-S curve) that explains a relationship between pseudo stiffness and a quantified damage state. Analogous to elastic cases, this pseudo-stiffness (C) is an instantaneous secant modulus used to characterized the structural integrity of the material as damage (S) grows. According to the model, any reduction in the pseudo stiffness is caused by the material's internal damage exclusively. The pseudo stiffness initiates from a value of 1.0 when the material is undamaged and this value decreases as damage grows under repeated cyclic loading. It should be noted that the C-S curve is a material intrinsic property independent of temperature, loading type, mode and other conditions such as loading amplitude and rate [10].

To address the quantification of damage, the work potential theory of Schapery (1984) [10], based on thermodynamics principles, is used in the S-VECD model. *Eq. 6* summarizes the damage evolution law:

$$\frac{dS}{dt} = \left(\frac{\partial W^R}{\partial S}\right)^{\alpha} \qquad \textit{Eq. 6}$$

Where W^R is the pesudostrain energy density function, α is the damage growth rate and S the internal state variable representing damage.

Finally, the relationship between the internal state variable representing damage (S) and pseudo-stiffness can be fitted as a power function represented by *Eq. 7*, where C_{11} and C_{12} are the model coefficients.

$$C(S) = 1 - C_{11}S^{C_{12}} \qquad \textit{Eq. 7}$$

In the laboratory, the C-S curve is usually determined by running cyclic direct tension fatigue tests. In this study, the standard method for determining the damage characteristic curve of asphalt mixtures from direct tension cyclic fatigue tests (AASTHO TP107-18) is performed.

In the direct tension cyclic tension test, a controlled and repeated cyclic loading is applied to a cylindrical asphalt concrete specimen until failure. The applied stress and on-specimen axial strain response are measured. All the test are performed at 3 different strain amplitudes, selected in such a way to create a spread of numbers of cycle to failure (Nf).

Failure condition of the samples is determined by observing the peak phase angle. The sharp decrease of the phase angle typically occurs around the failure point.

D^R Failure Criterion

The damage characteristic curve represents how damage grows in the material; however, a failure criterion is needed to predict the failure of the material. The fatigue failure of a mixture is indicated by the D^R failure criterion. D^R, expressed by *Eq. 8*, is defined as the average loss of integrity per cycle throughout the asphalt mixture's service life [13] and is used to calculate fatigue life as the number of cycles to failure (N_f).

$$D^R = \frac{\int_0^{N_f}(1-C)dN}{N_f} = \frac{sum(1-C)}{N_f} \qquad \textit{Eq. 8}$$

Where N is the number of load cycles and N_f is the number of cycles to failure. The D^R failure criterion is a constant and therefore independent of temperature, mode of loading and stress/strain amplitude [13].

Sapp Cracking index

To evaluate the fatigue life of an asphalt mixture, both the toughness and stiffness should be taken into account [14]. An asphalt mixture with the same fatigue resistance but with a higher stiffness will have a higher fatigue life than a lower stiffness mixture [15]. D^R value accounts only for the toughness. In order to represent the fatigue life of an asphalt mixture in a single indicator, Wang et al. (2020) [16] developed the Sapp cracking index based on the S-VECD theory. The Sapp is calculated using *Eq. 9* and have been found to distinguish the fatigue life of asphalt mixtures with different binders, RAP contents, air void and aggregate gradations. A higher Sapp value represents better fatigue resistance.

$$S_{app} = 1000^{\frac{\alpha}{2}-1} \frac{a_T^{\frac{1}{\alpha+1}} \left(\frac{D^R}{C_{11}}\right)^{\frac{1}{C_{12}}}}{|E^*|^{\frac{\alpha}{4}}} \quad \text{Eq. 9}$$

The results from the cyclic direct tension fatigue tests are imported to FlexMAT^{TM} cracking to obtain the damage characteristic curve coefficients C11 and C12, D^R and S_{app}.

FlexPAVETM Structural Model

FlexPAVE^{TM} uses S-VECD model to predict fatigue damage (as percentage of damage) within the pavement's cross-section throughout the pavement design life. The level of damage is calculated considering a reference cross-sectional area that is formed by two overlapping triangles as shown in Figure 1. The top inverted triangle has a 170-cm wide base that is located at the top of the surface layer and a vertex that is located at the bottom asphalt layer. The 120-cm wide base of the second triangle is located at the bottom of the bottom asphalt layer and its vertex is positioned at the surface layer [17].

The percentage of damage is defined as the ratio of the sum of the damage factors (N/N_f) within the reference cross-section area to the reference cross-section area itself [15], as shown in *Eq. 10*.

$$\%Damage = \frac{\sum_{i=1}^{M}(\frac{N}{N_f}) \times A_i}{\sum_{i=1}^{M} A_i} \quad \text{Eq. 10}$$

Where i is the nodal point number in the finite element mesh, M is the total number of nodal points, Ai is the area represented by a nodal point and N/Nf is the damage factor represented as the ratio between the number of load cycles (N) and the total load cycles to failure (N_f). The damage factor is 0 when there is no damage and 1 when the nodal point is fully damaged.

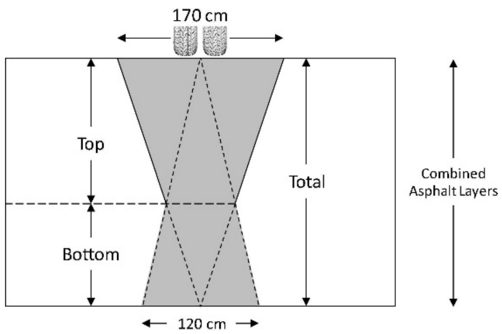


Figure 1. Reference cross-sections area used by FlexPAVE^{TM} to calculate fatigue damage. From [15]

It should be noted that the damage does not correspond to cracking. An empirical transfer function should be used to turn percent damage into percent cracking. Although preliminary transfer functions, developed in [18] are available, both for fatigue cracking and rutting, in this work, only damage is presented and no transfer function is applied. Thus, the percentage damage obtained from FlexPAVE should be taken as relative values.

2.1.3 Rutting performance

The pavement mechanical responses are also used for predicting rut depth by FlexPAVE™. The rutting performance of the asphalt mixtures in the pavement structure is evaluated using a permanent deformation model developed by Choi and Kim [19, 20] and called shift model. The shift model is based on the concept of time-temperature-stress superposition to simulate the effects of temperature, pulse time and stress on rutting.

In the shift model, the viscoplastic strain is defined as in *Eq. 11*.

$$\varepsilon_{vp} = \frac{\varepsilon_0 N_{red}}{(N_I + N_{red})^{\beta}} \qquad \textit{Eq. 11}$$

Where β, ε_0 and N_I are the model coefficients, and N_{red} is the number of load cycles at the reference temperature and reference vertical stress. N_{red} can be determined by shifting the actual number of load cycles by

$$N_{red} = N^{physical} \times 10^{a_{total}} \qquad \textit{Eq. 12}$$

$$a_{total} = p_1 log_{10}(\xi_p) + p_2 + (d_1 T + d_2)\left(log_{10}\left(\frac{\sigma_v}{p_0}\right) - 0.877\right) \qquad \textit{Eq. 13}$$

Where p_1, p_2, d_1 and d_2 are model parameters, ξ_p is the reduced pulse time and σ_v is the vertical stress due to vehicle loading.

The shift model coefficients are calibrated using the Stress Sweep Rutting (SSR) test (AASHTO TP 134). The SSR test is conducted at two test temperatures, referred to as TH (the high temperature) and TL (the low temperature) and under constant confining pressure of 69 kPa (10 psi) with three 200-cycle loading blocks of three deviatoric stress levels.

The four test results are used to calibrate the shift model. Once the model coefficients are calibrated, the model is able to predict the permanent strain under various load levels and at different temperatures. Thus, the software uses the shift model to compute the permanent deformation at each nodal point based on the obtained pavement responses and the climate data [18]. Next, the permanent deformation in each sublayer is determined by multiplying the permanent strain by the thickness of each sublayer. The total permanent deformation (rut depth) is the summation of the permanent deformation of each sublayer. For the permanent strain of the unbound layers, the program applies a mechanistic-empirical model [21].

Rutting index

Ghanbari, Underwook and Kim [22] proposed a rutting index parameter to assess the rutting resistance of asphalt mixtures using the SSR test and the permanent deformation shift model. The Rutting Strain Index (RSI) is defined as the ratio of the permanent deformation in an asphalt layer to the thickness of that layer at the end of a 20-year pavement service life with 30 million 18-kip (8 ton) standard axle load repetitions for a standard structure and it is dependent on the specific pavement layer and climate conditions.

The results of the SSR tests are imported to the Excel based software tool FlexMAT^{TM} for Rutting [23]. This tool characterizes rutting of asphalt mixture from the SSR test results. This is used to provide permanent deformation model coefficients to FlexPAVE^{TM} and to calculate the RSI index rutting parameter.

2.2 Experimental tests

2.2.1 Materials and Methods

In the FIBRA project, two different types of fibers have been investigated, fibres consisting of a combination of aramid and polyolefins (type A) and polyacrylonitrile fibres (type P), being the type A fibres used in the design of porous asphalt mixtures (FRPA) and type P fibres in the design of AC mixtures (FRAC). The composition and the mechanical performance of the fibre-reinforced asphalt mixtures (FRAM) designed can be consulted in D4.1 [24].

Since the main failure mechanism of PA mixtures, ravelling, is not predicted by FlexPAVE^{TM}, only AC mixtures are included in this study. The asphalt concrete (AC) mixtures designed and characterized in task 4.1 were compacted with the Gyratory compactor and sent to the Virginia Tech Transportation Institute for their characterization according to the AASHTO standards (378, TP107 and provisional standard TP134-19) using the asphalt mixture performance tester (AMPT).

Table 1. Reference and FRAC mixes included in this study

	REF16	**REF16_P**	**REF22_P**	**REF22**	**FRAC 16**	**FRAC22**	**FRAC22b**
Max. aggregate size	16	16	22	22	16	22	22
Type of bitumen	50/70	PMB 45/80-65	PMB 45/80-65	50/70	50/70	50/70	35/50
Bitumen / mixture (%)	4.3	4.3	4.4	4.2	4.6	4.4	4.2
Type of fibre	-	-	-	-	Type P	Type P	Type P
Voids content (%)	5.1	5.4	6.5	6.5	5.6	6.0	6.3

11 specimens from each mixture were sent to the Virginia Tech Transportation Institute. The samples were cored and cut according to the dimension required by each test (Figure 2). From the 11 mixtures, three specimens were used to determine the dynamic modulus (DMT), 4 specimens for the stress sweep rutting test (SSR) and 4 specimens for the S-VECD fatigue test (FT).

Figure 2. Specimens tested in Virginia Tech.

Dynamic modulus (AASHTO 378)

The standard test method for determining the dynamic modulus for asphalt mixtures using the Asphalt Mixture Performance Tester (Figure 3) was used. In this test, a specimen is subjected to a controlled sinusoidal compressive stress at various frequencies and at a specific temperature. The applied stresses and resultant axial strains are measured and used to calculate the dynamic modulus and phase angle.

Testing was performed on 100mm diameter by 150 mm tall test specimens. Test conditions:

- Temperature: 4.4ºC, 21.1ºC, 37.8ºC
- Frequency: 0.1, 0.5, 1, 5, 10, 25 Hz
- Number of specimens: 3

Figure 3. Asphal mixture performance tester (AMPT)

Direct Tension Cyclic Fatigue Test (AASHTO TP107)

The fatigue cracking performance is determined by direct tension cyclic testing and the simplified viscoelastic continuum damage (S-VECD) model. The standard test method for determining the damage characteristic curve and failure criterion using the AMPT (AASTHO TP107-18) was applied.

In this test, a controlled and repeated cyclic loading is applied to a cylindrical asphalt concrete specimen until failure. The applied stress and on-specimen axial strain response are measured. The relationship between the damage (S) and the pseudo secant modulus (C) is determined and expressed as the damage characteristic curve.

Testing was performed on 100mm diameter by 130 mm tall test specimens. Test conditions:

- Temperature: 21ºC.
- Fatigue test is conducted in 4 different levels of target peak-to-peak strain followed by the dynamic footprint test.
- Vertical deformations are measured using spring loaded linear variable differential transformers (LVDTs).

Stress sweep rutting test (Provisional standard AASHTO TP134-19)

The provisional standard method of test for Stress Sweep Rutting (SSR) Test using asphalt mixture performance tester was used to characterize the resistance of asphalt mixtures to rutting using the shift model.

The SSR test is conducted at two test temperatures, referred to as TH (the high temperature) and TL (the low temperature) and under constant confining pressure of 69 kPa (10 psi) with three 200-cycle loading blocks of three deviatoric stress levels. The load pulse is 0.4 s for each cycle. The rest period is dependent on the test temperature. The permanent axial deformation that occurs at each load cycle is measured using actuator displacement.

Testing was performed on 100mm diameter by 150 mm tall test specimens. Test conditions:

- Temperature: 20ºC and 46ºC were set as TL and TH respectively.
- 2 repetition for each temperature.

2.2.2 Results and discussion

Dynamic modulus results

The dynamic modulus master curves of the references and fibre-reinforced mixtures is shown in Figure 4. According to the results, the AC16 mixtures designed for the wearing course (REF16, REF16_P and FRAC16) present very similar master curves and phase angle (Figure 4 a and b). When comparing the fibre-reinforced AC22 (FRAC22) with the one with PmB (REF22_P) (Figure 4 c and d), higher complex modulus and lower phase angle are obtained by FRAC22 compared to the mixture with PmB indicating a better behaviour of the former. FRAC22 has also been compared with the AC22 mixture with 50/70 penetration grade bitumen (REF22) and the FRAC22 mixture with 35/50 penetration grade bitumen. In this case, as with the AC16 mixtures, the differences between the master curves of REF22 and FRAC22 are insignificant (Figure 4 e). A slightly higher modulus is obtained by FRAC22b likely due to the use of a harder bitumen.

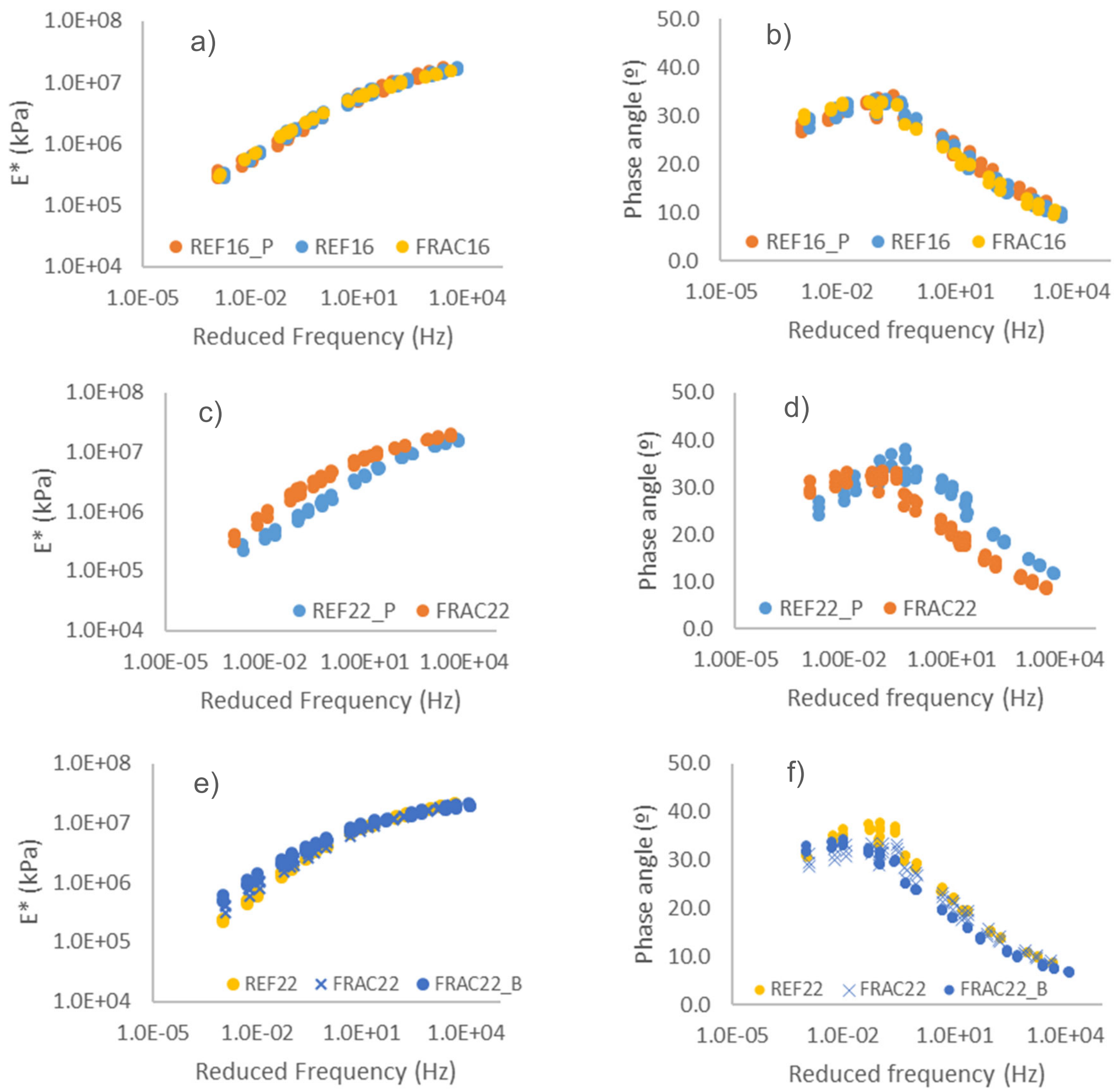


Figure 4. Dynamic modulus master curve and phase angle of the mixtures in table 1.

Very similar results in all the mixes were obtained when tested in task 4.1 in accordance with EN12697-26 (see [24]), which indicates a very good repeatability of the mixtures production and testing.

S-VECD Fatigue Test results

Damage Characteristic Curve

The Damage Characteristic Curve of the mixes is shown in Figure 5. Comparing the AC16 mixtures designed for the wearing course, almost identical S-C curves are obtained for the AC16 mixture with conventional bitumen (REF16) and the FRAC16. The reference mixture with PmB (REF16_P) presents a better fatigue behaviour, being able to maintain its integrity with a higher amount of damage than the other two mixtures. The AC22 mixes designed for the binder course are compared in Figure 5 (b). The fibre reinforced asphalt mixture (FRAC22) presents a better initial fatigue response. The reference mixtures with PmB (REF_22_P) deteriorates faster with damage than FRAC22. Later the damage characteristic curves intersect when the integrity of the mixture reaches a certain threshold being the response to fatigue better in the one with PmB. FRAC22 is compared with REF22, with conventional bitumen, in Figure 5 (c). A similar trend is observed for both mixtures but a slightly better fatigue performance is obtained for the reference mixture. The FRAC22_B with a harder penetration grade bitumen (35/50) presented irregular cycles to failure in three of the four specimens.

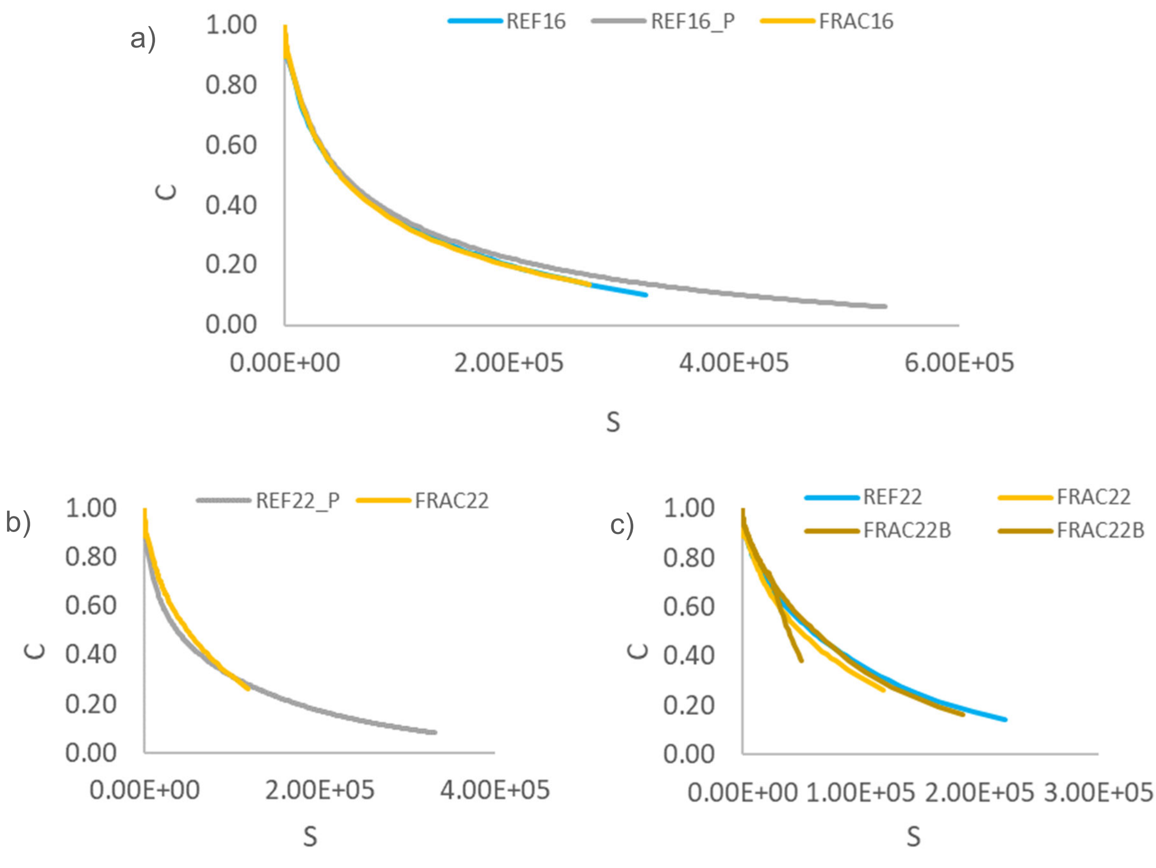


Figure 5. Damage characteristic curves (C vs S) of mixtures in table 1.

Sapp Cracking Index

As explained before, the S_{app} value is a good indicator for the fatigue resistance and therefore can be used to compare the fatigue performance of different mixtures. The S_{app} of the 7 mixtures is shown in Figure 6. A higher S_{app} value represents better fatigue resistance.

Based on the results, the asphalt mixtures with polymer modified bitumen clearly present the best fatigue performance comparing to the rest of the mixtures. On the other hand, the fiber reinforcement does not seem to significantly affect the fatigue performance of the asphalt concrete, since the mixtures with and without fibres present very similar results both for the AC16 and AC22 gradations.

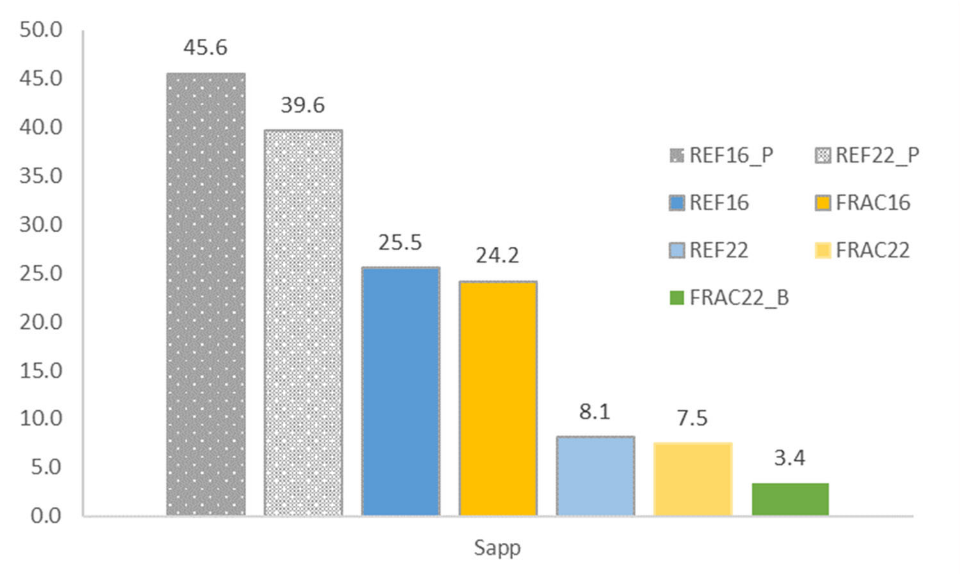


Figure 6. S_{app} Cracking index of mixtues in table 1.

The fatigue performance of the mixtures obtained in task 4.1 [24] when subjected to the 4-point bending test (EN 12697-24, annex D) or indirect tensile test (EN 12697-24, annex E), depending on the mixture, are shown in Figure 7. The four point bending test delivered similar results for the REF16 and FRAC16 mixtures than the AASHTO cyclic fatigue test (AASTHO TP107-18), with low differences between both mixtures (Figure 7 a). In the case of REF22_P, the results are also consistent, with the AC mixture with PMB presenting the better fatigue performance (Figure 7 b). However, in the case of the AC22 mixture with and without fibres, more differences are found between the mixtures in the EN12697.24 fatigue test than in the AASHTO test, being in the former, the performance of the FRAC22 better than that of the reference (REF22). The results of FRAC22_B are not compared due to the variability obtained in results of the AASHTO test.

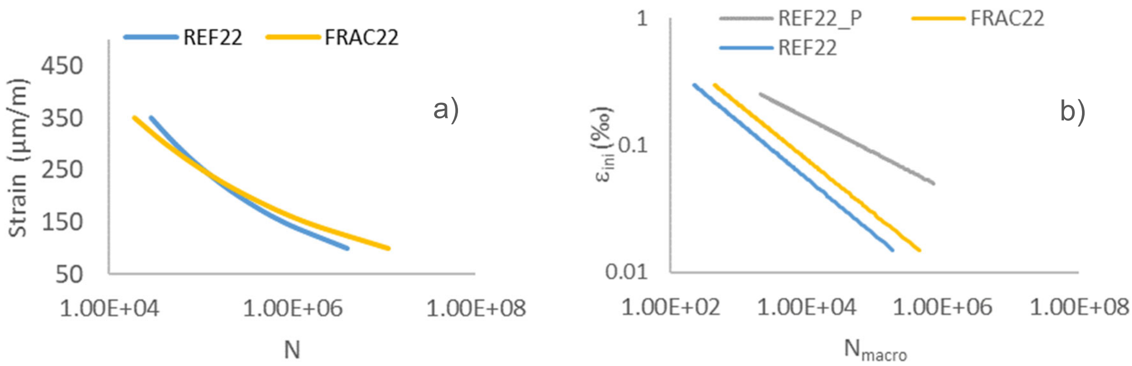


Figure 7. Fatigue performance based on EN12697-24 (annex D (Four point bending) left and E (Indirect tensile test), right).

SSR Test results and Rutting index

The results of the SSR test at the two temperatures are shown in Figure 8 for the mixtures designed for the surface, binder and base layers. The first temperature (TL) is a relatively low temperature and represents the average air temperature and the second temperature (TH) is a relatively high temperature and represents summertime temperatures [22].

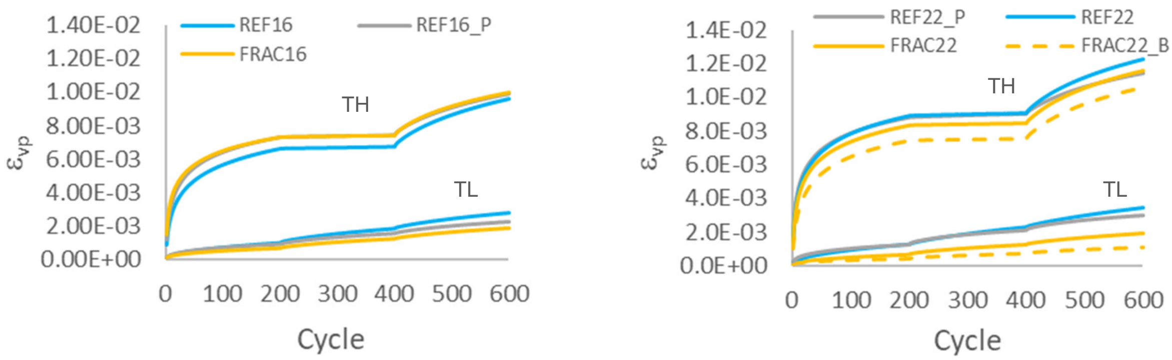


Figure 8. SSR results of mixtures from table1. Mixes designed for surface layer (left). Mixes designed for the binder and base layers (right)

In Figure 9 the rutting index, RSI, of the mixtures that are used in the same layer are compared also with the wheel tracking test (WTT) results obtained in task 4.1 [24]. When comparing the asphalt mixtures in the wearing course, the fibre-reinforced mixture (FRAC16) presents the highest resistance to permanent deformation, followed by the PMB mixture (Figure 9 a). In the intermediate and base layers, the asphalt mixtures with fibres (FRAC22 and FRAC22B) also show the best performance in terms of rutting resistance (Figure 9 b and c). FRAC22B presented the best behaviour due to the higher hardness of its bitumen. When comparing with WTT, similar results are obtained when ranked the mixtures except for the REF22_P that a better performance in terms of rutting resistance is obtained by this mixture with the WTT than with the SSR.

Table 2. RSI from the SSR test and rutting depth and slope from the WTT

	RSI index	WTT (Rutting depth - mm)	WTT (slope – mm/1000 cycles)
REF16	2.20	0.10	3.43
REF16_P	1.84	*	
FRAC16	1.46	0.03	2.37
REF22	1.36 (binder) 1.18 (base)	0.036	2.89
REF22_P	1.37 (binder) 1.24 (base)	0.016	1.42
FRAC22	1.25 (binder) 1.16 (base)	0.021	2.15
FRAC22_B	1.08 (binder) 1.02 (base)	0.009	2.5

*No data is available for the REF16_P mixture.

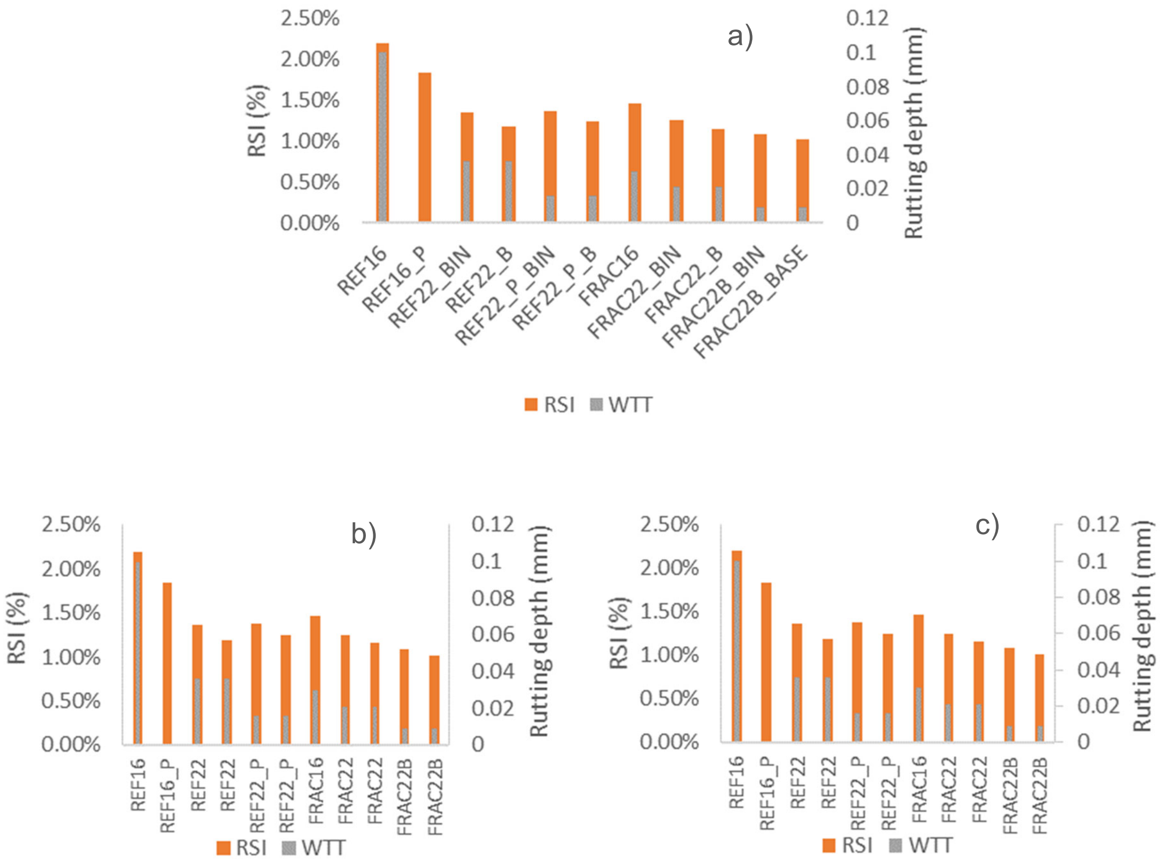


Figure 9. Comparison between RSI index and Rutting depth obtained with the WTT. a) wearing course, b) binder course and c) base course.

2.3 Pavement analysis

To evaluate the positive or negative effect of using FRAM in one or more asphalt layers within the pavement structure, the FlexPAVE^{TM} version 1.1 software was used.

Pavement structure

Different pavement sections were considered in this study with FRAM mixes placed in one or more asphalt layers (Figure 10). Reference pavement structures are also analysed with no FRAM in any of the layers.

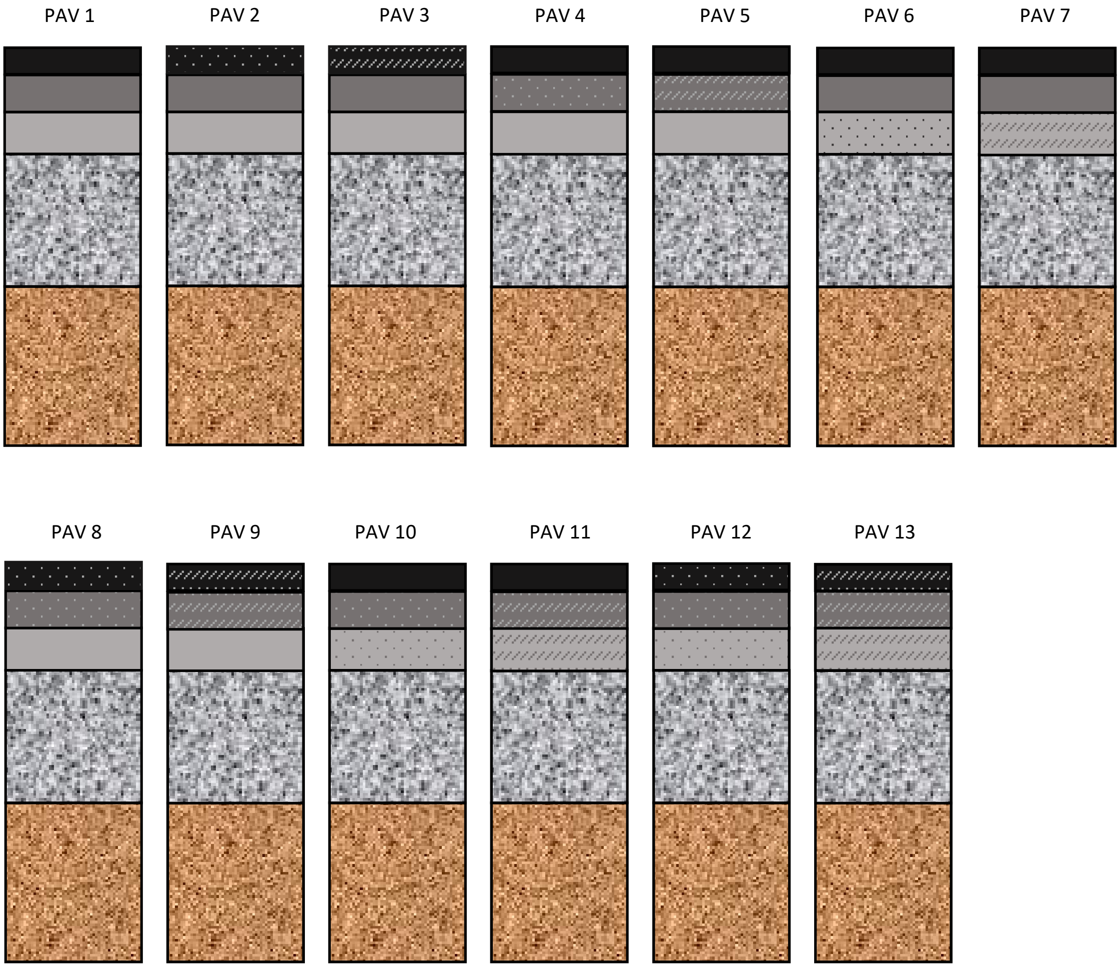


Figure 10. Pavement sections simulated with FlexPAVE^{TM}. See fig 11 for definitions of grey scale

Three asphalt layers (wearing, binder and base) are included in all the pavement sections with a total thickness of 20 cm, 5 cm for the wearing, 7 cm for the binder and 8 cm for the base course (Figure 11). Under the asphalt layers, all sections include the same subbase and subgrade. A 250 mm cement treated subbase under the asphalt layer and a 300 mm unbound aggregate subgrade under the subbase. The modulus value used are 500·MPa and 80 MPa respectively.

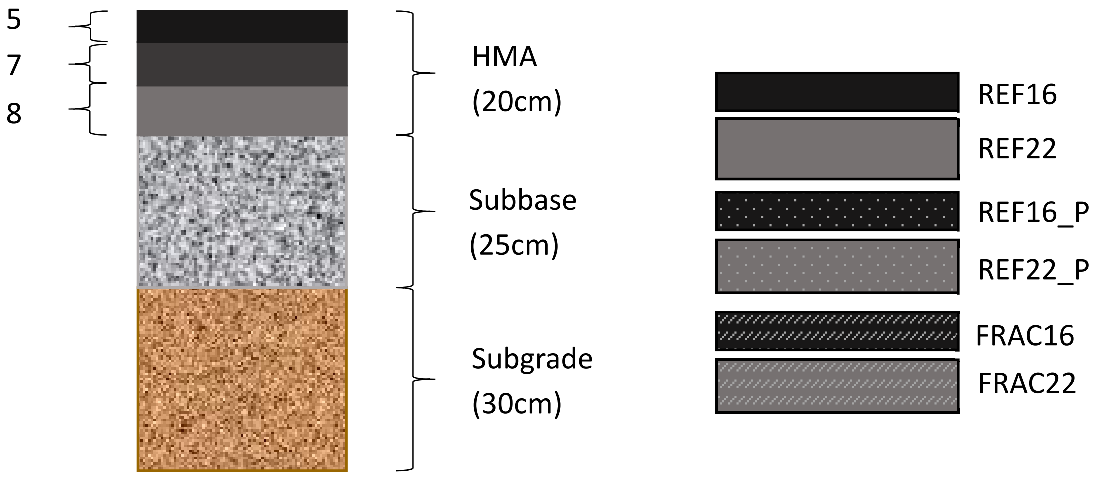


Figure 11. Type of pavement layers and thickness.

Traffic inputs

Concerning traffic inputs, FlexPAVE^{TM} uses vehicle speed and daily ESAL data. In this work, a single axle load is set as 65 kN with a tire pressure of 827 kPa. The number of passes of this traffic unit per day on the design lane is set at 6000 with a 2.0% annual growth. The vehicle speed is 97 Km/h.

A higher axle load (100 kN) has been input for a number of simulation runs to evaluate the effect this parameter has on the pavement structure performance.

Climate inputs

In addition to the pavement structure and traffic loads, for pavement analysis in FlexPAVE^{TM}, the user must provide the temperature profile of the pavement in an hourly base. The software allows the input of the temperature data in four different ways:

(1) from a database prepopulated using the EICM (Enhanced Integrated Climatic Model), only for US states,
(2) as an EICM text file. An hourly temperature text file can be prepared conformed to the format of the EICM text file. Information about the hourly vertical variation of temperature in the pavement need to be specified for one year.
(3) As an isothermal condition or
(4) Input manually.

The isothermal condition and the manual input option were discarded because one of the objectives of the study is the evaluation of the effect of pavement temperature in the prediction of pavement performance.

Concerning the EICM database, the software includes a complete database of temperature pavement profiles for all the states and major cities in the US. However, as can be seen in Figure 12, few similarities can be found between average annual temperature and precipitation between US states and major EU cities. For this reason, a database of temperature pavement profiles of several EU capital cities was created by UC in a former research project [25] that can be imported to FlexPAVE™. To create this database, the following steps were carried out:

1. Search and collection of temperature, wind and solar radiation (hourly data) for the selected EU cities (representative of each climatic region).
2. With the hourly data of temperature, wind and solar radiation the pavement temperature profile (hourly data) was calculated by means of the estimation model provided by the software TEMPS (Temperature Estimate Model for Pavement Structures) developed by the University of Nevada, Reno (US).
3. The hourly temperature profile of the asphalt pavement was prepared to conform with the format required by the FlexPAVE™ program. The vertical variation of temperature was defined by specifying the temperature at different nodes along the pavement depth.

For this study, three EU cities have been selected that belongs to different climate regions: Frankfurt (Cfb), Madrid (Csa) and Riga (Dfb). In Figure 13 and Figure 14 a comparison of the monthly average temperature and precipitation and pavement temperature profile of the three EU cities are shown, respectively.

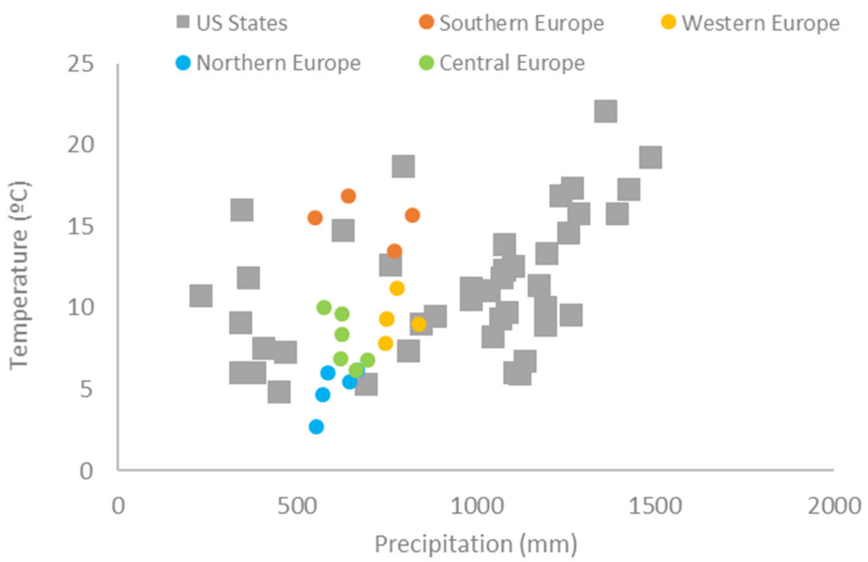


Figure 12. Average annual temperatures and precipitation of main EU and US states.

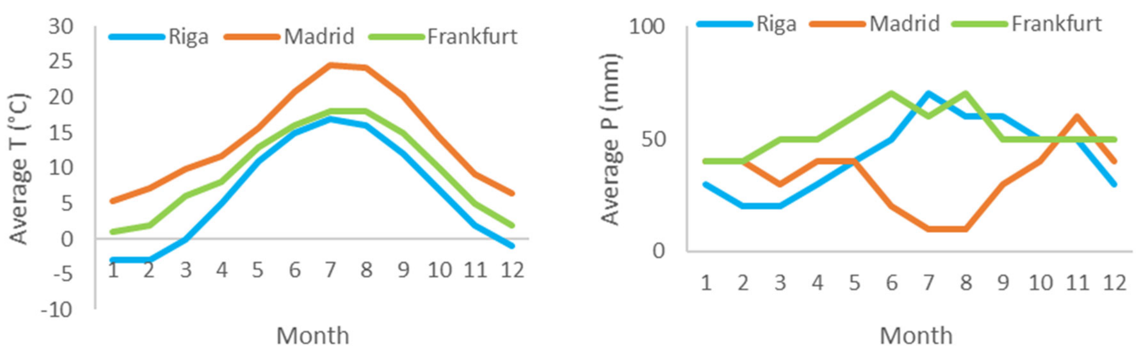


Figure 13. Average monthly temperatures and precipitation of Frankurt, Madrid and Riga.

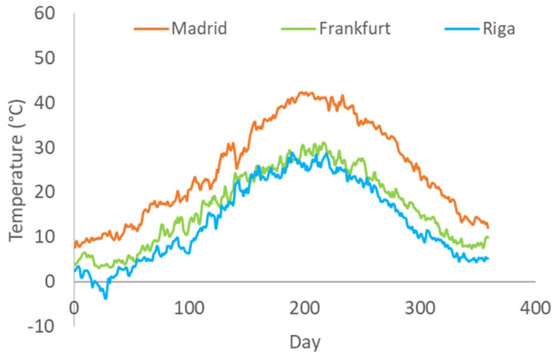


Figure 14. Pavement average daily temperature profiles

2.3.1 Results and discussion

Fatigue and rutting damage

The evolution with time of the fatigue and rutting damage in each section is shown in Figure 15 for Frankfurt climate conditions. The fatigue and rutting performance is predicted in a 30 year analysis period corresponding to a number of axle passes of $1.0 \cdot 10^8$. The increase or decrease in the percentage damage and rut depth of pavements PAV2 to PAV13 comparing to the reference pavement PAV1 is presented in

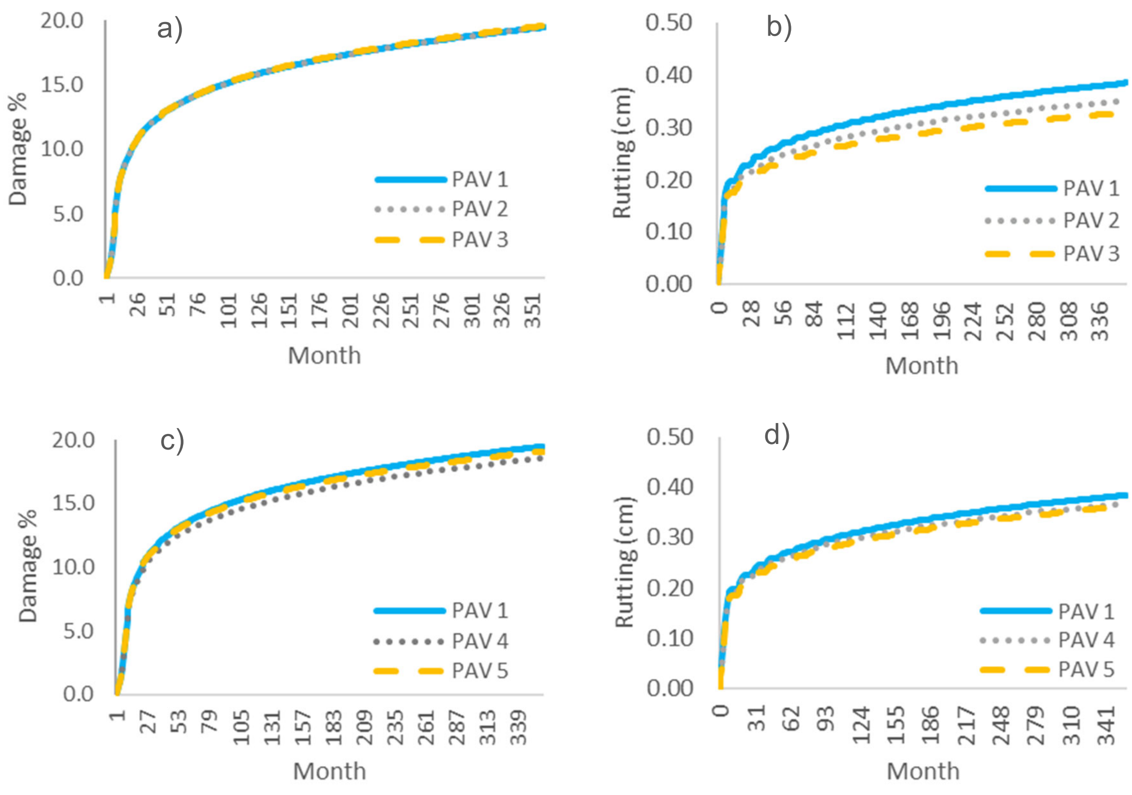
Table *3* for the climate region represented by Frankfurt pavement temperature profiles.

The effect of using either REF16, REF16_P or FRAC16 as the wearing course is shown in Figure 15 a) and b). Comparing the three sections, no differences are found between the three damage curves. It should be noted that the current version of FlexPAVETM does not include an aging model (to be incorporated in future versions). The incorporation of such a model would yield more top-down cracking and possibly will provide, in terms of fatigue damage, higher differences between the different mixes in the wearing course. On the other hand, when comparing the rutting performance, more differences are found, being the pavement with FRAC16 in the road surface the one with the better performance, almost 15% less rut depth is obtained in PAV3 comparing to PAV1 with REF16.

In Figure 15 c) and d), three pavement sections are compared: PAV1, PAV2, and PAV3. The difference between them is the use of different asphalt mixtures for the binder course: REF16, REF22_P and FRAC22 for PAV1, PAV2 and PAV3 respectively. The effect of using PMB or fibre reinforcement is very low in both failure mechanisms, fatigue and rutting. Actually, the highest effect in the fatigue performance of the pavements is observed when the REF22, REF22_P and FRAC22 are used in the base layer. In this case, the positive effect of using PMB is clearly observed in Figure 15 e). According to Figure 6, REF22_P is the asphalt mixture with the highest fatigue life and its use in the base layer results in a 35% reduction in the final percentage damage comparing to the reference pavement PAV1. REF16 and FRAC22 with a similar fatigue performance according to the laboratory results (Figure 5), present similar evolution of the pavement fatigue damage. Concerning rutting, the differences among the three pavements is not significant. The base layer is more prone to fatigue damage than permanent deformations and the improvement of the rutting behaviour of the mixture does not seem to significantly affect the overall rutting performance of the pavement.

From the pavement sections evaluated, PAV6, 10 and 12 present the best fatigue performance comparing to the reference pavement PAV1. The three pavements include in one or more layers, asphalt mixtures with polymer modified bitumen. PAV6 in the base layer, PAV10 in the binder and base layer and PAV12 in the three asphalt layers. However, the improvement achieved by using the REF22_P in the base layer reach a 35% while the further addition of REF22_P in the binder layer and the wearing course increase the reduction in the percentage damage only to 38.2% and 38.8%, which is coherent with the higher traction stresses that the base layer suffers.

Similarly, pavement sections PAV3, 9 and 13, the three of them with FRAM in one or more layers, present the best rutting performance comparing to the reference pavement PAV1. The rut depth reduction achieved by these pavements is 15%, 21% and 23% when the FRAM is used in the wearing, wearing+binder and wearing+binder+base layers respectively.



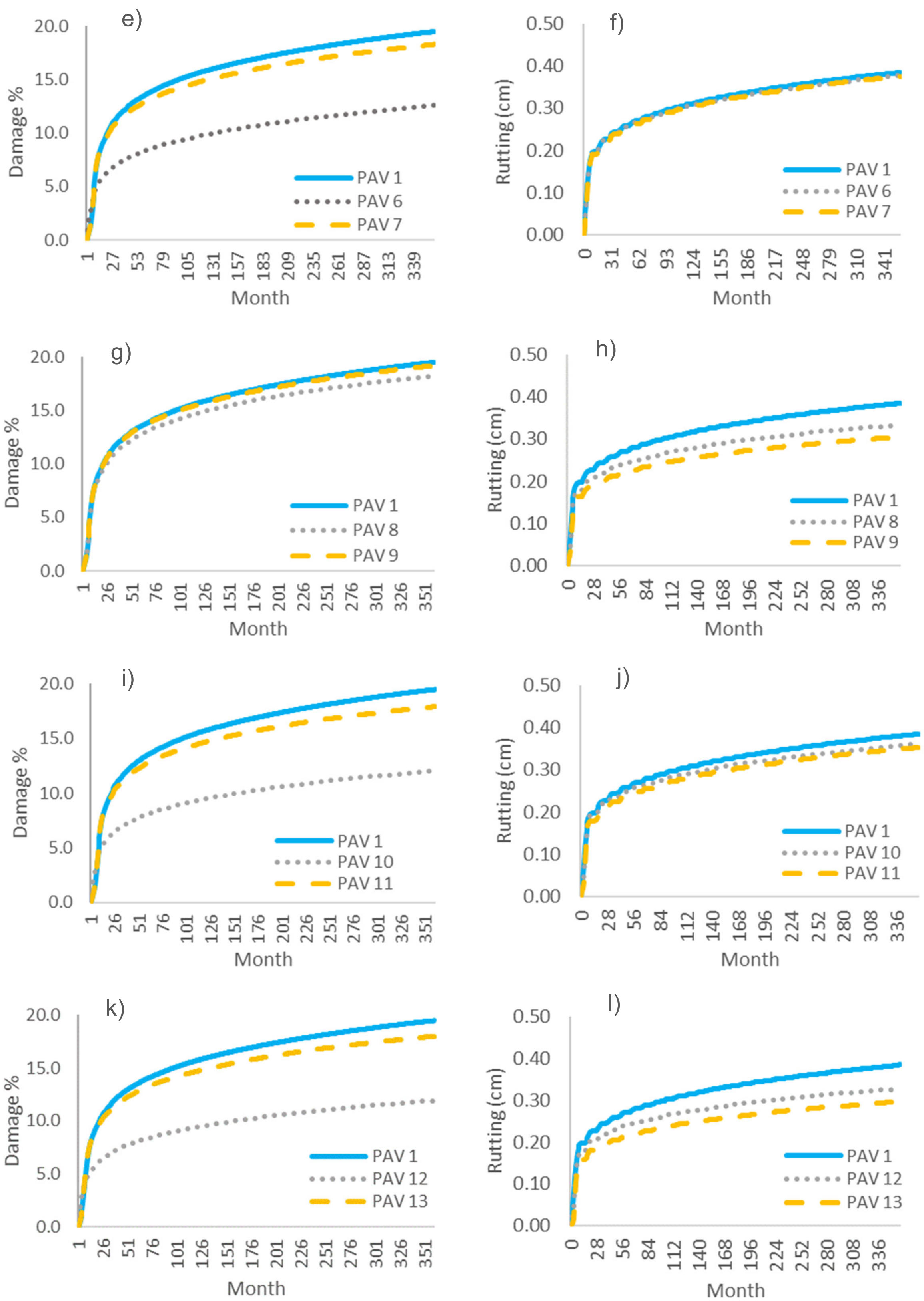


Figure 15. Evolution with time of the fatigue and rutting damage of pavement sections in Figure 11.

Table 3. Performance of the different pavement sections compared to reference PAV1 (increase or decrease in the damage percentage or rutting depth). Color red indicates a little or null improvement and green indicated a better performance.

PAV	1 n-n-n	2 p-n-n	3 f-n-n	4 n-p-n	5 n-f-n	6 n-n-p	7 n-n-f	8 p-p-n	9 f-f-n	10 n-p-p	11 n-f-f	12 p-p-p	13 f-f-f
Damage (%)	19.5	19.5	19.6	18.6	19.1	12.6	18.3	18.2	19.2	12.0	17.9	11.9	18.0
∆damage (%)	0.0	-0.1	0.6	-4.7	-2.1	-35.4	-6.1	-6.5	-1.6	-38.2	-8.0	-38.8	-7.6
Rutting (cm)	0.38	0.35	0.33	0.37	0.36	0.38	0.38	0.33	0.30	0.36	0.35	0.33	0.30
∆rutting (%)	0.0	-8.8	-14.8	-4.4	-5.9	-2.1	-2.3	-13.1	-20.7	-6.1	-8.2	-14.8	-23.0

* The code under the PAV number (x-x-x) indicates the presence of fibres (f), PmB (p) or none (n) in the wearing-binder-base layers.

The C-contours of the sections at the end of the analysis period are shown in Figure 16 for selected pavement sections. In these figures, the damage factor (N/Nf) value from 0 to 1 is colour represented on the cross-section of the asphalt layers. A high damage ratio is represented by the red colour and corresponds to the areas with high levels of damage. The material damage is seem to concentrate in the base layer. Thanks to the use of PMB in the bottom asphalt layer, section PAV6 presents a better performance than PAV1 and PAV7, both with a conventional penetration grade bitumen. As shown before, the use of fibres to reinforce the asphalt mixture do not significantly affect the fatigue performance. Another difference between PAV6 and PAV1/PAV7 is that the use of a better material in the base layer, slightly increase the concentration of damage in bottom of the second layer. The higher flexibility of the PMB mixture improves the resistance against fatigue of the pavement, being the damage level highly decreased. Now, the binder layer also contributes against fatigue although the stress that must support is low as can be seen in Figure 16 b).

The C-contour of PAV12 and PAV13 with all the asphalt layers incorporating PMB or FRAM is shown in Figure 16 d) and e) respectively. The use of PMB also in the binder layer reduce the damage in the bottom of this layer. As expected, the use of FRAM in all the asphalt layers (PAV13) presents little difference in terms of fatigue damage comparing to the reference PAV1 pavement.

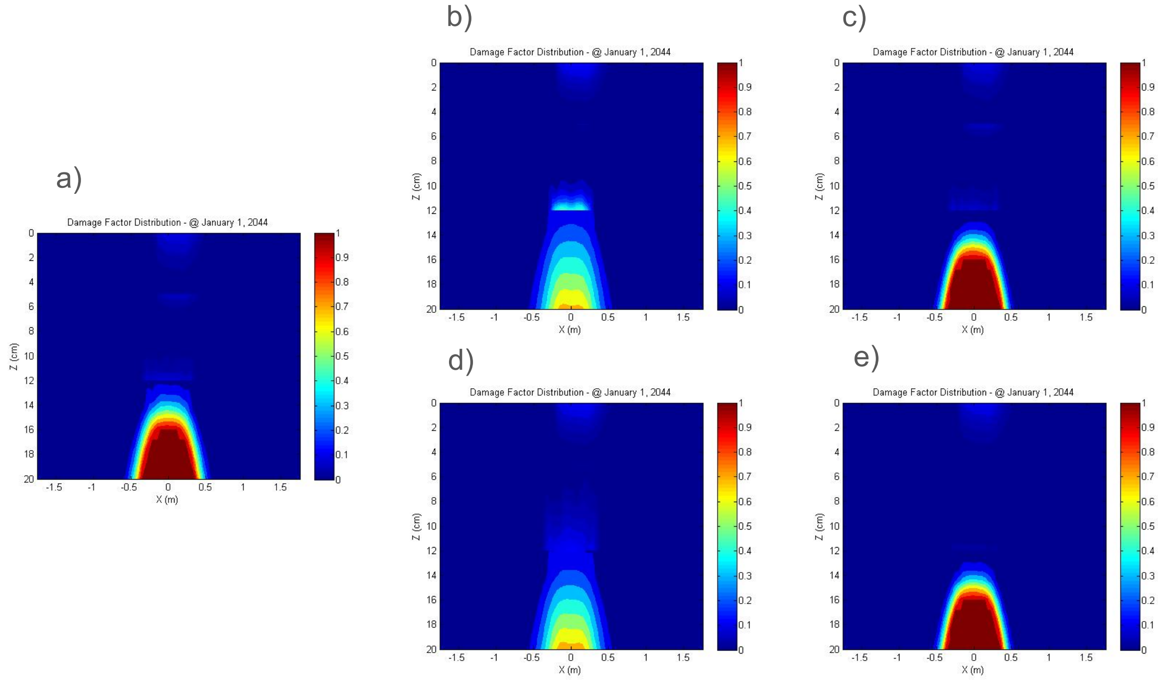


Figure 16. C-contours of the sections at the end of the analysis period: a) PAV1, b) PAV6, c)PAV7, d) PAV12 and e) PAV13

Considering previous results, a new pavement section was created that optimize both fatigue and rutting performance. This section was formed by REF22_P in the base layer and FRAC16 in the wearing course. The results of the fatigue and rutting performance of this section compared to PAV1 is shown in Figure 17. According to this, the new pavement PAV15 would reduce the % damage in 35% and the rutting depth in the asphalt layers by 21%.

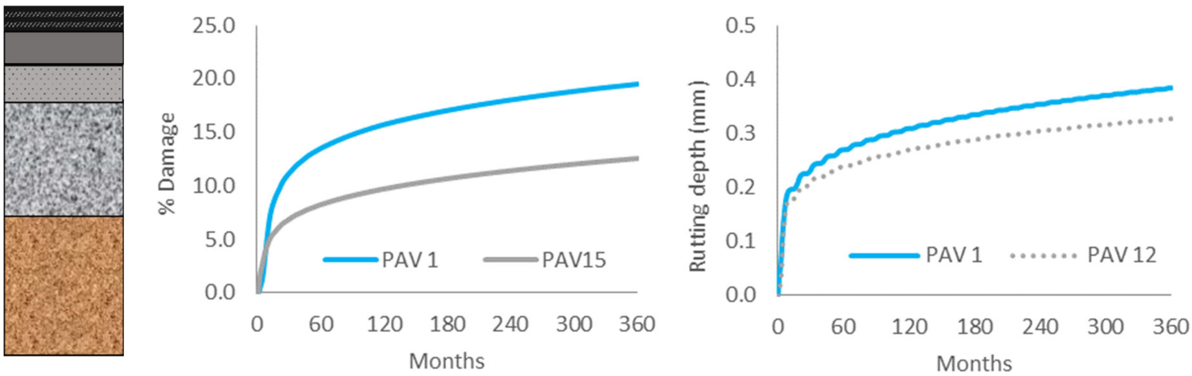


Figure 17. Fatigue and rutting performance of optimized PAV15 pavement section

Effect of climate

The results of % damage and rutting depth of each section for the three climate regions (Madrid, Frankfurt and Riga) are compared in Figure 18. A higher fatigue damage is observed in all sections in Madrid than in the other two climates. This might be due to the higher contrast in daily temperatures (bigger in Madrid than in Frankfurt and Riga) what would result in a higher fatigue damage. The increase in the % damage is in the range of 4 to 11%. Similarly, and as expected, the higher temperatures in the pavement result in higher rutting depths, up to 38% higher. When analysing the effect of the different type of mixtures in the fatigue performance of the pavement sections, slightly higher benefits are obtained when using PMB or fibres in hotter climates, but the effect is quite limited (Figure 19). In the case of the rutting performance, the use of FRAC16 in the wearing course results more beneficial as the temperature of the pavement increases. However, FRAC22 and the asphalt mixtures with PMB (REF16_P and REF22_P) increase their positive influence on the pavement in mild and cold climates. In any case, the effect of climate is reduced.

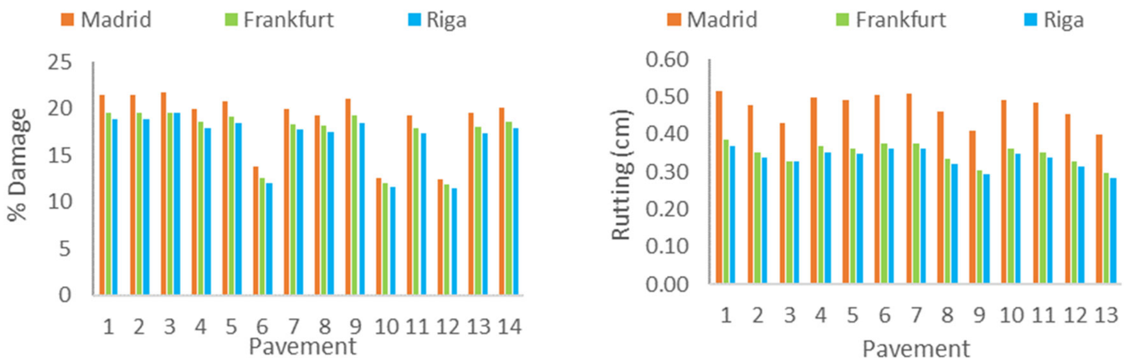


Figure 18. % Damage and rutting depth of sections in figure 11 for the three climates

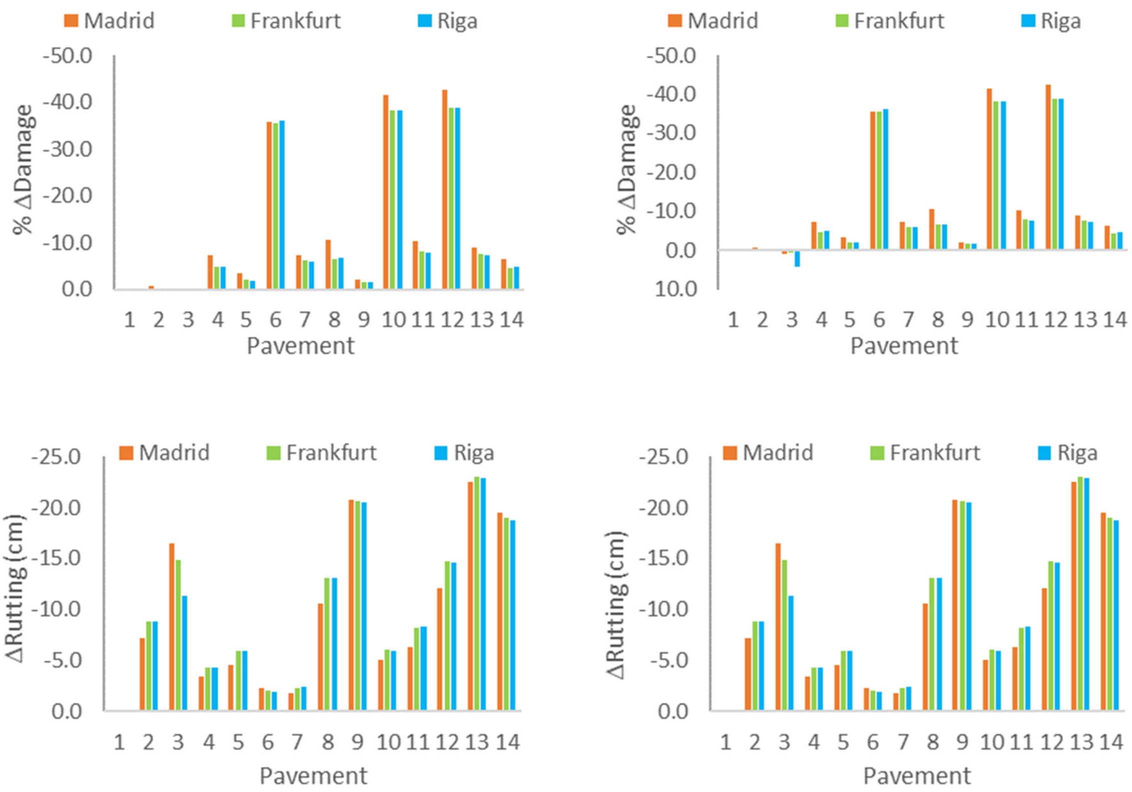


Figure 19. Fatigue and rutting performance comparing to PAV1 of the different pavement sections

3 Scaled MMLS3 tests

3.1 Motivation

New studies recently carried out at Empa have shown that the use of the model mobile load simulator MMLS3 is more efficient when the tests are conducted on mixtures produced in asphalt plants rather than at laboratory scale. Along with the plant production, the rolling compaction process used to prepare the test slabs is closer to the one followed in the construction field. Overall this type of test leads to a more accurate accelerated traffic simulation of the field performance expected for the experimental mixtures.

For this part of the project mixtures produced in the asphalt plants and used in the construction of road sections as test tracks (Task 5.1).by the project partners (BAM and Veidekke) in the Netherlands and Norway were sent to Empa for further testing

3.2 Materials

Four mixtures were tested using the MMLS3 at Empa. Two PA 8 and two AC 11. The detailed information on these mixtures can be found in deliverable 5.1 [26].

- Fibra 1, reference, conventional 2L-ZOAB 8 (PA 8) mixture with PMB with a production temperature of 185 °C.
- Fibra 4, 2L-ZOAB 8 (PA 8) with straight run bitumen and 0,05% aramid fibre with a production temperature of 165°C
- AC 11 produced with PmB. In situ air voids content of 3.4.
- AC11 with 70/100 bitumen and PAN fibres. In situ air voids content of 3.2.

The plant produced mixtures were sent to Empa. They were heated in an oven and compacted using a steel roller compactor.

3.3 Experimental procedure

The third-scale Model Mobile Load Simulator (MMLS3) (Figure 20) is a laboratory sized accelerated pavement testing machine for studying scaled pavement distress under repetitive rolling tires. The machine is 2.4 m long by 0.6m wide and 1.2 m high. It applies a downscaled load with four single pneumatic tires having a diameter of 0.3 m and a width of 0.11 m. Each tire loads the pavement width over a path length of 1.2 m with a load up to 2.1 kN, induced through a spring suspension system. At a maximum speed of 9 km/h, the MMLS3 allows approximately 7200 load applications per hour, corresponding to nearly a 2 Hz loading frequency rate. The slabs were compacted using a purposely built laboratory compactor. Density of corresponding Marshall samples was targeted.

MMLS3 was used in a fatigue testing mode in this study. As in a real pavement, the setup is designed to induce the failure of the slabs by progressing cracking with the accumulation of load applications. The asphalt slab was placed on transverse supports and the middle part was rested on a rubber to allow vertical movement. A 1cm deep transverse notch was sawed in the middle of the slab to initiate cracking. The progress of the damage of the slab was observed.

Because of initiation and progression of micro and visible cracks, the stiffness of the slabs decreases. This leads to an increase in bending deformation that was measured through the use of Linear Variable Differential Transducer sensors (LVDTs) as illustrated in Figure 20. The tests were conducted at room temperature of ca 20°C. Considering that the temperature and the loading speed are maintained constant, any change in the amplitude of the deformation cycles of the slabs represents a change in the stiffness. One slabs of each mixture type were tested [27].

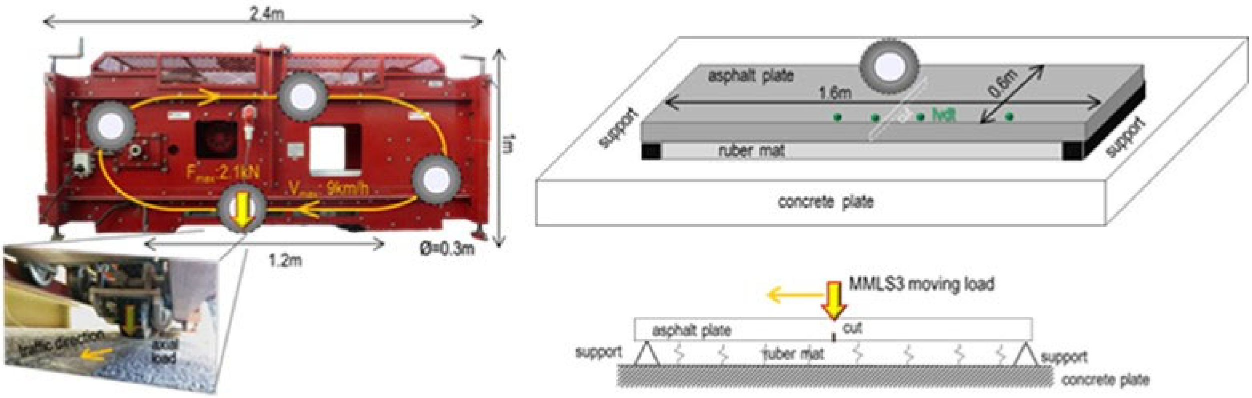


Figure 20. MMLS3 accelerated pavement testing device and testing setup [27].

3.4 Experimental results

The results of the MMLS experiments showing the number of loading cycles vs. deflection for AC 11 and PA 8 are shown in Figure 21 and Figure 22. The gap in the data in Figure 21 is due to the mandatory overnight pause and partial recovery during the experiment. Unfortunately, the mixture designated as Fibra1 failed early. As can be deduced from both these figures the reference mixtures containing PmB were more robust and both mixtures containing fibers reached catastrophic failure slightly before the mixtures with PmB. In the case of AC 11 with catastrophic failure occurring at 33,694 vs. 44,840 loading cycles, and in the case of PA 8 at 5,310 vs. 6,358 cycles. The fiber modified mixtures reached 75% and 84% of the loading cycles of PmB modified mixtures for AC 11 and PA 8 mixtures respectively. Furthermore, it can be seen that as expected, the PA mixtures fail much sooner than the AC mixtures.

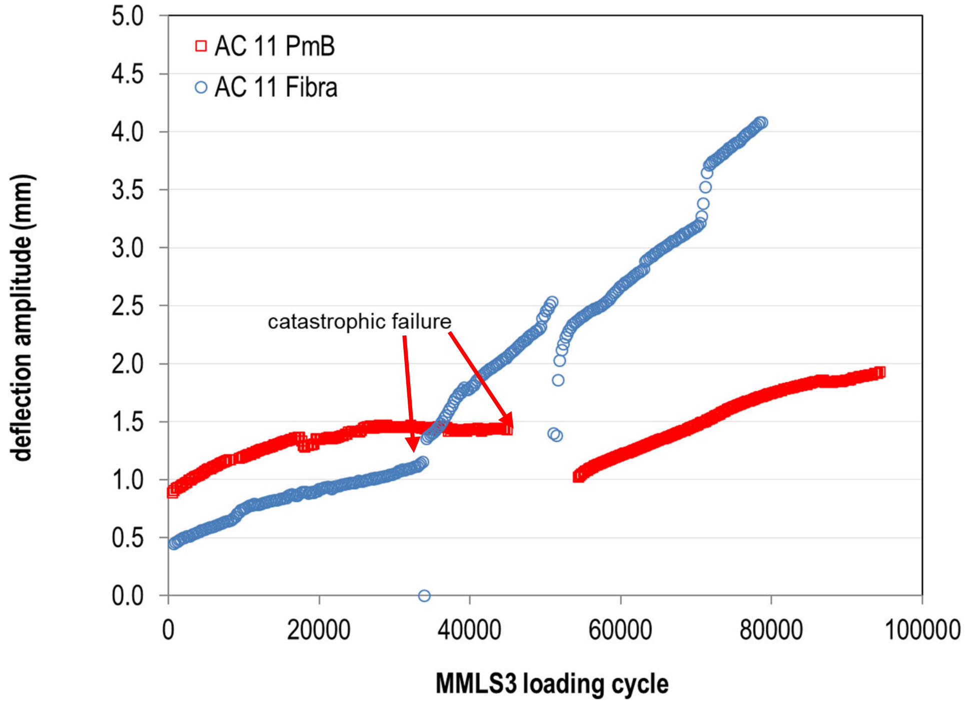


Figure 21. Number of loading cycles vs. deflection for the AC 11 mixtures

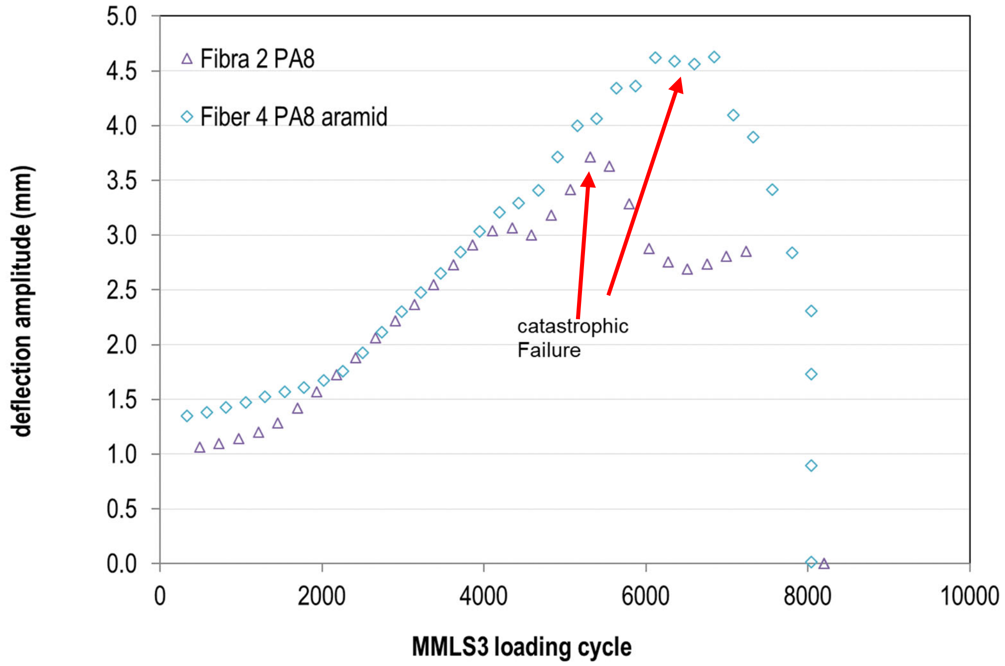


Figure 22. Number of loading cycles vs. deflection for the PA 8 mixtures

4 Conclusions and recommendations

Different pavement sections have been simulated to determine the long-term performance of pavements where FRAM mixes in one or more asphalt layers have been implemented. Their long-term behaviour is compared to conventional layers with conventional penetration grade bitumen without fibres or high performance asphalt mixtures with PMB. Different combinations of asphalt layers of standard and reinforced asphalt mixtures, traffic loads and climate conditions have been considered. The pavement responses to traffic and the fatigue damage and rutting evolution with time have been predicted by numerical analysis with FlexPAVE™.

Together with the numerical simulations, a model scaled evaluation has been carried out for the two mixtures implemented in the Netherlands and Norway (task 5.1). To do this, the special mobile load simulator MMLS3 has been used. This laboratory sized accelerated pavement testing (APT) machine studies scaled pavement distress under repetitive rolling tires.

In the light of the findings obtained from these studies, the following conclusions can be drawn:

- Fiber-reinforced asphalt concrete mixtures (FRAC), in their intact state (no aging is considered), do not have a significant effect on the fatigue life of the pavement. This is in line with the laboratory results obtained (EN 12697-24 and AASHTO TP107-18), where the fatigue performance of FRAM was similar to the reference mixture with penetration grade bitumen.
- In the tests and conditions evaluated in this study, FRAC mixtures do not achieve the fatigue performance of AC mixtures with PmB.
- The AC mixture with PmB (REF16_P and REF22_P) significantly increases the fatigue life of the pavement when it is implemented in the base layer. The effect of using these mixes in the wearing or binder course is very limited. It should be noted that current version of FlexPAVE™ does not include an aging model (to be incorporated in future versions). The incorporation of such a model would yield more top-down cracking and possibly will provide, in terms of fatigue damage, higher differences between the different mixes in the wearing course.
- The use of FRAM increases the resistance to plastic deformations of the asphalt layers in a greater extent than the asphalt layers with PMB. As expected, the use of FRAM in the wearing course has a higher impact on the rutting performance than when it is implemented in the binder or base layers.
- Very little differences have been found when analysing the impact of using FRAM in different climate regions. The weather, in terms of temperature, does not seem to be a significant variable.
- The use of FRAM in the wearing course and REF22_P in the base layer yields a pavement structure with an optimum long-term fatigue and rutting life.
- Using the MMLS3 the fiber-modified mixtures reached 75% and 84% of the loading cycles of PmB modified mixtures for AC 11 and PA 8 mixtures respectively. The result of AC mixture is in line with the numerical simulation with FlexPave™.
- Considering the overall results, in most examined cases, the fibres were more useful to decrease the rutting problems. PMB seems to be the best solution against fatigue failure at least at unaged state.

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