FIBRA

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Call 2017 New Materials FIBRA Final Report

September 2021

Call 2017 New Materials FIBRA Project Final Report

CEDR Contractor Report 2022-03

This report is an output from the CEDR Transnational Road Research Programme Call 2017 New Materials. The research was funded by the CEDR members of Austria, Belgium-Flanders, Denmark, Germany, Netherlands, Norway, Slovenia, Sweden and the United Kingdom.

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CEDR report: CR2022-03
ISBN: 979-10-93321-63-9

Executive Summary

Existing transport infrastructures are facing important challenges to maintain a reliable performance of the road network, which is being threatened by the increase of heavy traffic, the opening of new freight corridors and the effect of climate change, among others. Maintaining a satisfactory service level currently implies frequent roadworks that generate environmental, economic and societal impacts, reducing at the same time mobility and reliability of the road network and increasing the travel time.

In the last years, fibre-reinforcement has become a promising alternative to improve the mechanical properties and durability in road pavements. However, many uncertainties have been identified by National Road Authorities (NRAs) concerning the implementation of this technology.

The FIBRA project started with the objective of filling existing gaps in the state of knowledge about Fibre-Reinforced Asphalt Mixtures (FRAM) and thus identify and provide solutions to overcome potential technical barriers for their cost-effective use by NRAs. To achieve this objective and to increase the understanding of the functioning of fibres and reduce uncertainties and gaps in their large-scale implementation, different experimental, theoretical and real scaled studies have been carried out.

In the literature, a wide range of fibres can be found to have been already applied to asphalt mixtures. To identify and select the most promising type of fibre for this project and for their future use by NRAs, a literature and multicriteria decision-making analysis were done on the first place. Two fibres, polyacrylonitrile and a blend of aramid/polyolefin were selected.

Once selected the fibres, some mechanisms governing the microstructural properties of the asphalt matrix concerning fibre dispersion were analysed. In particular, thermal and chemical analysis, including differential scanning calorimetry, thermal gravimetric analysis, rheological analysis and Environmental Scanning Electron Microscope analysis with X-Ray spectroscopy option were performed. Main findings are that the fibres are homogeneously dispersed into the asphalt matrix and that none of them suffers thermal degradation during the asphalt mixture production. On the other hand, it was also found that the polyolefin melts during the production of the asphalt mixture but it does not modify the bitumen.

In parallel to the fibre and bitumen assessment and due to the important role of the asphalt mortar in the material response and the mechanical performance of the asphalt mixture, especially in PA mixtures, the impact of adding fibres in the asphalt mortar was evaluated. The most important result is that PAN fibres remarkably improved the resistance to permanent deformation in the asphalt mortar.

After evaluating the impact of the fibre at the binder and asphalt mortar level, the study focused on the asphalt mixtures. Thus, the impact of the fibre-reinforcement in the mechanical performance of the asphalt mixtures, both dense and open-graded mixes was carried out. PAN fibre was used to reinforce dense asphalt mixtures due to their higher rutting performance and ARAM/POL was selected to reinforced porous asphalt mixture. When reinforcing porous asphalt mixtures with ARAM/POL, a better resistance to water damage and ravelling were observed comparing to asphalt mixtures without fibres and with conventional penetration grade (PEN) bitumen, not reaching, however, the performance of the asphalt mixtures with Polymer modified bitumen (PmB). ARAM/POL fibres showed to increase the resistance of the PA mixtures at dry conditions with the same quantity of bitumen, this means fibres were useful to strengthen the samples without taking into consideration their capacity to retain the binder. Besides, it is

highlighted the need to add an extra amount of bitumen to adequately cover the fibres and avoid the water damage, and effectively achieve a reinforcement effect on the mixture in any conditions. Concerning, dense asphalt mixtures, the addition of fibres increase the rutting performance, reaching similar results than the reference with PmB. However, in terms of fatigue or low temperature cracking, FRAM do not reach the performance of PmB.

After the laboratory work, the production process of FRAM was transferred to the asphalt plant. The scaling-up was carried out in two different asphalt plants at two different European countries. Thus, the technology was validated for two type of mixtures (AC and PA), two different asphalt plants and two different countries with different specifications and methods (Norway and the Netherlands). Once the production process was up-scaled, two pilot sections were implemented, one in Norway and one in the Netherlands. Main outcomes from the upscaling of the production process and the implementation of the pilot sections are that the fibres can be produced, laid and compacted using standard facilities, equipment and procedures. In addition, the production temperature of FRAM is 20ºC lower than that of asphalt mixtures with PmB. In the case of fibre-reinforced asphalt concrete mixtures, a better resistance to the abrasion by studded tires was observed when comparing to the control mix with PEN bitumen.

Finally, an environmental and economic assessment was carried out. As part of the environmental analysis, the recyclability potential of FRAM layers was studied at the laboratory. The results indicate that FRAM mixes are recyclable to the same extent than conventional asphalt mixture. In addition, a cradle-to-grave Life Cycle Assessment of the two pilot sections was done. The addition of fibres increases the environmental impact of the road pavement in approx. 2-7% (depending on the case study) comparing to the use of an asphalt mixture with PEN bitumen. In order to be competitive, the road pavement should last about 0.5-2 (depending on the case study) years longer than the reference. Concerning the economic feasibility of using FRAM by NRAs, a Life Cycle Cost Analysis (LCCA) was performed to evaluate their long-term economic efficiency. For the technology to be cost-effective, a similar durability than the asphalt mixtures with PmB need to be achieved in the case of porous asphalt mixtures (the Netherlands case study) and a slightly higher durability than the asphalt mixture with PEN (around 10%) in the case of the dense asphalt mixtures (Norwegian case study).

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1. Definition of the Issue

1.1. Purpose and Scope

Existing transport infrastructures are facing important challenges to maintain a reliable performance of the road network, which is being threatened by the increase of heavy traffic, the opening of new freight corridors and the effect of climate change, among others. Maintaining a satisfactory service level currently implies frequent roadworks that generate environmental, economic and societal impacts, reducing at the same time mobility and reliability of the road network and increasing the travel time.

For decades, different fibres have been studied for improving the sustainability, resilience and durability of the asphalt mixtures. For example, Button & Hunter (1984)[1] investigated the use of eight different fibres in asphalt mixtures at the laboratory and as part of two field sections, which were monitored for 19 months. Conclusions indicated that synthetic fibres might potentially result in better fatigue performance, reduce rutting and provide greater resistance to crack propagation. No relevant improvements were observed from field tests. Cleven (2000)[2] observed improved fatigue and low-temperature characteristics for carbon fibre-modified asphalt (CFMA). Chen et al., 2009[3] found that adding polyester, polyacrylonitrile, lignin, and asbestos demand a larger amount of asphalt binder while resulting in higher air voids and Marshall stability. Besides, the possibility of incorporating polypropylene and polyester fibres was addressed by Simpson & Mahboub (1994)[4], showing the mixtures improved tensile strength and resistance to cracking.

In addition to numerous research studies, there exist commercially available fibres whose providers ensure pavement life extensions of at least a 50% by virtue of ravelling, rutting and fatigue cracking reductions[5]; or asphalt mixture life extensions of 200% by strengthening the mix and increasing the stiffness[6]. In this line, the company BAM, partner of the FIBRA project is also doing research with polyacrylonitrile fibres to prolong the life of Porous Asphalts (PA). BAM is conducting field tests with Rijkswaterstaat. Ravelling is the predominant type of damage in PA surface layers. Although no results are available yet, indications are that the ravelling service life of PA may be prolonged by the use of fibre. Because of the Paris agreement, the cost-effectiveness of applying fibres in asphalt has not only to do with the benefits in cost saving prolonging the service life but also savings in CO_2 emissions per year of usage.

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

- Which fibre should be used?
- Are fibres well dispersed?
- 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?

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[1] Button, J. W. & Hunter, T. G. Synthetic Fibers in Asphalt Paving Mixtures. Texas Transportation Institute, Texas A&M University System College Station, Texas, November 1984.

[2] Cleven, M. A. Investigation of the Properties of Carbon Fiber Modified Asphalt Mixtures. Master's thesis. Michigan Technological University, 2000.

[3] Chen, H., Xu, Q., Chen, S. & Zhang, Z. Evaluation and Design of Fiber-Reinforced Asphalt Mixtures. Journal of Materials and Design, Vol. 30, No. 7, 2009, pp. 2595–2603.

[4] Simpson, A. L., & Mahboub. K. C. Case Study of Modified Bituminous Mixtures: Somerset, Kentucky. 3rd Materials Engineering Conference, ASCE, San Diego, CA, Nov. 13–16, 1994, pp. 88–96.

[5] http://www.forta-fi.com/products/forta-fi/.

[6] http://lambdaphi.nl/?p=info&info=4.

The main objective of the FIBRA project was to give answers to these questions and thereby identify and provide solutions to overcome the technical barriers for the cost-effective implementation of FRAM by NRAs.

1.2. Methodology

As stated before, the overall objective of the project is to fill the existing gaps of the state of the knowledge concerning FRAM. To achieve this objective, the methodology shown in Figure 1 has been followed.

The first step in the project was the analysis of previous research studies and experiences concerning the use of fibres in asphalt mixtures. A multi-criteria decision making analysis (MCDMA) was carried out with the information obtained from the literature analysis including mechanical, economic and environmental criteria.

From the literature review and the MCDMA, two fibres were selected as the most promising for fibre-reinforcement. To understand the mechanisms through which these fibres function, the next step consisted of the study of the blending characteristics of the fibre with the rest of AM's components by means of advanced chemo-mechanical techniques as well as evaluating the influence of the fibres in the asphalt mortar mechanical and rheological properties.

The impact of fibre-reinforcement in asphalt mixtures (AMs) has been mostly studied in dense mixtures, being the fibre-reinforcement in porous asphalt mixtures less explored. Thus, to widen the scope from the current state of knowledge, asphalt concrete (AC) and porous asphalt (PA) mixtures were designed and characterized, using different gradations and binders. In addition, the potential recyclability of FRAM was assessed at the laboratory by artificially producing RAP from FRAM and using it to produce new mixtures which mechanical properties were then checked. The laboratory work concluded with the evaluation of the use of fibres on AM with high RAP content in order to identify a potential positive effect of fibres addition.

In addition to the extensive laboratory work and with the objective to define the most advantageous use of FRAM within the road pavement structure; in the surface, binder or base layer or in a combination of layers, the assessment of the long-term performance of the pavement was carried out through a numerical simulation using FlexPAVE^{TM} software. This tool, developed by the Carolina State University, is able to calculate the long-term deterioration of an asphalt pavement section in terms of fatigue damage and rut depth, accounting for the effects of the viscoelasticity of the pavement material,

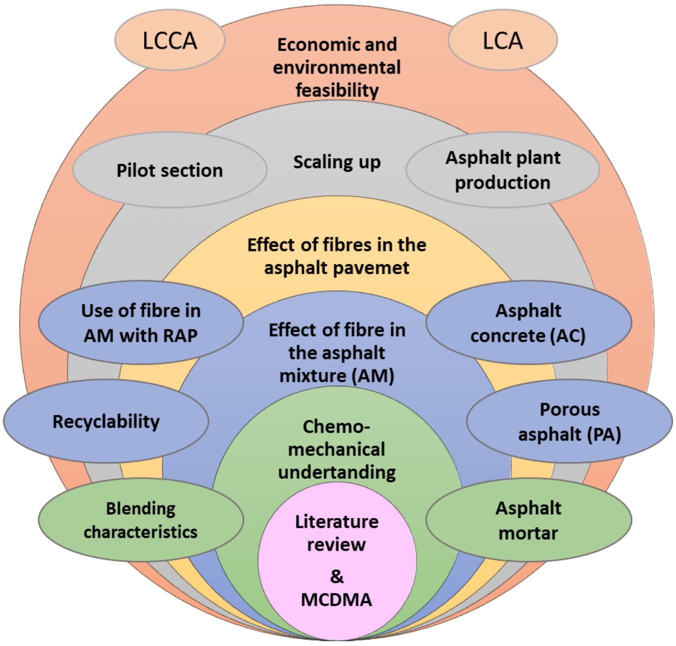

Figure 1. FIBRA project methodology

the temperature effect in the viscoelastic properties and the nature of the traffic load.

With the objective of transferring the technology to the practice, the upscaling of the manufacturing process was done. Thus, several FRAM were produced at two asphalt plants, one in the Netherlands and one in Norway and characterized at the laboratory. This activity enabled the adaption of the production process to identify potential technical barriers to the future implementation of the technology. In addition, thanks to the involvement of both National Road Authorities (NRA), Rijkswaterstaat in the Netherlands and Statens Vegvesen in Norway, it was possible to implement in a real road section the asphalt mixtures produced at both asphalt plants. This makes possible, firstly, the validation of the short-term performance after the paving process, carried out by FIBRA project partners, and secondly, the long-term performance evaluation of the test sections after the end of the project.

Finally, the environmental and economic feasibility of FRAM were assessed by applying a life cycle assessment (LCA) and a life cycle cost analysis (LCCA) to the two road sections implemented by the NRAs. The impacts of the FRAM layers were compared to those of the conventional layers used as references.

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.

Figure 2. Pilot section implementation (Norway)

2. Main findings

Different experimental and theoretical studies have been carried out in the FIBRA project to increase the understanding of the functioning of fibres and reduce uncertainties and gaps in their large-scale implementation. The materials, methods and main results are summarised in this section. Other alternatives to FRAM mixes such as asphalt mixes (AM) with penetration grade (PEN) bitumen or AM with Polymer-modified Bitumen (PmB) are included in the different studies so that the advantages and disadvantages of using FRAM are highlighted.

2.1. Literature review and MCDMA

Different types of fibres have been tested with the aim of increasing the mechanical performance and service life of asphalt mixtures. The most studied fibres found in the literature are polymeric, Cellulose, Geogrid and Glass, Fabric and Carpet, Carbon and Aramid fibres. The selection of the “best” fibre is a difficult task due to the lack of homogeneity in the literature concerning the evaluation and reporting of the benefits and drawbacks of these advance materials.

In the FIBRA project, a full analysis of the state of the art was performed in order to make a first selection of the most promising fibres for the reinforcement of asphalt mixtures. Several types of fibres were ranked based on their mechanical, economic and environmental performance and following the next procedure:

- Rutting, fatigue, toughness and indirect tensile strength were selected to evaluate the mechanical performance of FRAM due to the availability of data. An Analytics Hierarchy Process (AHP) was used to give weights to these criteria. Once the weights were defined, a Multi-criteria decision making assessment (MCDMA) and the Weighted Aggregated Sum Product Model (WASPAS) were applied.
- The environmental impact was estimated by comparing the production process of each fibre and the amount of fibre that is added to 1 t. A cradle-to-gate LCA of 1 ton of hot mix asphalt (HMA) for each fibre was carried out.
- A preliminary cost-benefit analysis was carried out by comparing the cost per kilometre of each FRAM layer. This preliminary analysis gives an idea of the minimum effectivity that should be provided by each fibre.
- The status of development of the fibres is also an important criteria to take into account. Thus, 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 AM reinforcement.

Based on the results obtained, the two fibres with best performance in all the selected criteria are Polyacrylonitrile fibres (PAN) and the blend of Aramid/Polyolefin fibres (ARAM/POL).

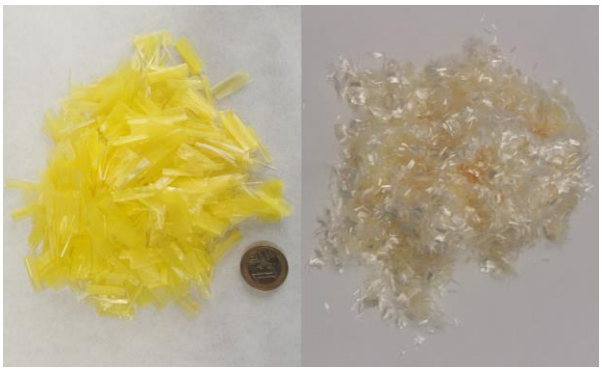

Figure 3. Selected fibres from literature & MCDM study

2.2. Chemo-Mechanical evaluation of FRAM

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, as well as the assessment of the rheological properties of bituminous binders recovered from the FRAM.

Differential scanning calorimeter (DSC) was used to investigate the thermal transitions of the three types of fibres (polyacrylonitrile, aramid and polyolefin) and the thermal stability of the fibres was analysed by thermal gravimetric analysis (TGA). For all the fibres the weight of the sample is kept constant until temperatures above 280ºC (Figure 4). Therefore, at conventional production temperatures of hot asphalt mixes (ca. 160ºC), none of the fibres suffer any thermal degradation.

The fibres were also thermally analysed for a large temperature range (from 20 ºC to 500– ºC) by calorimetry in order to study the thermal transitions of the fibres. Aramid and PAN fibres melt or decompose at temperatures over 300ºC so no chemical modification would occur during asphalt mixture production so any effect on the response of the FRAM will be due to a physical interaction. However, the polyolefin fibres showed a melting temperature of 124.5ºC, which is lower than production temperature (ca. 160ºC). Therefore, a potential modification of the binder influencing the behaviour of the FRAM could be expected.

To confirm the latter, the bitumen from FRAM samples was extracted and tested to carry out rheological analysis and measurements of its softening point. Softening point values, master curves and black curves of the bitumen recovered from FRAM are similar to those obtained from the reference mixtures. This indicates that the addition of these three fibres do not alter or modify the bitumen.

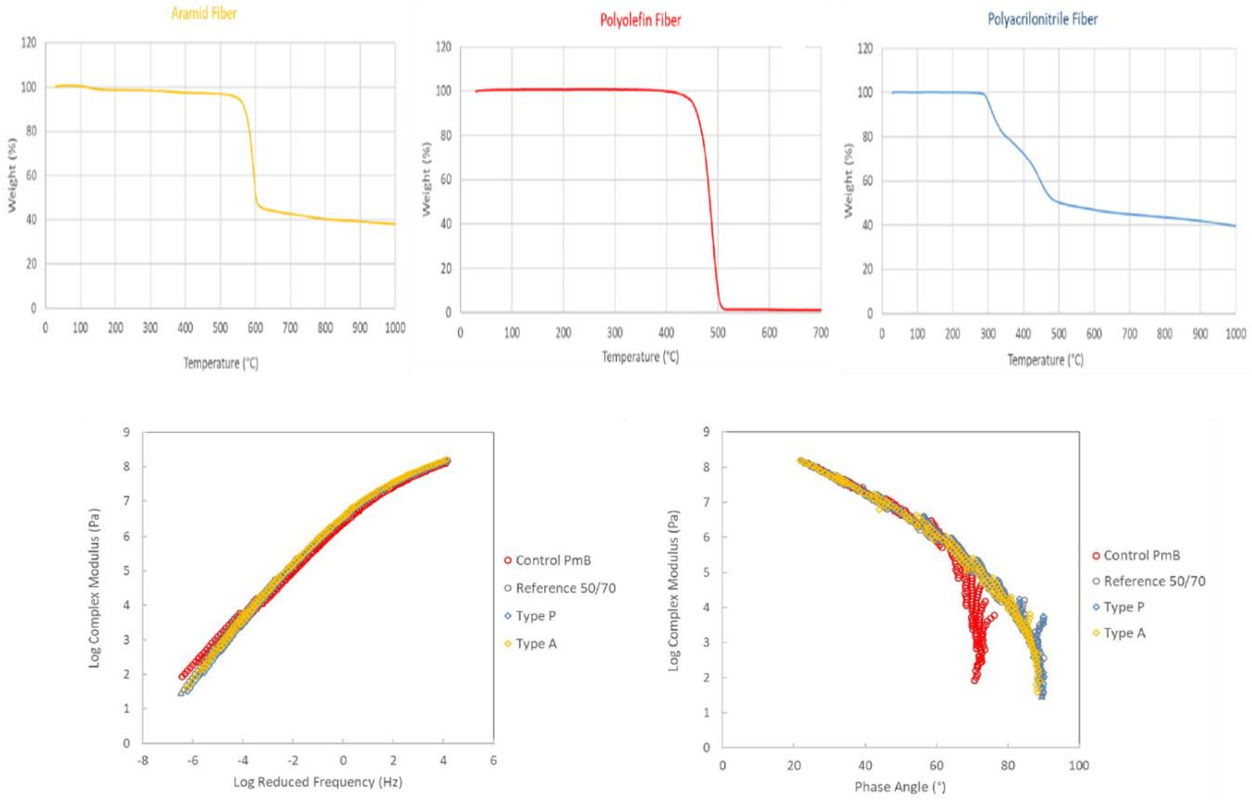

Figure 4. Fibres' weight loss vs T (up). Rheological analysis of bitumen (down).

Finally, dense asphalt mixtures reinforced with both types of fibres 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 aramid fibres and polyacrylonitrile fibres were detected and a homogeneous distribution was observed. Polyolefin are not detected probably because they melt during the mixing process.

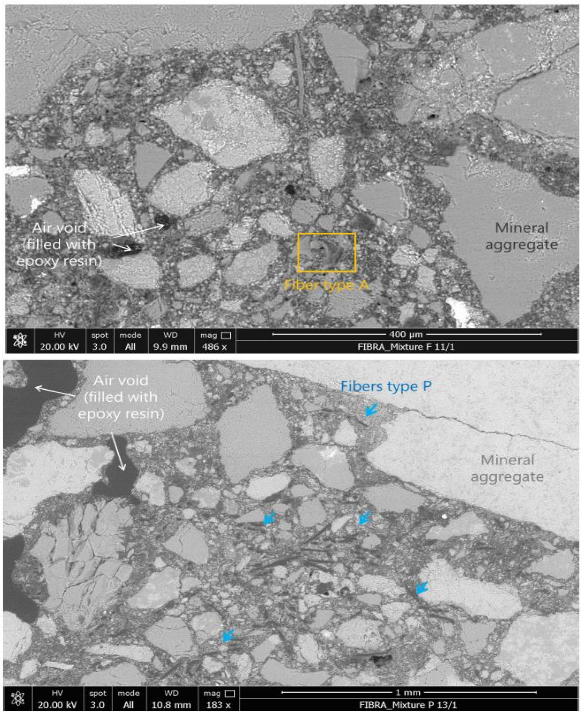

Figure 5. ESEM image. Top: FRAM with ARAM/POL fibres. Bottom: FRAM with PAN fibres.

2.3. Impact of fibres in the behaviour of the asphalt mortar

Due to the key role of the asphalt mortar in the material response and the mechanical performance of the asphalt mixture, especially in PA mixtures, the impact of adding fibres to this material was evaluated. Different asphalt mortars were prepared using different bitumen types (PEN and PmB), different type of fibres (ARAM/POL and PAN) and three aging conditions.

Several rheological tests were then conducted to the set of asphalt mortars in a wide range of temperatures. In this sense, the response of the mortar to permanent deformation was addressed by the Multiple Stress Creep and Recovery test (MSCRT) according to the AASHTO T350. MSCRT results indicate that mortars prepared with PAN fibres showed the highest value of recovery, suggesting remarkable benefits in terms of permanent deformation.

On the other hand, the fatigue resistance was evaluated through the Linear Amplitude Sweep test (LAS) and the Accelerated Fatigue Tests (AFT). Based on AFT results, ARAM/POL fibres work better in a modified bitumen and PAN fibres in PEN bitumen.

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 15ºC, no difference was found in the results of the different specimens. However, at lower temperatures (-15ºC), the addition of 0.3% of fibres significantly increases the ITS and fracture energy (FE) values of the mortar samples, with a greater influence in the case of ARAM/POL fibres (Figure 6).

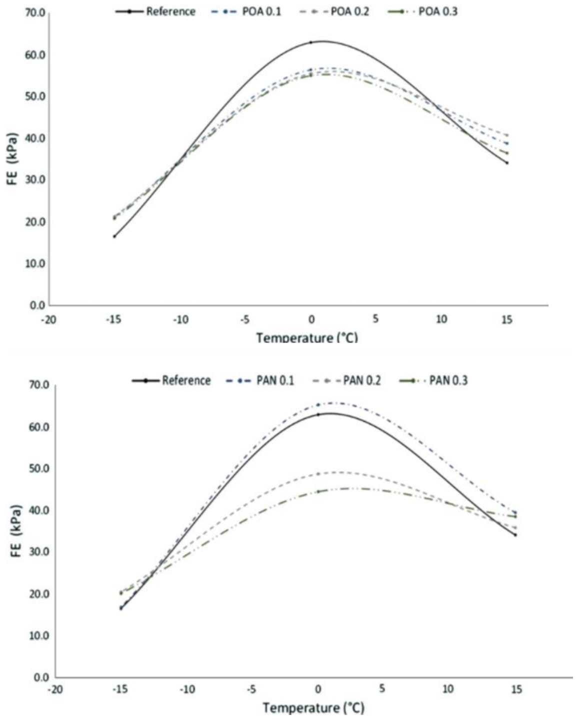

Figure 6. Relationship between the temperature and ITS and FE responses for both types of fibers.

2.4. Fibre selection depending on the type of mixture

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 asphalt mixtures.

Firstly, several asphalt mixtures, dense and open graded, were designed so that the influence of the different fibres was assessed. To analyse the mechanical performance of fibre-reinforced asphalt concrete (FRAC) mixes, water sensitivity (EN 12697-12), rutting resistance (EN 12697.22) and fatigue resistance (EN 12697-24) tests were performed. In the case of the fibre-reinforced porous asphalt mixture (FRPA), total air voids (EN 12697-8), interconnected voids (ASTM D7063-05), permeability, Cantabro (EN 12697-17) and water sensitivity (EN 12697-12) tests were done.

In relation with AC mixtures, the addition of fibres improves the Indirect Tensile Strength (ITS) compared to the asphalt mixtures without fibres, being the mixture with PAN the one with the best performance. As for the water sensitivity tests, similar good results were obtained for all the mixes. Regarding rutting resistance, PAN showed a similar performance comparing to the PmB mix, although ARAM/POL fibre obtained the worse result among all the mixes. Concerning fatigue, a lower performance than the asphalt mixture with PmB is obtained. Comparing to the asphalt mixture with PEN bitumen, FRAM improve fatigue response at lower strains while similar results are obtained at higher strain levels.

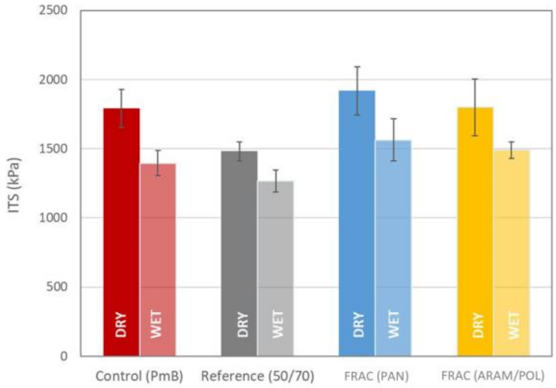

Figure 7. Indirect tensile strength (ITS) (AC mixtures)

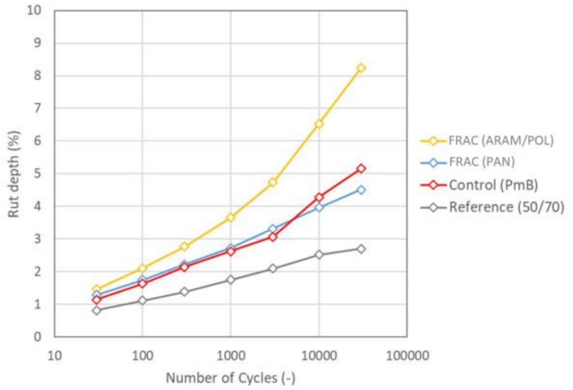

Figure 8. Rutting depth (AC mixtures)

Concerning the results in the PA mixtures, initially the same quantity of binder was employed to compare the mixtures at the same conditions. The use of fibres positively affects ravelling in dry conditions, obtaining improvements up to 40% when using ARAM/POL fibres. Nevertheless, the fibres did not improve the ravelling resistance in wet conditions but slightly reduce it. An increase of the binder content is recommended to ensure the fibre-aggregate matrix is completely covered by the bitumen to prevent their exposition to water.

Based on these and previous results, PAN fibres were selected for their use in AC fibre-reinforcement due to their highest rutting performance, while ARAM/POL fibres were selected for their use in PA mixtures due to the general best mechanical performance found in this type of mixtures.

2.5. Impact of fibre-reinforcement in Porous Asphalt mixes

Five PA mixtures with a nominal maximum aggregate size of 16mm were designed for their use in surface layers. Three of them were used as references, one with PEN bitumen, one with PmB and one with PEN bitumen and cellulose fibres (Table 1). As for the Fibre-Reinforced Porous Asphalt (FRPA) mixtures, ARAM/POL fibre (0.05% w/w of mixture) was added and two different bitumen content were tested. The following tests were carried out: air void, drain-down (EN 12697-18), Cantabro particle loss, moisture sensitivity and thermal cracking resistance tests (Thermal Stress Restrained Specimen (TSRST) (EN 12697-

46) and the Semi-Circular Bend (SCB) (EN 12697-44)).

Table 1. Porous asphalt mixtures for surface layer

	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	AR/PO	AR/PO
Fibre / mixture (%)	-	-	0.5	0.05	0.05

Below, the main findings obtained after the analysis and discussion of the laboratory results are summarized.

- Adding ARAM/POL fibres does not notably affect the functional performance of the mixtures and increases the ITS in both dry and wet conditions.
- FRPA presents a higher moisture resistance than the reference with conventional PEN bitumen (Figure 10).
- A significant difference performance is observed between the FRPA mixtures with different bitumen content. 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 with PEN bitumen, the FRPA increases the resistance to ravelling, although the performance of the PmB is not reached, especially in wet conditions (Figure 11).
- Finally, according to the TSRST and SCB results (Figure 12), the fibres do not affect the low temperatures performance of the asphalt mixture, achieving the FRPA and the reference with PEN bitumen similar results. The FRPA do not reach the performance at low temperatures achieved by the PmB.

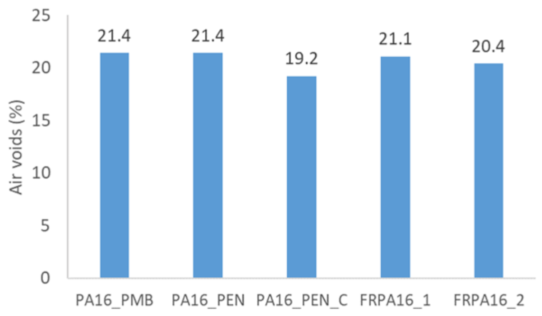

Figure 9. Air void content (%)

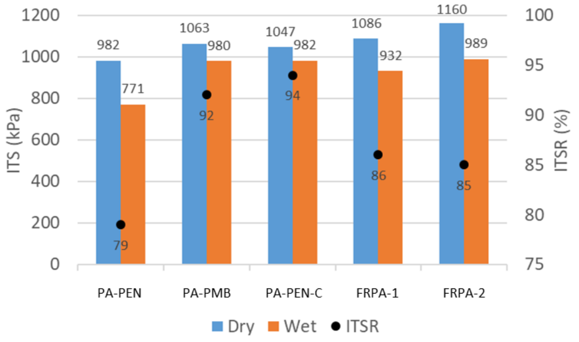

Figure 10. ITS results

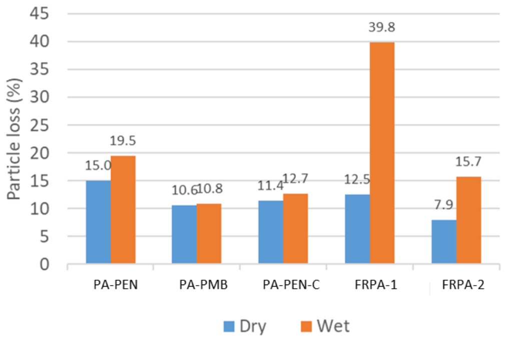

Figure 11. Particle loss results

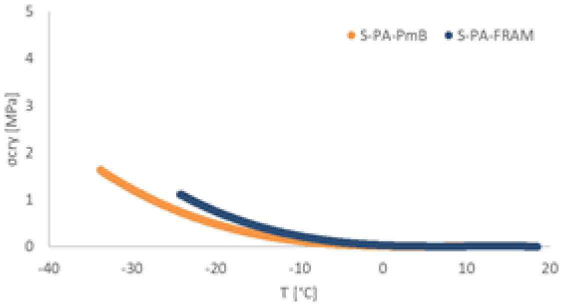

Figure 12. TSRST results (PA mixtures)

2.6. Impact of fibre-reinforcement in Dense Asphalt mixes

To evaluate the impact of fibre reinforcement in asphalt concrete (AC), the next approach was followed. Seven AC mixes were produced, three specifically designed for the surface, two for the binder and two for the base course (Table 2). In all cases, PAN fibres (0.15%) were added. ITS, moisture sensitivity, rutting, stiffness (EN 12697-26), fatigue resistance (EN 12697-24) and thermal cracking tests (TSRST and SCB) 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).

Table 2. AC mixtures

Layer	Mixtures ID	Bitumen type	Bitumen content (%)
Surface layer	REF16S FRAC16-1 FRAC16-2	50/70 50/70 50/70	4.3 4.3 4.6
Binder layer	REF22B-P FRAC22B	PmB 45/80-65 50/70	4.4 4.4
Base layer	REF22T FRAC22T	50/70 35/50	4.2 4.2

Below, the main findings obtained after the analysis and discussion of the laboratory results are summarized.

- The addition of fibres increases the ITS, although the resistance to water damage (ITRS) of some of the FRAM is similar or slightly lower.
- A remarkable rutting performance is obtained comparing to the reference with PEN bitumen, although similar outstanding results are obtained for the reference with PmB (Figure 14).
- All FRAM mixtures present similar results in terms of stiffness and phase angle than the reference mixtures with PEN bitumen. When comparing to PmB, FRAC showed higher stiffness and lower phase angle.
- FRAM mixes present similar results in terms of fatigue resistance than the control mixtures with PEN bitumen, according to both EN and AASTHO standards (see Sapp cracking index in Figure 15). However, in both tests, the mixtures with PmB present a significant better fatigue resistance.
- Based on 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 16), comparing to the reference with PEN bitumen. However, the use of a PmB significantly improves the low temperature performance of the asphalt mixture.

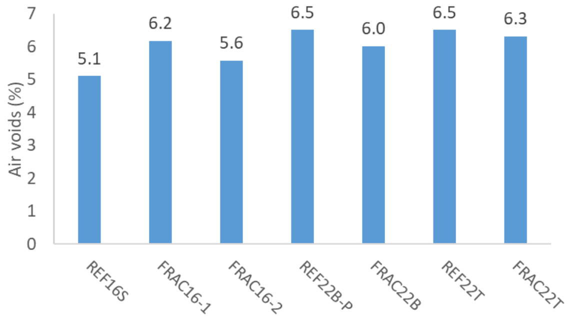

Figure 13. Air void content (%)

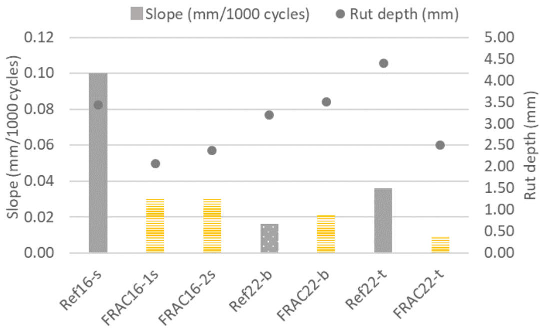

Figure 14. Results from rutting tests

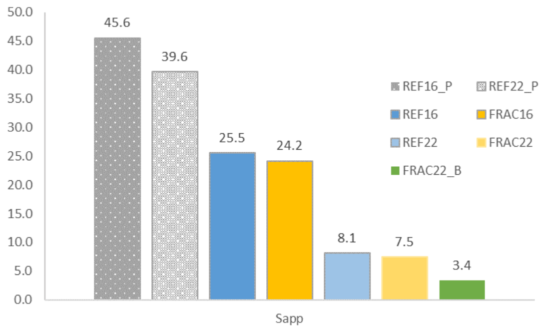

Figure 15. S_{app} Cracking index (Calculated from AASHTO TP107 fatigue test)

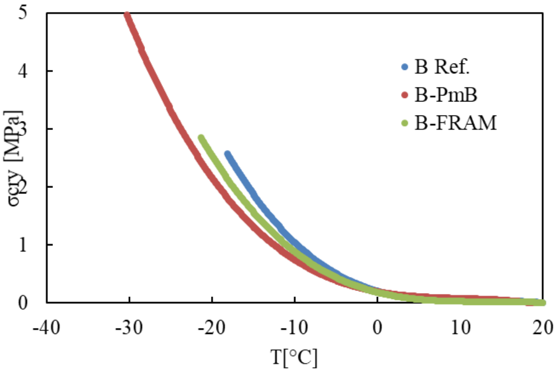

Figure 16. TSRST results (AC mixtures)

2.7. Impact of FRAM layers in 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^{TM} 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.

Different pavement sections have been simulated (Figure 17) with FRAM placed in one or more asphalt layers. Reference pavement structures are also analysed with no FRAM in any of the layers or with AC mixtures with PmB in one or more layers.

Based on the simulation carried out, the main findings of this study can be summarized as follows:

- FRAC increases the resistance to plastic deformations of the surface layer in a greater extent than the asphalt layers with PMB (Figure 18).
- As expected, using FRAM in the wearing course has a higher impact on the rutting performance than when built in the binder or base layers.
- 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 (Figure 18).

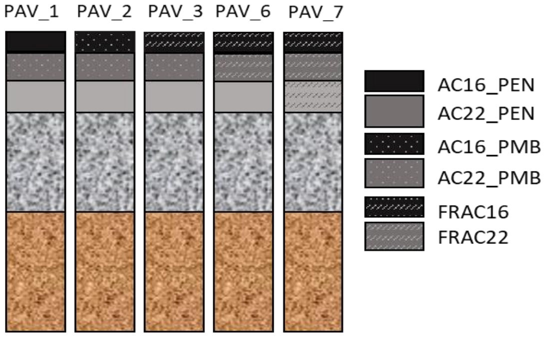

Figure 17. Pavement sections simulated with FlexPAVE^{TM}

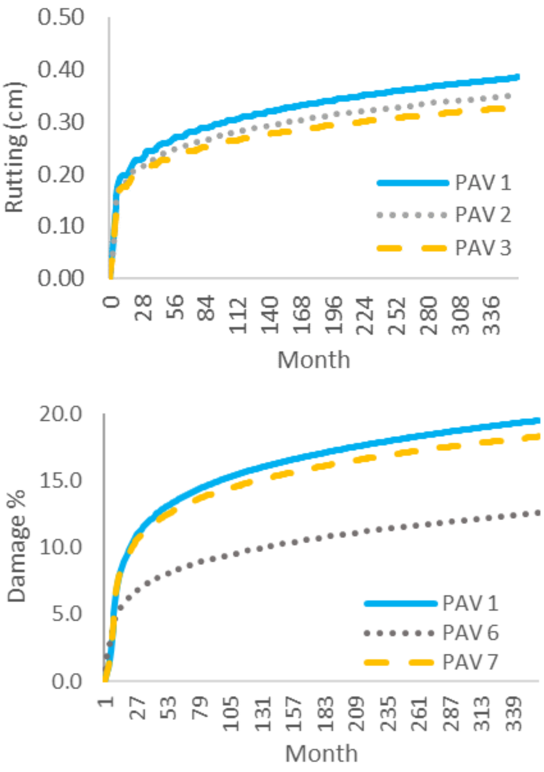

Figure 18. Evolution of the rutting (top) and fatigue (bottom) damage

2.8. Scaling-up and pilot section implementation

To identify potential technical barriers in the large-scale implementation of FRAM, the production process of the asphalt mixtures was upgraded to the industrial scale. The scaling-up was carried out in two different asphalt plants at two different European countries. Thus, the technology was validated for two type of mixtures (AC and PA), two different asphalt plants and two different countries with different specifications and methods (Norway and the Netherlands). Once the production process was up-scaled, two pilot sections were implemented, one in Norway and one in the Netherlands.

In the Dutch section, two experimental FRPA layers were implemented. In both cases, a top layer of a two-layer porous asphalt (2L-PA 8) mixture was selected, one reinforced with aramid fibre and the other one with PAN fibre. As control mixture, two 2L-PA 8 mixes without fibres, one with a PEN bitumen and the other with a PmB bitumen. In the Norwegian section, one experimental FRAC layer was built (an AC11 with PEN bitumen and reinforced with PAN fibres), As control mixtures, two AC11 without fibres, one with PEN bitumen and the other one with PmB.

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

- Synthetic fibres do not prevent binder drainage due to the limited amount of addition. Thus, a combination of synthetic fibres and cellulose fibres is recommended for applying in bitumen-rich mixtures such as the 2L-PA8.
- Synthetic fibres in combination with PEN bitumen allows reducing the production temperature by 20ºC compared to reference mixtures with PMB.
- FRAM can 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 homogenously distributed in the mixtures and no clusters are formed.
- The DSR mortar response test indicates that FRAM is less susceptible to aging than the reference mixtures without fibres.
- Functional properties of the 2LPA 8 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.
- Regarding abrasion by studded tires, FRAM and PmB mixtures performed similar and better than the asphalt mixture with PEN bitumen.

Figure 19. Laying and compaction of FIBRA mixtures (Top). CPX Noise measurement (Down)

2.9. Environmental and Economic impact

2.9.1. Recyclability potential

The recyclability potential of FRAM was analysed due to the importance this property has on the environmental impact. For this assessment, reclaimed asphalt pavement (RAP) from FRAM (PANRAP) was added in a percentage of 50% to two different asphalt mixture, an AC16 with 70/100 PEN bitumen (Ref-PANRAP) and an AC16 with 70/100 PEN bitumen and PAN fibres (FRAC-PANRAP). As it is assumed that the fibres present in the PANRAP are still valid, only 0.075% of PAN fibres were added to the FRAC-PANRAP mixture. To produce PANRAP, 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: ITS, moisture sensitivity, rutting, stiffness, fatigue and thermal cracking tests (TSRST and SCB) were carried out.

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 PANRAP) increases the ITS, the stiffness and the rutting resistance while reducing the fatigue resistance and the low temperature performance. Thus, the main finding of this study is that FRAM mixes are recyclable to the same extent than conventional asphalt mixtures.

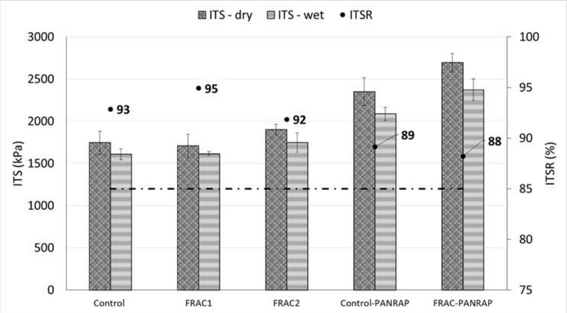

Figure 20. ITS and moisture sensitivity

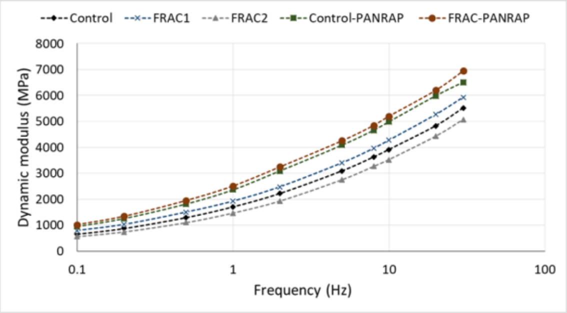

Figure 21. Dynamic modulus

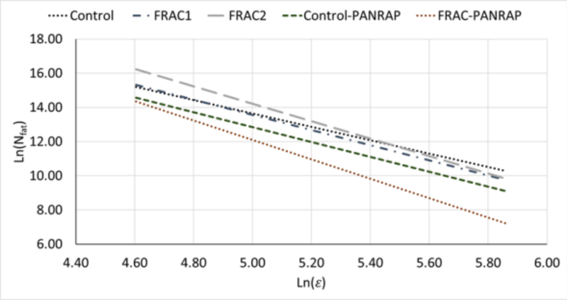

Figure 22. Fatigue testing

2.9.2. Environmental impact

To evaluate the environmental performance of road pavements that include a FRAM in their surface layers comparing to conventional pavement designs, a cradle-to-grave Life Cycle Assessment (LCA) was carried out. Two LCA were done that correspond to the two implemented pilot sections (Norway and the Netherlands).

The addition of fibres resulted in an increase of the environmental impact in approx. 2-7% depending on the case study. 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 2 extra years than the conventional AC11 section with PEN (Figure 23).

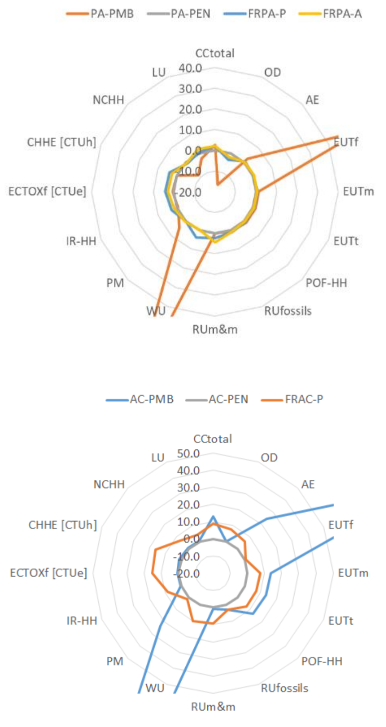

Figure 23. Cradle-to-gate. PA (top). AC (Bottom)

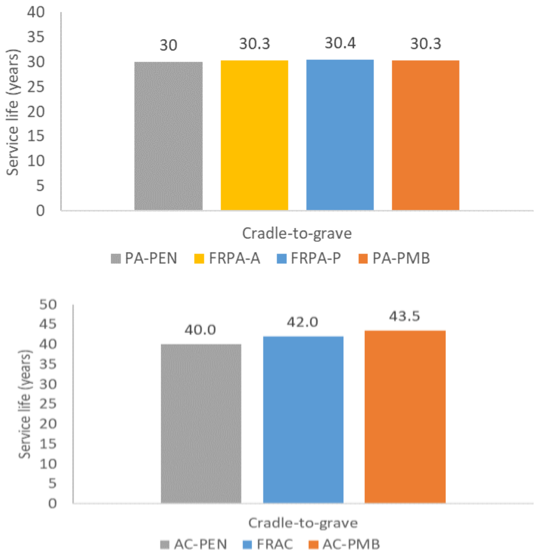

Figure 24. Minimum service life to equal environmental impact of the reference. PA (top). AC (bottom)

2.9.3. Economic impact of FRAM

To evaluate the economic feasibility of using FRAM by NRAs, a Life Cycle Cost Analysis (LCCA) was performed to evaluate their long-term economic efficiency. The LCCA methodology is applied to the two case studies (Norway and the Netherlands). To carry out the 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, and assuming the same service life, similar life cycle costs are obtained for all the alternatives evaluated in each case study (Figure 25). To consider FRAMs as an economically feasible alternative, a similar durability than the asphalt mixture with PmB needs to be achieved in the AC case study (Norway) and a slightly higher durability needs to be achieved (around 10%) than the asphalt mixture with PEN in the PA case study (the Netherlands) (Figure 25).

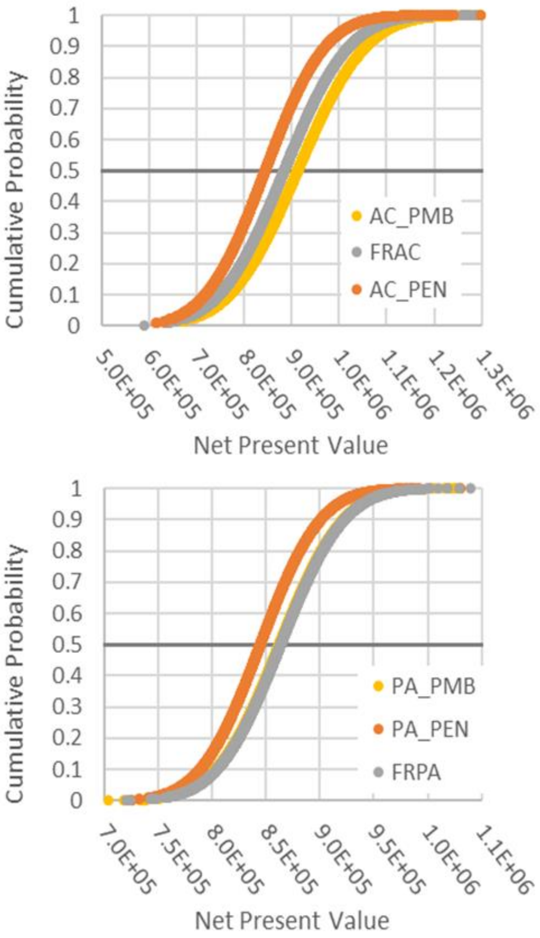

Figure 25. NPV for the different alternatives. AC case study (top); PA case study (bottom)

3. Conclusions

The technology presented in this document concerns the fibre-reinforcement of asphalt mixtures. The research has focus on two type 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:

- Fibre-reinforcement 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.
- It is expected that aged FRAM mixes could be recycled in a similar way than conventional asphalt mixtures with PEN bitumen.
- Production, laying 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 described above, possible applications for FRAM include the following:

- To maximize the benefits, FRAM, both FRAC and FRPA are recommended for the surface layers.
- FRAC are recommended in areas or regions prone to rutting damage, due to their excellent resistance to permanent deformation.
- On the other hand, a good rutting performance could also be achieved by applying FRAC mixtures with a softer bitumen. This could further contribute to improve fatigue resistance of surface layers by using fibres.
- FRAC might be applied in cold areas, since they have shown improved resistance to the damage caused by studded tires comparing to conventional AC mixes with PEN bitumen.
- Ravelling is the most relevant damage mechanism in PA mixes. Considering the positive effect of fibre-reinforcement in reducing particle loss, their lower production temperature and the possibility to be recycled, FRPA might be considered as a good alternative to PMB. However, further long-term performance data is necessary to confirm this.

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 in this project. Therefore, the cost-effectiveness of FRAM is not fully demonstrated since it is strongly linked with their potential service life extension. The long-term monitoring of both 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 phase 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 some extend to reduce binder drain-down so a higher percentage of bitumen is allowed.
- 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 wider understanding of this aspect will benefit the further application of fibre reinforcement.

- The long-term monitoring of the pilot sections is expected to continue after the end of the project. It is believed that the presence of the fibre retards ingression of the oxygen into porous asphalt mixtures during the aging process. This could delay the process of mortar aging so prolonging the service life. This hypothesis can only be verified through field monitoring followed by analysis of field data.
- The development of an automatic dosage system for fibre application is recommended. Such a system will contribute to worker safety and production efficiency.
- The creation of a portfolio of test sections by constructing more new sections is recommended.

4. Reports and scientific publications

The methodology, results and conclusions of the different technical studies within the FIBRA project have been detailed reported in the following **technical reports:**

- Deliverable 2.1 – Literature review on the use of fibres in asphalt mixtures
- Deliverable 3.1 – Mechanical response of FRAM and PA mortar properties
- Deliverable 3.2 – Chemo-mechanical understanding of FRAM.
- 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.
- Deliverable 5.1 – Scaling up of the production process and implementation of test sections.
- Deliverable 5.2 – Assessment of the environmental impact of FIBRA pavements
- Deliverable 5.3 – Assessment of the economic feasibility of Fiber-reinforced Asphalt Pavements.
- Deliverable 6.2 – Exploitation Strategy Plan
- Deliverable 6.3 – Guidance for the implementation

In addition, the following **scientific papers** have been published:

- 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.
- 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.
- Bueno, Moises & Poulikakos, Lily. (2020). Chemo-Mechanical Evaluation of Asphalt Mixtures Reinforced with Synthetic Fibres. Frontiers in Built Environment. 6.
- 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.
- 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.

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CEDR Contractor Report 2022-03

Final Report from CEDR Research Programme Call 2017 “New Materials” Project FIBRA

ISBN: 979-10-93321-63-9

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