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FIBRA

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

Deliverable 6.3

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Table of content

1. INTRODUCTION.....	6
2. MAIN FINDINGS OF THE FIBRA PROJECT	7
2.1 Review on FRAM and application of MCDM methodology	7
2.2 Chemo-Mechanical evaluation of asphalt mixtures reinforced with synthetic fibres....	10
2.3 Impact of fibres in the behaviour of the asphalt mortar	13
2.4 Impact of fibres in the mechanical performance of asphalt mixtures (AC and PA)	16
2.4.1 Fibre selection per type of mixture	16
2.4.2 Optimal design and mechanical characterization of FRAMs	18
2.4.3 Use of fibre-reinforcement in asphalt mixtures with RAP.....	22
2.4.4 Model-scaled evaluation	23
2.5 Recyclability potential of FRAM.....	25
2.6 Impact of fibres in the mechanical performance of the asphalt pavement	26
2.7 Scaling-up and pilot section implementation	28
2.8 Environmental impact assessment.....	30
2.9 Economic feasibility assessment.....	31
3. SWOT ANALYSIS.....	32
4. APPLICABILITY, LIMITATIONS AND RECOMMENDATIONS	33

List of Tables

Table 1. Minimum service life extension to achieve 10, 20 or 30% cost savings.....	8
Table 2. Asphalt mortars tested	13
Table 3. Summary of MSCRT results for mortars designed with PmB 40/100-65 bitumen ...	14
Table 4. Summary of MSCRT results for mortars designed with 50/70 PEN bitumen	14
Table 5. Dense asphalt mixtures.....	16
Table 6. Porous asphalt mixtures.....	16
Table 7. Porous asphalt mixtures for surface layer	18
Table 8. AC mixtures.....	19
Table 9. SWOT analysis of Fibra solutions	32

List of Figures

Figure 1. WASPAS service ranking.....	7
Figure 2. Minimum service life for each FRAM to equal the impact of the reference	8
Figure 3. Selected fibres from WP2 study. Left: Polyacrylonitrile (type P). Right: blend aramid/polyolefin (type A)	9
Figure 4. Fibres' weight loss vs T. a) Aramid, b) polyolefin, c) polyacrylonitrile.	10
Figure 5. Heat flow versus T. a) aramid, b) polyolefin, c) polyacrylonitrile..	11
Figure 6. Master curves and black curves of the different bitumen samples after extraction.	11
Figure 7. ESEM image. Left: FRAM with type A fibres. Right: FRAM with type P fibres.....	12
Figure 8. LAS tests. Shear stress vs. shear strain curves.....	14
Figure 9. N_{macro} results of AFT tests. (a) PmB 40/100-65, (b) PEN 50/70	15
Figure 10. AC mixtures results. Left: Indirect tensile strength (ITS); center: Rutting testing results; right: fatigue test results.	17
Figure 11. PA mixtures Particle Loss test results.....	17
Figure 12. PA mixtures ITS results (left) and particle loss (right)	18
Figure 13. TSRST results (left) and SCB results (right)	19
Figure 14. Results from the ITS (left) and rutting tests (right)	20
Figure 15. Dynamic modulus test (AASHTO 378).....	20
Figure 16. S_{app} Cracking index (Calculated from AASHTO TP107 fatigue test).....	21
Figure 17. TSRST results	21
Figure 18. Results from the ITS (left) and rutting tests (right)	22
Figure 19. Dynamic modulus and phase angle (wearing course mixtures).....	22
Figure 20. MMLS3 accelerated pavement testing device and testing setup	23
Figure 21. Number of loading cycles vs. deflection for the AC (left) and PA mixes (right).....	23
Figure 22. Results from the ITS (left) and rutting tests (right)	25
Figure 23. Dynamic modulus and phase angle (left and center) and fatigue curve (right). Wearing course mixtures	25
Figure 24. Pavement sections simulated with FlexPAVE™ (left). Type of pavement layers and thickness (right).....	26
Figure 25. Evolution with time of the fatigue damage of different pavement sections.	27
Figure 26. Evolution with time of the rutting damage of different pavement sections.	27
Figure 27. Pilot sections in the Netherlands (up) and in Norway (down).	28
Figure 28. Cradle-to-gate analysis. PA case study (left). AC case study (right)	30

Figure 29. Min service life to equal environmental impact of the ref. PA (left). AC (right).....	30
Figure 30. NPV differences (in %) between alterantives, PA (left) and AC (right)	31
Figure 31. Sensitivity analysis of varying FRPA (left) and FRAC (right) service life.	31

1. INTRODUCTION

In the last years, fibre-reinforced asphalt mixtures (FRAM) have become a promising alternative to improve the mechanical properties and durability in road pavements. However, many uncertainties that have been identified by National Road Authorities (NRAs) concerning the implementation of the technology, such as:

- Which fibre should be used?
- Are fibres well dispersed into the asphalt mixture?
- Are the fibres compatible with the asphalt mixture?
- Which are the benefits of using fibres?
- In which layer should the fibres be optimally used?
- Are FRAM recyclable?
- Which are the technical barriers of their large-scale application?
- Are FRAM cost-effective?
- Which is the environmental impact of FRAM?...

The main objective of the FIBRA project was to provide answers to these questions and thereby identify and overcome the technical barriers for the cost-effective implementation of FRAM by NRAs. To achieve this objective the following scientific and technological objectives were addressed:

- Review previous knowledge concerning fibre-reinforced asphalt mixtures (FRAM), including the application of a multicriteria decision making (MCDM) methodology for the selection of the most promising fibres for this application.
- Understand the functional mechanism of fibres including the evaluation of the blending properties of the fibre and the asphalt mixture components and the impact of fibre reinforcing in the asphalt mortar.
- Optimal design and mechanical characterization of fibre-reinforced asphalt mixtures. Two type of asphalt mixtures have been designed: fibre-reinforced asphalt concrete (FRAC) and fibre-reinforced porous asphalt (FRPA).
- Evaluate the impact of adding fibres to asphalt mixtures with high RAP content.
- Evaluate the effect of incorporating FRAM in different layers within the asphalt pavement by numerical simulation.
- Evaluate the recyclability potential of FRAM.
- Up-scaling, implementation of a pilot section and short-term assessment.
- Evaluate the economic and environmental feasibility of the technology.

This report presents the most significant outcomes of the FIBRA project and provides recommendations and suggestions for the applicability of FRAM according to the acquired knowledge.

2. MAIN FINDINGS OF THE FIBRA PROJECT

2.1 Review on FRAM and application of MCDM methodology

A full analysis of the state of the art was performed in order to achieve the most promising fibres for the reinforcement of asphalt mixtures. Several types of fibres were evaluated, including the analysis of their mechanical effect on the asphalt mixture, their production process and also the economic and environmental impact of this technology.

The most commonly types of fibres in the literature are polymeric, Cellulose, Geogrid and Glass, Fabric and Carpet, Carbon and Aramid fibres. Their functions can be divided basically in three groups: fibres used to modify asphalt, to retain bitumen, and to strengthen the mortar.

Mechanical Performance

In order to select the best fibre according to its mechanical performance, a multicriteria decision methodology (MCDM) was applied. The selection of the evaluation criteria was done considering the most analysed parameters and the available data according to the literature review performed. The mechanical parameters considered to carry out this activity were rutting, fatigue life, toughness and indirect tensile strength. An Analytics Hierarchy Process (AHP) to give weights to the different mechanical criteria by sending a questionnaire to worldwide experts was used. Once the weights were defined according to the priority of experts, the multicriteria decision methodology was applied with the Weighted Aggregated Sum Product Model (WASPAS). Polyacrylonitrile (type P) and aramid/polyolefin fibres (POA), a blend of polyolefin and aramid fibres, obtained the best result (Figure 1).

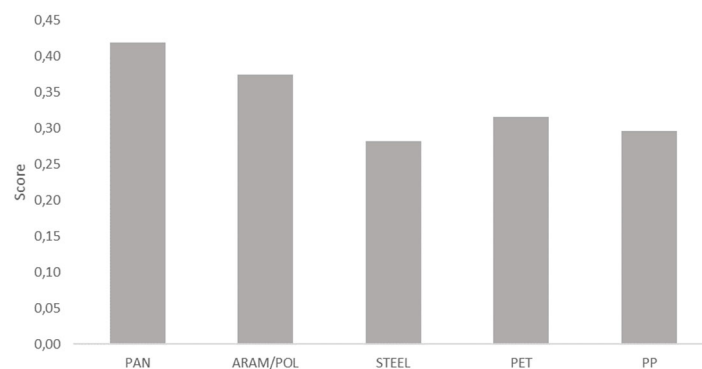


Figure 1. WASPAS service ranking

This analysis considered only the improvement of fibres when incorporated into asphalt dense mixtures due to the lack of information related to the use of fibre reinforcement in open grade asphalt mixes. As first conclusion, it can be noted that the application of fibres in dense mixtures has reached a higher development than in the case of Porous asphalt mixtures (PA), in which the fibres are basically used as a method to retain the binder.

Environmental analysis

The environmental impact was carried out by comparing the production process of each fibre and the mass of fibre that is usually added to the asphalt mixtures. Gabi 2017 database, Life cycle inventory and other data from the providers of the fibres were the sources to perform the

environmental analysis. A cradle to gate Life Cycle Assessment (LCA) of 1 ton of hot mix asphalt (HMA) with and without the incorporation of reinforcement fibres was carried out.

The environmental analysis showed that polyacrylonitrile fibres are the fibres with the lowest environmental impact in all the methods used. On the other hand, Nylon and steel fibres were in most of the cases at the bottom of the ranking (Figure 2).

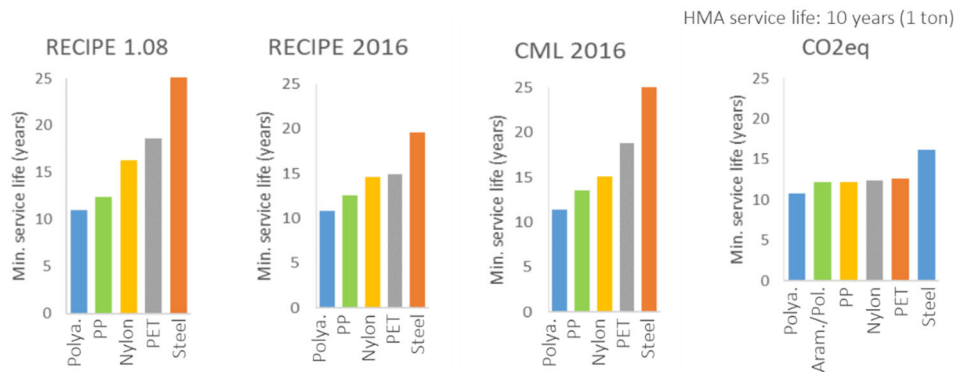


Figure 2. Minimum service life extension for each FRAM to equal the impact of the reference

Cost – benefit analysis

The cost-benefit analysis has been carried out by comparing the cost per kilometre of each FRAM layer. In order to calculate the cost increase due to the fibre addition, the cost of producing and laying a conventional HMA has been assumed in 65 €/ton. This preliminary cost benefit analysis gives an idea of the minimum effectivity that should be provided by each fibre. However, these results should be only considered when the effect of the fibres on the durability of the asphalt mixtures is known. According to the results, PET and Polyacrylonitrile fibres obtained the best economic impact, followed by Aramid / polyolefin and steel fibres.

Table 1. Minimum service life extension to achieve 10, 20 or 30% cost savings

Fibre	Service Life extension (%)		
	10% savings	20% savings	30% savings
Polyacrylonitrile	25	40	60
Aramid / Polyolefin	31	47	68
PET	21	37	56
NYLON	37	54	76
STEEL FIBRE	30	47	68
PP	33	50	71

State of development of the technology

In addition to the mechanical performance and the economic and environmental feasibility of the technology, the status of development of the fibres was also taken into account. Three categories were considered: 1) if the FRAM were explored in the laboratory, 2) if the FRAM were implemented in pilot sections and 3) if the fibres were commercially available for asphalt mixes reinforcement.

Fibre selection

According to the results and conclusions obtained in this first study, two fibres were selected: Polyacrylonitrile (type P) and the blend of aramid/polyolefin (type A).



Figure 3. Selected fibres from WP2 study. Left: Polyacrylonitrile. Right: blend aramid/polyolefin

More information

More information about the methodology followed and the results obtained can be found in:

- Deliverable 2.1 – Literature review on the use of fibres in asphalt mixtures
- Slebi-Acevedo, C. J., Lastra-González, P., Pascual-Muñoz, P., & Castro-Fresno, D. (2019). Mechanical performance of fibres in hot mix asphalt: A review. *Construction and Building Materials*, 200, 756-769. doi:10.1016/j.conbuildmat.2018.12.171
- Carlos J. Slebi-Acevedo, Pablo Pascual-Muñoz, Pedro Lastra-González & Daniel Castro-Fresno (2021) A multi-criteria decision-making analysis for the selection of fibres aimed at reinforcing asphalt concrete mixtures, *International Journal of Pavement Engineering*, 22:6, 763-779, DOI: 10.1080/10298436.2019.1645848

2.2 Chemo-Mechanical evaluation of asphalt mixtures reinforced with synthetic fibres

In this work, the most important mechanisms governing the microstructural properties of the asphalt matrix concerning the different fibre dispersions were analysed. In particular, thermal and chemical analysis were carried out on the two previously selected fibres when incorporated to asphalt mixtures. On the other hand, the assessment of the rheological properties of bituminous binders recovered from the FRAM were also performed.

Thermal characterization of the fibres

In order to investigate the thermal transitions of these three types of fibres (polyacrylonitrile, aramid and polyolefin), a differential scanning calorimeter (DSC) was used. Furthermore, the thermal stability of the fibres was analysed by thermal gravimetric analysis (TGA). For both fibres forming type A (aramid and polyolefin), the weight of the sample is kept constant until temperatures above 450°C and for fibre type P, the weight loss starts at a temperature close to 280°C (Figure 4). Therefore, at conventional production temperatures of hot asphalt mixes (ca. 160°C), none of the fibres suffer any thermal degradation.

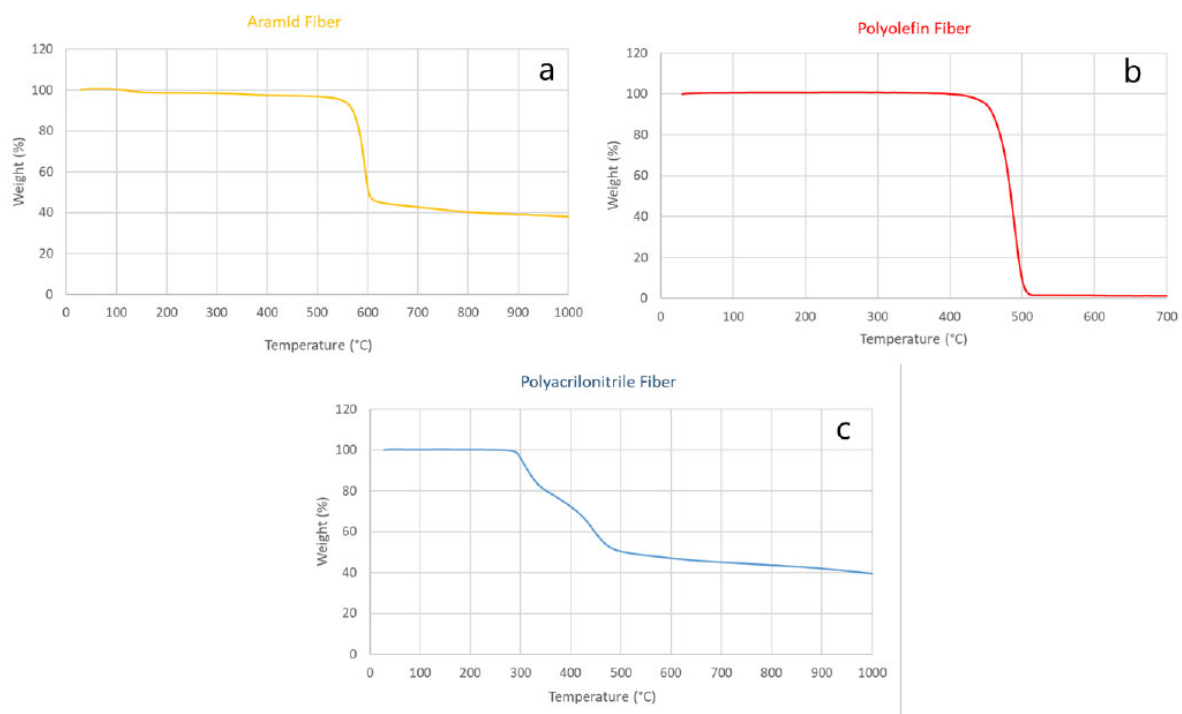


Figure 4. Fibres' weight loss vs T. a) Aramid fibre, b) polyolefin fibre, c) polyacrylonitrile fibre.

The fibres were also thermally analysed for a large temperature range (from 20 °C to 500 °C) by calorimetry in order to study the thermal transitions of the fibres. Aramid fibres melt at temperatures about 400°C so no chemical modification would occur during asphalt mixtures production so any effect on the response of the FRAM will be due to a physical interaction. Concerning the polyacrylonitrile fibres, the fibre starting to decompose at 300°C so, as in the case of the aramid fibre, far from the production temperatures of FRAM. On the other hand, the polyolefin fibres showed a melting temperature of 124.5°C, which is lower than production

temperature (ca. 160°C). Therefore, a potential modification of the bitumen influencing the behaviour of the FRAM could be expected.

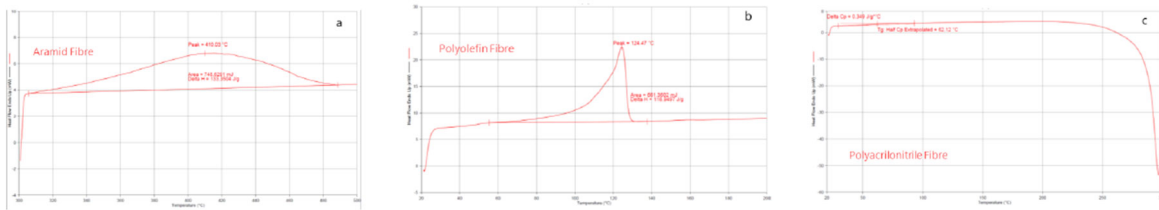


Figure 5. Heat flow versus T . a) aramid fibre, b) polyolefin fibre, c) polyacrylonitrile fibre.

Rheological analysis

The bitumen from FRAM samples was extracted and tested to carry out rheological analysis and measurements of its softening point. Softening point values of the bitumens recovered from FRAM are quite similar to those obtained from the reference mixtures. Similarly, in the rheological analysis, the master curves as well as the black curves obtained from the different bitumen samples indicate that the addition of fibres do not alter or modify the bitumen.

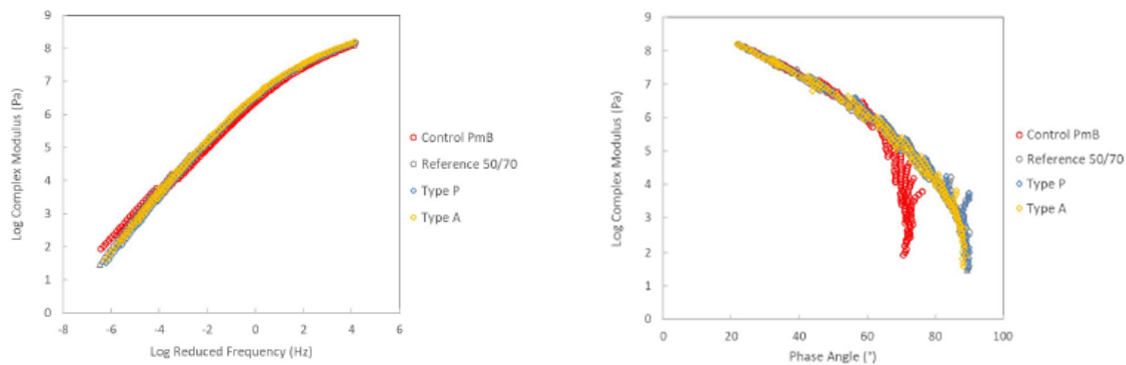


Figure 6. Master curves and black curves of the different bitumen samples after extraction.

Image analysis of FRAM

As part of the experimental plan designed for WP3, four dense asphalt mixtures were produced and cylindrical specimens were compacted: one control mixture with Polymer-modified Bitumen (PmB), one reference mixture with 50/70 penetration grade bitumen and two FRAM, one with polyacrylonitrile fibre and the other with a blend of aramid/polyolefin. Samples of the produced FRAM were evaluated using the Environmental Scanning Electron Microscope (ESEM). The ESEM analysis was performed with EDX (Energy Dispersive X-Ray Spectroscopy) option for chemical analysis.

The presence of some aramid fibres (identified by their unusual shape and chemical analysis can be identified in Figure 7 (left). Polyolefin are not detected probably because they melt during the mixing process. In Figure 7 (right), the presence of parts of type P fibre can be clearly observed and they are homogeneously distributed. The higher presence of type P in the image is probably a consequence of their higher concentration (0.15%) compared to type A fibres (0.05%).

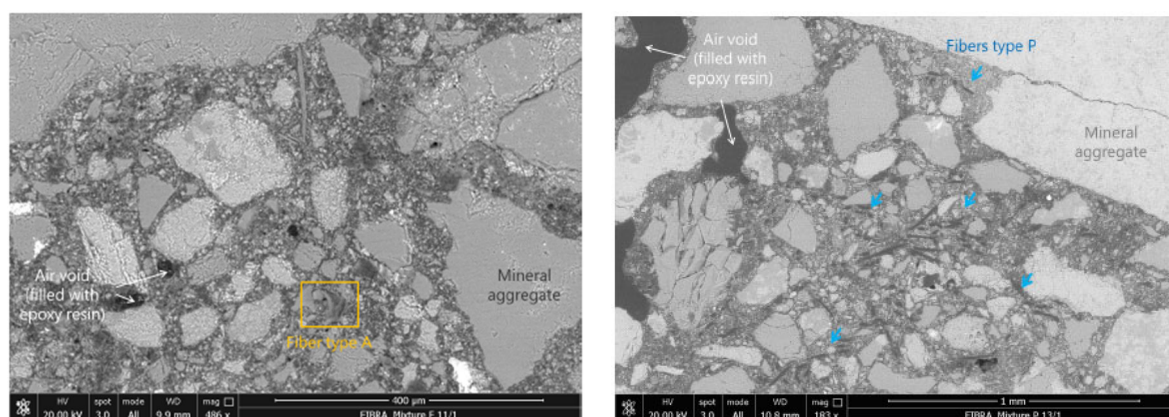


Figure 7. ESEM image. Left: FRAM with type A fibres. Right: FRAM with type P fibres.

More information

More information about the methodology followed and the results obtained can be found in:

- Deliverable 3.2 – Chemo-mechanical understanding of FRAM.
- Bueno, Moises & Poulikakos, Lily. (2020). Chemo-Mechanical Evaluation of Asphalt Mixtures Reinforced With Synthetic Fibres. *Frontiers in Built Environment*. 6. 10.3389/fbuil.2020.00041.

2.3 Impact of fibres in the behaviour of the asphalt mortar

Due to the important role of the asphalt mortar in the material response and the mechanical performance of the asphalt mixture, especially in porous asphalt mixtures, the impact of adding fibres was evaluated. 18 different asphalt mortars were prepared using different bitumen types (PEN and PmB), different type of fibres (type A and type P) and two aging conditions. The standard Rolling Thin Film Oven Test (RTFOT) and Pressure Aging Vessel (PAV) were applied to some asphalt mortars to simulate the short-term, long-term and double long-term aging conditions in the laboratory environment.

Table 2. Asphalt mortars tested

Classification Aging condition	asphalt mortar					
	40/100-65			50/70		
	No fibre	fibre A	fibre P	No fibre	fibre A	fibre P
Fresh	√	√	√	√	√	√
RTFOT	√	√	√	-	-	-
RTFOT+PAV	√	√	√	√	√	√
RTFOT+2PAV	√	√	√	-	-	-

* Pen: Penetration (0.1 mm), Soft: Softening point (°C),
√: prepared material, -: not prepared material

Rheological tests

Rheological tests were then conducted to the set of asphalt mortars in a wide range of temperatures. In particular, the following tests were applied:

- The response of the mortar to permanent deformation was addressed based on the Multiple Stress Creep and Recovery test (MSCRT) in a DSR based on the standard AASHTO T350.
- The Linear Amplitude Sweep (LAS) test was used to evaluate the fatigue resistance capability of the asphalt mortar based on the standard AASHTO TP101.
- A new testing method named Accelerate Fatigue Test (AFT), a fatigue testing method based on the same concept of LAS but relaying on stress control mode.
- Bending Beam Rheometer (BBR) based on the standard AASHTO T313.

Multiple Stress Creep and Recovery test

The numerical results for the mortars designed with PmB and PEN bitumen are reported in Table 3 and Table 4 respectively. MSCRT indicates that mortars prepared with Polyacrylonitrile fibres showed the highest value of recovery in mortars with PEN bitumen, suggesting remarkable benefits in terms of permanent deformation.

Table 3. Summary of MSCRT results for mortars designed with PmB 40/100-65 bitumen

Asphalt mortar		R percent recovery [%] under the loading stress [kPa]					Non-recoverable compliance, J_{nr} under the loading stress [kPa]				
		0.1	3.2	6.4	12.8	25.6	0.1	3.2	6.4	12.8	25.6
No fibre	Fresh	51.96	52.23	50.45	43.71	34.05	0.287	0.215	0.424	0.859	1.745
	RTFOT	56.27	51.82	50.55	44.11	34.28	0.143	0.149	0.294	0.588	1.207
	1PAV*	70.22	67.84	64.48	61.83	54.72	0.020	0.023	0.051	0.109	0.260
	2PAV*	82.69	75.36	73.63	68.29	59.06	0.008	0.009	0.019	0.049	0.138
Type A	Fresh	56.41	49.25	44.20	37.26	28.57	0.227	0.267	0.567	1.155	2.279
	RTFOT	61.30	54.77	49.31	42.85	33.93	0.103	0.134	0.327	0.727	1.522
	1PAV*	74.20	71.08	68.16	61.42	49.97	0.015	0.020	0.046	0.126	0.356
	2PAV*	84.22	76.42	72.60	72.77	63.78	0.004	0.007	0.015	0.035	0.102
Type P	Fresh	57.55	54.25	52.46	45.38	35.19	0.202	0.215	0.424	0.861	1.755
	RTFOT	60.56	52.88	52.20	46.51	37.09	0.095	0.116	0.235	0.472	0.966
	1PAV*	69.96	66.31	64.38	60.27	52.30	0.022	0.026	0.051	0.120	0.287
	2PAV*	76.60	71.13	67.71	61.29	48.30	0.008	0.011	0.026	0.064	0.190

1PAV*: RTFOT+PAV; 2PAV*: RTFOT+2PAV.

Table 4. Summary of MSCRT results for mortars designed with 50/70 PEN bitumen

Asphalt mortar		R percent recovery [%]		Non-recoverable compliance, J_{nr}	
		0.1 kPa	3.2 kPa	0.1 kPa	3.2 kPa
No fibre	Fresh	10.56	3.53	0.758	0.837
	1PAV*	11.63	4.71	0.554	0.602
Type A	Fresh	8.86	1.50	0.832	0.992
	1PAV*	11.00	3.71	0.697	0.771
Type P	Fresh	12.21	3.87	0.822	0.930
	1PAV*	11.27	4.18	0.596	0.661

1PAV*: RTFOT+PAV.

Linear Amplitude Sweep (LAS) and Accelerate Fatigue Test (AFT)

LAS tests were only performed on the mortar prepared with PEN bitumen 50/70. All the tested mortars presented similar curves even under the different aging conditions, except for the type P fibre mortar under the RTFOT+PAV that a significant reduction was found.

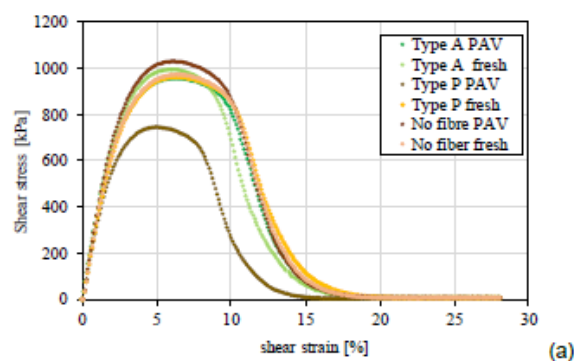


Figure 8. LAS tests. Shear stress vs. shear strain curves.

The AFT was performed on the entire set of mortars. The results are shown in Figure 9. According to this figure, type A fibre showed better performance for the fatigue resistance compared to type P in the mortars prepared with PmB. On the contrary, fibres type P presented more benefits in enhancing the fatigue resistance than fibres type A with mortars prepared with PEN bitumen. According to this, aramid fibres works better in a modified bitumen and polyacrylonitrile fibres in PEN bitumen.

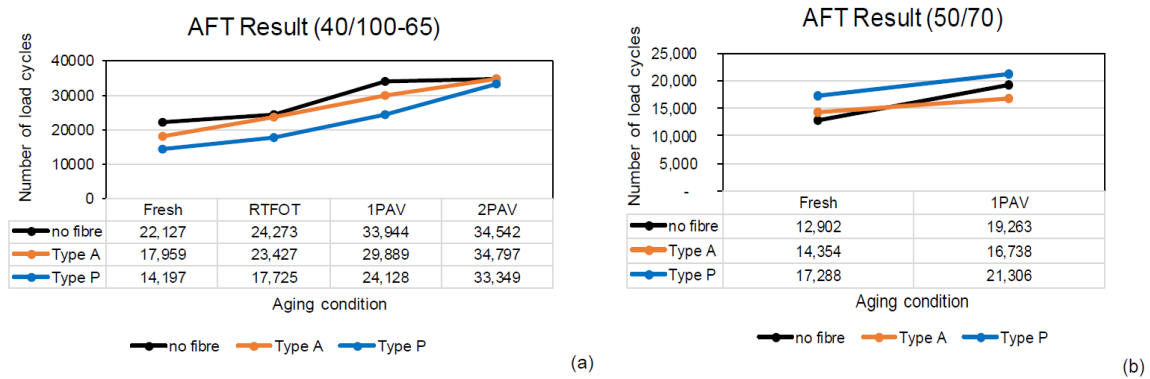


Figure 9. N_{macro} results of AFT tests. (a) PmB 40/100-65, (b) PEN 50/70

Indirect Tensile Test and fracture parameters

In addition to the rheological tests, the Indirect Tensile Test (IDT) was performed according to the European standard EN 1269747-23. The stress-strain curves were recorded so the energetic parameters of fracture were measured.

At 15°C, no difference were found in the results of the different specimens and at 0°C none of the fibres gives a positive impact on ITS or FE properties; even in some cases, the results were significantly lower, especially with type P fibres. However, at low temperatures (-15°C), the addition of 0.3% of both type of fibres significantly increases the ITS and FE values of the mortar samples, with a greater influence in the case of aramid/polyolefin fibres (type A).

More information

More information about the methodology followed and the results obtained can be found in:

- Deliverable 3.1 – Mechanical response of FRAM and PA mortar properties
- Slebi-Acevedo, C. J., Lastra-González, P., Castro-Fresno, D., & Bueno, M. (2020). An experimental laboratory study of fibre-reinforced asphalt mortars with polyolefin-aramid and polyacrylonitrile fibres. Construction and Building Materials, 248 doi:10.1016/j.conbuildmat.2020.118622.

2.4 Impact of fibres in the mechanical performance of asphalt mixtures (AC and PA)

A complete research work was performed at the laboratory level with the aim of understanding how FRAM work and how fibres affect the mechanical performance of the asphalt mixture.

2.4.1 Fibre selection per type of mixture

Initially, two different asphalt mixtures, an asphalt concrete and a porous asphalt, were designed using different fibres (type A or type P), so the optimum fibre can be selected for each type of asphalt mixture. Four dense asphalt mixtures (Table 5) and eight different porous asphalt mixtures (Table 6) were designed to evaluate their mechanical properties. Two different lengths for the type P fibres (4 and 12mm) and two different filler contents (high-H and low-L) were also evaluated in the PA mixtures.

Table 5. Dense asphalt mixtures

Mixture	Binder	Fibre (%)
ACB22H-Control	PmB 45/80 – 65	-
ACB22H-Reference	50/70	-
ACB22H-type P	50/70	0.15
ACB22H-type A	50/70	0.05

Table 6. Porous asphalt mixtures

	Bitumen		Fibre		Filler
	Type	Dosage ¹	Length	Dosage ¹	Dosage ²
Ref H	50/70	4.3	-	-	4.9
type A-H	50/70	4.3	19	0.05	4.9
type P12-H	50/70	4.3	12	0.05	4.9
type P4-H	50/70	4.3	4	0.05	4.9
Ref L	50/70	4.3	-	-	4.3
type A-L	50/70	4.3	19	0.05	4.3
type P12-L	50/70	4.3	12	0.05	4.3
type P4-L	50/70	4.3	4	0.05	4.3

¹ Dosage: (% b/w of mix); ²Dosage: (%b/w of agg.)

To analyse the mechanical performance of fibre-reinforced asphalt concrete (FRAC) mixes, water sensitivity test (EN 12697-12), rutting resistance test (EN 12697.22) and fatigue resistance test (EN 12697-24) were performed. In the case of the fibre-reinforced porous asphalt mixture (FRPA), volumetric properties such as the bulk specific gravity (EN 12697-6), total air voids (EN 12697-8), interconnected voids (ASTM D7063-05) and permeability with the radial flow falling head permeameter were evaluated, as well as the Cantabro test (EN 12697-17), the Indirect tensile test (En 12697-23).

ITS, rutting resistance and fatigue tests results are shown in Figure 10. The addition of fibres improves the ITS compared to the asphalt mixtures without fibres, both in dry and wet conditions, being the mixture with fibre type P the one with the best performance. As for the water sensitivity tests, similar good results were obtained for all the mixtures. Regarding rutting resistance, type P showed a similar performance comparing to the PmB mixture, although type A fibre obtained the worse result among all the mixtures. Concerning fatigue, a lower

performance comparing to the asphalt mixture with PmB is obtained. Comparing to the asphalt mixture with PEN bitumen, FRAM could improve fatigue response at lower strains while similar results are obtained at higher strain levels.

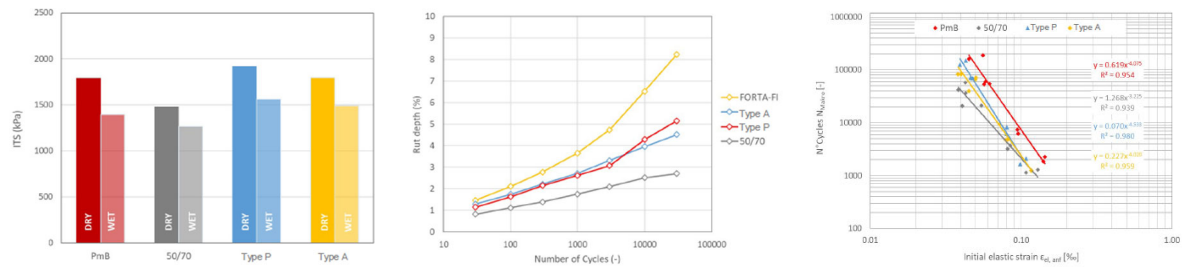


Figure 10. AC mixtures results. Left: Indirect tensile strength (ITS); center: Rutting testing results; right: fatigue test results.

Concerning the volumetric results in the PA mixtures, although the addition of fibres reduce the total air voids in the mixture, its functionality (permeability) is not severely affected, being in all the FRPA higher than 100 m/day (1.2 mm/s). As for the particle loss, the use of fibres positively affects ravelling in dry conditions (Figure 11), obtaining improvements up to 40% when using fibres type A and low filler concentrations. Nevertheless, the fibres did not improve the ravelling resistance in wet conditions. An increase of the binder content is suggested to completely coat the fibre-aggregate matrix to prevent their exposition to water.

Based on these results and on the results obtained in previous sections, type P fibres (4mm) were selected for its use in AC fibre-reinforcement due to their highest rutting performance, while type A fibres were selected for their use in PA mixtures due to the general best mechanical performance found in these types of mixtures.

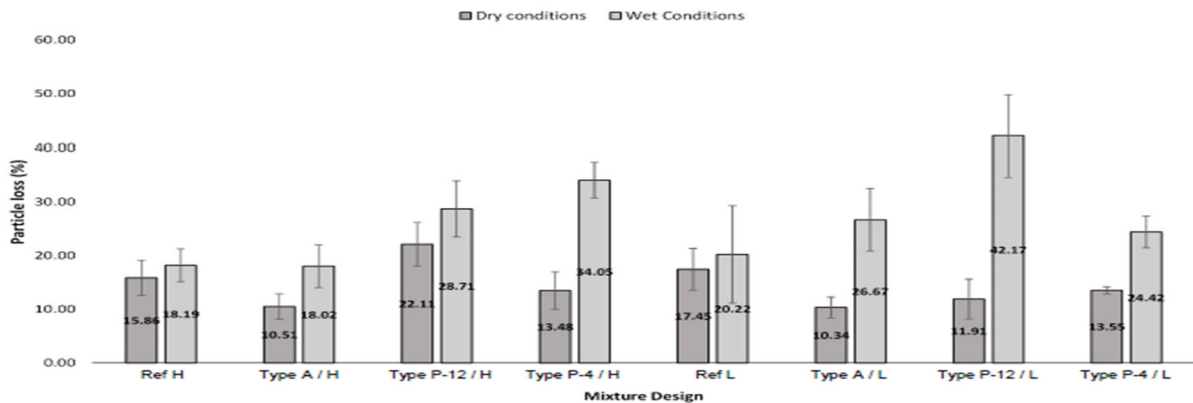


Figure 11. PA mixtures Particle Loss test results.

2.4.2 Optimal design and mechanical characterization of FRAMs

Once selected the fibres for each type of mixture, a more detailed laboratory research was done to evaluate the reinforcing effect of the fibre in AC and PA mixtures.

Fibre-reinforced Porous Asphalt (FRPA) mixes

Five PA mixtures with a nominal maximum aggregate size of 16mm were designed for their use in surface layers (Table 7). Three of the five mixtures were used as references, one with PEN bitumen, one with PmB and one with PEN bitumen and cellulose fibres. As for the FRPA mixtures, two different bitumen content were tested.

Table 7. Porous asphalt mixtures for surface layer

PA16	Ref 1	Ref 2	Ref 3	FRPA-1	FRPA-2
Bitumen / mixture (%)	4.5	4.5	5	4.5	5
Type of bitumen	50/70	PMB	50/70	50/70	50/70
Type of fibre	-	-	Cellulose	type A	type A
Fibre / mixture (%)	-	-	0.5	0.05	0.05

Air void (EN 12697-8), drain-down (EN 12697-18), Cantabro particle loss (EN 12697-17), ITS (EN 12697-23), moisture sensitivity (EN 12697-12) and thermal cracking resistance tests were carried out. Thermal cracking resistance tests included the Thermal Stress Restrained Specimen (TSRST) (EN 12697-46) and the Semi-Circular Bend (SCB) (EN 12697-44).

The incorporation of type A fibres does not notably affect the functional performance of the mixtures, with both FRPA mixture having porosities over 20%. On the other hand, fibres increase the ITS values in both dry and wet conditions, being the FRPA with the higher bitumen content, the mixture with the highest values (Figure 12 (left)). Concerning water sensitivity, FRPA increases the moisture resistance of the mixtures with conventional PEN grade bitumen.

As for the Cantabro test results, the effect of increasing the bitumen content is clearly seen in Figure 12 (right). A significant difference performance is observed between both FRPA mixtures (1 and 2). It seems that an extra amount of bitumen is needed to adequately cover the fibres and effectively achieve a reinforcement effect on the mixture. Comparing to the reference mixture with PEN bitumen, the FRPA increase resistance to ravelling. However, the performance of the PA mixture with PmB is not reached.

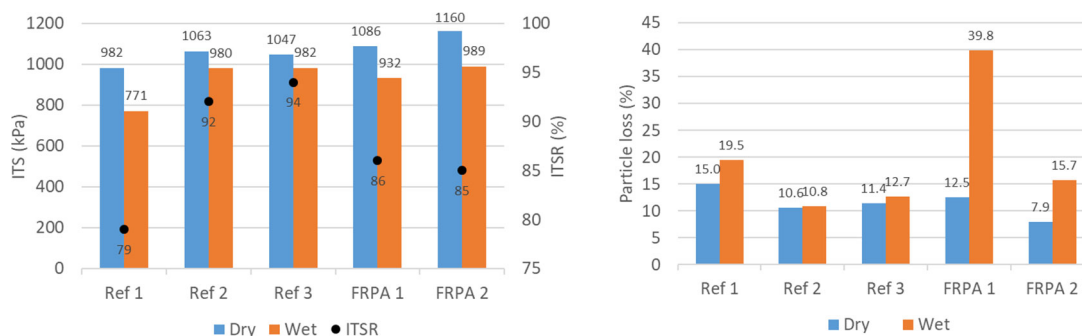


Figure 12. PA mixtures ITS results (left) and particle loss (right)

Thermal cracking resistance and fracture energy were only determined for Ref-2 and FRPA-2 mixes. According to the TSRST and SCB results (Figure 13), the FRPA mixtures do not reach the performance at low temperatures achieved by the PmB mixture.

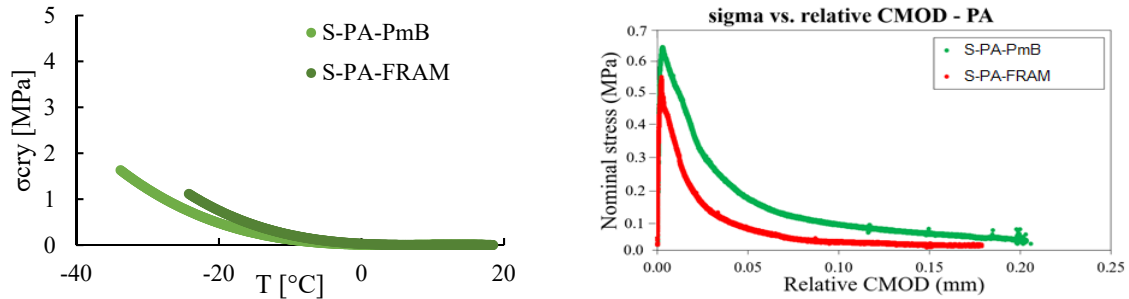


Figure 13. TSRST results (left) and SCB results (right)

Fibre-reinforced Asphalt Concrete (FRAC) mixes

Seven AC mixes have been produced, three specifically designed for the surface, two for the binder and two for the base course. In all cases, fibre type P (0.15%) was added (Table 8).

Table 8. AC mixtures

Layer	Mixtures ID	Bitumen type	Bitumen content (%)
Surface layer	REF16	50/70	4.3
	FRAC16-1	50/70	4.3
	FRAC16-2	50/70	4.6
Binder layer	REF22-P	PmB 45/80-65	4.4
	FRAC22	50/70	4.4
Base layer	REF22	50/70	4.2
	FRAC22B	35/50	4.2

Volumetric properties (EN 12697 – 6), ITS (EN 12697 – 23), moisture sensitivity (EN 12697-12), rutting (EN 12697-22), stiffness (EN 12697-26), fatigue resistance (EN 12697-24) and thermal cracking tests (TSRST (EN 12697-46) and SCB (EN 12697-44)) were carried out. Fracture energy parameters (FE, PE and toughness) were also determined. In addition to the previous tests, the dynamic modulus (AASHTO 378), as well as the rutting (AASHTO TP134-19) and fatigue damage (AASHTO TP107) were also evaluated according to AASHTO standards and using the Asphalt Mixture Performance Tester (AMPT).

Concerning ITS and moisture sensitivity, in general, the addition of fibres increases the ITS in both dry and wet conditions (Figure 14, left), although the ITSR of some of the FRAM are similar or slightly lower (comparisons are made among the mixtures designed for the same layer). On the other hand, a remarkable improvement in the rutting performance is obtained when adding fibres to asphalt mixture with conventional PEN graded bitumen. When comparing to asphalt mixtures with PmB, similar outstanding results are obtained.

D4.1 Practical instructions for the design and characterization of FRAM

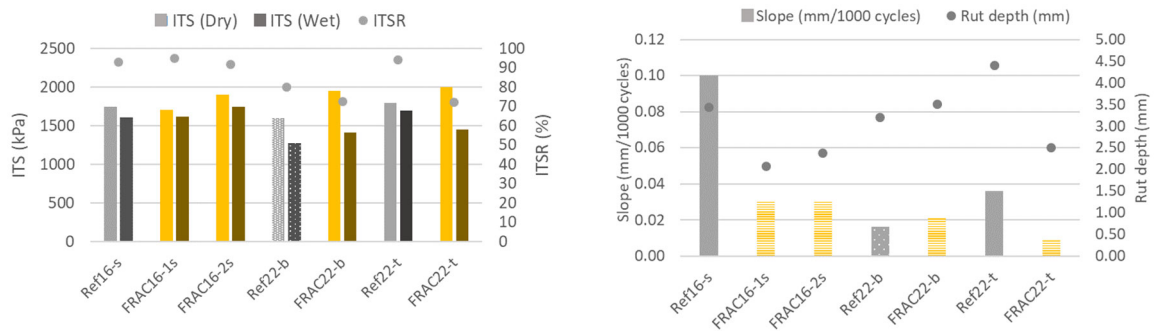


Figure 14. Results from the ITS (left) and rutting tests (right)

Regarding stiffness, all the FRAM mixtures have similar or better results than the reference with PEN bitumen. In particular, the asphalt mixtures designed for the wearing course presented almost the same curves. For the asphalt mixtures designed for the binder course, similar or even better mechanical properties can be achieved by using fibres. The mixture designed with PmB has a lower stiffness and higher phase angle than both FRAM and AC mixture with PEN grade bitumen.

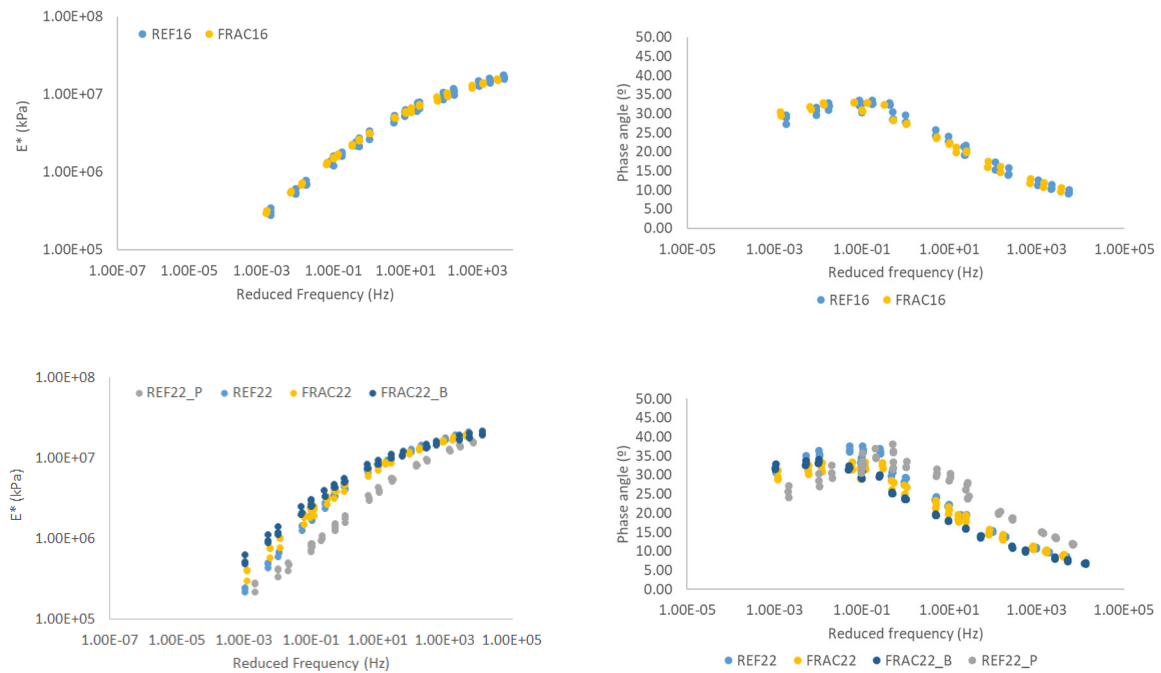


Figure 15. Dynamic modulus test (AASHTO 378)

The fatigue performance of the mixtures following AASHTO standards are shown in Figure 16. FRAM mixes present similar and slightly better results than the reference mixtures with PEN bitumen according to both AASHTO and EN standards. In both tests, the reference mixture with PmB presents a significant better fatigue resistance.

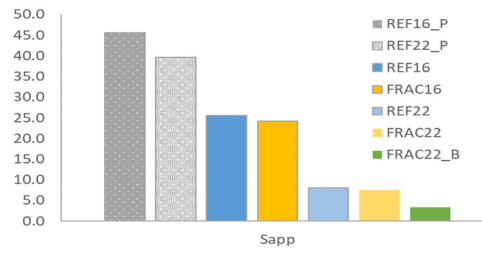


Figure 16. S_{app} Cracking index (Calculated from AASHTO TP107 fatigue test)

According to the results obtained in the TSRST and SCB tests, a low affection in the thermal cracking and the fracture energy at low temperatures is observed when fibres are added (Figure 17), comparing to the mixtures with PEN bitumen. On the other hand, the use of a PmB significantly improves the low temperature performance of the asphalt mixture.

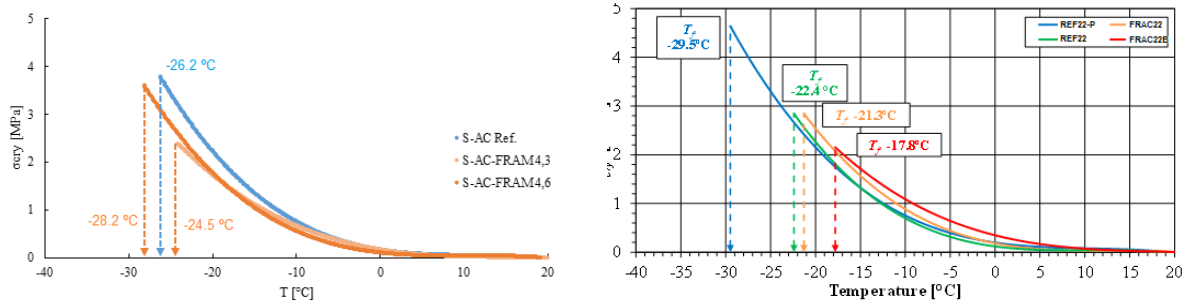


Figure 17. TSRST results

2.4.3 Use of fibre-reinforcement in asphalt mixtures with RAP

The impact of adding fibres to asphalt mixture with RAP was also explored. Two percentages of RA were incorporated (30% and 50%). The low percentage (30%) was added to the mixtures designed for the wearing course: an AC16 mixture prepared with a 50/70 PEN bitumen (Ref16-30%RA) and an AC16 mixture prepared with 50/70 PEN bitumen and 0.15% of type P fibres (FRAC16-30%RA). The higher percentage (50%) was added to the mixtures designed for the binder course: an AC22 mixture prepared with a PmB 40/100-65 (Ref22-50%RA) and an AC22 mixture prepared with 50/70 PEN bitumen and 0.15% type P fibres (FRAC22-50%RA)

The following tests were carried out to evaluate the mechanical performance of the mixtures: Volumetric properties (EN 12697 – 6), ITS (EN 12697 – 23), moisture sensitivity (EN 12697-12), rutting (EN 12697-22), stiffness (EN 12697-26), fatigue resistance (EN 12697-24) and thermal cracking tests (TSRST (EN 12697-46) and SCB (EN 12697-44)) were carried out. Fracture energy parameters (FE, PE and toughness) were also determined.

In general, the performance of the mixtures is quite similar (Figure 18 and Figure 19). The impact of the fibres was less evident due to the effect of the RAP increasing the stiffness and rutting resistance.

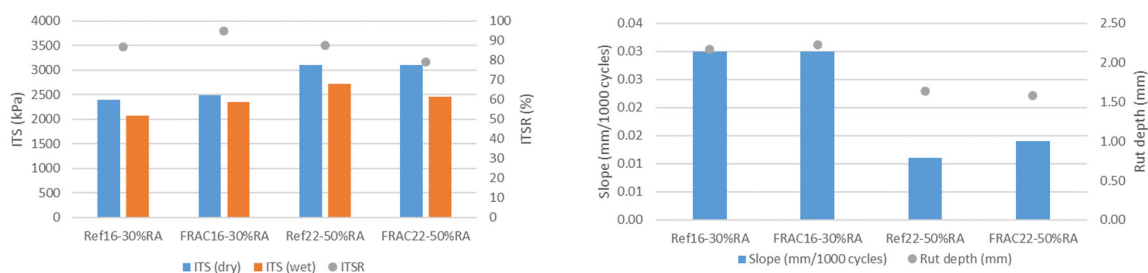


Figure 18. Results from the ITS (left) and rutting tests (right)

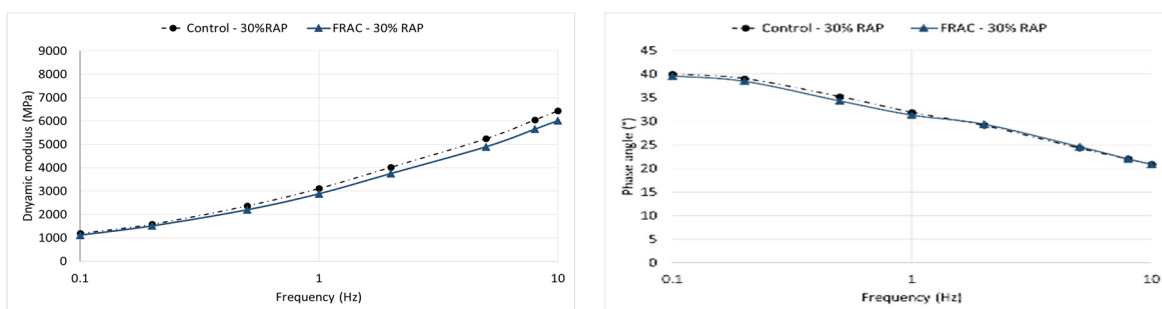


Figure 19. Dynamic modulus and phase angle (wearing course mixtures)

2.4.4 Model-scaled evaluation

A middle-scaled evaluation of FRAM was carried out through the third-scale Model Mobile Load Simulator (MMLS3) available at Empa (Figure 20). This equipment is a laboratory sized accelerated pavement testing machine for studying scaled pavement distress under repetitive rolling tires. MMLS3 was used in a fatigue-testing mode in this study. Four mixtures have been tested using the MMLS, the same that were later implemented in the pilot sections. Two porous asphalt mixtures produced by BAM in the Netherlands and two asphalt concrete mixtures produced by Veidekke in Norway:

- Ref-PA, 2L-ZOAB 8 (PA 8) mixture with PMB.
- FRPA, 2L-ZOAB 8 (PA 8) with 70/100 bitumen and 0,05% aramid fibre.
- Ref-AC, AC11 mixture with PMB.
- FRAC, AC11 with 70/100 bitumen and 0.15% type P fibres.

According to the results (Figure 21), reference mixtures designed with PmB are more robust, the fibre modified mixtures reached 75% and 84% of the loading cycles of PmB modified mixtures for AC 11 and PA 8 mixtures respectively.

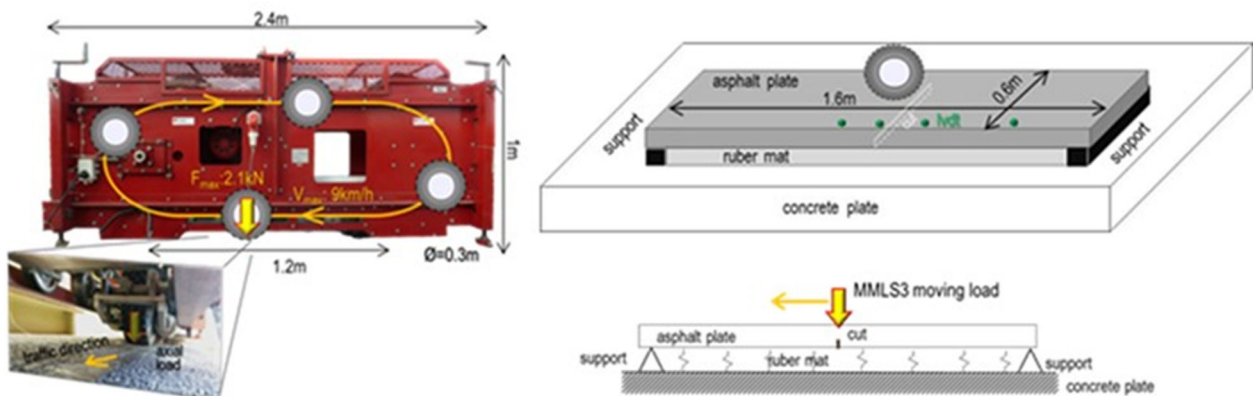


Figure 20. MMLS3 accelerated pavement testing device and testing setup

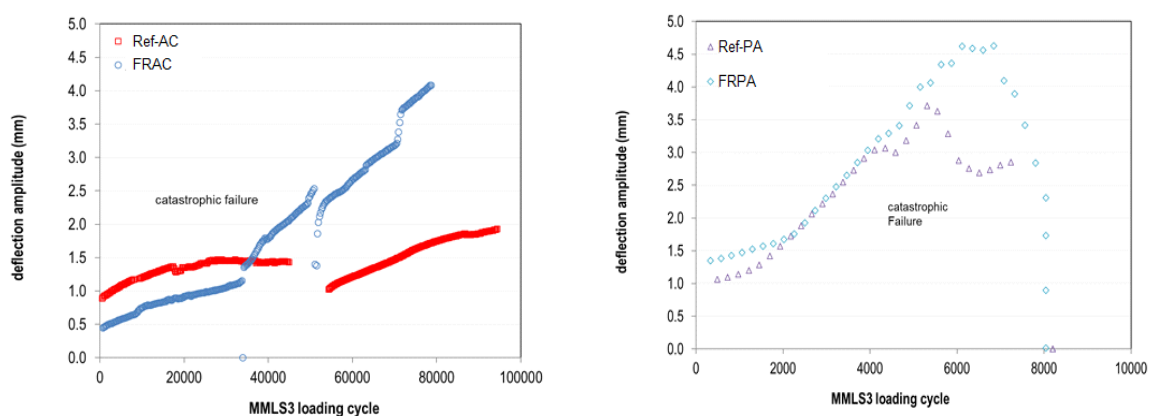


Figure 21. Number of loading cycles vs. deflection for the AC (left) and PA mixes (right)

More information

More information about the methodology followed and the results obtained can be found in:

- Deliverable 4.1 – Practical instruction for the design and characterization of FRAM.
- Deliverable 4.2 – Practical instruction for the structural design of pavements containing FRAM.
- Slebi-Acevedo, C. J., Lastra-González, P., Indacoechea-Vega, I., & Castro-Fresno, D. (2020). Laboratory assessment of porous asphalt mixtures reinforced with synthetic fibres. *Construction and Building Materials*, 234 doi:10.1016/j.conbuildmat.2019.117224.

2.5 Recyclability potential of FRAM

The recyclability of FRAM was analysed due to the importance this has on the environmental performance of asphalt mixtures. RAP from FRAC (type PRAP) was added in a percentage of 50% to two different asphalt mixture, an AC16 mixture with 70/100 PEN bitumen (Ref-type PRAP) and an AC16 mixture with 70/100 PEN bitumen and fibres type P (FRAC-type PRAP). As it is assumed that the fibres present in the type PRAP are still valid, only 0.075% of type P fibre was added. Concerning the type PRAP, due to the unavailability of real RAP with fibres, FRAC mixes were artificially aged according to a standard procedure (AASTHO R30).

The following tests were carried out to evaluate the mechanical performance of the mixtures: Volumetric properties (EN 12697 – 6), ITS (EN 12697 – 23), moisture sensitivity (EN 12697-12), rutting (EN 12697-22), stiffness (EN 12697-26), fatigue resistance (EN 12697-24) and thermal cracking tests (TSRST (EN 12697-46) and SCB (EN 12697-44)) were carried out. Fracture energy parameters (FE, PE and toughness) were also determined.

In general, a good mechanical performance was obtained by both recycled mixtures. Comparing to the mixtures without RAP and, as occurs with conventional asphalt mixtures, the addition of a high percentage of RAP (in this case type PRAP) increases the ITS, the stiffness and the rutting resistance while reducing the fatigue resistance and the low temperature performance. Thus, the main conclusion of this study is that FRAM mixes are recyclable to the same extent than conventional asphalt mixtures. On the other hand the extra addition of fibres improves the ITS and rutting performance while stiffness, fatigue and low temperature performance are not affected.

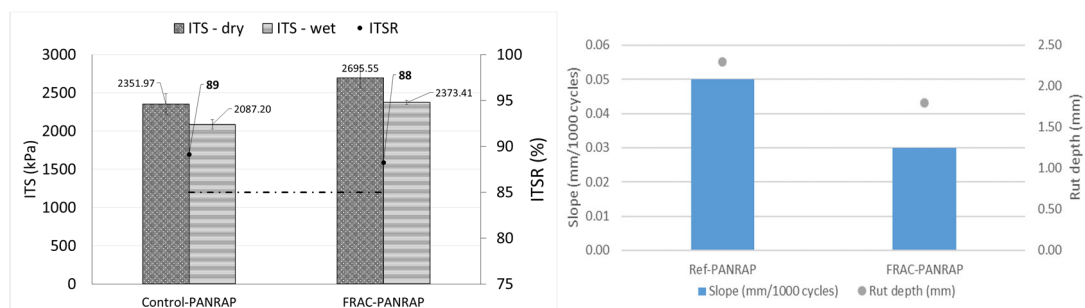


Figure 22. Results from the ITS (left) and rutting tests (right)

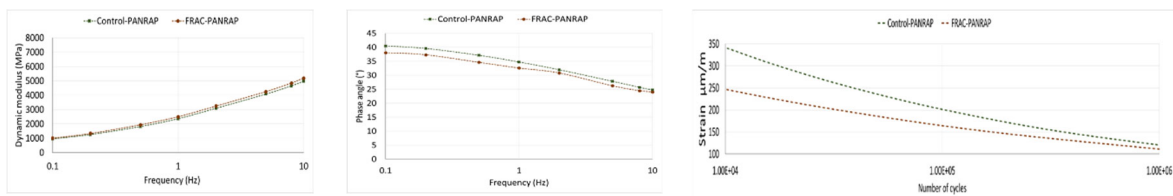


Figure 23. Dynamic modulus and phase angle (left and center) and fatigue curve (right). Wearing course mixtures

More information

More information about the methodology followed and the results obtained can be found in:

- Deliverable 4.1 – Practical instruction for the design and characterization of FRAM.

2.6 Impact of fibres in the mechanical performance of the asphalt pavement

To analyse the impact on the durability of road pavements of implementing FRAM in one or more asphalt layers, the pavement structural analysis program FlexPAVE™ was used. This tool, developed by researchers at the North Carolina State University (NCSU), is able to calculate the long-term deterioration of an asphalt pavement section in terms of fatigue damage and rut depth. In FlexPAVE™, the viscoelastic continuum damage (VECD) model¹ is employed to address fatigue cracking and the permanent strain shift model is used to address rutting². To feed the models, the needed parameters were obtained from the laboratory tests (AASHTO standards) described in section 2.4.2.

Different pavement sections were studied with FRAM placed in one or more asphalt layers. Reference pavement structure are also analysed with no FRAM in any of the layers or with AC mixtures with PmB in one or more layers (Figure 24).

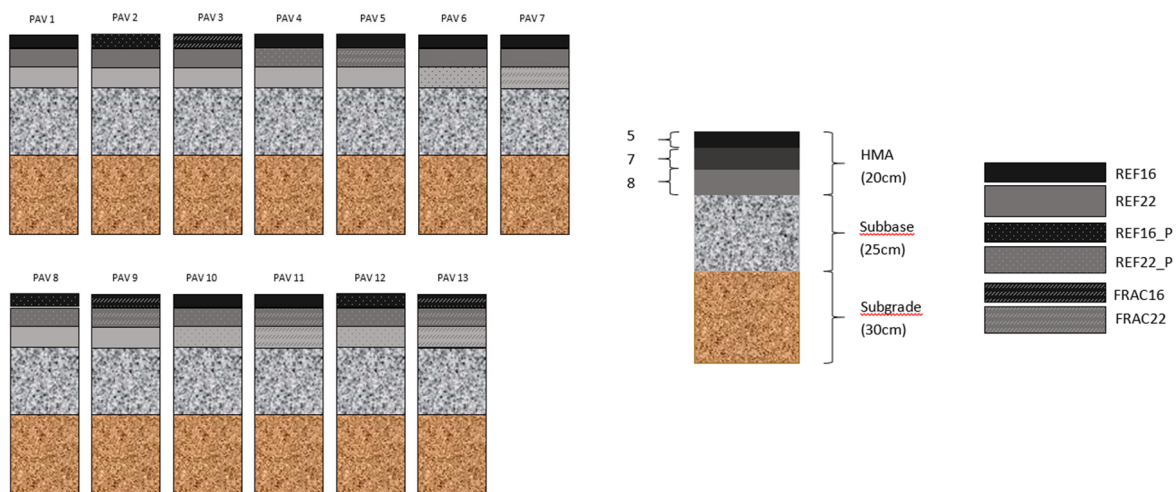


Figure 24. Pavement sections simulated with FlexPAVE™ (left). Type of pavement layers and thickness (right)

The software analysis showed that FRAC do not have a significant effect on the fatigue life of the pavement, being the AC with PmB in the base course the best configuration to improve this property (35% lower damage) (Figure 25). However, the use of FRAC increases the resistance to plastic deformations of the surface layer in a greater extent than the asphalt layers with PMB (15% depth reduction versus 9%). On the other hand, 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 (Figure 26).

¹ Kim, Y.R., H.J. Lee, and D.N. Little, "Fatigue Characterization of Asphalt Concrete Using Viscoelasticity and Continuum Damage Theory," Journal of the Association of Asphalt Paving Technologists, Vol. 66, 1997, pp. 520-569.

² Choi, Y.T. and Y.R. Kim, "Implementation and Verification of a Mechanistic Permanent Deformation Model (Shift Model) to Predict Rut Depths of Asphalt Pavement," Road Materials and Pavement Design, Vol. 15, No. 1, 2014, pp. 195-218.

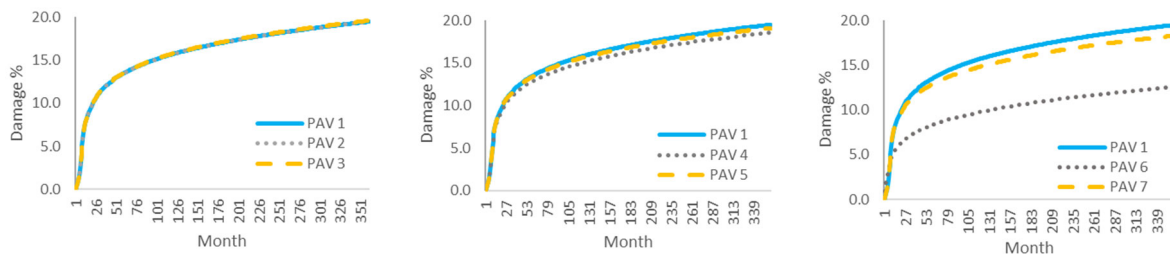


Figure 25. Evolution with time of the fatigue damage of different pavement sections.

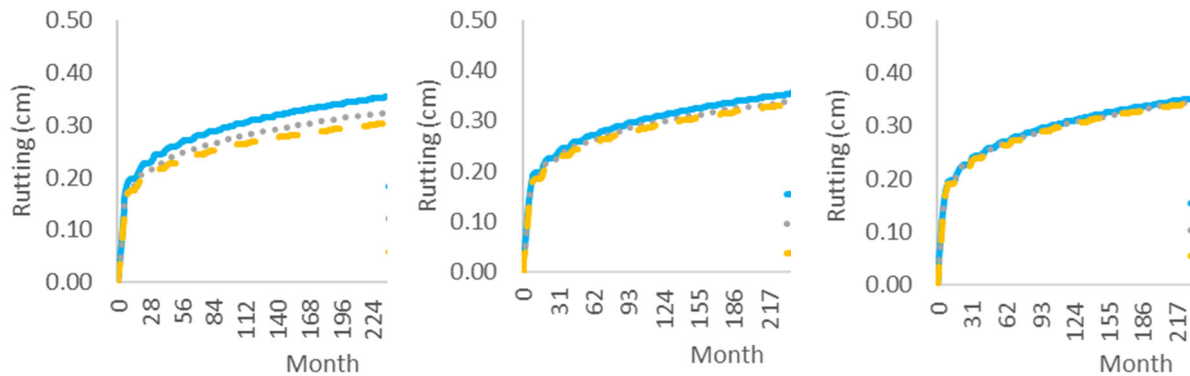


Figure 26. Evolution with time of the rutting damage of different pavement sections.

More information

More information about the methodology followed and the results obtained can be found in:

- Deliverable 4.2 – Practical instruction for the structural design of pavements containing FRAM.

2.7 Scaling-up and pilot section implementation

The production process of the asphalt mixtures designed and characterized at the laboratory was upgraded to the industrial scale by the two industrial partners of the project. The upscaling of the PA mixtures was carried out by BAM in the Netherlands and the upscaling of the AC mixtures by VEIDEKKE in Norway. This way, the technology is validated for two type of mixtures, in two different asphalt plants and in two different countries with different specifications and methods. Both comtype Pies carried out a laboratory adaptation of the mixture compositions according to the specifications of the materials, pilot section's requirements and the standards and specifications of each country.

Concerning the pilot section in the Netherlands, two experimental FRPA layers were proposed. In both cases, a two-layer porous asphalt (2L-PA) mixture was selected, one reinforced with aramid fibre and the other one with polyacrylonitrile fibre. As control mixtures, two 2L-PA mixes without fibres, one with 70/100 PEN bitumen and the other with a 40/100-65 PmB were also implemented. The four sections were built on a two-lane (one directions) motorway with an AADT of 50,000 vehicles (Figure 27).

In Norway, one experimental FRAC layer was implemented in the pilot section. An AC11 mixture with a 70/100 PEN bitumen reinforced with type P fibres. As control mixtures, also two AC11 mixtures without fibres, one with a 70/100 PEN bitumen and the other with a 40/100-65 PmB. The three sections were built on a two-lane (two directions) national road with an AADT of 3000 vehicles (Figure 27).



Figure 27. Pilot sections in the Netherlands (up) and in Norway (down).

Main outcomes from the upscaling of the production process at the asphalt plants and the pilot sections implementation can be summarised as follows:

- The use of synthetic fibres does not prevent binder drainage due to the limited amount of added fibre. Thus, a combination of synthetic fibres and cellulose fibres is recommended in bitumen-rich mixtures such as the 2L-PA8.
- The use of synthetic fibres in combination with PEN bitumen allows to reduce the production temperature by 20°C compared to reference mixtures with PMB.
- FRAM can well be produced in an existing asphalt plant. Addition of fibres can be carried out manually with a pre-packed low-melt bag.
- Production speed of FRAM is slightly lower than that of the reference mixtures because of the manual addition of the fibres comparing to the automatic process of the conventional mixes.
- Production, laying and compaction can be carried out with regular equipment and procedures.
- In both pilot sections, the fibres are homogeneously distributed in the mixtures and no clusters are formed.
- The DSR mortar response test show that FRAM shows less aging susceptibility than that of the reference mixtures without fibres.
- Functional properties of the 2LPA mixtures are not altered by the addition of fibres. Drainage capacity and noise-reducing performance are not affected by the addition of fibres since all the mixtures obtained similar results.
- Concerning abrasion by studded tires, FRAM and PMB mixtures performed better than the asphalt mixture with PEN bitumen.

More information

More information about the methodology followed and the results obtained can be found in:

- Deliverable 5.1 – Scaling up of the production process and implementation of test sections.

2.8 Environmental impact assessment

Cradle-to-gate and cradle-to-grave Life Cycle Assessments (LCA) were carried out to evaluate the environmental performance of road pavements that include a FRAM in the surface layer comparing to conventional pavement designs. Two LCA were carried out that correspond to the two pilot sections implemented. T

When a cradle-to-grave analysis is carried out, the effect of adding fibres or PmB is highly attenuated. Actually, the addition of fibres results in an environmental impact increase of less than 2-7% in both analysed case studies. Therefore, the use of FRAM increase the environmental of the road pavement, although in a limited way. In the PA case study (the Netherlands), if FRPA mixtures are used, the road pavement should last just only 0.5 years longer than the reference in order to match the environmental impact. In the case of the AC case study (Norway), the pilot section with the FRAC mixture should last two extra years than the conventional AC11 section with PEN (Figure 29).

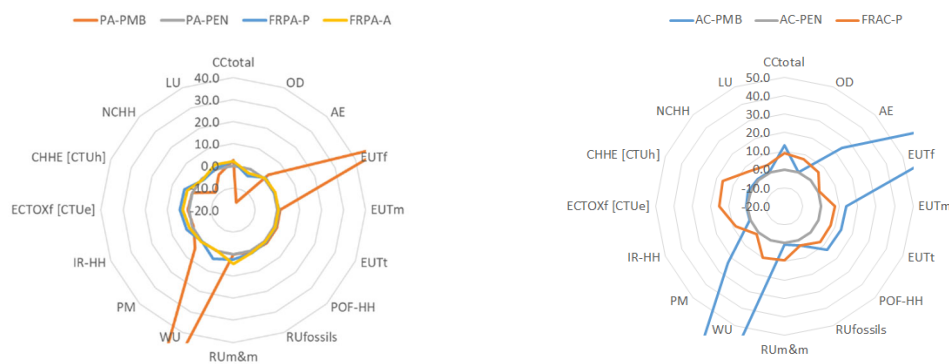


Figure 28. Cradle-to-gate analysis. PA case study (left). AC case study (right)

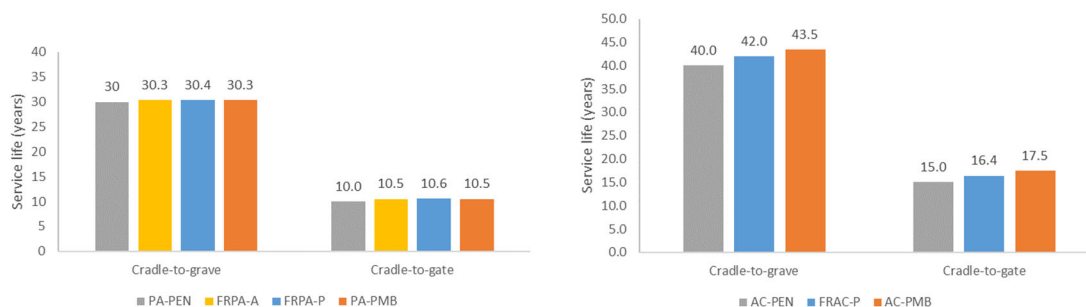


Figure 29. Minimum service life to equal environmental impact of the reference. PA (left). AC (right)

More information

More information about the methodology followed and the results obtained can be found in:

- Deliverable 5.2 – Assessment of the environmental impact of FIBRA pavements

2.9 Economic feasibility assessment

A Life Cycle Cost Analysis (LCCA) was performed to evaluate the long-term economic efficiency of FRAM. The LCCA methodology is applied to two case studies. The first one corresponds to the pilot section built in the Netherlands. In this section, the type of mixture used was a 2 layer porous asphalt (2L-PA). The second one corresponds to the pilot section built in Norway, where asphalt concrete (AC) mixtures were implemented. To carry out this analysis, all the significant present and future costs were calculated over the life of the pavement and expressed in present value (Net present value – NPV). Monte-Carlo simulations were carried out to take into account uncertainties in discount rate and service life.

For the conditions analysed in this study, and assuming the same service life, similar life cycle costs are obtained for all the alternatives evaluated in each case study (Figure 30). To consider FRAMs as an economically feasible alternative, a similar durability than the asphalt mixture with PmB needs to be achieved in case study n1 and a slightly higher durability needs to be achieved (around 10%) than the asphalt mixture with PEN in case study n2 (Figure 31).

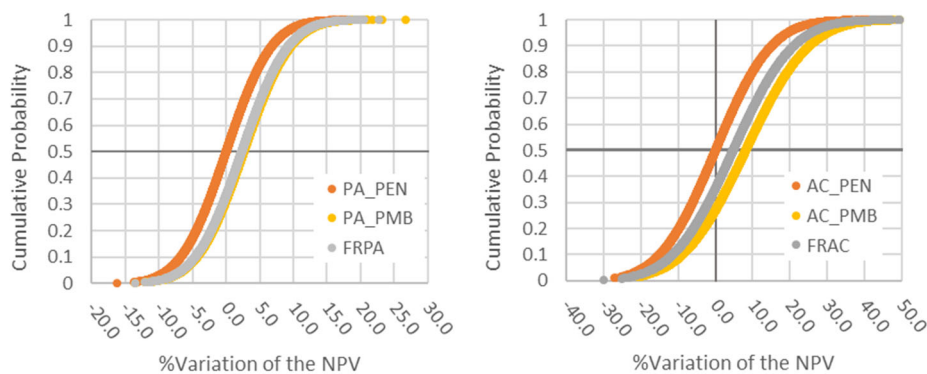


Figure 30. NPV differences (in %) between alternatives, PA mixes (left) and AC mixes (right)

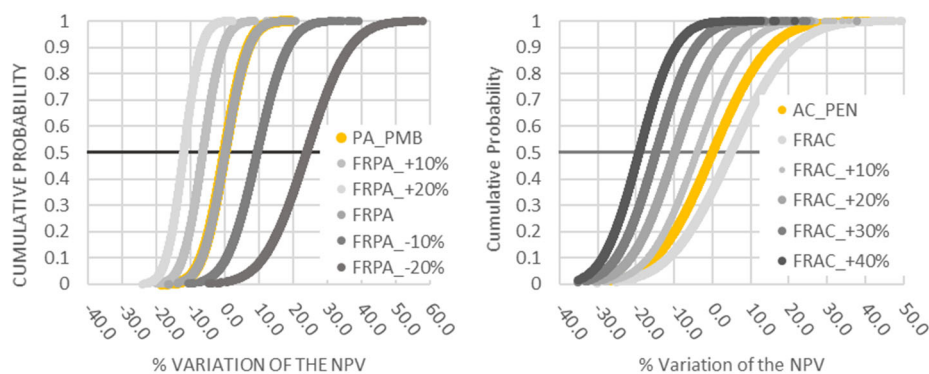


Figure 31. Sensitivity analysis of varying FRPA (left) and FRAC (right) service life.

More information

More information about the methodology followed and the results obtained can be found in:

- Deliverable 5.3 – Assessment of the economic feasibility of Fibre-reinforced Asphalt Pavements.

3. SWOT ANALYSIS

A "Strengths, Weakness, Opportunities and Threats" (SWOT) analysis was also carried out to identify where the technology of the FIBRA project stands and its real potential. Thus, the SWOT analysis facilitates the visualization of the current state and the market situation with respect to the solution for the decision-making process (Table 9).

Table 9. SWOT analysis of Fibra solutions

	HELPFUL To exploit the result	HARMFUL To exploit the result
INTERNAL ORIGIN (attributes of the technology)	STRENGTHS <ul style="list-style-type: none"> - FRAC improves ITS and rutting resistance of AC mixtures comparing to reference mixtures with PEN bitumen without negatively affecting other properties. - FRPA improves the ITS and particle loss resistance comparing to reference mixtures with PEN bitumen. - Better mechanical properties comparing to reference mixtures with PEN bitumen but still lower production temperatures (15-20°C) than mixtures with PMB. - No special equipment or uncommon mix sequences are needed to produce FRAM. No initial investment is needed. - No modifications of the layer construction processes (i.e. laying and compaction) are needed. - Recyclability is not affected by the addition of fibres. 	WEAKNESS <ul style="list-style-type: none"> - FRAM's mechanical performance at aged condition has not been analysed. The evaluation of their long-term performance in real environments is a crucial step for the wider application of FRAM. - Further testing and verification is needed to ensure a cost-efficient use of the technology. - The initial cost of the asphalt mixes is increased due to the cost of the fibres.
EXTERNAL ORIGIN (attributes of the environment)	OPPORTUNITIES <ul style="list-style-type: none"> - PMB cannot be recycled. This makes FRAM a most suitable solution under the environmental point of view. - Asphalt mixtures with PMB need to be produced at higher temperatures, impacting negatively in their environmental impact. - New regulations and standards are shifting to more resource and cost-efficient materials and procedures. - Maintenance costs are the main matter of concern to all National Authorities. Solutions are sought to increase durability of road pavements. - Providers of fibres are very interested in road applications and new products can be developed (i.e. fibres from recycled materials). 	THREATS <ul style="list-style-type: none"> - Other new technologies with also promising results concerning the increase of service life. - PMB obtain better results in several mechanical tests and it is well consolidated.

4. APPLICABILITY, LIMITATIONS AND RECOMMENDATIONS

The technology presented in this document consists of the fibre-reinforcement of asphalt mixtures. The research has focus on two types of fibres (polyacrylonitrile and aramid based fibres) and two type of asphalt mixtures, AC and PA. According to the research carried out within the FIBRA project, the following advances and features of the technology can be highlighted:

- The technology can be successfully applied, in terms of their mechanical performance to both dense and open-graded mixes.
- Fibre-reinforcement can be applied to AC mixtures to improve rutting performance. To obtain the highest positive effect, FRAM should be implemented in the surface layer.
- Fibre-reinforcement can be applied to PA mixtures to improve resistance to ravelling. So, a positive effect on the long-term performance of the surface course is expected.
- The technology can be applied to the surface course of any traffic category road. In this project, AC and PA mixtures were designed to comply with the technical requirements of the most demanding traffic categories.
- Aged FRAM mixes can be recycled in a similar way than conventional asphalt mixtures with PEN bitumen.
- Production, lying and compaction of FRAM can be carried out with regular equipment, standards and procedures. No special equipment or uncommon mix sequences are needed to produce FRAM. No initial investment is needed.

Considering the features and limitations described above, the most suitable applications for FRAM include the following:

- FRAM, both FRAC and FRPA should be implemented in the surface layer.
- FRAC are recommended in areas or regions prone to rutting damage, due to their excellent resistance to permanent deformation.
- On the other hand, the good rutting performance also would allow the use of a softer bitumen in the design of AC mixtures. This could contribute to improve fatigue resistance of surface layers by using fibres.
- FRAC can also be applied in cold areas. FRAC have shown improved resistance to the damage caused by studded tires comparing to conventional AC mixtures with PEN bitumen.
- Ravelling is the most relevant damage mechanism in PA mixtures. Considering the positive effect of fibre-reinforcement in reducing particle loss, their lower production temperature and the possibility to be recycled, FRPA is considered a good alternative to PMB.

On the other hand, during the development of the FIBRA project, the following limitations have been found:

- The aging performance of FRAM has not been evaluated. Therefore, the cost-effectiveness of FRAM is not still demonstrated since it is strongly linked with their

potential service life extension. The monitoring of the pilot sections in Norway and the Netherlands will bring some light to this issue.

Considering the results and conclusions obtained from the project, the following recommendations are proposed:

- Care should be taken during the FRPA design since fibres should be properly covered by the bitumen to ensure an adequate mixture behaviour at wet conditions. On the other hand, the fibres have also been found to reduce binder drain-down so a higher percentage of bitumen is allowed.
- The long-term performance monitoring of the built pilot sections is expected after the end of the project. It is believed that the presence of the fibre retards ingress of the oxygen into porous asphalt mixtures during the aging process. This will delay the process of mortar aging so lengthening the service life. This hypothesis can only be verified through field monitoring followed by analysis of field data.
- A further optimization of fibre type, aspect ratio (length/diameter) and dosage is recommended in terms of mechanical performance, ageing resistance, ravelling resistance and weathering resistance. In this work, recommendations from providers were followed. A comprehensive understanding in this aspect is important for further application of fibre reinforcement.
- The formation of a portfolio of test sections by constructing more new sections is recommended.
- The development of an automatic dosage system for fibre application is recommended. Such a system will contribute to worker safety and production efficiency.