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FIBRA

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

Deliverable 5.2

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Executive summary

This report presents two research studies. In the first one, the evaluation of the chemistry of the fibre material and the identification of potential critical compounds are addressed. In the second one, a Life Cycle Assessment of a road pavement that include fibre reinforced asphalt mixtures (FRAM) was carried out. The methodology and main results of these works are described in this document.

Concerning the pollutants identification, measurement and toxicity assessment of FRAM, the fibres were analysed for the presence of chlorinated paraffins, especially for short-chain CPs (SCCPs, C10-C13) and medium-chain-CPs (MCCPs, C14-C17) and polybrominated diphenyl ethers (PBDEs). Neither CPs, nor PBDEs could be detected in organic extracts of the three examined plastic materials. On the other hand, we could also not detect other organic compounds in the tested materials that could be used as marker compounds to study the leaching properties of respective fibre-reinforced asphalt materials. More analytical work is needed to specify and search for other potential target compounds, which can be attributed to PAN fibre-based plastic materials.

Regarding the Life Cycle Assessment (LCA), the main objective is the evaluation of the environmental performance of road pavements that include FRAM comparing to conventional pavement designs. Both, cradle-to-gate and cradle-to-grave assessments were carried out. The LCA has been performed following the overall framework provided by the international standard ISO 14044 (2006) including the goal and scope definition, the life cycle inventory analysis, the life cycle impact assessment and the optional normalization and weighting steps. In the case of the cradle-to-grave study, the stages recommended by the standard EN 15804 were selected: A. Product + construction, B. use phase, C. end-of-life and D. beyond the end-of-life.

Two LCA were carried out to verify if the use of FRAM might result beneficial from the environmental point of view in relation to conventional mixes. These LCA correspond to the two pilot sections implemented both, in the Netherlands and Norway and takes into account, when possible, the specificities of each section (type of mixture, raw materials, grid mix, pavement sections, etc.). Concerning the evaluation of the environmental impacts associated with FRAM, possible negative burdens that could be related to FRAM, such as those associated with the production of the fibres were analysed.

For the conditions analysed in this study, an assuming the same service life for both the reference and the FRAM, the results indicate that the use of FRAM increases the Life cycle impact of the road pavement but only to a limited extent (less than 10%). However, the addition of fibres is expected to increase the service life of the wearing course and consequently the life expectancy of the road pavement. According to the results, with an increment of 2 years in service life of the road pavement, the environmental benefits associated with this life extension outweigh the negative impacts generated by the fibre production and transportation.

List of Tables

List of Figures

Table of content

1 Introduction

FIBRA project

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. Therefore, fostering the implementation of innovative solutions, like the addition of fibres in asphalt mixtures that improve their mechanical performance and durability and consequently the service life of the whole pavement is indispensable.

Despite the promising results achieved in previous research works and the availability of commercial fibres whose providers ensure a pavement life extension of at least a 50% and asphalt mixture life extension of around 200% (depending on the type of fibre and provider), the use of reinforced-asphalt mixtures is not as widespread as could be expected. This is principally due to the existence of gaps in the state of the knowledge that make National Road Administrations be reluctant to their incorporation.

In order to promote its utilization, the objective of the FIBRA project is to overcome the technical barriers for the safe and cost-efficient implementation of fibre-reinforced asphalt mixtures (FRAM) by NRAs with which an increase in the asphalt pavements durability could be achieved. In order to achieve this objective several activities were proposed and developed. Among these activities, the identification of potentially toxic and hazardous pollutants and a Life Cycle Analysis (LCA) were planned.

For the pollutants identification, the chemistry of the two selected fibres (polyacrylonitrile and a blend of aramid/polyolefin) and the identification of critical compounds was addressed. By specific chemical analyses, levels of potential pollutants should be determined for the different materials.

Regarding the LCA. the objective was the quantification of the environmental impacts of using fibres to increase the service life of asphalt mixtures and the comparison of these impacts with conventional practices. The LCA has been performed following the overall framework provided by the international standard ISO 14044 (2006) and the standard EN 15804 (2012) + A1 (2013) and the primary tool used was GaBi v.8. The standard EN15804 offers the product category rules (PCRs) for all construction products and services, with the aim to ensure transparency and harmonization in environmental product declarations (EDPs). In this work, a crade-to-gate and a cradle-to-grave studies have been performed.

CEDR Transnational Research Programme

The CEDR Transnational Research Programme was launched by the Conference of European Directors of Roads (CEDR). CEDR is the Road Directors' platform for cooperation and promotion of improvements to the road system and its infrastructure, as an integral part of a sustainable transport system in Europe. Its members represent their respective National Road Authorities (NRA) or equivalents and provide support and advice on decisions concerning the road transport system that are taken at national or international level.

The participating NRAs in the **CEDR Call 2017: New Materials** are **Austria, Belgium-Flanders, Denmark, Germany, Netherlands, Norway, Slovenia, Sweden** and the **United Kingdom**. As in previous collaborative research programmes, the participating members have established a Programme Executive Board (PEB) made up of experts in the topics to be covered. The research budget is jointly provided by the NRAs as listed above.

2 Pollutants identification, measurement and toxicity assessment of FRAM

2.1 Introduction and motivation

The use of fibre materials to improve properties of asphalt mixtures is gaining more attention. This also offers new opportunities for the re-integration of recycled materials. Several projects to reuse recycled plastic materials are under investigations. Not only the physical properties of fibre-reinforced asphalt mixtures (FRAM) and their durability are important to know, also their impact on human health and the environment have to be assessed. We use a two-phase approach to assess new or recycled plastic materials for the production of FRAM.

In a first phase, the chemistry of the plastic fibre material itself and the identification of critical compounds is addressed. By specific chemical analyses, levels of potential pollutants should be determined for the different materials. If critical compounds are detected in the fibre, their release from it should be studied. If suitable tracer compounds or tracer elements could be identified in the fibre, the leaching properties from FRAM should be evaluated under simulated lab conditions and finally during real-world exposure.

If hazardous compounds have been identified in the fibre material and in run-off waters of roads, abatement strategies might be implemented to minimize such risks. For example, a pre-treatment of the fibre might lower levels of critical compounds.

So far, this approach has been applied in projects to recycle tar-containing asphalt pavements, to re-use of crumb rubber from old tires and to recycle plastic materials of various origins. Herein we studied three plastic fibre materials and searched for the presence of critical compounds.

2.2 Chemistry of plastic materials, identification of critical compounds

The list for potential hazardous compounds in plastic and with it the list of potential analytical targets is enormous and quickly growing. To search for all of these compounds is beyond the scope of this study. We have identified four classes of compounds that we consider relevant.

Polycyclic aromatic hydrocarbons (PAHs), among them the sixteen priority PAHs, are important constituents of binders. PAHs are present in bitumen and to a larger extent in tar. We have not investigated PAH levels in the three plastic fibre materials.

Another important class of plastic additives are phthalate diesters (PDEs), which are used at large scales as plasticizers. Some of these PDEs have been banned recently due to their hormone-like properties.

The diverse class of chlorinated paraffins (CPs), which are widely used as plasticizers and flame retardants too, especially in polyvinylchloride (PVC) plastic, together with polybrominated diphenyl ethers (PBDEs) are relevant compounds as well. Short-chain CPs, which include chlorinated paraffins with carbon chain length of C10-C13, are now regulated under the Stockholm Convention on persistent organic pollutants and should not be used in plastic any longer. Also PBDEs, once widely used as flame-retardants in plastic for electronic devices, are banned under the Stockholm Convention. CPs and PBDEs are considered as persistent, bioaccumulating and toxic pollutants. In other words, the re-integration of old plastic materials, recovered from waste plastic, may contain such additives.

The list of plastic additives is steadily growing. Various additives are used to produce the plastic, e.g. catalysts supporting the polymerisation or additives to protect plastic during the use phase.

Polymerisation catalysts e.g. radical initiators, propagators, inhibitors, vulcanization accelerators, cross-linking agents etc. typically remain in the plastic material.

Additives such as flame-retardants, UV stabilizers, pigments, dyes, antioxidants and plasticizers may also be present in recycled plastic materials.

In other words, the identification of critical compounds in plastic, which may be toxic (e.g. Cd, Ni, Pb, As, Sb), carcinogenic, mutagenic (e.g. PAHs), with endocrine activity (e.g. phthalates) or persistent and bio-accumulating (e.g. CPs, PBDEs) is not an easy task.

With the given time and resources, we investigated the three plastic fibre materials for the presence of CPs and PBDEs.

2.3 Experimental approach

2.3.1 Plastic fibre materials studied

Figure 1 displays photos of the three materials tested. Two fibrous plastic materials A (Forta 1) and B (Forta 2) and a polyacrylonitrile fibre (PAN) were studied.

2.3.2 Extraction of plastic material

Samples of the three materials were extracted with dichloromethane at reflux in a soxhlet apparatus for 4 h. Aliquots of the organic extracts were analyzed for the presence of chlorinated paraffins, especially for short-chain CPs (SCCPs, C10-C13) and medium-chain-CPs (MCCPs, C14-C17) and polybrominated diphenyl ethers (PBDEs). Prior to analysis, the extracts were spiked with labelled standard materials and fractionated.

2.3.3 Chemical analysis by GC-UHR-MS

A gas chromatographic system coupled to an ultra-high resolution mass spectrometer (Orbitrap, QExactive) was used to investigate for CPs and PBDEs. Respective SCCP materials (Ehrenstorfer) and ^{13}C-labelled PBDEs were used as reference materials.

2.3.4 Leaching tests from reinforced asphalt mixtures

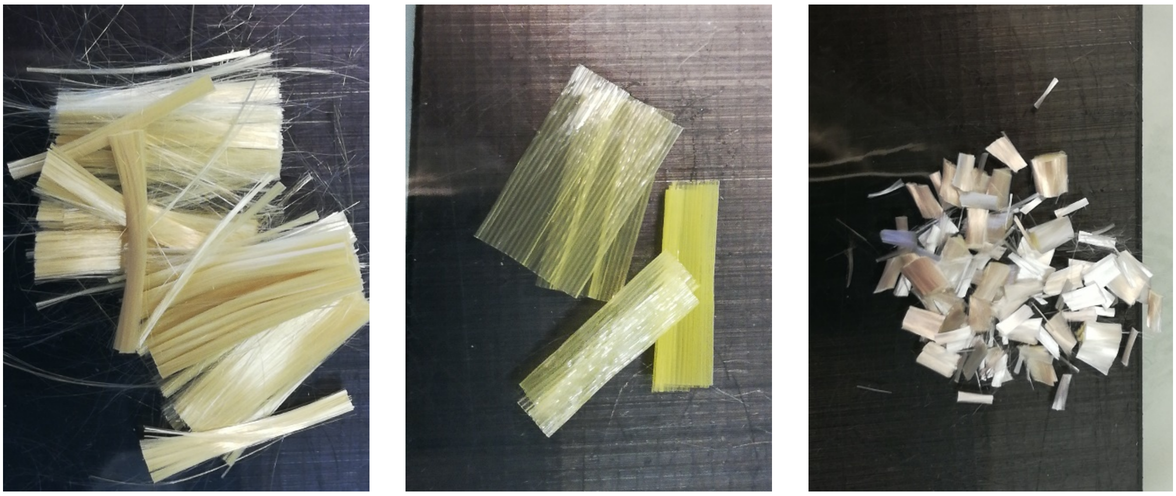
So far, no critical pollutants could be detected in the organic extracts of the fibre materials. Hence leaching tests from fibre-reinforced asphalt mixtures were not performed.

2.4 Results and discussions

Figure 1 displays photos of the three materials tested. Two fibrous plastic materials A (Forta 1) and B (Forta 2) and a polyacrylonitrile fibre (PAN) were studied.

Visible inspection of the three fibres showed their fibrous nature and in case of samples A

(Forta 1) and C (PAN), a tendency of the fibres to form larger bundles.



A: Forta 1 B: Forta 2 C: PAN

Fig. 1 Plastic materials tested. Two fibrous materials A (Forta 1) and B (Forta 2) and polyacrylonitrile fibres, were studied.

Dichloromethane extracts of the three materials were analysed for the presence of short- and medium-chain chlorinated paraffins (SCCPs and MCCPs) and polybrominated diphenyl ethers (PDPEs).

Figure 2 displays chemical structures of CPs, PBDEs and phthalate diesters (PDEs), which are widely used as plasticizers and flame retardants in plastic materials. Of the 209 PBDE congeners possible, the presence of those 10 congeners shown in **Fig. 2** were tested. These PBDE congeners are abundant in technical PBDE products.

A negative chemical ionization (NCI)-GC-UHR-MS method was used to detect SCCPs and MCCPs. The MS was operated at a mass resolution of m/Δm >100'000, which allows the non-interfered analysis of CP homologues up to a chain length of C17.

Neither short- nor medium-chain CPs could be detected in the dichloromethane extracts of the three fibre materials.

An electron-impact ionization (EI) GC-UHR-MS method was applied to detect polybrominated diphenyl ethers. The MS was also operated a mass resolution of m/Δm >100'000.

In none of the dichloromethane extracts of the three materials could we detect PBDEs. Of the 209 PBDE congeners known, we specifically searched for PBDE-28, -47, -99, -100, -153, -154, -183, -197, -206 and PBDE-209. This selection includes tri-, tetra-, penta-, hexa-, hepta-, octa-, nona- and deca-bromo-diphenyl ether congeners (**Fig. 2**).

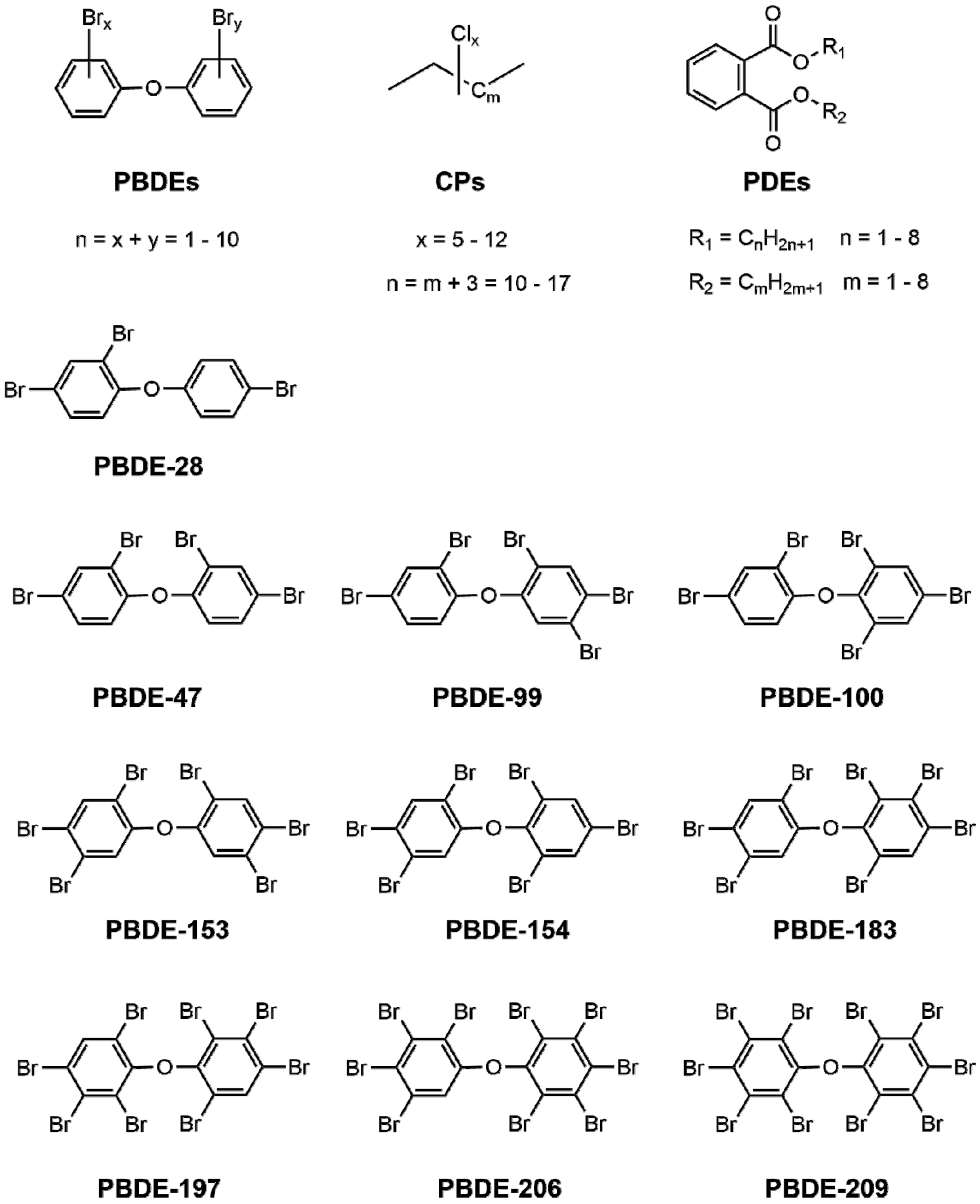


Fig. 2 Chemical structures of chlorinated paraffins (CPs), polybrominated diphenyl ethers (PBDEs) and phthalate diesters (PDEs) used as plasticizers and flame retardants in various plastic materials. PBDE-28, -47, -99, -100, -153, -154, -183, -197, -206 and PBDE-209 are abundant in technical PBDE products.

2.5 Conclusions

The number of potential plastic additives is enormous. With it, it is a challenge to select appropriate analytical targets. Not knowing what specific additives have been used to produce and process the investigated plastic fibre materials, we searched only for a small selection of potential target compounds. We focused on now banned plastic additives, the short-chain chlorinated paraffins (SCCPs) and the polybrominated diphenyl ethers (PBDEs). Both classes of compounds are used as flame retardants, but should not be used any longer because they are listed in the Stockholm Convention as persistent, bio-accumulating and toxic compounds.

With the applied GC-UHR-MS methods, which allow a specific and sensitive analysis of these compounds, we should have been able to detect these analytes in nano-gram quantities. Neither CPs, nor PBDEs could be detected in organic extracts of the three examined plastic materials.

With respect to these critical plastic additives, we can conclude that no relevant levels of CPs and PBDEs are present in these materials.

So far, we could also not detect other organic compounds in the tested plastic materials that could be used as marker compounds to study the leaching properties of respective fibre-reinforced asphalt materials.

More analytical work is needed to specify and search for other potential target compounds, which can be attributed to PAN fibre-based plastic materials.

If PAN fibre-reinforced asphalts will be used at large scales in roads, it may be necessary to perform toxicity-based assessments of road run-off waters or dust particles from road abrasion.

3 Life Cycle Assessment

3.1 Goal and scope definition

3.1.1 Goal and scope

The goal of this LCA is to demonstrate the sustainability of using fibres to extend the life service of asphalt mixes by comparing the environmental impacts the new FRAMs (cradle-to-gate) and the road sections incorporating FRAMs (cradle-to-grave) produce with the ones generated by traditional asphalt mixtures and pavements.

With this in mind, the four pilot sections implemented by BAM in the Netherlands (two FRAM and two references) and the three (one FRAM and two references) implemented by VEIDEKKE in Norway will be analysed.

Porous asphalt – The Netherlands (BAM)

As part of the FIBRA project, BAM and its NRA, Rijkswaterstaat (RWS), have built a road section to test the following mixtures:

- FIBRA-PA1, reference, conventional 2L-PA 8 mixture with PMB.
- FIBRA- PA2, reference, 2L-PA 8 with penetration grade bitumen (70/100).
- FIBRA- PA3, 2L-PA 8 with pen grade bitumen (70/100) and 0.15% panacea fibre.
- FIBRA- PA4, 2L-PA 8 with pen grade bitumen (70/100) and 0.05% aramid fibre.

The definition of the **functional unit** for the cradle-to-grave analysis, that is common for the four asphalt sections, is as follows:

- 1 km of a two lanes road (one way) with an annual average daily traffic of 50000 vehicles. Total width: 11m.
- Three asphalt layers: 2L porous asphalt (FIBRA PA-X), binder (AC) and base (AC) layer.
- The period of the study is 30 years. The wearing course is assumed to be replaced in years 10 and 20 and the three asphalt layers (wearing, binder and base course) are removed in year 30.

In year 30, it is expected that the road pavement will still be used, so new asphalt layers will be laid on it (not included in this analysis). No end-of-life phase is considered but as part of the replacement information module (B4) the milling of the asphalt layers (C1) and the transportation of the RA to the asphalt plant (C2) are included.

The **declared unit** for the cradle-to-gate analysis, that is common for the four asphalt mixtures, is as follows:

- 1 ton of a porous asphalt mixture (FIBRA PA-X) produced at the asphalt plant.

The service life of the PA mixtures is assumed the same for the 4 alternatives: 10 years. The end-of-life phase will include the milling of 1 ton of asphalt mixture and the transportation of the RA to the asphalt plant (C2). In module D, 100% reuse of the mixtures is considered.

Asphalt concrete – Norway (VEIDEKKE)

VEIDEKKE and its NRA, Statens Vegvesen, agreed in the implementation of the following asphalt layers in the test section built in Norway:

- FIBRA-AC1, binder 70/100, reference.
- FIBRA-AC2, binder 70/100, PAN fibre.
- FIBRA-AC3, binder PMB.

The definition of the **functional unit** for the cradle-to-grave analysis, common for the three asphalt sections, is as follows:

- 1 km of a two lanes road (two-way) with an annual average daily traffic of 1300 vehicles with a 13% of heavy traffic. Total width: 9m.
- Three asphalt layers: wearing course (FIBRA-AC-X), binder and base layer.
- The period of the study is 40 years (The Norwegian EPD Foundation, 2017). The wearing course is assumed to be replaced in year 15 (The Norwegian EPD Foundation, 2017) and the three asphalt layers (wearing, binder and base course) are removed in year 40.

In year 40, it is expected that the road pavement will still be used, so new asphalt layers will be laid on it (out of the scope of this study). No end-of-life phase is considered but as part of the replacement information module (B4) the milling and RA transportation are included.

The **declared unit** for the cradle-to-gate analysis, that is common for the four asphalt mixtures, is as follows:

- 1 ton of an AC11 mixture (FIBRA AC-X) produced at the asphalt plant.

The service life of the AC mixtures is assumed the same for the 3 alternatives: 15 years. The end-of-life phase will include the milling of 1 ton of asphalt mixture and the transportation of the RA to the asphalt plant (C2). In module D, 100% reuse of the mixtures is considered.

3.1.2 Life cycle of the road system

The Life cycle assessment has been carried out based on the ISO 14040:2006 (ISO, 2006a) and ISO 14044:2006 (ISO, 2006b) standards, which specify the requirements and guidelines that should be follow during the analysis. A cradle-to-gate and a cradle-to-grave analysis will be done mostly based on the stages defined in the standard UNE-EN-15804:2012+A2:2020 (*Figure 1*).

	CONSTRUCTION WORKS ASSESSMENT INFORMATION															
	CONSTRUCTION WORKS LIFE CYCLE INFORMATION															ADDITIONAL INFORMATION BEYOND THE END-OF-LIFE
	PRODUCT STAGE			CONSTRUCTION PROCESS STAGE		USE STAGE							END-OF-LIFE STAGE				BENEFITS AND BURDENS BEYOND THE END-OF-LIFE
	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
	Raw material supply	Transport	Production	Transport	Construction process	Use	Maintenance	Repair	Replacement	Refurbishment	operational energy use	Operational water use	Demolition	Transport	Waste processing	Disposal	Potential of reutilization, recovering and recycling
Cradle-to-gate	X	X	X										X	X			X
Cradle-to-grave	X	X	X	X	X	X	X		X				*	*			X

* included as part of B2 and B4

Figure 1. Stages of the Cradle-to-gate and cradle-to-grave analyses.

According to UNE-EN-15804:2012+A2:2020, the cradle-to-gate analysis cover the supply of raw materials, transportation and production, including the end-of-life and the additional information beyond the end-of life (modules A1-A3, C and D), and is calculated per ton of asphalt mixture.

On the other hand, according to EN-15804:2012+A2:2019, the cradle-to-grave analysis cover the modules A, B, C and D, and is based on the functional unit defined in section 2.1. However, not all the stages B1 to B7 or C1-C4 have been considered in the study. Module B3, B5, B6 and B7 are considered not relevant for asphalt mixtures (more focused on buildings) since B2, and B4 already cover the needed operations during the life cycle of the asphalt pavement. Finally, the end-of-life stage has not been included as a separate module because the road pavement will continue active after the study period, so the demolition and transport of the reclaimed asphalt (C1 and C2) are included within the B4 module "replacement".

3.1.2.1 Product stage: information modules A1-A3

The information module (A1-A3) includes:

- A1: extraction and processing of raw materials (bitumen, aggregates, fibres) including the processing of inputs that constitute secondary materials (i.e. RAP if applicable).
- A2: transportation to the asphalt plant of all the raw materials.
- A3: asphalt mixture production at the asphalt plant.

Including the supply of all materials, products and energy as well as the waste management.

3.1.2.2 Construction process: information modules A4-A5

The production stage includes:

- A4: transportation of the produced asphalt to the worksite.
- A5: laying and compaction of the asphalt mixtures.

Including the supply of all materials, products and energy as well as the waste management.

The impacts and all aspects related with possible material losses in the construction process (A5) are not included in the study.

3.1.2.3 Use stage: information modules B1 – B4

The use stage includes the following modules:

- B1: in this phase, the leaching of the bituminous mixtures is included in the analysis. The particulate emissions related to surface wear are not included due to the lack of harmonized and accurate test methods.
- B2: in this phase, the milling and overlay of the wearing course is included. B2 involves all stages information modules from A1 to A5 and C1-C2 for the materials in the road surface.
- B4: in this phase, the milling and RA transportation is included. B4 involves the milling of the three asphalt layers and the RA transportation to the asphalt plant.

Possible consequences on traffic flow of B3 and B4 are not included in the study. The duration of the work and the traffic management for all the alternatives will be the same. On the other hand, the importance of congestion in the LCA depends on the decided strategy (i.e. working during the night) or the type of road. This will make difficult to assess the differences in the environmental impacts of road pavements with or without fibres.

3.1.2.4 Additional information beyond the EoL (D)

Additional module D will include the RA that is not considered in the life cycle of the pavement under study. If the binder and base course include a 60% of RA in their composition, this amount is subtracted from the total RA available at the end-of-life of each bituminous mixture. The bitumen and the aggregates from the RA are assumed 100% recyclable without any loss of their main properties.

3.2 Life cycle inventory

3.2.1 Production stage (A1-A3)

This stage includes the identification and quantification of the material consumed and emissions generated during the extraction and processing of the materials (aggregates, filler, bitumen, fibres (cellulose, pan and aramid) and their transportation to the asphalt plant as well as the manufacturing of the different asphalt mixtures.

The processing of RAP that is used within the system boundaries has been included in this stage. In the Dutch test section, the use of RAP was limited to the binder and base layers in a 60% by weight. In the Norwegian section, no RAP is considered in none of the asphalt layers.

In Table 1 and Table 2, the formulas, thickness and density of the asphalt mixtures tested in the Netherlands and Norway are shown.

Table 1. Exact formulation of the reference and experimental mixtures built in the Netherlands

	TEST SECTION - THE NETHERLANDS					
	SURFACE COURSE				BINDER COURSE	BASE COURSE
	FIBRA-PA1	FIBRA-PA2	FIBRA-PA3	FIBRA-PA4	AC 16 bin/base 30/45 60% RAP	AC 22 bin/base 30/45 60% RAP
PEN bitumen (%)	0	5.3	5.3	5.3	1.51	1.48
PMB bitumen (%)	5.3	0	0	0	0	0
Aggregate (%)	89.1	88.9	88.8	88.9	38.01	37.92
Filler (%)	4.6	4.6	4.6	4.6	0.29	0.29
Filler baghouse dust (%)	1	1	1	1	0	0
Cellulose Fibre (%)	0	0.2	0.15	0.15	0	0
PAN fibre (%)	0	0	0.15	0	0	0
Aramid Fibre (%)	0	0	0	0.05	0	0
RAP (%)	0	0	0	0	60.19	60.31
Density (ton/m^3)	1.902	1.945	1.936	1.957	2.482	2.497
Thickness (m)	0.025	0.025	0.025	0.025	0.06	0.16

Table 2. Exact formulation of the reference and experimental mixtures built in Norway

	TEST SECTION - NORWAY				
	SURFACE COURSE			BINDER COURSE	BASE COURSE
	FIBRA-AC1	FIBRA-AC2	FIBRA-AC3	AC11/ACG11	AG16
PEN bitumen (%)	0	5.6	5.6	5.8	4.6
PMB bitumen (%)	5.6	0	0	0	0
Aggregate (%)	86.6	86.6	86.5	84	89
Filler (%)	7.8	7.8	7.8	10	6
Filler baghouse dust (%)	0	0	0	0	0
Cellulose Fibre (%)	0	0	0	0	0
PAN fibre (%)	0	0	0.15	0	0
Aramid Fibre (%)	0	0	0	0	0
RAP (%)	0	0	0	0	0
Density (ton/m^3)	2.508	2.505	2.505	2.500	2.500
Thickness (m)	0.04	0.04	0.04	0.03	0.09

The sources for the life cycle inventory (LCI) of the materials considered in this stage are included in Table 3.

Table 3. Sources of the production stage LCI

Aggregates	GaBi V8.1
Filler	GaBi V8.1
Penetration grade bitumen	Eurobitume, 2020 (Eurobitume, 2020)
Polymer modified bitumen	Eurobitume, 2020 (Eurobitume, 2020) + GaBi V8.1 (SBS)
Cellulose fibre	GaBi V8.1
PAN fibre	GaBi V8.1
Aramid fibre	GaBi V8.1
RAP processing	UNPG, 2011c (UNPG , 2011)
Asphalt mixture manufacturing	Thermodynamic model adapted from Peinado et al. (2011). Specific temperature and moisture data from BAM and VEIDEKKE were used for the calculation of energy consumption (Peinado, et al., 2011)

Truck transportation	Gabi V8.1	
Natural gas combustion	Natural gas combusted in industrial boiler (NREL)	
Natural gas mix	GaBi V8.1: Natural gas mix (Country specific: NL)	GaBi V8.1: Natural gas mix (Country specific: NO)
Electricity grid mix	GaBi V8.1: Electricity grid mix (country specific: NL)	GaBi V8.1: Electricity grid mix (country specific: NO)
Diesel	GaBi V8.1: Diesel mix at filling station (Country specific: NL)	GaBi V8.1: Diesel mix at filling station (Country specific: EU)
Diesel combustion	Diesel combusted in industrial equipment (NREL)	

The distances to calculate the transportation impact in A2 are indicated in Table 4.

Table 4. Distances to calculate transportation impact in module A2

Transportation of raw materials to the asphalt plant	Distance (Km)	
	Dutch section	Norwegian section
Pen bitumen	115	150
PMB bitumen	530	200
Aggregates	53 km inland ship 933 km ocean ship	30
Filler	150	100
Cellulose	100	-
PAN fibre	150	171 km by ferry 1483 km by truck
Aramid fibre (twaron 1080)	230	-

3.2.2 Construction stage (A4-A5)

The construction stage includes the transportation of the asphalt mixtures from the asphalt plant to the roadwork in addition to their paving and compaction. The transportation distance from the asphalt plan to the worksite is shown in Table 5 for each scenario.

Table 5. Distances from the asphalt plant to the worksite

Transportation	Distance (Km)
Asphalt plant (BAM) to A73	40
Asphalt plant (VEIDEKKE) to FV30	72

The fuel consumption of the equipment during the laying and compaction processes depends on the type of equipment and fuel used (diesel, vegetable oil…). Although the diesel consumed by the paver and rollers were collected during the implementation of the Dutch section, in this study, diesel and average consumption and patterns data will be used, as shown in Table 6.

Table 6. Fuel consumption of equipment during laying and compaction

Equipment	Diesel consumption (l/m^2)		
Paver	0.007	0.011	0.019
Roller	0.013		

3.2.3 Use stage (B1-B4)

3.2.3.1 Maintenance (B2) and replacement (B4)

The maintenance schedule considered for the two test sections is shown Table 7.

Table 7. Maintenance schedule

	The Netherlands	Norway
0	Initial construction	Initial construction
10	Mill & overlay Wearing course	
15		Mill & overlay Wearing course
20	Mill & overlay Wearing course	
30	Mill & overlay 3 asphalt layers	Mill & overlay Wearing course
40		Mill & overlay 3 asphalt layers

The impacts of this stage involve those related to the milling and overlay (M&O) of the wearing course at year 10/20 and 15/30 and the milling of the whole asphalt layers at year 30 and 40 for the for the Dutch and Norwegian test sections respectively. Processes included in the M&O operation are milling of the deteriorated asphalt layer (C1), the transportation to the recovery centre (C2), the production of the materials (A1, A2 and A3), their transportation to the roadwork (A4) and the construction of the new layer (A5).

For road milling, data from previous research will be used (Lizasoain-Arteaga, et al., 2019).

For all the maintenance works, same distances as in A2 and A4 are considered for transporting raw materials to the asphalt plant and the hot mix asphalt to the worksites. Concerning the transportation of RA from the worksite to the asphalt plant or recovery centre (C2), a distance of 40 km and 72km were used for The Netherlands and Norway respectively.

3.3 Life cycle impact assessment

The same category impacts and methods specified in EN 15804:2012 + A2:2019 have been selected for this study. The amended EN15804 has aligned the impact assessment models, indicator's units and characterization factors used in the previous version with the corresponding ones developed within the Environmental Footprint (EF) method. The EF is an initiative of the European Commission stablishing a common methodological approach for quantifying the environmental performance of any good or service throughout its life cycle.

Table 8 presents the environmental impact indicators (core and additional), units and recommended characterization methods that are applied.

Table 8. Environmental impact indicators

Core environmental impact indicators			
Impact category	**Indicator**	**Unit**	**Recommended default LCIA method**
Climate change (total)	Radiative forcing as Global Warming Potential (GWP-total)	kg $CO_{2\ eq}$	Baseline model of 100 years of the IPCC (based on IPCC 2013)
Climate change (fossil)	Radiative forcing as Global Warming Potential of fossil fuels (GWP-fossil)	kg $CO_{2\ eq}$	Baseline model of 100 years of the IPCC (based on IPCC 2013)
Climate change (biogenic)	Radiative forcing as Biogenic Global Warming Potential (GWP-biogenic)	kg $CO_{2\ eq}$	Baseline model of 100 years of the IPCC (based on IPCC 2013)
Ozone depletion	Ozone Depletion Potential (ODP)	kg CFC-11 $_{eq}$	Steady-state ODPs 1999 as in WMO assessment
Acidification	Accumulated Exceedance (AE)	mol $H+_{eq}$	Accumulated Exceedance (Seppälä et al. 2006, Posch et al, 2008)
Eutrophication, freshwater	Fraction of nutrients reaching freshwater end compartment (P)	kg P_{eq}	EUTREND model (Struijs et al, 2009b) as implemented in ReCiPe
Eutrophication, marine	Fraction of nutrients reaching marine end compartment (N)	kg N_{eq}	EUTREND model (Struijs et al, 2009b) as implemented in ReCiPe

Eutrophication, terrestrial	Accumulated Exceedance (AE)	mol N $_{eq}$	Accumulated Exceedance (Seppälä et al. 2006, Posch et al, 2008)
Photochemical ozone formation, human health	Tropospheric ozone concentration increase	kg NMVOC $_{eq}$	LOTOS-EUROS model (Van Zelm et al, 2008) as implemented in ReCiPe
Resource use, minerals and metals	Abiotic resource depletion (ADP ultimate reserves)	kg Sb $_{eq}$	CML 2002 (Guinée et al., 2002) and van Oers et al. 2002.
Resource use, fossils	Abiotic resource depletion – fossil fuels (ADP-fossil)	MJ	CML 2002 (Guinée et al., 2002) and van Oers et al. 2002
Water use	User deprivation potential (deprivation-weighted water consumption)	m3 world $_{eq}$	Available WAter REmaining (AWARE) Boulay et al., 2016
Additional environmental impact indicators			
Particulate matter	Impact on human health	disease incidence	UNEP recommended model (Fantke et al 2016)
Ionising radiation, human health	Human exposure efficiency relative to U235	kBq U235 $_{eq}$	Human health effect model as developed by Dreicer et al. 1995 (Frischknecht et al, 2000)
Ecotoxicity, freshwater	Comparative Toxic Unit for ecosystems (CTU_e)	CTUe	USEtox model, (Rosenbaum et al, 2008)
Human toxicity, cancer	Comparative Toxic Unit for humans (CTU_h)	CTUh	USEtox model (Rosenbaum et al, 2008)
Human toxicity, non-cancer	Comparative Toxic Unit for humans (CTU_h)	CTUh	USEtox model (Rosenbaum et al, 2008)
Land use	Soil quality index	Dimensionless (pt)	Soil quality index based on LANCA (EC-JRC)

In LCA, according to ISO 14044, normalization and weighting are optional steps of the Life Cycle Impact assessment. The normalization express the total impact of a reference region for a certain impact category in a reference year and weighting allows the identification of the most relevant impact categories. Any weighting scheme inherently involves value choices that will depend on policy, cultural and other preferences. However, weighting is useful to increase the practical use of LCA and to ease decision-making.

In this study, two different weighting schemes are applied:

- The weighting set provided by the JRC to be used for the EF will be applied (Sala, et al., 2018).
- The environmental costs indicator (MKI) proposed by Rijkswaterstaat (van der Klauw, 2019). The environmental sustainability of any infrastructure asset is calculated on the basis of environmental costs in an LCA-based method following EN 15804 and is provided in one indicator in order to make sustainability an integral part of the procurement process. In order to apply MKI, the midpoint categories and units of CML2001 (2016) are calculated.

3.4 LCA results

3.4.1 Porous asphalt section (2L-PA)

3.4.1.1 Cradle-to-gate analysis (A1-A3 + C)

Results presented in Table 9 quantify the cradle-to-gate environmental impacts of the four alternative asphalt mixtures evaluated in this study. These results do not include module D. the effect of the potential benefits beyond the end-of-life is considered separately.

Table 9. Results of the cradle-to-gate analysis of the four PA mixure alternatives.

			FIBRA-PA1	**FIBRA- PA2**	**FIBRA- PA3**	**FIBRA- PA4**
			PMB	Reference	PAN fibre	Aramid fibre
CC_{total}	Climate change (total)	[kg CO_2 eq.]	7,61E+01	6,61E+01	7,41E+01	7,36E+01
$CC_{biogenic}$	Climate change (biogenic)	[kg CO_2 eq.]	7,53E-02	7,63E-02	8,50E-02	9,61E-02
CC_{fossil}	Climate change (fossil)	[kg CO_2 eq.]	7,60E+01	6,60E+01	7,39E+01	7,35E+01
OD	Ozone depletion	[kg CFC-11 eq.]	2,63E-13	8,78E-13	7,52E-13	8,08E-13
AE	Acidification	[Mole of H^+ eq.]	7,01E-01	6,26E-01	6,46E-01	6,41E-01
EUT_f	Eutrophication, freshwater	[kg P eq.]	2,51E-03	8,31E-04	8,37E-04	8,51E-04
EUT_m	Eutrophication, marine	[kg N eq.]	1,80E-01	1,68E-01	1,75E-01	1,72E-01
EUT_t	Eutrophication, terrestrial	[Mole of N eq.]	1,97E+00	1,84E+00	1,92E+00	1,88E+00
POF-HH	Photochemical ozone formation, human health	[kg NMVOC eq.]	5,16E-01	4,84E-01	5,05E-01	4,96E-01
$RU_{m\&m}$	Resource use, minerals and metals	[kg Sb eq.]	4,97E-06	4,96E-06	5,66E-06	6,20E-06
$RU_{fossils}$	Resource use, fossils	[MJ]	3,32E+03	3,23E+03	3,39E+03	3,37E+03
WU	Water use	[m^3 world eq.]	1,98E+01	4,15E+00	4,90E+00	4,12E+00
PM	Particulate matter	[Disease incidence]	9,77E-06	8,17E-06	8,25E-06	8,31E-06
IR-HH	Ionising radiation, human health	[kBq U_{235} eq.]	4,24E+00	4,34E+00	4,95E+00	4,66E+00
$ETOX_f$	Ecotoxicity, freshwater	[CTU_e]	3,55E+00	3,41E+00	4,30E+00	4,03E+00
CHHE	Human toxicity, cancer	[CTU_h]	1,62E-07	1,62E-07	2,00E-07	1,88E-07
NCHH	Human toxicity, non-cancer	[CTU_h]	1,33E-06	2,29E-06	2,21E-06	2,23E-06
LU	Land use	[Pt]	2,00E+02	2,33E+02	2,39E+02	2,59E+02

Figure 2 shows the relationship (in percentage) between the environmental impact indicators of each PA mixture (FIBRA-PA1, FIBRA- PA3 and FIBRA- PA4) and those of the reference FIBRA- PA2.

The PA mixture with PMB (FIBRA-PA1) presents a similar result (less than 10% of difference) in 10 of the impacts, a better result in 3 impacts and a significant worse result (more than 10% difference) in 6 impacts, specially freshwater eutrophication and water use. Negative results are mostly due to the PMB production and the increase of temperature that is needed in the asphalt plant when this bitumen is used. The positive results are linked with the use by the reference mixture of cellulose fibres.

Fibre-reinforced PA mixtures (FIBRA- PA3 and FIBRA- PA4) present a similar behaviour. Both mixtures, FIBRA- PA3 and PA-4 have a similar impact than the reference (less than 10% variation) in 10 and 12 indicators respectively. Regarding the rest of indicators, both mixtures present a low to moderate increase in the impact between 11 to 26%.

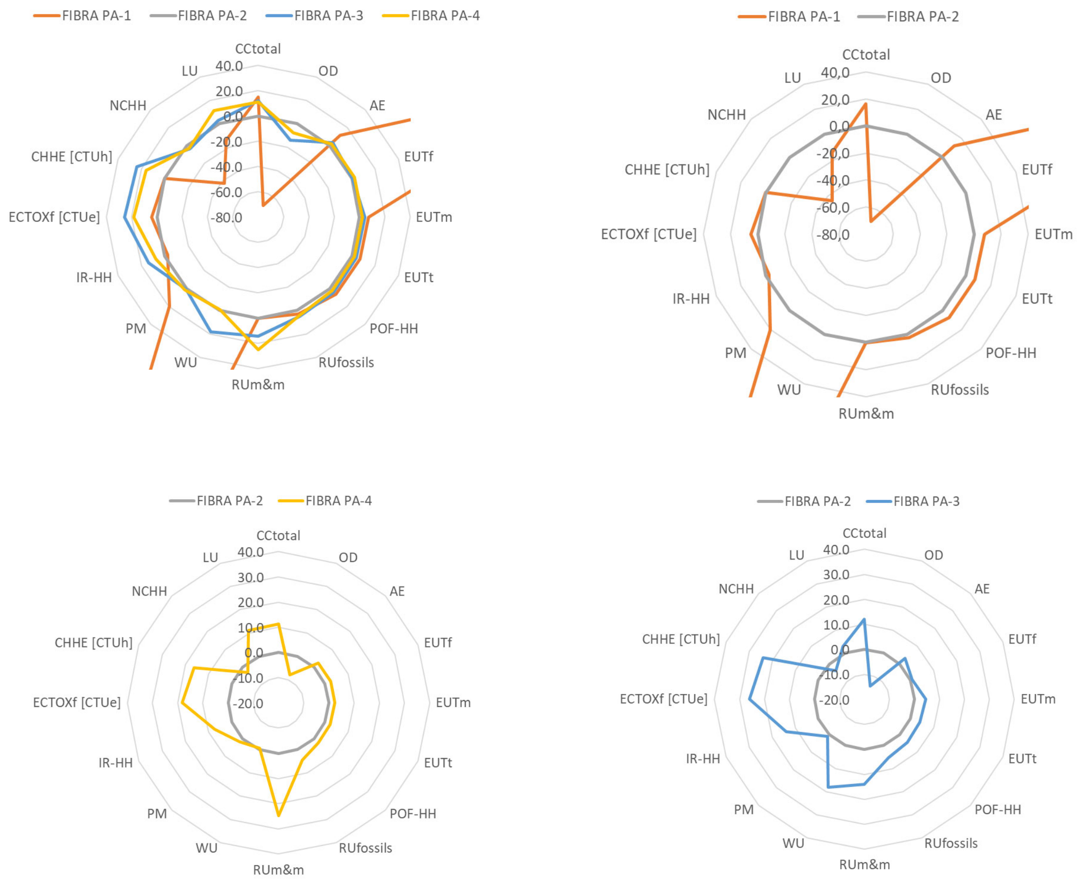


Figure 2. Cradle-to-gate analysis. Spider chart representing the increase/decrease (%) in the environmental impacts indicators of the 4 PA mixtures under study comparing to the reference FIBRA-PA2 (assigned 100%).

3.4.1.2 Cradle-to-grave analysis (A1-A5 + B3 + B4)

Results presented in Table 10 quantify the cradle-to-grave environmental impacts of the four alternative asphalt mixtures evaluated in this study. These results do not include module D since the effect of the potential benefits beyond the end-of-life is considered separately.

Table 10. Results of the cradle-to-grave analysis of the four PA mixure alternatives.

			FIBRA-PA1	**FIBRA- PA2**	**FIBRA- PA3**	**FIBRA- PA4**
			PMB	Reference	PAN fibre	Aramid fibre
CC_{total}	Climate change (total)	[kg $CO_{2\ eq.}$]	6.10E+05	5.94E+05	6.06E+05	6.06E+05
$CC_{biogenic}$	Climate change (biogenic)	[kg $CO_{2\ eq.}$]	6.37E+02	6.38E+02	6.52E+02	6.69E+02
CC_{fossil}	Climate change (fossil)	[kg $CO_{2\ eq.}$]	6.09E+05	5.93E+05	6.05E+05	6.05E+05
OD	Ozone depletion	[kg CFC-11 $_{eq.}$]	4.90E-09	5.86E-09	5.67E-09	5.75E-09
AE	Acidification	[Mole of $H^+_{\ eq.}$]	4.87E+03	4.76E+03	4.79E+03	4.78E+03
EUT_f	Eutrophication, freshwater	[kg $P_{eq.}$]	7.31E+00	4.67E+00	4.68E+00	4.70E+00
EUT_m	Eutrophication, marine	[kg $N_{eq.}$]	1.39E+03	1.37E+03	1.38E+03	1.38E+03
EUT_t	Eutrophication, terrestrial	[Mole of $N_{eq.}$]	1.53E+04	1.51E+04	1.52E+04	1.51E+04
POF-HH	Photochemical ozone formation, human health	[kg $NMVOC_{eq.}$]	3.91E+03	3.86E+03	3.89E+03	3.88E+03
$RU_{m\&m}$	Resource use, minerals and metals	[kg Sb $_{eq.}$]	2.08E+07	2.07E+07	2.09E+07	2.09E+07
$RU_{fossils}$	Resource use, fossils	[MJ]	4.34E-02	4.34E-02	4.45E-02	4.53E-02
WU	Water use	[m^3 world $_{eq.}$]	5.44E+04	2.99E+04	3.11E+04	2.98E+04
PM	Particulate matter	[Disease incidence]	5.69E-02	5.44E-02	5.46E-02	5.47E-02
IR-HH	Ionising radiation, human health	[kBq $U_{235\ eq.}$]	3.27E+04	3.28E+04	3.38E+04	3.33E+04
$ETOX_f$	Ecotoxicity, freshwater	[CTU_e]	3.29E+04	3.27E+04	3.41E+04	3.37E+04
CHHE	Human toxicity, cancer	[CTU_h]	1.55E-03	1.55E-03	1.61E-03	1.60E-03
NCHH	Human toxicity, non-cancer	[CTU_h]	1.61E-02	1.76E-02	1.74E-02	1.75E-02
LU	Land use	[Pt]	1.88E+06	1.93E+06	1.94E+06	1.97E+06

Figure 3 shows the relationship (in percentage) between the environmental impact indicators of each PA mixture (FIBRA-PA1, FIBRA- PA3 and FIBRA- PA4) and those of the reference FIBRA- PA2.

As expected, when the analysis is done from the cradle to the grave, the potential differences between the different PA mixtures are attenuated. In the case of the fibre-reinforced PA mixtures, the differences between the figures in all the environmental impact indicators are less than 10% and in most cases less than 5%. In the case of FIBRA-PA1, the freshwater eutrophication and the water use are still significantly higher (58% and 88%) than in the other three mixtures. On the other hand, this mixture reduce the impact in ozone depletion (OD) comparing to the reference. The rest of the indicators present less than 10% variation.

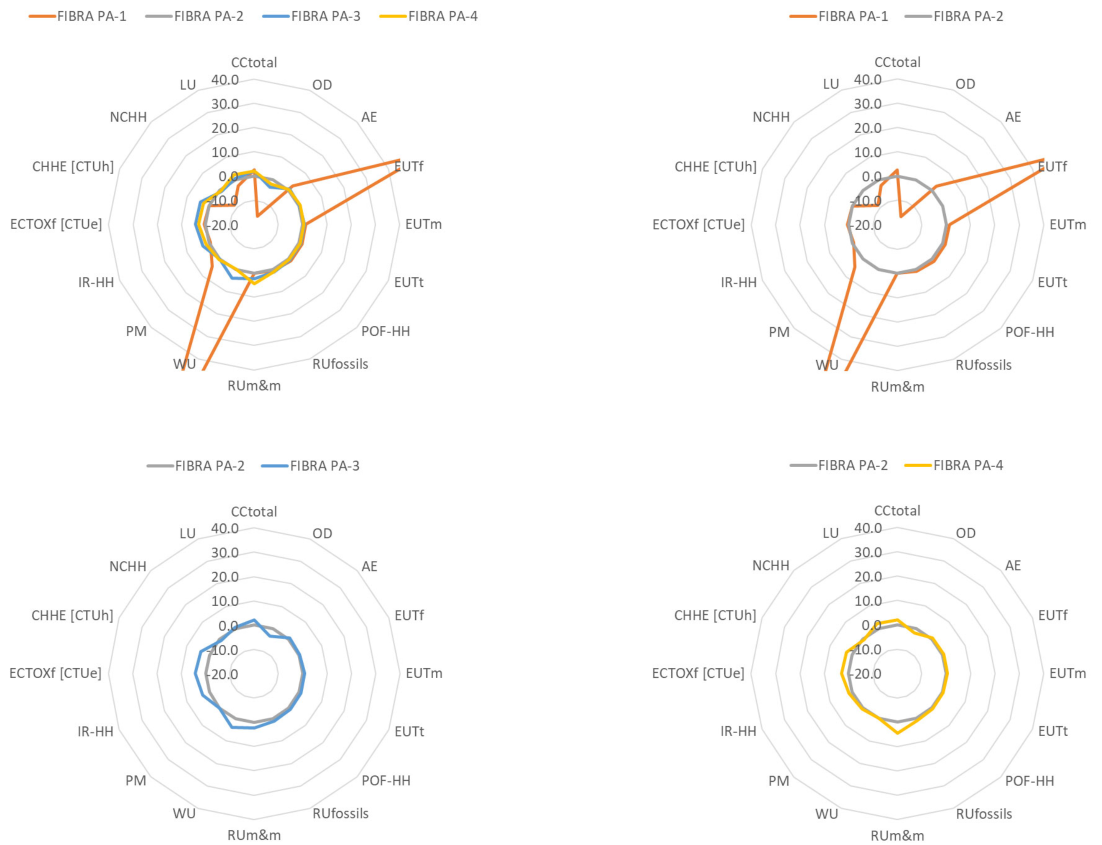


Figure 3. Cradle-to-grave analysis. Spider chart representing the increase/decrease (%) in the environmental impacts indicators of the 4 PA mixtures under study comparing to the reference FIBRA-PA2 (assigned 100%).

3.4.1.3 Normalization and weighting

In order to understand the LCA results presented above, normalization and weighting is applied. As explained in section 4, two different weighting schemes are used in this study: EF 2.0 and MKI. In Figure 4, the relationchip (in %) between the LCA indexes of each PA mixture and that of the reference are shown. Concerning the Cradle-to-gate analysis, the highest environmental impact corresponds to the PA mixture with PMB with a difference higher than 10% (only with the MKI). The Fibre-reinforced PA mixes although with a higher environmental impact than the reference, the variation is kept below 10%. When the analysis cover all life cycle stages (cradle-to-grave), the differences between the environmental impact among the four mixtures are low (less than 4%).

Finally, assuming 10 years of service life for the reference mixture FIBRA- PA2 and 30 years for the complete pavement, the other three mixtures/pavements need to reach a minimum service life in order to match the environmental impact of the reference. Figure 5 shows the results of this calculation considering both analyses, cradle-to-gate and cradle-to-grave. The needed increase in the service life of the FRPA mixtures is minimal (less than half a year).

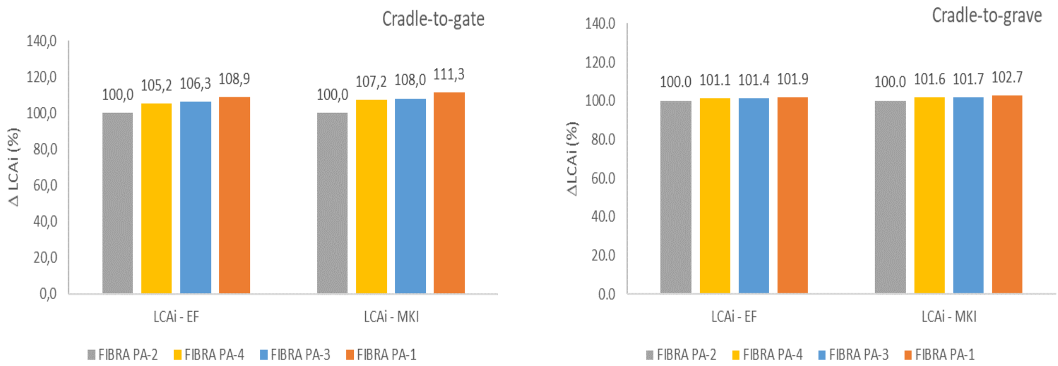


Figure 4. Variation (%) in the LCA index of the 4 PA mixtures under study comparing to the reference FIBRA-PA2 assigned 100%). Left: cradle-to-gate; Right: cradle-to-grave.

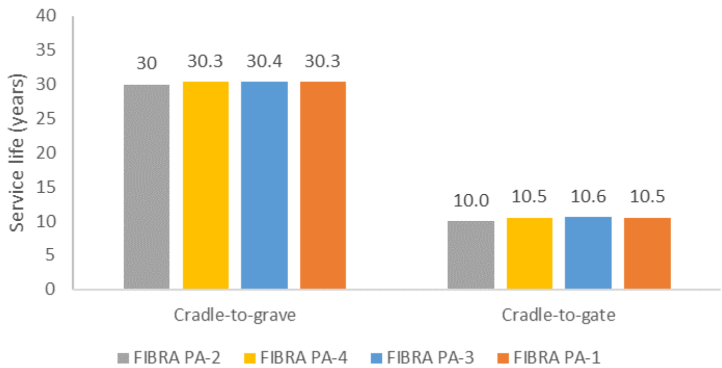


Figure 5. Minimum service life that need to reach FIBRA-PA1, -3 and -4 in order to match the environmental impact of FIBRA- PA2.

3.4.1.4 Beyond the EoL Module (D)

The positive impact of reusing the asphalt mixes at the end of their lives is represented in Figure 6 and Figure 7. To calculate module D, several assumptions have been made: 1) Polymer modified bitumen loss its properties when reused (it is considered as a conventional pen bitumen), 2) the fibres in FRPA mixes maintain their properties after being reused, 3) 100% RA is reused in new asphalt mixtures without downgrading and 4) As 60% of RA is used in the binder and base layers, only 40% of the RA in these layers is included in this Module.

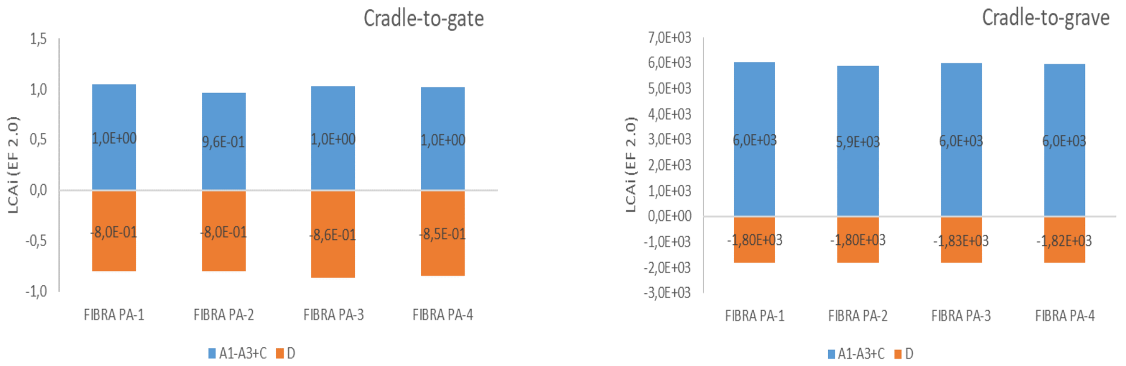


Figure 6. LCA index for A1-A3+C modules (blue) vs. LCA index of module D (orange).

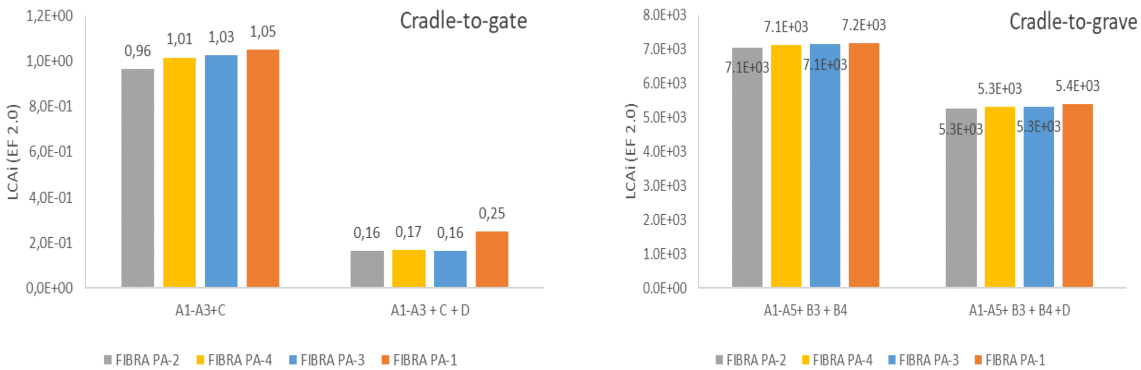


Figure 7. LCA index without and with module D. Cradle-to-gate (left) and Cradle-to-grave (right)

3.4.2 Asphalt concrete section (AC11)

3.4.2.1 Cradle-to-gate analysis (A1-A3+C)

Results presented in Table 11 quantify the cradle-to-gate environmental impacts of the three alternative AC mixtures evaluated in this study. These results do not include module D. the effect of the potential benefits beyond the end-of-life is considered separately, in section 5.2.3.

The mixture FIBRA-AC1 with PMB presents similar results in 10 environmental impact indicators but shows the worst figures in 9 of them, specially Acidification, eutrophication, water use and particle matter with increases beyond 30% and up to 436%. On the other hand, the mixture FIBRA-AC3 reinforced with fibres shows a worse environmental performance in 14 indicators with increases ranging from 14 to 45%.

Table 11. Results of the cradle-to-gate analysis of the three AC11 mixure alternatives.

			FIBRA-AC1	**FIBRA-AC2**	**FIBRA-AC3**
			PMB	Reference	PAN fibre
CC_{total}	Climate change (total)	[kg CO_2 $_{eq.}$]	5,92E+01	4,73E+01	5,54E+01
$CC_{biogenic}$	Climate change (biogenic)	[kg CO_2 $_{eq.}$]	5,85E-02	5,83E-02	6,75E-02
CC_{fossil}	Climate change (fossil)	[kg CO_2 $_{eq.}$]	5,91E+01	4,72E+01	5,53E+01
OD	Ozone depletion	[kg CFC-11 $_{eq.}$]	1,89E-13	1,89E-13	2,18E-13
AE	Acidification	[Mole of H^+ eq.]	2,57E-01	1,66E-01	1,90E-01
EUT_f	Eutrophication, freshwater	[kg P $_{eq.}$]	2,64E-03	8,39E-04	8,49E-04
EUT_m	Eutrophication, marine	[kg N $_{eq.}$]	6,10E-02	4,57E-02	5,44E-02
EUT_t	Eutrophication, terrestrial	[Mole of N $_{eq.}$]	6,61E-01	5,00E-01	5,87E-01
POF-HH	Photochemical ozone formation, human health	[kg NMVOC $_{eq.}$]	1,80E-01	1,38E-01	1,62E-01
$RU_{m\&m}$	Resource use, minerals and metals	[kg Sb $_{eq.}$]	3,29E+03	3,11E+03	3,28E+03
$RU_{fossils}$	Resource use, fossils	[MJ]	3,92E-06	3,87E-06	4,59E-06
WU	Water use	[m^3 world $_{eq.}$]	2,05E+01	3,83E+00	4,60E+00
PM	Particulate matter	[Disease incidence]	6,16E-06	4,28E-06	4,40E-06
IR-HH	Ionising radiation, human health	[kBq $U_{235\ eq.}$]	3,66E+00	3,66E+00	4,28E+00
$ETOX_f$	Ecotoxicity, freshwater	[CTU_e]	2,13E+00	2,10E+00	3,01E+00
CHHE	Human toxicity, cancer	[CTU_h]	9,46E-08	9,14E-08	1,33E-07
NCHH	Human toxicity, non-cancer	[CTU_h]	1,05E-06	1,03E-06	1,21E-06
LU	Land use	[Pt]	1,65E-02	1,64E-02	1,80E-02

Figure 8 shows the relationship (in percentage) between the environmental impact indicators of each AC mixture (FIBRA-AC1 and FIBRA-AC3) and those of the reference FIBRA-AC2.

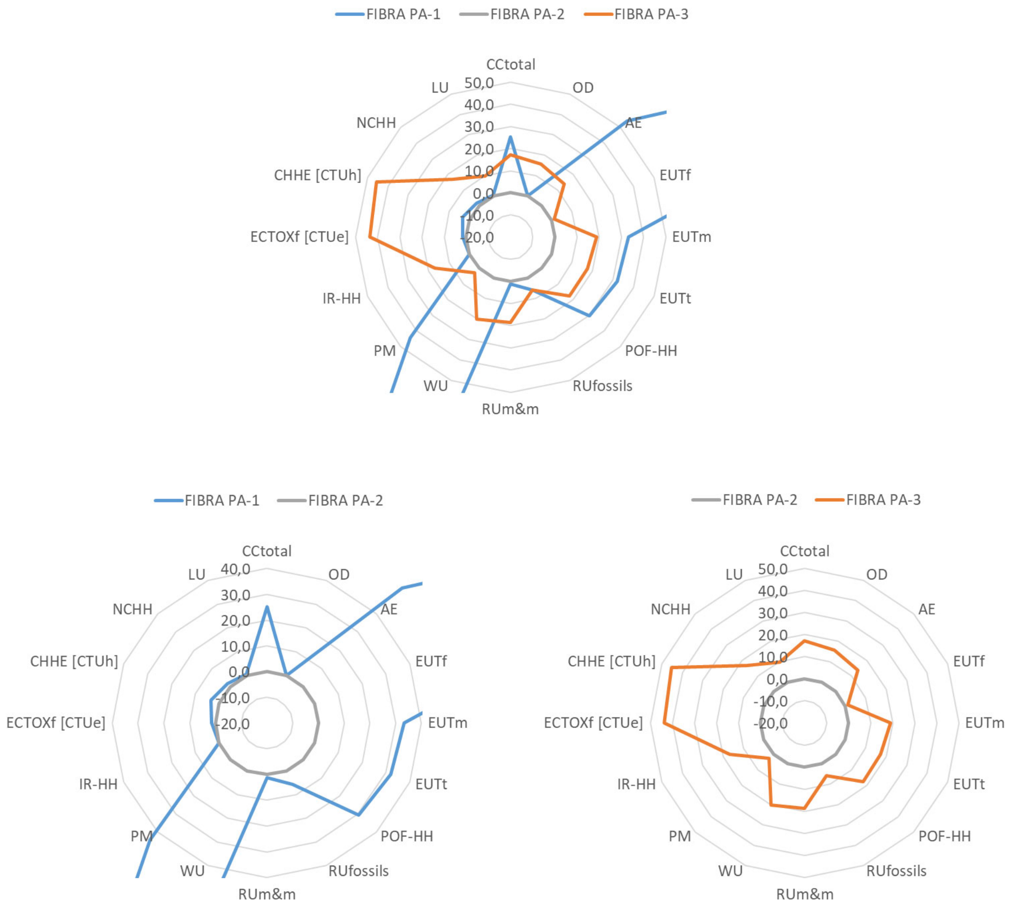


Figure 8. Cradle-to-gate analysis. Spider chart representing the increase/decrease (%) in the environmental impacts indicators of the 3 AC mixtures under study comparing to the reference FIBRA-AC2 (assigned 100%).

3.4.2.2 Cradle-to-grave analysis (A1-A5 + B3 + B4)

Results presented in

Table 12Table 10 quantify the cradle-to-grave environmental impacts of the three alternative AC mixtures evaluated in this study. These results do not include module D since the effect of the potential benefits beyond the end-of-life is considered separately, in section 5.2.4.

As occurred with the PA mixes, when the analysis is carried out from the cradle to the grave, the potential differences between the different mixtures are attenuated. In the case of the fibre-reinforced AC mixtures (FIBRA-AC3), still presents slightly worse environmental performance in almost all the impact indicators. However, only three of them: Freshwater Ecotoxicity, Cancer Human Health Effect and Water Use show an increase higher than 10% with respect to the reference, specifically 15.4, 16.3 and 10.1 respectively. On the other hand, The AC mixture with PMB (FIBRA-AC1) presents a similar result (less than 10% of difference) in 10 of the impacts, a slightly lower environmental performance in 5 and a significant lower environmental performance (more than 20% difference) in 4 impacts, especially in the freshwater eutrophication and water use indicators. The increase in the environmental impact is mostly due to the production of fibres in the case of FIBRA-AC3 and the PMB production and higher temperature needed in the asphalt plant when this bitumen is used (FIBRA-AC1).

Table 12. Results of the cradle-to-grave analysis of the three AC11 mixtures alternatives.

			FIBRA-AC1	FIBRA-AC2	FIBRA-AC3
			PMB	Reference	PAN fibre
CC_{total}	Climate change (total)	[kg CO_2 eq.]	2,83E+05	2,50E+05	2,72E+05
$CC_{biogenic}$	Climate change (biogenic)	[kg CO_2 eq.]	3,48E+02	3,47E+02	3,72E+02
CC_{fossil}	Climate change (fossil)	[kg CO_2 eq.]	2,82E+05	2,50E+05	2,71E+05
OD	Ozone depletion	[kg CFC-11 eq.]	1,01E-09	1,01E-09	1,09E-09
AE	Acidification	[Mole of H^+ eq.]	1,24E+03	9,99E+02	1,06E+03
EUT_f	Eutrophication, freshwater	[kg P eq.]	9,19E+00	4,32E+00	4,35E+00
EUT_m	Eutrophication, marine	[kg N eq.]	3,42E+02	3,00E+02	3,24E+02
EUT_t	Eutrophication, terrestrial	[Mole of N eq.]	3,73E+03	3,29E+03	3,53E+03
POF-HH	Photochemical ozone formation, human health	[kg NMVOC eq.]	9,74E+02	8,59E+02	9,25E+02
$RU_{m\&m}$	Resource use, minerals and metals	[kg Sb eq.]	1,62E+07	1,57E+07	1,62E+07
$RU_{fossils}$	Resource use, fossils	[MJ]	2,16E-02	2,14E-02	2,34E-02
WU	Water use	[m^3 world eq.]	6,58E+04	2,06E+04	2,27E+04
PM	Particulate matter	[Disease incidence]	2,72E-02	2,21E-02	2,25E-02
IR-HH	Ionising radiation, human health	[kBq U_{235} eq.]	1,97E+04	1,97E+04	2,14E+04
$ETOX_f$	Ecotoxicity, freshwater	[CTU_e]	1,62E+04	1,61E+04	1,86E+04
CHHE	Human toxicity, cancer	[CTU_h]	6,97E-04	6,88E-04	8,01E-04
NCHH	Human toxicity, non-cancer	[CTU_h]	6,90E-03	6,85E-03	7,32E-03
LU	Land use	[Pt]	1.03E+06	1.03E+06	1.07E+06

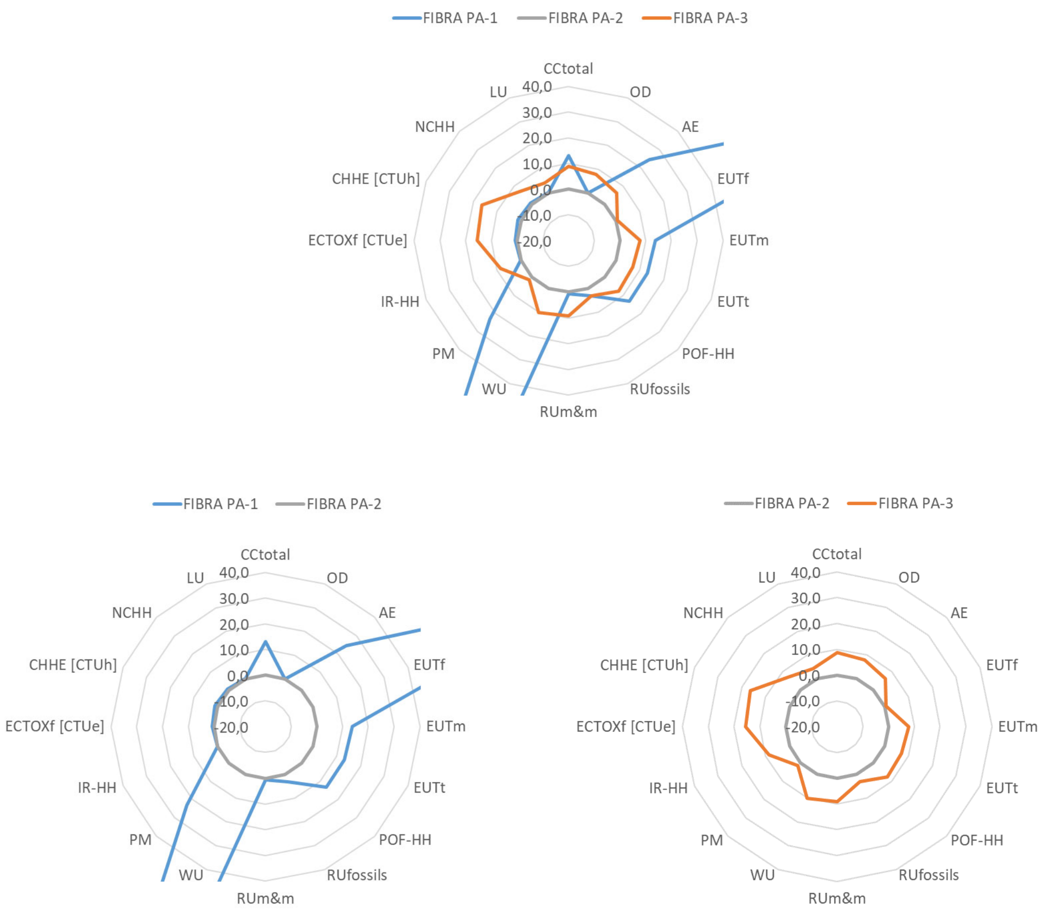


Figure 9. Cradle-to-grave analysis. Spider chart representing the increase/decrease (%) in the environmental impacts indicators of the 3 AC mixtures under study comparing to the reference FIBRA-AC2 (assigned 100%).

3.4.2.3 Normalization and weighting

FIBRA-AC1 and FIBRE AC-3 present opposite results depending on the environmental impact indicator we look at. Due to this, and in order to extract conclusions from the obtained results, the normalization and weighting processes are applied. In Figure 10, the relationship (in %) between the LCA index of each AC mixture and that of the reference are shown. Concerning the Cradle-to-gate analysis, both the FRAC and the mixture with PMB present a higher environemental impact index than the reference, being the mixture with PMB the one with the lowest environmental performance, with a LCA index around 17 to 23% higher than the reference. When the analysis cover all life cycle stages (cradle-to-grave), the differences between the environmental impact among the three mixtures are lower. The mixture with PMB still present the highest enviornmental impact but now the increase is limited to 9 to 12%.

Finally, assuming 15 years of service life for the reference mixture FIBRA-AC2 in the cradle to gate analysis and 40 years for the pavement structure, the other two alternatives need to reach a minimum service life in order to match the environmental impact of the reference. Figure 11 shows the results of this calculation considering both analyses, cradle-to-gate and cradle-to-grave. The needed increase in the service life when using fibres is higher than in the case of PA mixes, around 1.5 years for the mixture and 2 years for the pavement.

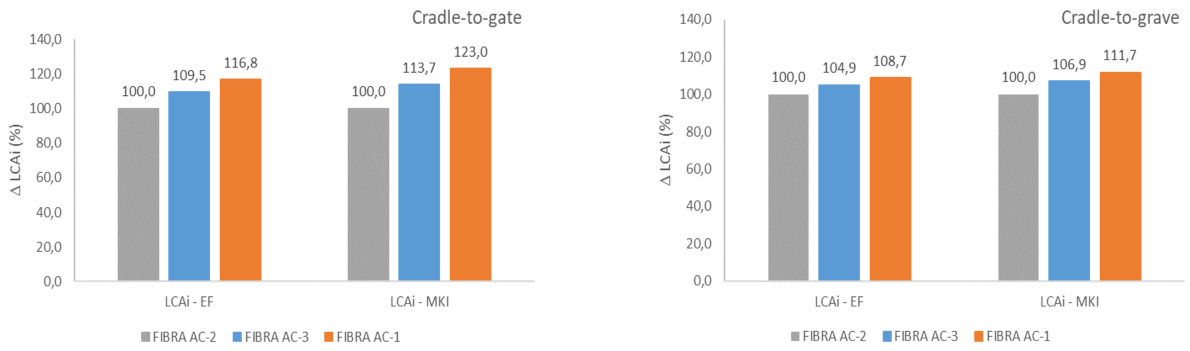


Figure 10. Variation (%) in the LCA index of the 3 AC mixtures under study comparing to the reference FIBRA-AC2 assigned 100%). Left: cradle-to-gate; Right: cradle-to-grave.

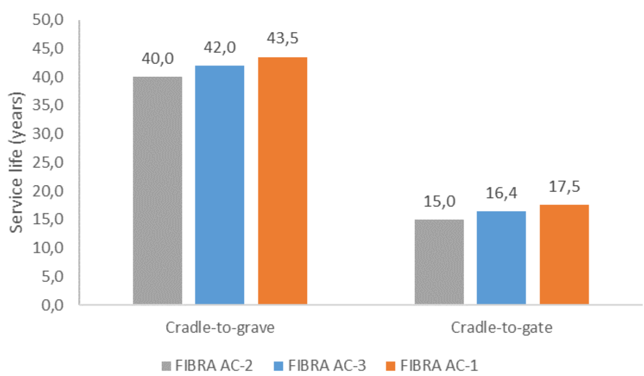


Figure 11. Minimum service life that need to reach FIBRA-AC1 and -3 in order to match the environmental impact of FIBRA-AC2.

3.4.2.4 Beyond the EoL Module (D)

The positive impact of reusing the asphalt mixes at the end of their lives is represented in Figure 12 and Figure 13.

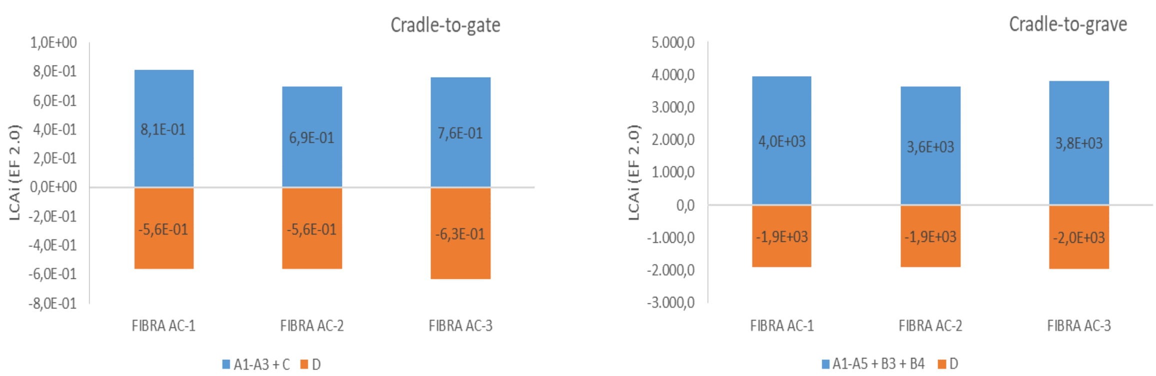


Figure 12. LCA index for A1-A3+C modules (blue) vs. LCA index of module D (orange).

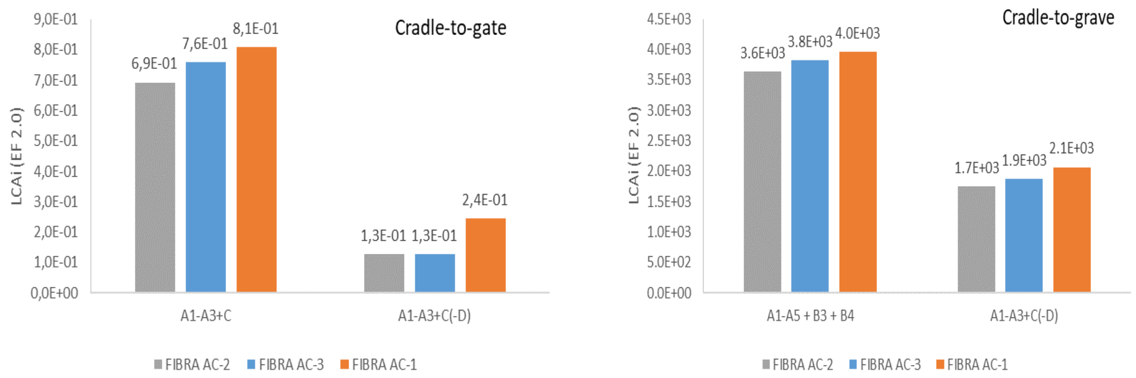


Figure 13. LCA index without and with module D. Cradle-to-gate (left) and Cradle-to-grave (right)

3.5 Conclusions

In this study, the environmental impact of using fibres to reinforce asphalt mixtures have been evaluated and compared to the impact of two reference asphalt mixtures, one using a conventional penetration grade bitumen and the other one incorporating PmB. The analysis has been on the pilot sections implemented in the FIBRA project including the specific conditions of each country and road.

After analysing the different stages of the road cycle according to the characterization models, normalization and weighting factors proposed by the European Commission in their Environmental Footprint (EF) framework, the following conclusions are drawn:

- Small differences in the environmental impact of the 4 PA mixtures implemented in the Netherlands have been found compared to the results obtained with the 3 AC mixtures placed in Norway. Aggregates in the Netherlands should be transported from Norway and the high environmental impact associated with the transportation process masks the effect of using fibres or PmB.
- When a cradle-to-grave analysis is carried out, the effect of adding fibres or PmB bitumen is highly attenuated. Actually, the addition of fibres results in an environmental impact increase of less than 2-7% in both analysed sections.
- The use of PmB increases the environmental impact comparing to both the reference mixture with penetration grade bitumen and the FRAM. The production process of PmB bitumen and the higher temperature that is needed in the asphalt plant, affect negatively its environmental performance. However, the effect is attenuated when the study is carried out considering all the road life cycle stages.
- The addition of fibres as reinforcement increase the environmental impact of the road pavement, although in a limited way. In the Netherlands, if FRPA mixtures are used, the road pavement should last just only 0.5 years longer the reference in order to match the environmental impact. In the case of Norway, the pilot section with the FRAC mixture should last 2 extra years than the conventional AC11 section.
- There is not a significant difference in using polyacrylonitrile or aramid fibre to reinforced asphalt mixtures in terms of their effect on the environmental impact.
-

4 Use of long-term performance estimations in the LCA

4.1.1 Long-term performance of FRAM (fatigue)

In task 4.4 of the FIBRA project, two different studies have been carried out to estimate the long-term performance of the asphalt mixtures and pavement structures of FRAM (FIBRA project, 2021) In the first work, two asphalt mixtures (reference and experimental) produced at both asphalt plants (BAM and VEIDEKKE) have been tested at Empa using the mobile load simulator MMLS3. The performance of the experimental and reference mixtures have been compared in terms of their fatigue resistance. The following mixtures have been tested:

- FIBRA-PA1, reference, conventional 2L-ZOAB 8 (PA 8) mixture with PMB.
- FIBRA-PA4, 2L-ZOAB 8 (PA 8) with straight run bitumen and 0,05% aramid fibre.
- FIBRA-AC1 produced with PmB.
- FIBRA-AC3 with 70/100 bitumen and PAN fibres. In situ air voids content of 3.2.

According to the results, using the laboratory scale traffic simulator, FIBRA PA4 and FIBRA AC2 reached 84% and 75% of the loading cycles of PMB mixtures FIBRA AC3 and FIBRA PA1 respectively.

In Figure 14, the cradle to gate results of FRAM and the reference mixtures with PMB are compared assuming the same durability (blue and orange points on the right). The rest of blue points indicate the annualized LCA index when lower durabilities of FRAM are assumed. Inevitably, the environmental impact of FRAM (FIBRA PA4 and FIBRA AC3) worsens as the assumed service life is reduced from 0 to 30%, increasing the impact from -3.4% up to 38%.

If the 84% and 75% values obtained in the model scale tests are taken as valid for estimating their service life (very unlikely in the case of the PA since the main failure mechanisms is not fatigue but ravelling), the impact of FRAM would be 15% and 25% higher comparing to the reference mixtures. However, it should be noted that the long-term performance in terms of aging of the mixtures is not taken into account. The potential effect (positive or negative) of fibre reinforcement in the aging behaviour of the asphalt mixture is still unknown. The long-term performance of the two pilot sections built in the FIBRA project will provide some light in this regard.

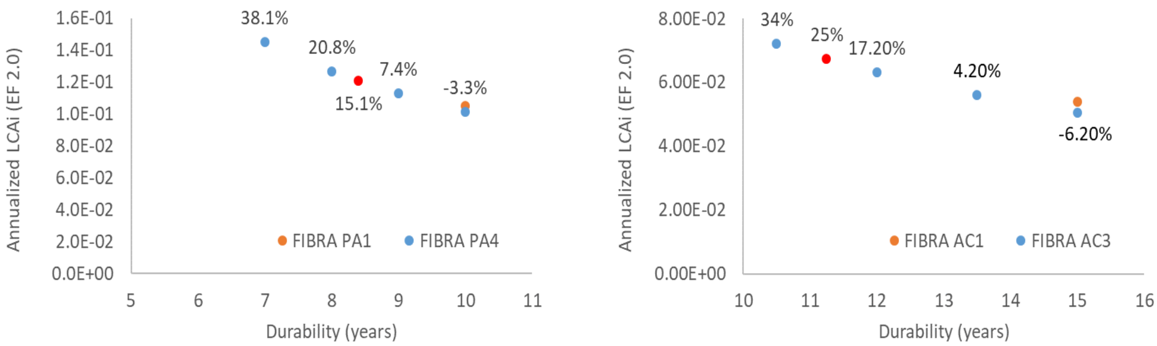


Figure 14. Annualized LCA index. FIBRA PA1 and PA4 (left) and FIBRA AC1 and AC3 (right)

4.1.2 Long-term performance of pavement

The second study comprises the numerical simulation of different pavement sections where FRAM mixes in one or more layers have been implemented. The long-term behaviour of these sections have been compared to conventional layers with conventional penetration grade bitumen without fibres or high performance asphalt mixtures with PMB. The pavement responses to traffic and the fatigue damage and rutting evolution with time have been predicted by numerical analysis with FlexPAVE™. One of the conclusions of this study recommends the use of FRAM in the wearing course and the use of PMB in the base asphalt layer (Figure 15) (FIBRA project, 2021). This optimum pavement section (OPT) would reduce the %damage (in terms of fatigue) in 35% and the rutting depth by 21% comparing to a reference section (REF) built with conventional mixtures with penetration grade bitumen. The cradle to grave analysis of the experimental and the reference sections are compared in Figure 16. If the same service life is considered for the two pavement sections, a worse environmental performance is obtained by the "optimum" pavement section in all the impact categories, with a significant increase between 10% and 20% in 9 impacts and an increase higher than 50% in 2 (water use and Freshwater Eutrophication). In the rest of categories, the increase is lower than 10%.

Assuming 40 years of service life for the reference pavement section, the "optimum" section need to reach a minimum service life of 43.5 years to match the environmental impact of the reference (Figure 17). Considering the results from the numerical simulation, in which a significant reduction in the damage and the rut depth is obtained, the increase in the service life of the pavement by more than 3.5 years seems feasible.

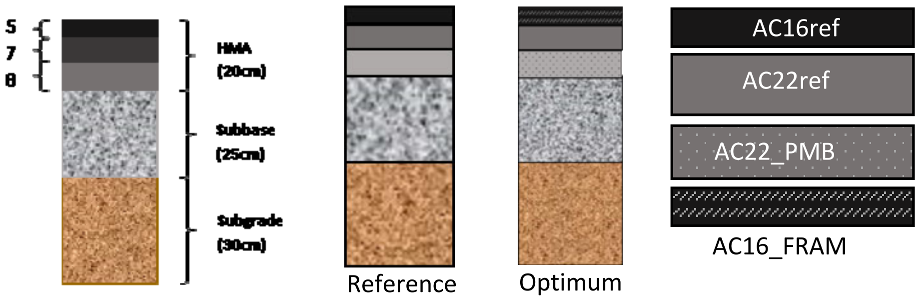


Figure 15. "Reference" and "Optimum" pavement section.

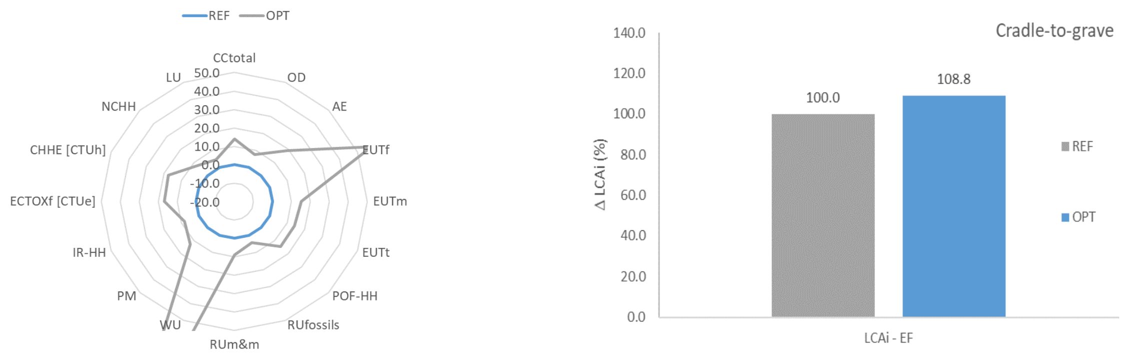


Figure 16. Cradle-to-grave analysis. Spider chart representing the increase/decrease (%) in the environmental impacts indicators of the „optimum" pavement section compared to the reference pavement (assigned 100%) (left). Variation (%) in the LCA index of the 2 pavements (reference pavement assigned 100%) (right).

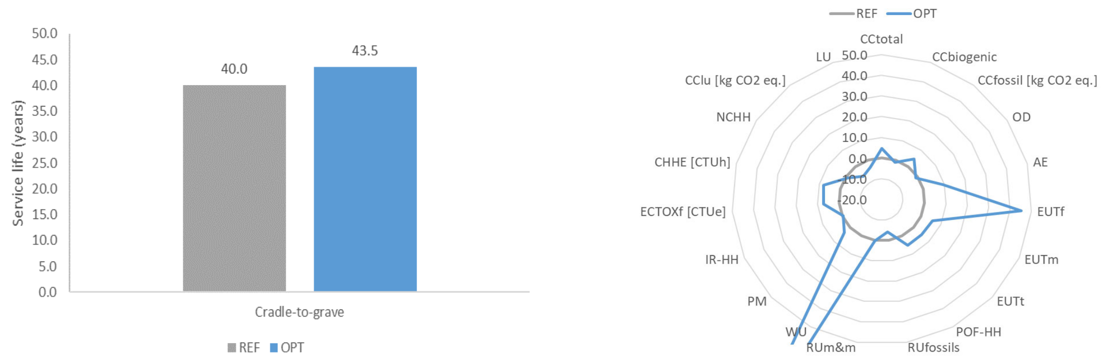


Figure 17. Cradle-to-grave analysis. Minimum service life that need to reach OPT to match the environmental impact of REF (left).. Spider chart representing the increase/decrease (%) in the environmental impacts indicators of the „optimum" pavement section compared to the reference pavement (assigned 100%) and assuming a service life of 40 for REF and 43.5 for the OPT (Right).

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