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Synthesised Results and Applicable Findings of CEDR Call 2017 New Materials (SyRAF)

FIBRA

PavementLCM

CRAB for OERE

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SyRAF - Synthesised Results and Applicable Findings of CEDR Call 2017 New Materials

by

Davide Lo Presti (UNott, UniPa)
Konrad Mollenhauer (UniKassel)
Irune Indacoechea Vega (Unican)
Gabriella Buttitta (UniPA)

Report "Synthesised Results and Applicable Findings of CEDR Call 2017 New Materials" summarises and synthesizes the output from the projects funded within 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.

The Project Executive Board for this programme consisted of:

Arash Khojinian (Highways England)
Boris Tomsic (Slovenia)
Dirk van Troyen (Flanders, Belgium)
Finn Thøgersen (Denmark)
Joralf.Aurstad (Vegvesen, Norway)
Reinhard Llohmann-Pichler (Austria)
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Robert-Ingemar Karlsson (Sweden)
Rob Hofman (the Netherlands)

Consortium Partners:

Universität Kassel (UniKassel), Germany

Università degli Studi di Palermo, Italy

University of Cantabria, Spain

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Executive summary

The aim of SYRAF Project is to synthetize the findings obtained within the CEDR Call 2017 “New materials”. Within this CEDR call, three projects were funded:

- “Pavement LCM – A complete package for Life Cycle Management of green asphalt mixtures and road pavements” which aims at supporting European National Road Authorities to introduce sustainability at the core of their practices by providing training on the Life Cycle Management techniques and a user-friendly package to support their widespread implementation.
- “CRAB for OERE – Cold recycled asphalt bases for optimized energy & resource efficient pavements” which provides complete guidelines to apply cold recycling materials in new and rehabilitated pavements.
- “FIBRA – Fostering the implementation of fibre reinforced asphalt mixtures by ensuring its safe, optimized and cost-efficient use” aims to assess the potential benefits of fibre-reinforcement in the asphalt pavement performance and provide the NRAs with guidelines and recommendations about the use of these materials in asphalt mixtures.

This report summarizes the main findings within the three projects and aims at harmonizing the results obtained in terms of environmental impacts of the two different technologies studied in this call. Therefore, the Life Cycle Assessment (LCA) methodology established within "Pavement LCM" project is applied on cold recycled asphalt mixtures (studied in CRAB4OERE) and fibre reinforced asphalt mixtures (studied in FIBRA).

1. Pavement LCM - A package for implementing Life Cycle Management of road pavement

PavementLCM is a 2 year international project aiming at supporting European National Road Authorities to introduce sustainability at the core of their practices by providing training on Life Cycle Management techniques and a user-friendly package to support their widespread implementation.

Life Cycle Management (LCM) is a business management approach that can be used by all types of organizations in order to improve their products and/or services while strengthening their overall sustainability performance. Its purpose is to ensure more sustainable value chain management. LCM can be used to target, organize, analyze and manage product-related information and activities towards continuous improvement along the product life cycle. Along these lines, the PavementLCM project proposes the introduction of LCM practices for National Road Authorities (NRAs) by a systematic use of the results of Sustainability Assessment (SA) exercises as a support for decision making.

On this basis, the Pavement LCM provides NRAs with a package that has the ambition of being user-friendly enough for a wide-spread use across European NRAs and that could allow CEDR members to plan a harmonized implementation of these practices. This report provides NRAs with the main findings and further recommendations, together with the purpose, the scope and the methodology adopted to carry out the project. Furthermore, in order to facilitate the wide-spread distribution of the package, the main project products have been shaped in the form of 2- 8 pages tech briefs, presented within the final report and on the project website (http://pavementlcm.eu), made to be used as a stand-alone information documents.

The PavementLCM package can be found here (https://www.pavementlcm.eu/pavementlcm-package/) and includes:

- State of the Art" of the use of Sustainability Assessment for road pavements
- PavementLCM "Framework" to identify the Sustainability Assessment exercises for producers, contractors and road authorities
- PavementLCM "Guidelines" with a 7-steps approach for implementing Life Cycle Management of road pavement according to EN 15643-5-2017
- PavementLCM "Tools" as a support to carry out the Sustainability Assessment exercises
- PavementLCM "Resources" as a support for the implementation of project findings

2. CRABforOERE: Proposal of mix design of cold recycled materials (CRM) for base layers and adoption rule for empiric pavement design.

The analysis of national specification documents on mix design for CRM resulted in the proposal of a 7-step approach for optimizing the mixture composition. This procedure contains recommendations for Sampling (1) and assessment (2) of RA as relevant source material compound in CRM, where it is considered as granulate particles. Its assessment according to the standardised methods for natural aggregates needs to be complemented by rise-in-pH-tests and fragmentation tests to address chemical activity and strength of RA particles respectively. After evaluating the required grading (3) with added fine natural aggregates (if required), the water content (4) is assessed by compatibility, consistency and cohesion tests. The type and content of bitumen emulsion and additional mineral binders (5) depends on the local climatic and worksite conditions. For pavements with moderate and high traffic loading, a cement content of 1,5% to 2,5% combined with a bitumen emulsion content which results in a bitumen/cement ratio of 1/1 to 1,5/1 (residual bitumen from a slow-breaking bitumen emulsion) could be recommended. In laboratory mix design assessment (6) CRM mix is prepared and specimens are compacted to a void content comparable of the compaction on site. Curing conditions for specimens (temperature, moisture) affect the evolution kinetics of strength and stiffness of the specimens. In situ curing depends on the regional climate of the pavement location, weather conditions, structure of the roadway and road traffic. Therefore, a perfect simulation in the laboratory is illusory. In order to achieve some harmonisation it is proposed to cure specimens at 40 °C for 3 days for high temperature conditions (southern Europe) and at 20 °C for 28 days for moist climate conditions (northern Europe). In order to consider the moisture in field, CRM specimens should be sealed (e. g. in a plastic bag) if the layer is covered shortly after construction by an asphalt surface or unsealed, if the CRM layer is left without cover at dry conditions. For quality assessment (7), the specimens void content shall be lower than 15 % and at least strength (e. g. indirect tensile strength according to EN 12697-23) and water sensitivity (EN 12697-12) shall be assessed.

For 17 existing flexible pavements with Cold recycled asphalt base layers (CRAB) throughout Europe a common pavement design strategy could be observed. By assessment of surface conditions, traffic and climatic loading and materials mix design these pavements showed a durability similar to expectations on usual flexible pavements composed of hot-mix asphalt (HMA). From these structures, a simple empiric design adoption was derived, where the thickness of the usually used HMA base layers can be increased by factors of 1,5 (or 1,2, if a stabilised subbase below the CRAB is applied).

The applicability of these design rules was shown in a demonstration pavement structure in San Marino. The conducted LCA study showed a potential of a reduction of at least 40 % of environmental impact factors, including global warming potential (-42 % of CO_2-eq.) by use of CRM instead of hot-mixed asphalt.

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

The FIBRA project was born 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 gasp 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 (PAN) and a blend of aramid/polyolefin (ARAM/POL) 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 suffer thermal degradation during the asphalt mixture production. On the other hand, it was also found that the polyolefin fibres melt 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 mixture due to their higher rutting performance and ARAM/POL was selected to reinforced dense asphalt mixture. When reinforcing porous asphalt mixtures with PAN, a better resistance to water damage and ravelling was 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). On the other hand, it is highlighted the need to add an extra amount of bitumen to adequately cover the fibres and effectively achieve a reinforcement effect on the mixture. 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 reference mixture 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 increase the environmental impact of the road pavement in less than 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. CEDR Transnational Road Research Program Call 2017 New materials & techniques

The Conference of European Directors of Roads, CEDR, though their Transnational Road Research Program, launch in an annual basis, transnational research calls to promote cooperation between European road administrations in relation to road research activities. These annual call topics address the needs of European road authorities, aiming to produce results that can be implemented by CEDR members.

The CEDR Transnational Road Research Programme Call 2017 is funded by Austria, Belgium-Flanders, Denmark, Finland, Germany, Ireland, Norway, the Netherlands, Slovenia, Sweden and UK and the administration of the programme is taken over by the Austrian Research Promotion Agency which is responsible of the organization of the Call for Proposals, the programme co-ordination, the financial governance and the general project management. In this call, three research programmes were proposed: 1) new materials and techniques, 2) automation and 3) collaborative planning of infrastructure and spatial planning.

The main objective of the "New materials & techniques" programme is to ease and foster the implementation of existing research results related to the efficient use of resources as well as to the efficient use of alternative solutions to optimize pavement durability with the final aim of improving sustainability and reducing the environmental impact and carbon footprint of road's infrastructure. This general objective is supported by participating NRAs that have provided test areas (demonstrators) and after the call they have committed to their long-term monitoring. This programme covered three different topics:

a. **Reliable life cycle and social cost-benefit analysis of "green asphalt",** that looks for the steps that are necessary to realize practical, correct and reliable estimation of both sustainability and durability of road constructions.
b. **Simplifying the use of RAP**, looking for support in the simplification of the use of reclaimed asphalt pavements (RAP).
c. **Usability of super materials,** which seeks to obtain support for NRAs in the usability of "super materials", understanding "super material" as a "material that has one or more enhanced performance or functional related indexes" (i.e. natotechnology, fibres, etc.).

After an open Call (November 2017 to March 2018), the Programme Executive Board, established by the participating members and made up of experts in the topics to be covered, selected three successful projects, one giving answer to the three mentioned topics:

- "Pavement LCM – A complete package for Life Cycle Management of green asphalt mixtures and road pavements" which aims at supporting European National Road Authorities to introduce sustainability at the core of their practices by providing training on the Life Cycle Management techniques and a user-friendly package to support their widespread implementation.
- "CRAB for OERE – Cold recycled asphalt bases for optimized energy & resource efficient pavements" which provides complete guidelines to apply cold recycling materials in new and rehabilitated pavements.
- "FIBRA – Fostering the implementation of fibre reinforced asphalt mixtures by ensuring its safe, optimized and cost-efficient use" aims to assess the potential benefits of fibre-reinforcement in the asphalt pavement performance and provide the NRAs with guidelines and recommendations about the use of these materials in asphalt mixtures.

For more information, please visit https://cedr.eu/peb-new-materials-and-techniques.

2. Executive summary of each project

2.1. PavementLCM – A complete package for Life Cycle Management of green asphalt mixtures and road pavement

2.1.1. PavementLCM Factsheet

Project title: A complete package for Life Cycle Management of green asphalt mixtures and road pavement (PavementLCM).

Coordinator: Nottingham Transportation Engineering Centre/ University of Nottingham

Consortium Partners: TNO, VTI, University of Palermo, VGTU: Vilnius Gediminas Technical University, FCEI: French Circular Economy Institute, CEREMA, FHWA Sustainable Pavement Technical Working Group, AECOM, EAPA: European Asphalt Pavement Association, STA: Smart Transport Alliance
Website: https://www.pavementlcm.eu/

Duration: 01/10/2018 to 30/09/2020

Budget: 562.689€

2.1.2. Background and objectives

This report summarises the results of the research project " PAVEMENTLCM: life cycle management of green asphalt mixtures and road pavement", which was funded by CEDR within the call 2017 "New materials".

Sustainability is often defined as the balance between people, planet and profit. For national road authorities, these aspects are important to take into account when considering their asset management and project planning. However, there is no single way to assess the sustainability of assets. There are many different methods, tools and databases claiming to support sustainability assessment, but there is not one method defined as the most appropriate for National Road Authorities (NRAs). Amongst all available methods there is a core principle, namely that the impacts of a project or product should be analysed over its whole life cycle and that this impact can be quantified. This principle is generally referred to as Life Cycle Thinking and comprises amongst others environmental Life Cycle Assessment (LCA) and Life Cycle Costing analysis (LCC, sometimes referred to as LCCA). For these methodologies, not only general approaches exist but also specific standards for example the ISO 14040-14044 which describes the standard procedures for LCA, the ISO 15686-5 standard for LCCs of buildings and constructed assets, the EN 15804 standard for creating Environmental Product Declarations (EPDs) of building products, etc. Furthermore, a framework for sustainability assessment (SA) of civil engineering works has been recently defined in the european standard on Sustainability of Construction Works: Civil Engineering Works – Framework (EN 15643-5-2017) and Sustainability of Construction Works: Assessement of Environmental Performance of Buildings – Calculation method (EN 15978:2011). ***Using the results of these SA exercises in support of decision-making for road asset managers is what is here defined as Pavement Life Cycle Management.***

Despite these techniques are now widely used and despite the existence of ostensibly clear standards, their application within the road pavement industry is not unambiguous. There is a need of standardization of functional units, system boundary, improved data quality and reliability and broadening of study scopes. Another big issue is data uncertainty of both inputs and results. In fact, Road pavement LCM analyses are based on limited data, frequently of poor quality, and require assumptions (including durability) that are difficult to verify, and predictions of future evolutions of technology and processes. The subsequent problem is that over the past years many different approaches have been followed, datasets created, and tools developed for LCM of pavements. This increase in available tooling, and the lack of synergies and communication amongst NRAs, has however not led to clear and comparable information, but merely to an overload of slightly or hugely differing information sources.

Hence, the next steps towards simpler and better sustainability assessment for CEDR NRAs, are explicated in the three main objectives of the PAVEMENTLCM project as follows:

1) *Tailor guidelines towards the introduction of Life Cycle Management (LCM) in National Road Authorities with a focus on Sustainability Assessment.*
2) *Create as a platform for interactive transfer of knowledge on best practices on sustainability assessment and Life Cycle Management to generate reliable durability data for green asphalt.*
3) *Produce tools, guidelines, datasets, roadmaps and recommendations to introduce life cycle management practices in road authorities*

2.1.3. Scope

This final report aims to provide a summary of the several interconnected findings obtained during the project lifetime. In fact, the PavementLCM delivered a complete package to stimulate the conversation related to life cycle management of road pavements and allow NRAs, and other stakeholders, to introduce sustainability assessment exercises at the core of their practices. The project built-up over findings of a previous project, namely CEDR 2012 call - Allback2Pave, and it has been already applied to harmonise LCA results amongst the other two projects of the CEDR 2017 call CRABforOERE and FIBRA. The ambition is to be a reference for the implementation of life cycle management practices within NRAs and to be a milestone for the initiation of the “SA Knowledge Transfer Platform” allowing NRAs to share best practices, also with other stakeholders (e.g. EAPA) as well as learning from academics and experts from all over the world.

Details regarding the background of this final summary can be obtained from the deliverable reports from Work Package 2 to Work package 6 each of which discusses selected topics under research within the project, see Table 1.

Table 1 – main reports discussing details of project findings

No	Deliverables / Reports in the PavementLCM Package (https://www.pavementlcm.eu/pavementlcm-package/)	where in the Package
1	D1.5 Project final report	RESOURCES
2	D2.1a Pavement LCM State-of-the-Art	STATE OF THE ART
3	D2.1b Pavement LCM Sustainability Assessment Framework	FRAMEWORK
4	D3.1 Sustainability data analysis, including datasets and recommendations to perform LCA of road pavements	RESOURCES
5	D4.1 Durability data analysis, including datasets useful to estimate a value for a reference service life of wearing courses	RESOURCES
6	D5.1a: PavementLCM Sustainability Assessment Guidelines	GUIDELINES
7	D5.1b: PavementLCM Recommendations to use Multi-Criteria analysis for Decision Making (originally D5.4)	GUIDELINES
8	D5.2: Sustainability Assessment tools (originally only SA lookup tool): - Sustainability Assessment Compass - LCA data collection template - LCA result uncertainty analysis - Durability distribution from expert opinion	TOOLS
9	D5.3: Harmonization of environmental databases for road pavement in EU	RESOURCES
10	D6.1 State of the art and knowledge agenda of circular economy topics in pavement LCM D6.2: European NRAs and Circular economy D6.3 Circular models to favour the uptake of green asphalts	RESOURCES

2.1.4. Methodology and Main findings

In order to achieve the stated goals, the strategy behind the workplan has been to follow a time-flow that would allow researchers to first gather information from partners and advisory board, carry out a review of practices and only then create the framework, case studies, guidelines, recommendations, datasets, roadmaps and tools within 6 work packages as follows:

- Coordinating and ensuring quality of project products through an advisory board (WP1)
- A platform to transfer knowledge on sustainability assessment to/from/amongst NRAs (WP2)
- Innovation in sustainability assessment (WP3,5)
- Introducing durability within sustainability Assessment (WP4)
- Progress in terms of implementation of Circular Economy in the pavement industry (WP6)

As can be seen in figure 1, the project was developed in three levels:

PLCM Level 1	PLCM Level2	PLCM Level 3
What is SA?	**How do I perform SA?**	**Pavement LCM Package**
• State of the Art • Interviews • Advisory workshops	• PavementLCM Framework *according to standardised procedure (EN CEN TC 350)*	• PavementLCM Guidelines • PavementLCM Tools • PavementLCM Resources

Figure 1- PavementLCM project development levels

LEVEL 1 – *State of the Art on Sustainability Assessment (SA) – WP2*
This level is dedicated to NRAs which has not yet implemented any SA in their practices and need to understand what SA is, why they should use it and how to start. The outcome of Level 1 is the **PavementLCM State-of-the-Art (more details in D2.1a)**, aimed to cover the content of Level 1 as follow:

- by helping the road authorities in their sustainability knowledge
- by performing a series of interviews with NRAs in order to better understand the variety of current practices around Europe, identify and share existing best practices as well as creating a state-of-the-art of international practices and standards.
- by creating and implementing a platform for knowledge transfer through a series of tailored advisory workshops/webinars aimed at involving NRAs in the project development as well as providing an opportunity to learn and share about the complex issue of engineering sustainability within the road industry

LEVEL 2 – *PavementLCM "Sustainability Assessment Framework" – WP2*
This level is dedicated to NRAs which already know about SA practices and would benefits from Pavement LCM Framework and Guidelines to perform SA exercises according to the most recent standards. The outcome of Level 2 is the **PavementLCM SA Framework (more details in D2.1b)**, aimed to cover the content of Level 2 by providing the general information for carrying out the assessment for NRAs but also for Manufacturers and Contractors.

The framework indicates to divide the SA in into main two groups: *Pavement Materials* and *Pavement Activities*, and identifies five different exercises as in the following figure:

- Pavement materials/products must be used to build, repair, replace and maintain road pavements and their components. The SA exercise for these products should be the responsibility of material/products manufacturers (i.e. asphalt manufacturer).

  - Manufacturers: must perform the SA of each material and/or products supplied to Contractors and/or NRAs for the construction of a new road pavement and/or the maintenance of existing road pavements. Furthermore, manufacturers might be asked by NRAs to assess the sustainability of the proposed innovative materials/products.

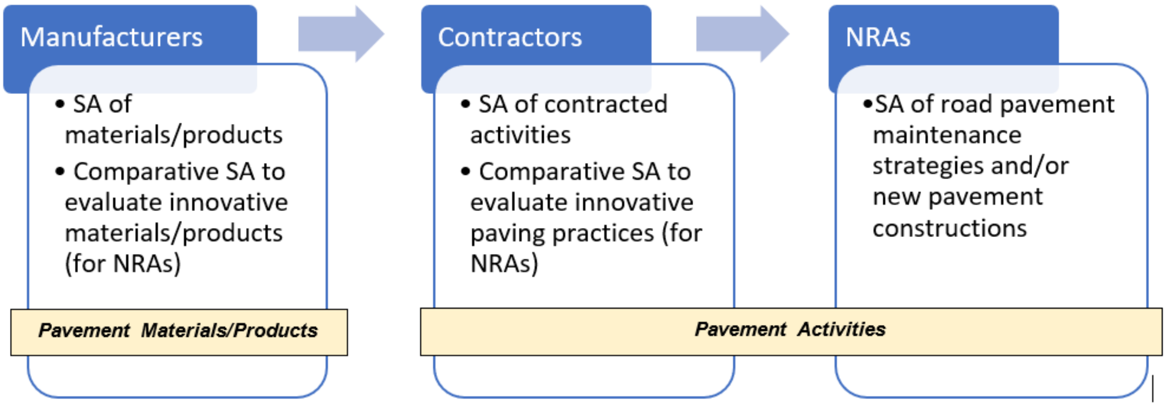


Figure 2 - SA exercises proposed by the Pavement LCM Framework

- Pavement activities must be carried out to build, repair, replace and maintain the functional and technical requirements of a road pavement and its components. The SA exercises for these activities should be the responsibility of paving contractors and road owners. In particular:

  - Contractors: must perform the SA of the contracted activities, such as the construction of a new road pavement and/or the replacement of the road pavement component/element (i.e., wearing course). Furthermore, contractors might be asked by NRAs to assess the sustainability of proposed innovative technologies related to installations of road pavement components

  - Road owners (i.e., NRAs): must support their decision-making process by performing the SA of selected maintenance strategies and/or projects to be procured or awarded related to the "flexible road pavement level" or at a "Part level" of the model (see 2.2.1 or the Framework).

The Framework also introduced a set of indicators, chosen according to the outcomes of the three advisory workshops as well as on the literature review. In fact, according to EN 15804:2012+A2:2019 and JRC Technical Report published in 2018, there are some core environmental indicators which have a main role in environmental assessment due to their potential burdens, furthermore the following list cover economic impacts and technical and functional requirements as suggested by the EN standard on SA for civil engineering works. The list of indicators still lacks for "social" indicators since the standard for Social LCA came out on mid-2021 and it is the opinion of the authors that the relative indicators still need to be investigated in order to be introduced within this framework.

The indicators have been grouped in macro-areas as follows in Table 2 and detailed in D2.1b

Table 2 – Indicators for the Sustainability Assessment of pavement materials and activities

Related to	SA Indicator	Object of assessment
Environment	**Global Warming Potential (GWP- total)**	Pavement materials and activities
Environment	**Acidification**	Pavement materials and activities
Environment	**Eutrophication**	Pavement materials and activities
Environment	**Natural resources consumption**	Pavement materials and activities
Environment	**Air pollution**	Pavement materials and activities
Environment	**Energy use**	Pavement materials and activities
Environment	**Secondary materials consumption**	Pavement materials and activities
Economy	**Cost** *This indicator differs for materials and activities:* - Cost - Net Present Value/ Whole life cycle cost	Pavement materials Pavement activities
Technical and functional requirements	**Tyre-pavement noise**	Pavement activities
Technical and functional requirements	**Durability**	Pavement activities
Technical and functional requirements	**Optional indicators**	Pavement activities

LEVEL 3 – *PavementLCM "Sustainability Assessment Package*" - *WP3, WP4, WP5, WP6*
This level is focused on delivering a series of "products" that will support NRAs to carry out SA exercise. The Package, accessible through the PavementLCM website (https://www.pavementlcm.eu/pavementlcm-package/), is composed of four sections that have been tailored to carry out the SAexercises for pavement materials/products and activities:

1. SA State of The Art (level 1)

2. SA exercises Framework (level 2)

3. SA Guidelines (level 3)
   contains a step-by-step process to setup and perform the Sustainability Assessment of pavement materials/products, as well as pavement activities (pavement components and road pavement). The guidelines are aimed at tailoring the European standards for SA that at the moment specify the details of this process for buildings but not yet for road infrastructure. The guidelines are presented with two separate deliverables as follows:
   - D5.1a report focuses on the PavementLCM Guidelines to carry out SA exercises according to EN 15643-5-2017
   - D5.1b has been created as an addendum, due to the extent of information, to provide NRAs with recommendations to use Multi-Criteria analysis for Decision Making.

4. SA Tools (level 3)
   The PavementLCM "Tools" are part of the packaging process that aims at providing NRAs with tools that can facilitate the implementation of the SA exercises. These are:
   - Sustainability Assessment compass, aimed at providing an overview and guidance on the best tools available for NRAs

- LCA Data collection template, to guide NRAs on data collection to perform both pavement materials and pavement components LCA
- A tool to account for advanced calculation of uncertainty of LCA results for asphalt mixtures
- A tool to calculate the distribution of the estimation of durability of a pavement component (e.g. wearing course) on the basis of the experts' opinion

5. <u>SA Resources (level 3)</u>
The PavementLCM "Resources" provides NRAs with documents that can facilitate the implementation of the project results, and more specifically the SA exercises. These are:
- D1.5 PavementLCM Final report
- D3.1 with Sustainability data analysis, including datasets and recommendations to perform LCA of road pavements
- D4.1 Durability data analysis, including datasets useful to estimate a value for a reference service life of wearing courses
- D5.3 Roadmap towards harmonised environmental database for road pavements
- D6.1_6.2_6.3 Recommendations to introduce Circular Economy concepts within NRAs
- Technical briefs of the main project products

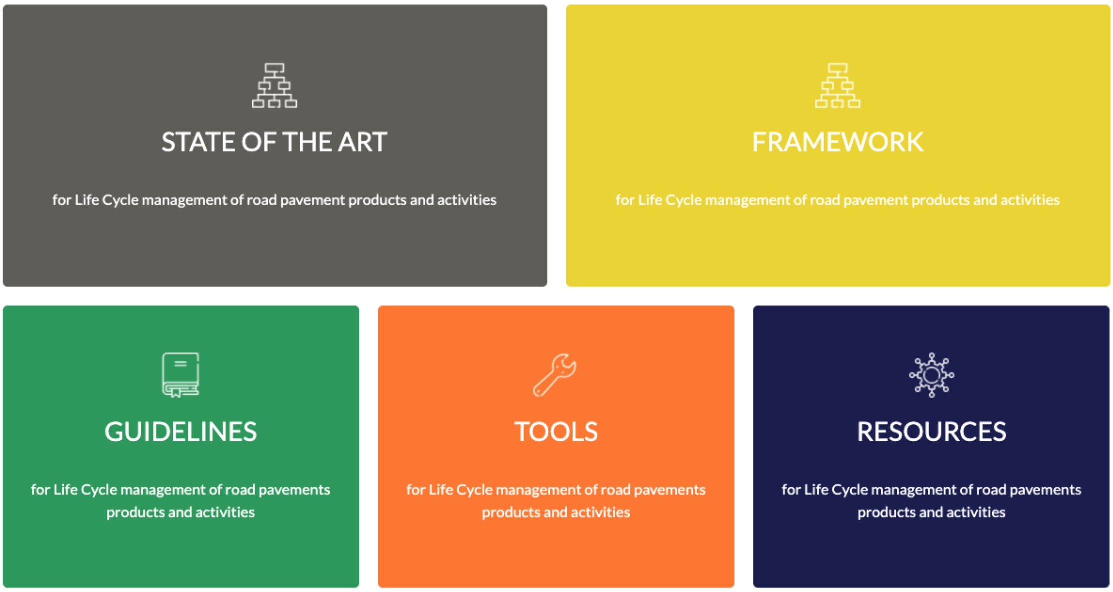


Figure 3 - PavementLCM Package

2.1.5. Proposal for implementation

The deliverables developed in this project aimed to serve the individual NRAs in implementing results within their organisation and at the core of their practices. Hence, implementation should start at the national context, however NRAs should continue with international cooperation towards a harmonized methodology for pavement life cycle management. The PavementLCM package contains framework, guidelines, resources and tools that can be used to start/evolve the utilisation of LCM practices. Furthermore, the project delivered products that are flexible enough to upgraded and updated and are ready-to-be-used by individual NRAs as well as from CEDR for future harmonization purposes. CEDR can also use the project results to develop European standards for LCM practices, for example together with bodies like CEN or ISO, or to support other association of stakeholders (i.e. EAPA) to define their Product Category Rules.

The results will not only be delivered for implementation in the NRA practices, but they will also be integrated into further research projects and communicated within the scientific community. Hence, this research will not stop after the project deadline, in fact it fits within the ongoing research portfolio of the consortium partners on engineering sustainability of road infrastructures.

Having said that, considering the complexity of the topic and in order to really make a change in the industry targeting sustainable development goals, it is of paramount importance that CEDR would keep the **"Transfer of Knowledge Platform"** initiated by this project. This would first of all allowing a continuous exchange of good practices amongst NRAs. Also, the platform has already demonstrated the potential of being a valid channel to foster direct contamination with other industry stakeholders (i.e EAPA, ERF, etc..) and experts from academia and industry also from other countries (i.e FHWA). Furthermore, providing specific support to keep this effort ongoing will allow performing tailored research towards a continuous development of the PavementLCM package composed of State-of-the Art information, SA framework, as well as SA guidelines, tools and resources for their implementation (Figure 3)

2.1.6. Conclusions

PavementLCM Project had three main objectives:

1) Tailor guidelines towards the introduction of Life Cycle Management (LCM) in National Road Authorities with a focus on Sustainability Assessment.
2) Create a platform for interactive transfer of knowledge on best practices on sustainability assessment and Life Cycle Management to generate reliable durability data for green asphalt.
3) Produce tools, guidelines, datasets, roadmaps and recommendations to introduce life cycle management practices in road authorities

With regards to objective 1 and 3, the consortium was able to:

- deliver internationally recognized guidance on LCM for National Road Authorities through a package with State-of-the-art information on the topic;
- a framework to implement LCM practices amongst the road pavement industry stakeholders;
- Guidelines to carry out Sustainability Assessment exercises according to the most recent standards on the topic;
- together with several Tools and Resources created to facilitate the implementation at both European and national level.
- At last, with regards to objective 2, the project initiated a platform that for the first time in Europe allows NRAs to discuss and learn sustainability assessment best practices with other stakeholders as well as with academics and experts from several part of the world.

2.2. CRAB for OERE – Cold Recycled Asphalt Bases for Optimised Energy & Resource Efficient Pavements

2.2.1. CRABforOERE factsheet

Project title: Cold Recycled Asphalt Bases for Optimised Energy & Resource Efficient Pavements (CRABforOERE).

Coordinator: University of Kassel

Consortium Partners:

Universität Kassel (Germany)

Università Politecnica delle Marche (UPdM), Italy

Institut français des sciences et technologies des transports, de l'aménagement et des réseaux (IFSTTAR), France

Nottingham Transportation Engineering Centre (NTEC), UK

Statens väg- & transportforskningsinstitut (VTI), Sweden

Università degli Studi di Palermo, Italy

Website: https://www.crabforoere.eu/

Duration: 01/08/2018 to 31/08/2021

Budget: 601 961 €

2.2.2. Background and objectives

Compared to the usually applied hot-mix asphalt pavements, the use of cold recycled asphalt base layers (CRAB) in flexible pavements is less common in road construction. However, several European countries have a long experience in these materials, which are usually composed of high contents of reclaimed asphalt (> 75 %), bitumen emulsion and cement. Recently, harmonised test procedures and material requirements were proposed for cold asphalt mixtures with bitumen emulsion within CEN 336/WG1 (EN 13108-31, EN 12697-53 to -56). However, for the wider use especially in countries with less experience in cold recycling some aspects of these road materials need to be assessed. The short-term performance which is highly dependent on the development of moisture within the CRM layer and therefore of climatic conditions is not fully understood so far and therefore cannot be properly adopted during mix design properly. Furthermore, durability as well as failure modes need to be examined in order to introduce sustainable pavement design procedures.

Within CRAB for OERE project, following steps further for establishing harmonised standards for cold recycling technologies were aimed:

- Assessment of long-term performance of existing cold recycling and/or cold asphalt pavement structures
- Validation and – if necessary – adaption of existing test methods and qualification procedures for RA aggregates.
- Validation of laboratory curing and performance assessment procedures for CRM
- Demonstration of harmonised mix design procedures based on EN 12697-53ff and EN 13108-31

- Demonstration of pavement design procedures for pavements with structural layers composed of cold recycling materials
- Scientific supervision of new test pavements with optimised energy efficiency allowing the application of sensors and monitoring of short-term performance
- LCA- and Risk analysis for assessment of environmental and economic benefits by using cold recycled materials and evaluate applications risks (e. g. weather during construction, RA variability)

2.2.3. Methodology

Within CRABforOERE project, the information required for drafting these guidelines were elaborated within six work packages (WP) by following means, compare Figure 4.

By assessing 17 existing pavement structures with cold recycled asphalt bases within their structures, information about the width of experience within Europe were learned. This includes especially various binder concepts with different contents of bitumen emulsion, foamed bitumen and/or cement. Further differences and commons regarding pavement design were assessed in detail. The actual surface conditions were assessed and together with pavement design compared to the actual pavement design, traffic loading parameters and age of the structures (WP2).

Nine reclaimed asphalt materials, sampled in five European countries were assessed by application of aggregate test methods, because of the role of the RA conglomerates as grains within the CRM (WP3).

The mix design procedures applied in five European countries were assessed in detail and the different methods for binder content selection, specimen compaction, curing and mechanical testing were practically applied for comparing the resulting materials performance. From the results, summarising conclusions for harmonised maximix design procedures could be obtained (WP4).

By comparing five national pavement design procedures applied for road structures with CRAB and with more experienced fully hot-mixed asphalt layers, the existing trust and expectations in these road materials were analysed. Three empirical pavement design procedures were applied on model pavements defined by given traffic loading and subsoil conditions as well as on the 17 assessed existing structures. Later results were compared to the actual pavements condition and age (WP5).

A demonstration pavement structure was built by incorporating sensors for measuring the moisture and temperature within the CRM layer. Further, core specimens were assessed 28 and ~300 days after construction of the pavement for assessment of the site curing effects. By implementing falling weight deflectometer (FWD) tests, the overall bearing capacity could be measured at the beginning of service life and after one year of service (WP6).

The environmental and cost benefit to be expected by the application of CRAB in flexible pavements were assessed for two pavement structures in central and southern Europe (WP7).

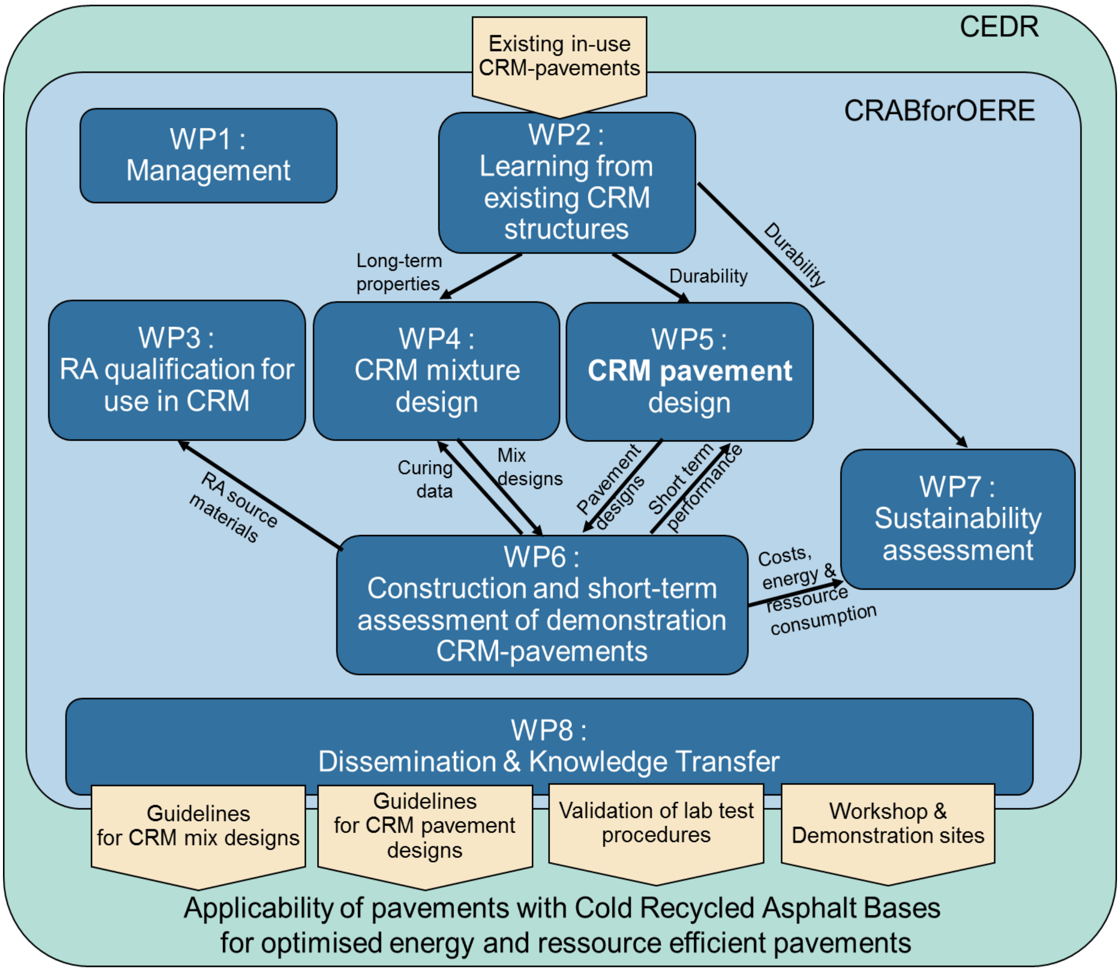


Figure 4. Organisation structure within CRABforOERE project.

2.2.4. Main findings

By assessing mix design, pavement design and service conditions of 17 existing road structures, which contain a CRM base layer, the wide range of mix designs regarding applied binder contents (bitumen and cement) could be confirmed. The pavements applied in Sweden and France followed a cold asphalt mix "grave emulsion" principle with low or no addition of reclaimed asphalt (≤ 30 %) and without any mineral binder. In the structures evaluated in UK and Italy, moderate cement contents (1,5 – 2,0 %) and RA contents of up to 90 % were applied in Cold recycled asphalt mixtures (CRA). The mix designs applied in Germany could be characterised by cement-bitumen treated materials (CBTM) with cement contents of ≥ 2 % and high RA contents ≥ 90 %.

Within CRM, the RA granulates takes the role of aggregates, as its binder is not reactivated by any heating. By testing of nine RA samples, derived from stockpiles of nine asphalt plants in Sweden, UK, France, Germany and Italy it could be shown, that the usually applied test procedures for assessing the properties of natural aggregates according to EN 13043 or 13242 can be applied also for the assessment of RA. The tests procedures don't need any modification but for reducing the temperature for oven-drying to 40 °C.

The range of material compositions applied in the evaluated mix design specifications of Sweden, Germany, UK, France and Italy were comparatively analysed in a laboratory mix design study by application of the same test conditions. As a result, it could be concluded, that the addition of cement is required for reaching strength and stiffness properties at young service life for enabling high traffic loads already shorty after construction. In order to avoid shrinkage cracking and enable flexible material behaviour, the content of cement shall be limited to 2 % at maximum. The content of added emulsified or foamed bitumen shall be in a range resulting in a bitumen:cement ratio of 1:1 to 1,5:1. High contents of added bitumen would reduce the materials strength.

If no cement is applied within the CRM, the applied bitumen emulsion has to be carefully adopted to the aggregate composition used in the mix granulate. By measuring the pH development of the bitumen emulsion or its aqueous phase after mixing with the fine fraction of mix granulate (RA and added aggregates) suitable emulsifiers and their contents can be derived. This is not necessary, if cement is added to the mix granulate even at proportions of 1 %, as its reactivity overrules the differences of the applied minerals. Further it could be shown, that two standard bitumen emulsion of the same category obtained in Italy and Germany result in similar CRM properties.

The results obtained during the laboratory test program to compare various laboratory test procedures for CRM compaction (gyratory, vibratory, static/Duriez), specimen curing temperature (20 °C and 40 °C), moisture (ambient and sealed) and duration (3, 14 and 28 days) identified following results:

- Compaction procedure and energy affect void content and mechanical properties,
- Compaction procedure is less important than curing procedure if similar void contents are achieved,
- Curing time, temperature and moisture strongly affects strength and stiffness of specimens,
- Accelerated curing at higher temperature is possible when low cement contents are applied,
- First days of curing (here: 2) predominates long-term performance for CRM with cement,
- For laboratory-curing, moisture and temperature during site curing shall be considered, which vary by weather conditions and construction procedure (sealing of CRAB by surface layer),
- The compaction protocol and the mechanical tests carried out (geometry, stress, temperature) influence the mixtures performance properties. To reach comparable quality levels, a harmonisation is recommended between the various national mix design procedures,
- The nationally applied specification documents seem to specify the materials on a different quality level.

The pavement designed identified within the 17 assessed existing CRAB structures were verified against the empirical pavement design procedures applied usually for pavements with CRAB layers in Germany, Italy and the UK. Except of two German (in which tar-contaminated material was uses as granulates) and one UK pavement (which was paved on top of a cement-stabilised layer), the applied CRAB pavements follow a similar overall design, in which the thickness of the asphalt layers (CRAB and HMA) depend from the traffic loading, see Figure 5.

All assessed CRAB sections with traffic loading between some few (10) up to 11.000 heavy vehicles per day which were under traffic between 5 to 13 years of service didn't show substantial deterioration, except of two sections. In one Germany section, transversal cracking could be linked to shrinkage cracking due to high cement content in the CRM and on Italian section, which were actually designed as interim pavement structure, showed fatigue cracking. The cracking conditions of these sections as well as of the less severe used CRAB sections could be linked

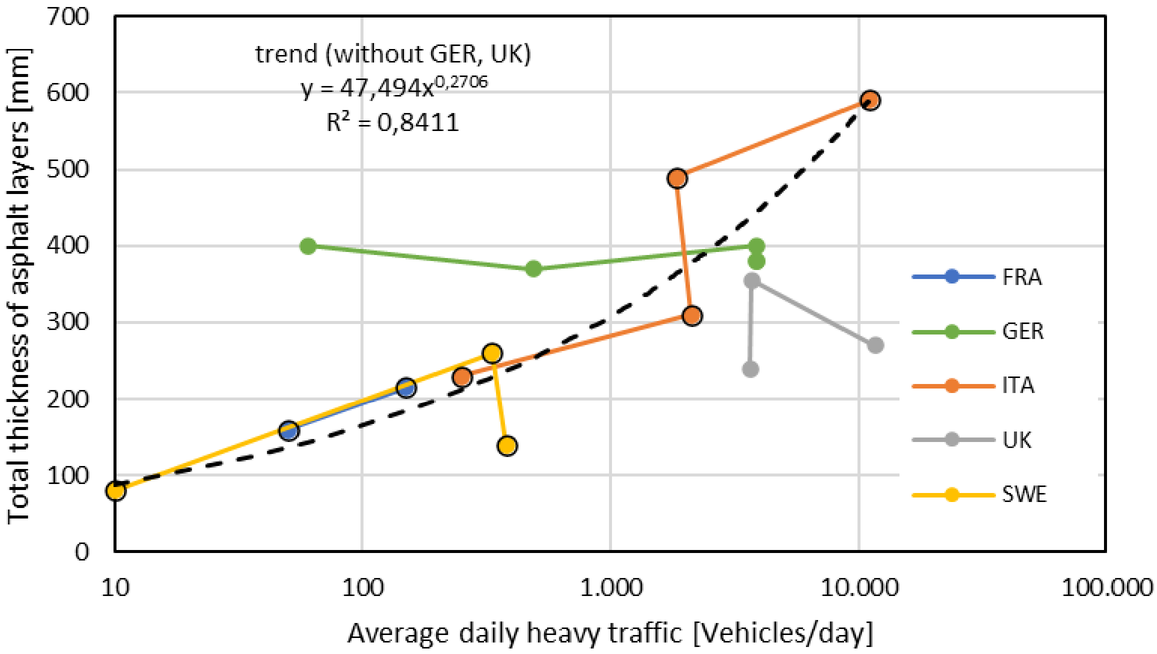


Figure 5. Comparison of total asphalt layers thickness in assessed pavements (including CRAB and hot-mix asphalt layers) and traffic loading

The empirical pavement design procedures according to German, Italian and UK specifications were applied to the 17 assessed pavement structures. Here, the discrepancy between designed thickness and actually received traffic loading between construction and condition assessment could be linked to the crack condition assessed from the surface condition. The same model wasapplied, which is usually applied for HMA pavements. This led to the conclusion, that CRAB pavements are implied wih a very similar risk of premature failure as the usual HMA pavement structures without any additional risk, when carefuly designed.

Because of the usually reduced stiffness of these materials, the asphalt base layer thickness should be increased by a specific factor. When comparing the approaches according to the assessed national pavement design specifications, a factor of 1,5 seems to be feasible and reliable. If a subbase layer is added, e. g. by a cement stabilisation of existing granular material or by a lime stabilization of existing clayey subground, an asphalt layer thickness increase of 20 % is proposed (see *Table 3*).

Table 3. Applied and proposed thickness adjustment factors for the total asphalt layers for exchange of HMA base layer by a CRAB layer.

	SWE	FRA	UK	ITA	GER
According to Design guides	1,0	1,65	1,1 – 1,2	1,4 – 1,8	1,1 – 1,8
According to model pavements	1,0	1,2	1,0 – 1,4	1,2	1,1 – 1,8
Proposal	1,5 (1,2, when stabilised subbase is added)				

The application of moisture sensors and repeated bearing capacity testing and assessment of cores enabled the assessment of the short- and mid-term service life of a cold recycled binder layer in San Marino. From the results some of the laboratory mix design conclusions could be verified, e. g. the adoption of compaction energy or application of curing conditions. Moisture and and bearing capacity tests identified that after 22 days of curing at dry weather conditions at elevated summer temperatures properties were reached, which were within10 % the same as after 371 days of site curing.

The compaction energy required by the construction specifications (100 gyrations) overestimated the actual compaction energy applied in the field. Consequently, the cores extracted from the pavement had higher voids and lower stiffness with respect to the gyratory-compacted specimens. However, considering the difference in voids level, field and laboratory curing led to similar stiffness evolutions. The measured moisture stabilised shortly after construction at a value of 4 % and then changed afterwards only slightly – influenced by precipitation conditions. This behaviour can be explained considering that the upper and lower surfaces of the layer were sealed using bituminous coats and that, in the long-term, the moisture of the pavement must reach an equilibrium with the surrounding soil. These curing conditions could be simulated in the laboratory by sealing the specimens using, for examples, plastic bags.

By assessing the cradle-to-gate emissions of in-plant and in-situ production of CRM, the environmental impact of all investigated CRABs was calculated to be at least 40% lower than a conventional HMA in almost all analysed impact categories. This can be explained by the reduced energy demand by mix preparation at ambient temperature rather than at material temperatures of around 150 °C as well as by the high RA contents possible when producing CRM.

2.2.5. Proposal for Implementation

From the research results a seven-step procedure for mix design for CRM as well as a simple empiric pavement design adoption as an eight step could be identified:

1. Sampling of RA

Due to the usually very high proportions of RA within the mix granulate of CRAB, special care is to be taken for sampling. The requirements regarding homogeneity are equal to what is usually experienced for RA use in HMA (hot recycling). Therefore, the sampling rules specified in EN 13108-9 (section 5.4 to 5.6) shall be applied to RA for the use in CRAB in the same way.

2. RA assessment

The RA aggregate to be used in CRM should be assessed following the same general scheme adopted for assessing natural aggregate as described, for example, in European standards like EN 13043 or EN 13242.

For mix design of CRM, it is essential to determine at least the particle size distribution (black curve) and the water absorption on representative RA samples. The first is needed to correctly design the grading of the mix granulate, the second is needed to correctly evaluate the design water content of the mixture and the need for a water addition in the recipe. For the same reason, in the mixing phase of CRM, both in-plant and in-place, it is essential to constantly monitor the water content of the aggregate (RA and natural).

When no cement or lime is used as secondary binder, measuring the reactivity of the RA using the rise in pH test, will help in selecting the most appropriate emulsion formulation. However, when cement is used, it will control the reactivity of the mix granulate and using an emulsion with high mixing stability (Class 10 breaking behaviour) is recommended.

The Fragmentation test can be used within in-place recycling projects as a quality-control tool to obtain a quick assessment of the aggregate stability and homogeneity during construction.

3. Grading of mix granulate

In all assessed specifications, the mix granulate shall meet a dense mix composition. As freshly milled reclaimed asphalt usually has low contents of fines (< 0,063 mm) and fine particles (< 2 mm), usually fine natural aggregate and/or fillers are added to the mixture in order to achieve a favourable gradation with a maximum grain size between 10 mm to 20 mm for based course mixtures.

4. Compaction water content

In general, the sequence of incorporation of the components and the mixing duration must reproduce the aspect intended by the mix designer. A study of the compatibility of the components must be carried out to enable the coating quality, the mix consistency and its cohesion have to be checked. This also makes it possible to set the optimum water content and to evaluate the formula sensitivity to avoid mix behavior that is too liquid or too dry. This laboratory approach is necessary but will require to be completed with the plant one to set the mix design.

For evaluating the added water content for the mix preparation, the moisture of aggregate and the bitumen emulsion water content are subtracted from the optimum water content

5. Binder and binder content selection

Cold mixes are characterized by their short-term evolutionary behaviour. Such a property is initiated from manufacturing stage by adding bitumen emulsion and – if required – additional binders or active fillers, like cement. This development, which depends on the mix design and the climatic conditions of the worksite, results in a more or less rapid increase in cohesion of the loose mixture. Workability depends on the friction contact of the mixture and on evolution of the cohesion within the mixture (aggregates, bitumen content, water content, emulsion/aggregate reactivity). Controlling the mixtures' workability is a major issue for transport, laying and compaction. The cohesion increase shall be initiated by compaction of the layer and additionally is supported by traffic loading. Depending on the target traffic and the type of mixture targeted in the pavement structure, the grade of the bitumen within the emulsion, the bitumen emulsion content as well as the addition of cement needs to be defined.

For pavements with moderate and high traffic loading, following binder contents are recommended:

- Cement: 1,5 %-2,5 %,
- bitumen/cement ratio: 1 – 1,5 (residual bitumen from a slow-breaking bitumen emulsion or foamed bitumen).

For pavements with low traffic loading also mix designs without any cement additions is applicable. However, in this case the compatibility between bitumen emulsion and mix granulate has to be carefully assessed in order to achieve the desired emulsion breaking process.

6. Laboratory mixing, compaction and curing

The laboratory compaction shall result in similar compaction success as site compaction. Therefore, the applied compaction energy in most nationally applied laboratory compaction procedures needs to be adjusted.

Curing conditions (temperature, moisture) affect the evolution kinetics of strength and stiffness of the specimens. In situ curing depends on the regional climate of the pavement location, weather conditions, structure of the roadway and road traffic. Therefore, a perfect simulation in the laboratory is illusory. In order to achieve some harmonisation, following procedures are proposed:

- for high temperature conditions (southern Europe): Curing at 40 °C for 3 days
- for low and intermediate temperature conditions (northern Europe): Curing at 20 °C for 28 days

The moisture during curing shall be selected according to the site and construction conditions:

- In case of a quick covering of the CRAB with seal or a surface or binder asphalt layer within 24 h, the curing shall be done in sealed conditions (e. g. in a plastic bag).
- In case of several-days drying of the CRAB layer without cover, the laboratory curing shall be conducted at unsealed specimens.

7. Specifications on void content, strength (ITS), stiffness, water sensitivity

Due to the wide varying compaction, curing and test parameters applied within existing mix design procedures, no commonly applicable specification values can be identified from the conducted studies. However, following strategy is recommended for the mix design of CRM:

Based on the selected mix granulate and cement content the bitumen emulsion content shall be varied in at least three stages. After compaction, the void content shall be lower than 15 %. If this is not reached, the mix granulate composition needs adjustment. After curing, strength (e. g. indirect tensile strength according to EN 12697-23) and water sensitivity (EN 12697-12) shall be assessed.

8. Pavement design for flexible pavements with CRAB

The assessment of the existing CRAB pavements showed that observed surface conditions in CRAB pavements can be linked to their structural design properties (structural thickness, subbase layers) and service lifetime. A pavement design "rule of thumb" could be derived, which would allow the application of national empirical pavement design procedures. Here, the HMA base layer can be changed to a CRAB layer by considering a higher layer thickness:

- $h_{CRAB} = 1{,}5 \cdot h_{HMA\ base}$, or
- $h_{CRAB} = 1{,}2 \cdot h_{HMA\ base}$, when a cement stabilization is applied below the CRAB.

Generally, mechanical-empirical design procedures can be applied for pavements including CRAB layers.

2.2.6. Conclusions

Compared to the usually applied hot-mix asphalt pavements, the use of cold recycled asphalt base layers (CRAB) in flexible pavements is less common in road construction. However, several European countries have a long experience in these materials, which are usually composed of high contents of reclaimed asphalt (> 75 %), bitumen emulsion and cement. The analysis of national specification documents as well as of existing pavements with CRAB identified a wide range of mix and pavement designs applied but also commons in the used design methods. The existing pavements with CRAB perform very similar to asphalt pavements composed of hot-mixed asphalt base layers even at high traffic loading. At the same time, the production of cold recycled materials (CRM) will result in a reduction of at least 40 % of environmental impact factors, including global warming potential (-42 % of CO_2-eq.), acidification of freshwater (-51 % of P-eq.), eutrophication of freshwater (-58 % of P-eq.) or fossil energy resources (-61 %). The assessment of 17 existing CRAB pavements allows the conclusion, that these benefits are not reduced by higher maintenance demands of the pavements, if feasible mix and pavement design principles are followed.

Especially the mix design procedures applied for optimising the properties of CRM needs some European harmonisation in order to facilitate their application. Regarding the pavement design rules, a simple and conservative "rule of thumb" was proposed, which will allow the application of CRAB layers in road construction and rehabilitation projects.

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

2.3.1. FIBRA Factsheet

Project title: Fostering the implementation of fibre reinforced asphalt mixtures by ensuring its safe, optimized and cost-efficient use (FIBRA).

Coordinator: University of Cantabria

Consortium Partners:

University of Cantabria,

SINTEF AS,

EMPA, Swiss Federal Laboratories for Materials Science and Technology Road Engineering Laboratory,

ISBS Institute für Straßenwesen (Technische Universität Braunschweig),

BAM Infra bv, Veidekke Industri AS

Website: https://www.giteco.unican.es/proyectos/fibra/index.html

Duration: 02/07/2018 to 30/06/2021

Budget: 632 418 €

2.3.2. Background and objectives

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.

In the last years, fibre-reinforcement has become a promising alternative to improve the mechanical properties and durability in road pavements. Fibres have been proposed as one of the most important additives for the development of reinforced asphalt mixtures, and numerous research studies report multiple benefits on mechanical properties. However, the state of the art presents gaps that are related to the difficulty of comparing the performance of the different fibres, the limited experience in open grade mixtures (except for cellulose fibres) or the reluctance to declare negative aspects of the technology. In addition, many uncertainties have been identified by National Road Authorities with regard to the implementation of this technology, such as:

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

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 fibre reinforced asphalt mixtures (FRAM).

2.3.3. Methodology

In order to fill the existing gaps of the state of the knowledge concerning Fibre-Reinforced Asphalt Mixtures (FRAM), the project was developed following different stages, starting with the selection of the fibres and finalising with the environmental and economic feasibility study of the technology (Figure 6). Thus, the first stage 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. 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 by means of advanced chemo-mechanical techniques as well as evaluating the influence of the fibres in the asphalt mortar mechanical and rheological properties.

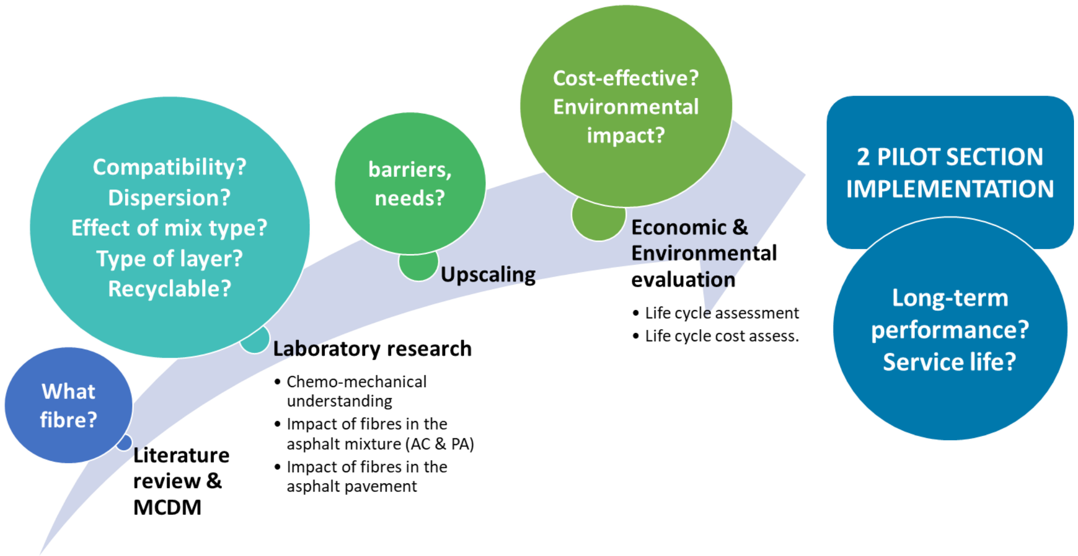


Figure 6. FIBRA project methodology

Following the chemo-mechanical assessment, and to widen the scope from the current state of knowledge, two asphalt mixtures, an asphalt concrete (AC) and a porous asphalt (PA) 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 asphalt mixtures with high RAP content in order to identify a potential positive effect of fibres addition. With the aim of defining the most advantageous use of the fibres within the road pavement structure, the assessment of the long-term performance of the pavement was carried out through a numerical simulation using FlexPAVE™ 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, the temperature effect 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 by the construction companies involved in the project. The asphalt mixtures were implemented in a real road section thanks to the involvement of both National Road Authorities (NRA), Rijkswaterstaat in the Netherlands and Statens Vegvesen in Norway. This activity enables the upscaling of technology to identify potential technical barriers and the short-term and long-term performance validation of the FRAMs.

Finally, a life cycle assessment (LCA) and a life cycle cost analysis (LCCA) were applied to the two road sections implemented in the project. The impacts of the FRAM layers were compared to those of the conventional layers used as references.

2.3.4. Main findings

As outlined before, 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 concerning the large-scale implementation of FRAMs. Main findings and outcomes from the FIBRA project are summarised in this section.

From the **review of the state of knowledge and the MCDMA** carried out in the first stage of the project, Polyacrylonitrile fibres (PAN) and a blend of Aramid/Polyolefin fibres (ARAM/POL) were selected due to their best performance in all the considered criteria: mechanical performance, cost-benefit, environmental impact and status of development of the fibres.

As part of the **chemo-mechanical evaluation of FRAMs**, differential scanning calorimeter and thermal gravimetric analysis were used to investigate the thermal transitions of the selected fibres. According to the results, none of the fibres suffers any thermal degradation at conventional production temperatures (ca. 160ºC) and from the three fibres analysed, only the polyolefin was found to melt at temperatures lower than the production temperature. However, the softening point, master curves and black curves of the bitumen recovered from FRAMs confirmed that no modification of the bitumen occurs.

Figure 7. Polyacrilonitrile fibre (left), Aramid fibre (right), FRAM (center)

The **impact of the fibre-reinforcement in the mechanical performance** of the asphalt mixture was assessed at the laboratory level by the optimal design of both, asphalt concrete (AC) and porous asphalt (PA) mixtures with and without fibres and by evaluating their mechanical performance. The results from this extensive study showed that the Indirect Tensile Strength (ITS) and the rutting resistance of AC mixtures increases when fibres are added, being the rutting resistance similar to that obtained with AC mixtures incorporating polymer-modified bitumen (PMB). On the other hand, the fatigue resistance and the low temperature performance is not affected by the addition of fibres. Therefore, FRAMs do not achieve the high level performance of the AC mixtures with PMB. As for the impact of fibre-reinforcement in PA mixtures (FRPA), the functional performance of the mixtures in terms of air void content or permeability are not notably affected but FRPA mixtures greatly outperform PA mixtures with conventional penetration grade bitumen concerning ravelling resistance and water sensitivity. However, the performance of PA mixes with PMB in terms of water sensitivity, ravelling (wet conditions) or low temperature cracking resistance is not reached. Another important outcome from this study is that an extra amount of bitumen is needed to adequately cover the fibres and effectively achieve a reinforcement effect on the mixture.

In this study, the impact of the fibre-reinforcement in AC mixtures was evaluated not only for the wearing course but also for their potential effect in mixes intended for the binder and base layers in the asphalt pavement section. The mechanical properties of all these experimental mixtures were used in the pavement structural analysis programme called FlexPAVE™ to **analyse the impact on the durability of the road pavement** of implementing FRAMs on one or more asphalt layers. Based on the different pavement structures simulated in FlexPAVE, FRAC increases the resistance to plastic deformations of the surface layer in a greater extent than the asphalt layers with PMB but they do not have a significant effect on the fatigue life of the pavement, being the AC mixture with PMB placed in the base course the best configuration to improve this property.

The **upscaling of the production process** and the **implementation of two pilot sections** provided very valuable information to identify future barriers in the implementation of the technology. The upscaling was carried out in two different asphalt plants at two different European countries (Norway and the Netherlands). 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. After the upscaling, two pilot sections were built, one in Norway and one in the Netherlands. **Main outcomes from the upscaling and the implementation** are 1) FRAM can be produced in existing asphalt plants by manually adding the fibres in pre-packed low-melt bags, 2) the production, laying and compaction are carried out with regular equipment and procedures and 3) synthetic fibres in combination with penetration grade bitumen allows reducing the production temperature by 20ºC compared to the control mixture with PMB. In addition, the fibres were homogeneously distributed, the road surface's functional properties were nor altered by the addition of fibres and in the case of the FRAC, the resistance to abrasion by studded tires was improved comparing to the control AC mixture with penetration grade bitumen. On the other hand, as these synthetic fibres do not prevent binder drainage, the addition of cellulose fibres is recommended in bitumen-rich mixtures.

Figure 8. Laying and compaction of FIBRA mixtures

Finally, the **environmental and economic feasibility** of using fibres to increase the service life of asphalt mixtures were analysed. Regarding the environmental impact, a **cradle-to-grave LCA** was done on the two pilot sections. The addition of fibres resulted in a very limited and increase of the environmental impact of approx. 2-7% depending on the case study. As part of the environmental feasibility study, the **recyclability potential** of FRAM was analysed, being the main finding that FRAM mixes are recyclable to the same extent than conventional asphalt mixtures with penetration grade bitumen. As for the economic feasibility, a **LCCA** was performed to evaluate the long-term economic efficiency of using FRAM layers. Similar life cycle costs are obtained for all the alternatives. Thus, to be economically feasible, a similar durability than the control mixtures with PMB need to be achieved by FRAM layers. When comparing to control mixtures with penetration grade bitumen a slightly higher durability should be reached by FRAM layers (5-10%).

Several reports detailing all these results and findings are available at the CEDR Research Call 2017 New Materials and Techniques: ***https://www.cedr.eu/peb-new-materials-and-techniques***

2.3.5. Proposal for implementation

The research carried out in the **FIBRA project has given answers to several questions** related to the usability of fibres, providing extensive information about 1) how fibres function within the asphalt mixture, 2) the impact of fibre-reinforcement in the mechanical asphalt mixture's performance, 3) the optimal position of FRAM layers in the pavement section, 3) potential recyclability of FRAMS, 4) real scale production process and FRAM layers construction and 5) the economic and environmental feasibility of FRAM.

However, some limitations in this study have left some **remaining unresolved gaps.** One important remaining issue is the effect fibre reinforcement has in the final durability of the pavement section. Therefore, the cost-effectiveness of FRAM is not fully demonstrated since it is strongly linked with the service life extension. However, it is expected that the long-term monitoring of both pilot sections in Norway and the Netherlands will bring shed light to this issue.

In the same line, a further optimization of the 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.

On the other hand, it is believed that the presence of the fibre retards ingression of the oxygen into PA 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.

Finally, based on the results, the following applications are recommended:

- FRAC mixtures are recommended in areas or regions prone to rutting damage due to their excellent resistance to permanent deformation.
- The use of FRAM, both FRAC and FRPA is recommended in the wearing course to maximize the benefits.
- On the other hand, the good rutting performance would also allow the use of a softer bitumen in the AC mixture design, contributing this way 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.

2.3.6. Conclusions

In order to move fibre-reinforcement from theory to practice, the FIBRA project has addressed several issues concerning their functioning, usability, benefits, sustainability and cost-efficiency.

In general terms, it can be highlighted that fibre-reinforcement can be successfully applied, in terms of mechanical performance, to both dense and open graded mixtures, being possible to improve key mechanical characteristics of conventional asphalt mixtures (with penetration grade bitumen) but, in general, not reaching the performance level of the asphalt mixtures with PMB. Thus, FRAC mixes present an excellent rutting resistance, and FRPA mixes show a better resistance to ravelling and water sensitivity, indicating a possible positive effect on the long-term performance of the road surface. Care should be taken during the FRPA design phase to properly cover the fibres with the bitumen, so the adequate mixture behaviour at wet conditions is ensured.

On the other hand, fibre-reinforcement can be applied to the road surface of any traffic category road. It should be noted that in the FIBRA project, FRAC and FRPA mixes have been designed to comply with the technical requirement of the most demanding traffic categories.

Concerning the large-scale application, the production, laying and compaction of FRAM can be done with regular equipment, standards and procedures. No special equipment or uncommon mix sequences are needed to produce these mixtures. Thus, no initial investment is needed.

As for the environmental and economic feasibility, information about the final durability of the FRAM is needed to draw conclusions. Although it can be remarked that, if the same durability is assumed, the differences in the environmental and economic impact of the different alternatives evaluated are very low. Finally, the study of the recyclability potential of FRAM suggests that aged FRAM mixes could be recycled in a similar way than conventional asphalt mixtures with penetration grade bitumen.

3. Harmonised sustainability assessment (Cradle-to-Grave LCA) of road pavements activities for FIBRA and CRABforOERE - METHODOLOGY

SYRAF Project aims at providing a synthesis of the results of CEDR 2017 Call "New Materials" by also proposing two harmonised LCA exercises by looking at alternatives included in CRABforOERE and FIBRA projects. In both LCAs, the aim was to understand if the new technology studied is more "environmentally friendly" than the respective conventional one.

Concerning CRABforOERE, the chosen cases studies were representative of two different production scenarios: in-plant recycling (Republic of San Marino) and in-situ recycling (Germany).

Concerning FIBRA, the comparative analysis was carried out between asphalt mixtures for surface courses namely: a conventional 2L-PA8 produced at 185ºC and a Fibre-reinforced 2L-PA, produced at 165ºC.

For each case study, results have been analyzed in order to address which life-cycle stage is the most impactful. Furthermore, a first sensitivity analysis on the transport distances from asphalt plant to site was undertaken in CRABforOERE, while a second was carried out on changing materials in FIBRA. The following "flowchart" provides a summary of the processes followed for the harmonized LCA study.

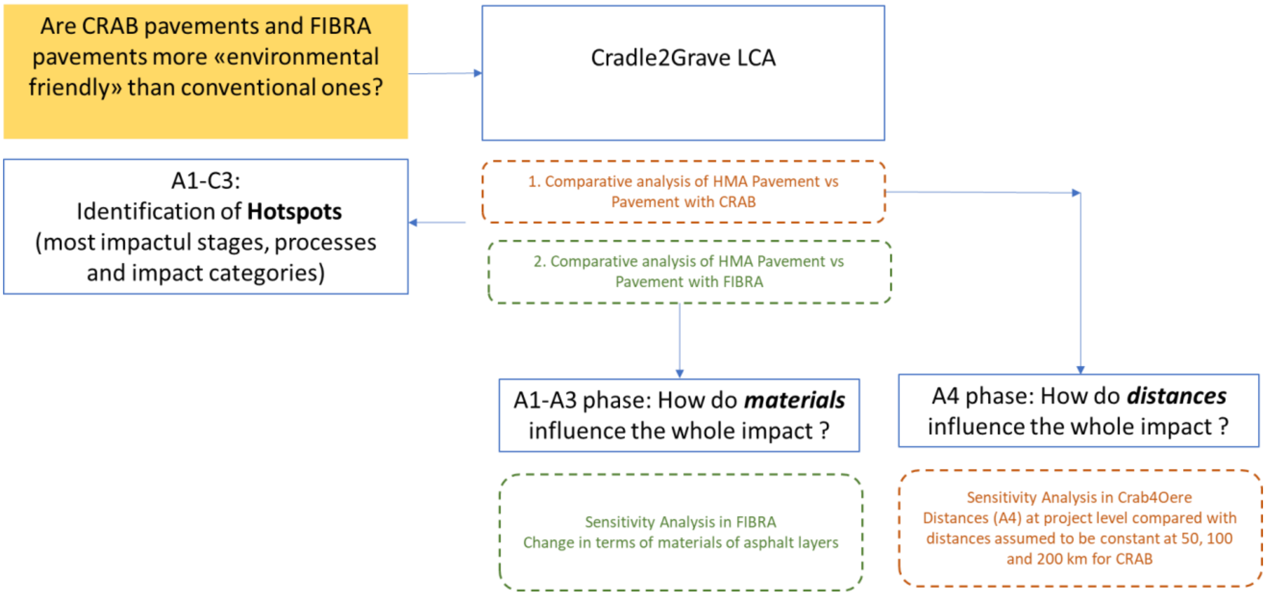


Figure 9. Harmonised LCA of road pavements activities for FIBRA and CRABforOERE

In the following sections, the explanation of the methodology is followed by the details of each separate LCA exercise, expressed in terms of case studies description and main results, some general conclusion and recommendations. The LCA of each exercise is detailed and reported in the Annex.

3.1. Methodology according to the PavementLCM Framework and guidelines

The harmonisation was carried out by performing the two different LCA exercises along the seven steps suggested by the PavementLCM Framework and Guidelines (Figure 10). The following step-by-step list has the aim of highlighting the common points of the analyses as well as some differences in the approaches:

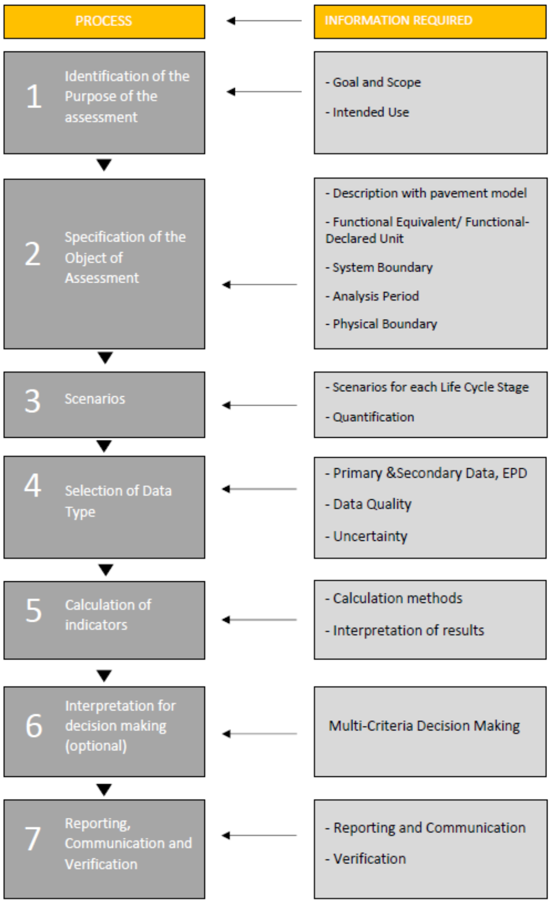


Figure 10 - Sustainability Assessment Steps according PavementLCM Guidelines

Step 1: identification of the purpose of the assessment

Goal: The main goal is to calculate the environmental impacts of different contracted activities for the maintenance of a road pavement with:

- cold mixtures as binder course or base course within CRABforOERE
- fibre-reinforced asphalt mixtures in the surface course within FIBRA

Scope: The main scope is the Pavement Activity, considered its full Life Cycle.

Intended use: For both projects, the intended use are

- understanding whether the hypothetically more sustainable asphalt mixtures and paving practices proposed in both projects, are more environmental-friendly than conventional options (hot mix asphalt);
- Understanding the pros and the cons of using the C4O technologies when compared to currently used construction methods
- Helping decision-making of asphalt mixture producers

Step 2: specification of the object of the assessment

Object of the assessment: For both projects, the object of the assessment is the pavement activity and, specifically, the proposed exercise is related to the comparative LCA of innovative paving practices as indicated in the PavementLCM framework and detailed in the Figure below.

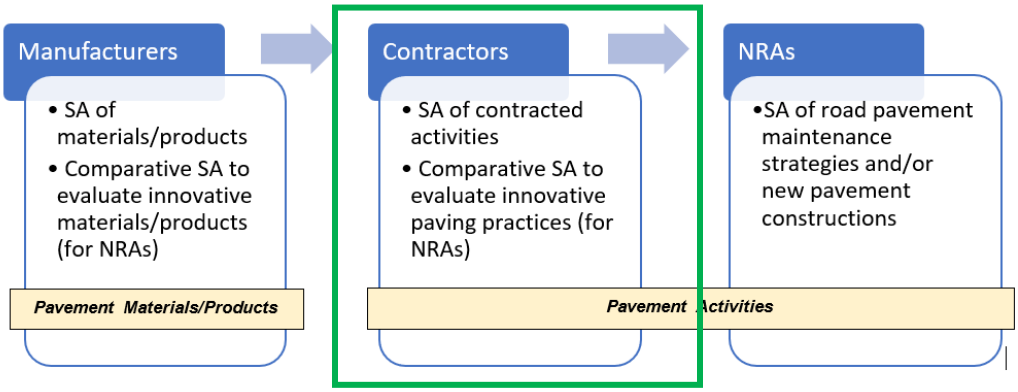


Figure 11 - Selection of LCA exercise according to the PAVEMENTLCM framework (pavementlcm.eu)

Specifically, two innovative paving practices are compared with conventional ones:

- The first one is linked with CRABforOERE Project and it consists of two different maintenance strategies representative of two case studies:
  1. the replacing of the binder course, conventionally made with HMA, with a cold mix asphalt in Republic of San Marino.
  2. the replacing of the conventional base course, made with AC32TS, with a cold asphalt in Germany.
- The second one was developed inside FIBRA Project and consists of conventional 2L Porous Asphalt mixture (2L-PA) including a polymer modified bitumen, compared to a fibre-reinforced 2L-PA including a penetration grade bitumen (70/100) and 0.15% of Polyacrylonitrile fibres.

System boundaries: The system boundaries, in both case studies, is the full Life Cycle (cradle-to-grave) which considers the Production (A1-A3), the installation (A4-A5), the Use (B3-B4) and the end-of-life (C1-C3) as explained in the figure and the table below. In particular, in FIBRA, concerning the B phase, only B4 (refurbishment) was taken into account, while in CRABforOERE also the B3 (Repair) in Republic of San Marino was considered.

Table 4 - Explanation of System Boundaries

Phases	Description	Remarks
A1 to A3	Production stages including Raw materials supply and transportation to the asphalt plant and the asphalt mixture production at the plant.	Included
A4 to A5	Construction stage includes the transportation of materials to the workzone and the installation of the three asphalt layers.	Included
B1	Use stage (use). Release of substances from the asphalt pavement to soil or ground water.	Not included.

		Particulate emissions related to surface wear were not included due to the lack of harmonized and accurate test methods.
B2	Use stage (maintenance). Minor maintenance activities such as applying salt, removing waste, maintaining permeability in porous asphalt mixtures, etc.	These processes are carried out when needed and are not planned. Thus, the impact of these processes are not included.
B3	Use stage (Repair). Minor maintenance activities such as filling cracks or sealing of cracks, pothole repair, etc.	This stage was included only in San Marino case studies, where a maintenance activity linked to the cracks was taken into account.
B4	Use stage (replacement). Replacement of the surface course. This module includes milling of the old surface, production of the asphalt and the raw materials and laying the new surfacing layer. Processes involved in waste treatment (i.e. RAP) and waste transportation are also included	Included
B5	Use stage (refurbishment). A major change in the pavement functionality.	Not included. A change in the pavement functionality is out of the scope of this analysis.
B6 to B7	Use stage (operational energy and water). Processes related to the operation of buildings.	Not included. It is considered not applicable to roads.
C1 to C3	End-of-life stage. These modules include the milling of the three asphalt layers at the end of their service life and the transportation of the reclaimed asphalt to a recycling site.	Included
D	Possible recycling strategies. Loads related to crushing of the RAP. Benefits related to the aggregates, fibres (if applicable) and bitumen which are replaced in the new system. The amount of RAP used in this road system is subtracted from the RAP leaving the system.	Included. This module is reported separately.

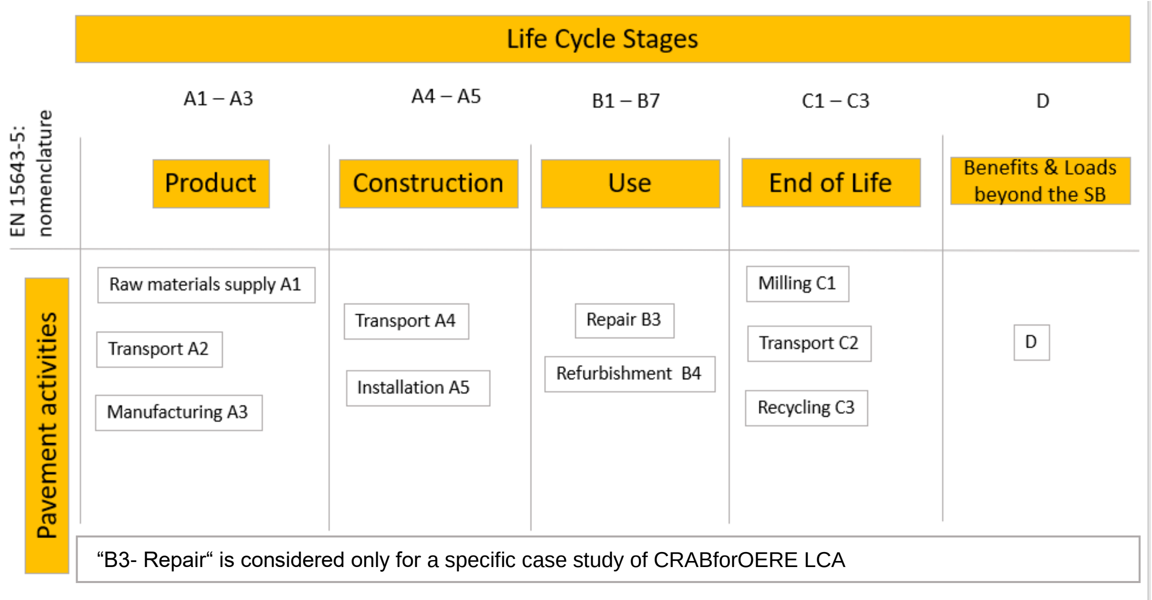


Figure 12 - System boundaries and life cycle stages for both Case Studies

Functional unit: As reported in PavementLCM Guidelines, the functional unit can be chosen as:

- The exact volume (or weight) of the road pavement to be contracted and/or built as required at project-level, as assumed in CRABforOERE project;
- 1 m^2 of surfaced pavement, together with a clear description of the physical boundaries to account for the total volume of paved material, as assumed in FIBRA.

Analysis period: For both case studies, the analysis period was considered equal to the reference service life of the contracted activities, which differs for each case study (details in the next sections).

Physical boundaries: The portions of pavement structure to be considered part of the pavement system are:

- CRABforOERE: wearing course + binder course in Republic of San Marino

  Wearing course + binder course + base course in Germany
- FIBRA: Wearing course + binder course + base course

<u>Step 3</u>: <u>Scenarios</u>

Scenarios: In both cases, as described above, the object of the assessment is the maintenance strategy. For this reason, all the activities taken into account are those included and necessary in the analysis period, as described in the next sections.

The materials used differ in terms of mix design and typology, according to the specific case study.

Quantification: All the quantities necessary for the scenarios are described in the following sections.

- Gross and Net amount: In order to carry out the LCA, the following assumptions on material and energy quantifications have been considered:

   - No asphalt plant stack emissions were considered.
   - When used, RA stockpile and processing are considered to be located at the asphalt plant, therefore, transport distance of RA is zero.
   - No ancillary materials in the asphalt plant or on the work zone (A3, A5 and C1) are considered.
   - In the RAP treatment (A1), only energy consumption during crushing and sieving is included. No data is available concerning diesel consumption for materials movement inside the plant.
   - No data is available concerning the waste and/or over consumption of energy and materials generated during the production at the asphalt plant
   - Material waste and energy over-consumption during installation or dismantling of pavement components is assumed zero,
   - Reclaimed asphalt obtained from the milling process is assumed to be 100% recyclable.
- Reference/Estimated Service Life (RSL): for both projects, only estimated values were available and each of them is reported in each case study.

<u>Step 4: Selection of Data type</u>

The data collection has been carried out with the support of the partners. Primary Data was used when available, secondary data was taken mostly from GaBi and Ecoinvent 3.0 databases. The LCIA methodology chosen was EF 2.0.

Type of Data: In both projects, primary and secondary data were used. The primary ones were directly provided by the partners/producers, while the secondary ones, used when the others were not available, were taken from different databases, according to the LCA software used:

- CRABforOERE: GaBi ts Database, as GaBi software was used;
- FIBRA: Ecoinvent Database, as SimaPro software was used.

Data Quality: the assessment of the data used in the LCA was carried out into two different ways, linked, once again, to the software used:

- CRABforOERE: Data Quality according to the table provided by the JRC Report (2016), (as available in GaBi ts)
- FIBRA: Data Quality according to the Pedigree Matrix (through SimaPro)

Uncertainty: not being a mandatory step, in CRABforOERE it was not calculated, while in FIBRA a MonteCarlo Simulation was carried out.

<u>Step 5: Calculation of indicators</u>

In PavementLCM Framework some indicators were identified, related to different aspects of the Sustainability Assessment. In this case, only the environmental performance was assessed, performing a Life Cycle Assessment (LCA) using the EF2.0 Methodology for calculating the impacts related to all indicators suggested in the Framework.

Table 5. Environmental impact indicators

Indicator		Unit	Recommended default LCIA method
Global warming potential (total)	Global warming potential – GWP fossil fuel	kg $CO_{2\ eq}$	Baseline model of 100 years of the IPCC (based on IPCC 2013)
	Global warming potential – GWP biogenic	kg $CO_{2\ eq}$	Baseline model of 100 years of the IPCC (based on IPCC 2013)
	Global warming potential - GWP luluc	kg $CO_{2\ eq}$	Baseline model of 100 years of the IPCC (based on IPCC 2013)
Acidification Potential	Acidification Potential: Accumulated Exceedance (AE)	mol H+ $_{eq}$	Accumulated Exceedance (Seppälä et al. 2006, Posch et al, 2008)
Eutrophication Potential	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)
Air pollution	Respiratory Inorganics	deaths	UNEP recommended model (Fantke et al 2016)
	Photochemical ozone formation - human health	kg NMVOC $_{eq}$	LOTOS-EUROS model (Van Zelm et al, 2008) as implemented in ReCiPe
Natural resources	Water scarcity	m3 world $_{eq}$	Available WAter REmaining (AWARE) Boulay et al., 2016
	Land use	Dimensionless (pt)	Soil quality index based on LANCA (EC-JRC)
	Resource use, mineral and metals	kg Sb $_{eq}$	CML 2002 (Guinée et al., 2002) and van Oers et al. 2002.
	Resource use, energy carriers	MJ	CML 2002 (Guinée et al., 2002) and van Oers et al. 2002
Energy Resources	Use of renewable energy resources	MJ	No LCIA applied
	Use of nonrenewable energy resources	MJ	No LCIA applied
Secondary materials	Secondary materials	tons	No LCIA applied

The LCAs are reported in detail in the next sections. They were carried out following the actual standards and according to the suggestions provided by the Guidelines. Nevertheless, they present some little differences, as presented in the table below. These differences are due to different choices, aims and software used, but they are absolutely consistent with the methodology.

Table 6 - Main differences between the two LCAs

	CRABforOERE LCA	FIBRA LCA
HotSpot analysis	Performed for: - LCA phases (A1-A3, A4-A5, B, C1-C3); - Impact categories	Performed for: - LCA steps (A1, A2, A3, A4,A5, B, C1, C2, C3); - Processes; - Impact categories
Sensitivity analysis	Performed to understand how distances (A4) influence the impacts	Performed to understand how some materials influence the impacts
Data quality and Uncertainty	As mentioned before, Data Quality was performed according to the indications provided by the JRC Report and no uncertainty was calculated.	As mentioned before, Data Quality was performed using the Pedigree Matrix and uncertainty was calculated with the Monte Carlo Simulation.

Step 6: Interpretation for decision making (optional)

Decision making through the application of Multi-criteria approaches was not performed for this case study.

Step 7: Reporting, communication and verification

Since this exercise was only related to harmonisation of environmental LCA, please refer to the results interpretation and general conclusions defined in the "Conclusions, limitations and recommendations of each case study.

3.2. LCA of innovative paving activities with "CRABforOERE" technologies

This LCA was performed to understand the environmental benefits of pavements with CRAB, a technology which uses a high quantity of Reclaimed Asphalt (RA) and is produced at ambient temperature, when compared with a pavement realized with a conventional Hot Mix Asphalt (HMA). Two case studies were analysed, representative of two different production techniques: in-situ recycling and in-plant recycling. Here below the case studies are detailed followed by the main results and conclusions. The LCA explained step by step is reported in the Annex

3.2.1. Case studies

The presented case studies have been selected as representative of two different manufacturing processes of CRAB materials as well as for the subsequent installation and maintenance strategy of road pavement components. The two case studies are real projects recently carried out at the Republic of San Marino and in Germany. Hence, they differ in terms of geographical location, pavement structure, traffic level and above all, construction methods: in-plant recycling for San Marino and in-situ recycling for Germany.

The table below summarizes the main information directly collected from contractors and/or project partners. As it can be seen in both cases the project consists of a major maintenance activity that includes the use of a cold mix asphalt (CRAB), in place of conventional hot asphalt mixtures, for binder layers (San Marino) or for base layers. (Germany).

Table 7 - Main information of Case Studies

Pavement course	In-Plant recycling: Republic of San Marino		In-Situ recycling: Germany	
	original	*with CRABs*	*original*	*with CRABs*
Section Width	4m		12,5m	
Section Length	80m		150m	
Wearing	Asphalt (HMA – AC12) 40 mm		Asphalt (HMA-SMA8) 40 mm	
Binder	Asphalt (HMA-AC12) 70 mm	CRAB 100 mm	Asphalt (AC16) 80 mm	Asphalt (AC16) 65 mm
Base	-	Recycled materials treated with cement 150 mm	Asphalt (AC32) 220 mm	Asphalt (AC32TS) 120 mm
Sub-Base	**-**	-	-	CRAB 200 mm

- **In-plant recycling case study: Republic of San Marino**

<u>Location</u>: The case study consists of a repaving operation on a two-lane dual carriageway road section part of Via XXV Marzo. According to the available data, the pavement can be divided into subsections, which differ in terms of materials, distresses and type of interventions. The average daily traffic used for the design of the pavement is 4.000 vehicles per day.

Figure 13- Republic of San Marino Site Location

<u>Production and Construction methods:</u>

- In-plant recycled CRAB materials are produced within the asphalt plant facilities of Cooperativa Braccianti and then transferred to the site. Regarding the construction procedure, at first, the reclaimed asphalt was produced by milling the existing pavement and transferred to stockpiling facilities, then the CRAB is produced at the plant, transported and fed into a paver followed by a roller. It's installed over a tack coat made of bitumen emulsions and mineral filler.
- Conventional asphalt mixtures are manufactured at the asphalt plant of Cooperativa Braccianti and then installed by using mineral filler and bitumen emulsion as a tack coat over the binder layer and then a paver and a roller will complete the construction.

The design formula of the materials used in the “in-plant recycling” case study (San Marino) are provided in Table 15.

Table 8 – Republic of San Marino asphalt pavement composition

PAVEMENT MATERIALS – Republic of San Marino case study	
Mix specifications for all mixes used on the project. These should include (at the very least) aggregate type and content, asphalt content and any modifiers used in the mix.	**Asphalt Concrete- modified bitumen (Surface)** - Aggregate 90.5% - Filler 4% - Total binder content: 5.5% - Type of binder: Bitumen - No added fibres, additive or modifiers **CRAB mix (Binder)** - Aggregate 89.5% (84.5% Reclaimed Asphalt) - Filler 4% - Total binder content: 4.5% - Type of binder: Bitumen emulsion - Cement: 2% - This binder substituted the conventional mix, assumed to be the same of surface. **Cement treated material (Base)** - Aggregate 97% - Total binder content: 3% - Type of binder: Cement - No added fibres, additive or modifiers

Transport distances: locations of interest for the different phases from material sourcing to pavement installation are shown in Figure 24.

- Conventional
  - Refinery (bitumen, modified binder and bitumen emulsion): Bologna, Italy - 125 km
  - Fine and Coarse Aggregate Quarry: Forlì, Italy (fine) – 65 km / Castel Viscardo, Italy (coarse) - 235 km
  - Filler Quarry: Serra San Quirico, Ancona, Italy - 150 km
  - Asphalt manufacturing and paving equipment storage: Cooperativa Braccianti Riminesi in San Leo, Rimini, Italy – 15 km
- CRABs
  - Refinery (bitumen emulsion): Bologna, Italy – 125 km
  - Fine Aggregate Quarry: Ravenna, Italy – 65 km
  - Filler Quarry: Gubbio, Italy – 145 km
  - Additives storage: Moselice, Padova, Italy – 210 km
  - Asphalt plant, RA processing and Stockpile (asphalt manufacturing and paving equipment storage): Cooperativa Braccianti Riminesi in San Leo, Rimini, Italy – 15 km

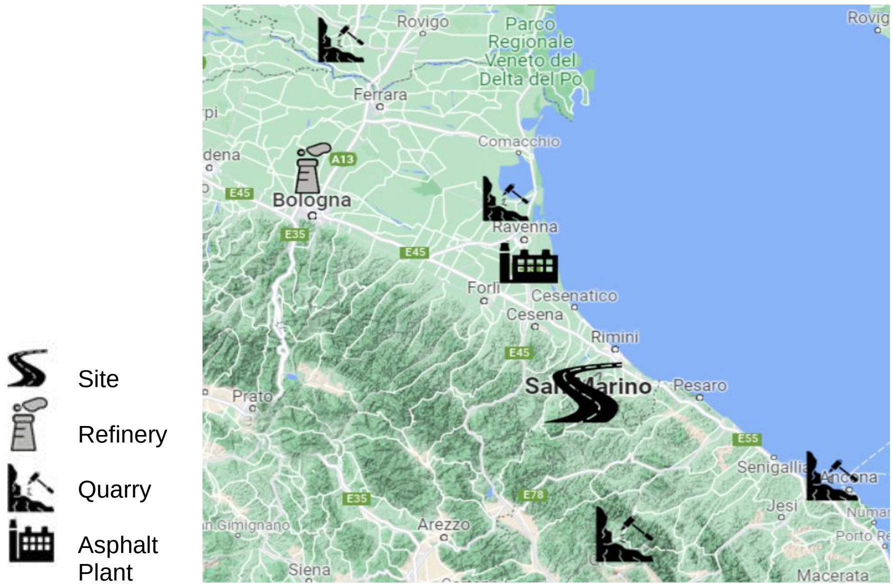


Figure 14 – Republic of San Marino- Locations of interest

<u>Selected subsection and maintenance activity:</u>

A conventional pavement, with hot mix asphalt layers, is partially substituted, according to the scheme in Figure 4. The selected subsection 2 showed a series of interconnecting cracks caused by repeated traffic loading, high-severity level of the fatigue cracking, combined with a localized depression due to the settlement of the foundation. The maintenance of subsection 2 (Figure 4) requires the milling of 29 cm of the old pavement, laying and compaction of 15 cm of cement treated recycled materials, spreading of the prime coat (bituminous emulsion with dosage of 1.00 kg/m2 of residual bitumen and saturation with mineral filler), laying and compaction of 10 cm of cold recycled mixture, spreading of the tack coat (bituminous emulsion with dosage of 0.45 kg/m2 of residual bitumen and saturation with mineral filler) and laying and compaction of 4 cm of asphalt concrete (maintenance work code: P-4c)

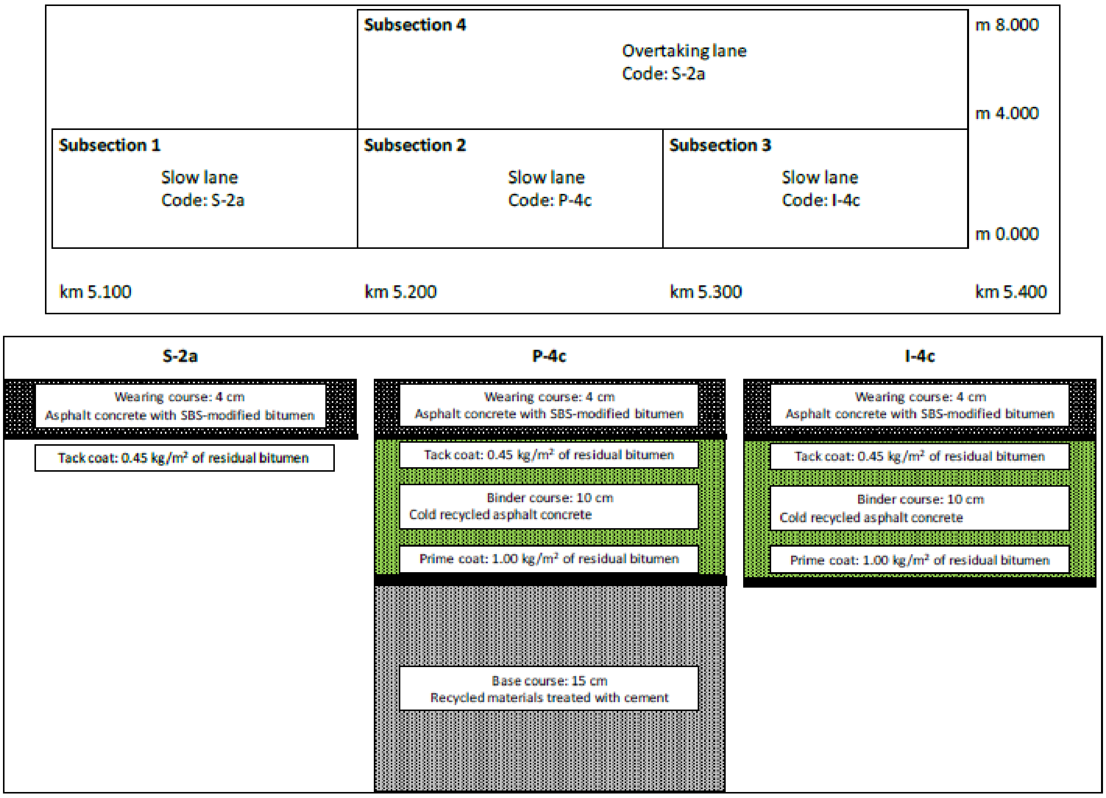


Figure 15- Scheme of the working sections and maintenance methods

- **In-situ recycling case study: Germany**

Location: The case study consists of a repaving operation on section of 150 m x 12.5 m, which is part of E44 in Trier.

Manufacturing and Construction method:

- In-situ recycled CRAB materials are manufactured on-site, hence allowing to minimize the transport for the reclaimed asphalt milled directly from the site. At first the reclaimed asphalt is milled, then there is a levelling with a grader, tack coat is added with a spreader, then a recycler (mix paver, water tank and bitumen tank) manufactures the CRAB with the addition of bitumen emulsion and cement and lays down the crab material which is then compacted with a roller.
- Conventional asphalt mixtures are manufactured at the Asphalt Plant in Trier and then installed by using bitumen emulsion as a tack coat over the binder layer and then a paver and a roller will complete the construction.

The design formula of the materials used in the "in-site recycling" case study (Germany) are provided in Table 16.

Table 9 - Germany asphalt pavement composition

PAVEMENT MATERIALS – Germany case study	
Mix specifications for all mixes used on the project. These should include (at the very least) aggregate type and content, asphalt content and any modifiers used in the mix.	**SMA 8 S (Surface)** - Aggregate: 83% - Filler 10% - Total binder content: 7% - Type of binder: Bitumen - No added fibers, additive or modifiers **AC16BS (binder)** - Aggregate 90.5% - Filler 5% - Total binder content: 4.5% - Type of binder: Bitumen - No added fibers, additive or modifiers **CRAB_G (Cold Asphalt Base)** - Reclaimed Asphalt 93.6% - Total binder content: 4% - Type of binder: Bitumen emulsion - Additive (cement): 4 % This CRAB substituted the conventional **base (AC32TS)** - Aggregate 89.5% - Filler 7% - Total binder content: 3.5% - Type of binder: Bitumen - No added fibers, additive or modifiers

Transport distances: locations of interest for the different phases from material sourcing to pavement installation are shown in Figures 6:

- Refinery (bitumen emulsion): Bonn, Germany – 163 km
- Aggregate Quarry: Neumagen-Dhron, Germany – 94 km
- Filler Quarry: Neumagen-Dhron, Germany – 94 km
- Additives Storage: Allmendingen, Germany – 392 km
- Asphalt plant (asphalt manufacturing and paving equipment storage): Basalt-Actien-Gesellschaft, Trier, Germany – 2.9 km

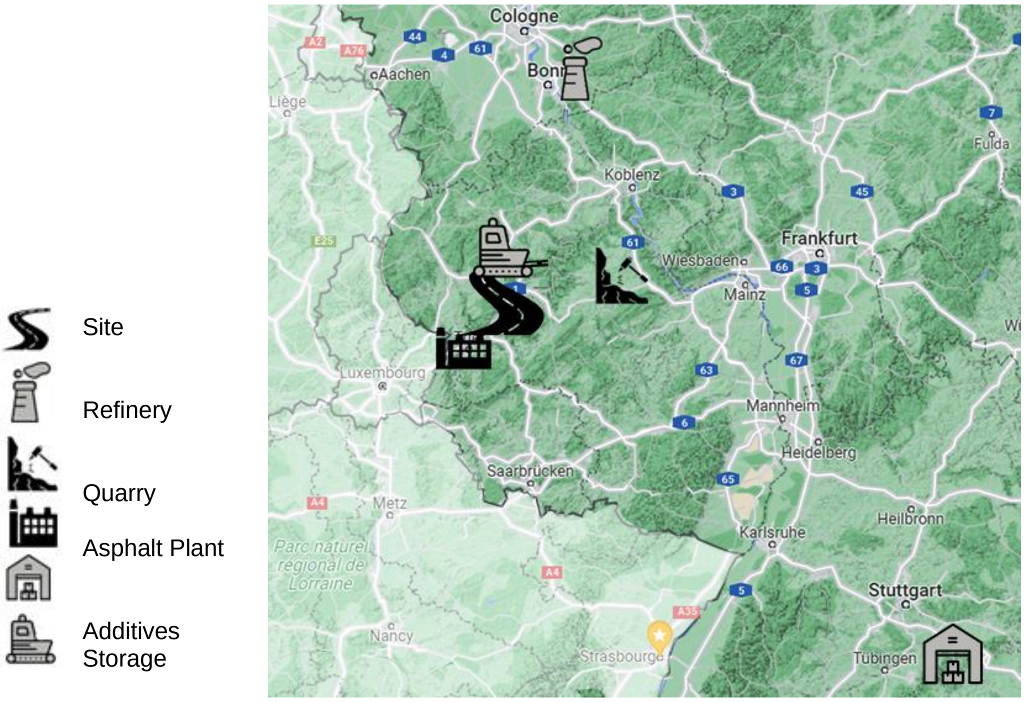


Figure 16 - Germany - Locations of interest

<u>Selected subsection and maintenance activity:</u> For this case study the sub-section III was selected having a total width of 12.50m (currently divided in 4 lanes). According to German design the rehabilitation of this section would have had a pavement structure made of asphalt concrete with 4cm SMA8 over 8cm AC16 and 22cm AC32TS. The same design method suggests using a solution with CRAB material with bitumen emulsion and the following pavement design: 4cm of wearing course (SMA8), 8 cm of binder (AC16 made), 12cm of base (AC32) and finally 20cm of CRAB materials.

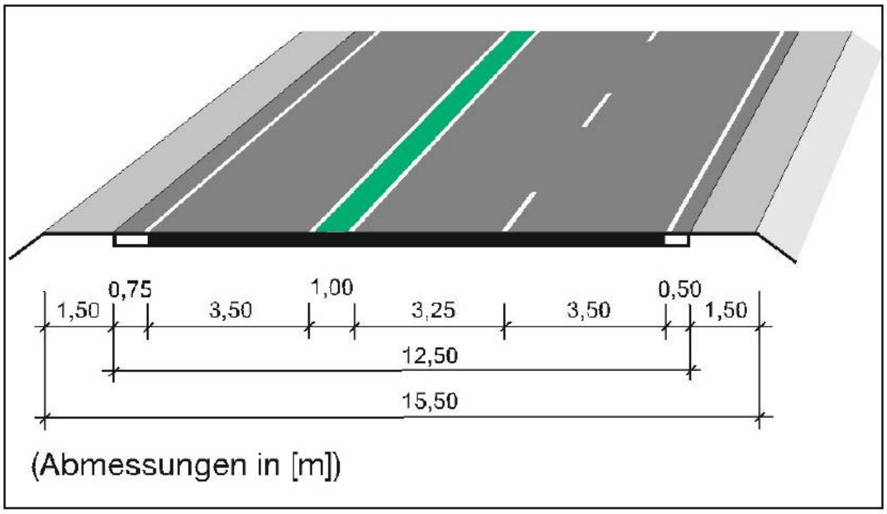


Figure 17 - German subsections

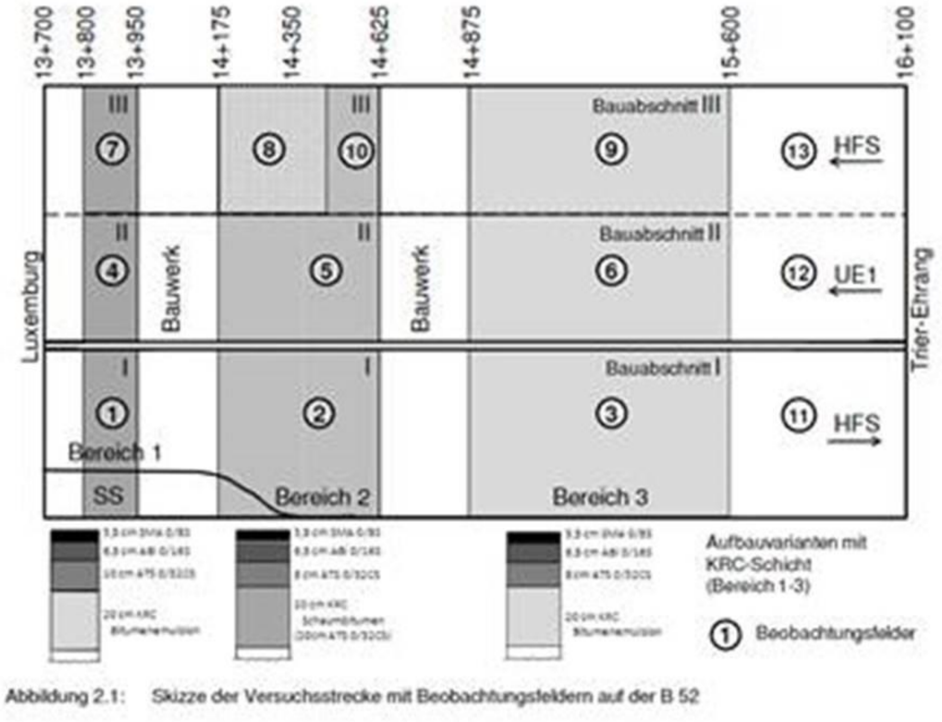


Figure 18 - German Maintenance

The described case studies were analyzed in terms of environmental impacts in a cradle-to-gate approach.

- **Selected maintenance strategies and general assumptions**

The C4O technologies have been used to demonstrate the improvement in terms of environmental emissions, compared with conventional mixtures.

In order to account these benefits, a similar maintenance strategy has been defined for both case studies, consisting of milling and paving surface course, complemented with interventions on binder course and on base course too (this one at the end of 50 years).

This will consider as common assumption that the road pavement foundation and sublayers will not deteriorate and the asphalt will only last for its full estimated lifetime with no under/over performance.

Table 10 – Germany - Maintenance strategy

	Maintenance information
Maintenance Treatment	Surface treatments with periodic inlay of wearing course and occasional inlay of binder and base course. Maintenance is undertaken in one carriageway (two lane), or one lane at a time, with the traffic diverted onto the other carriage/lane.
Materials for maintenance strategies	• Republic of San Marino: Current asphalt mixture used for binder course will be compared with a C4O mix technology (90%RA, 10%sand).

<table>
<tr><td></td><td colspan="4"><u>Germany</u>: Current asphalt mixture used for base will be compared with the C4O mix composed of RA, Cement (4%), Bitumen Emulsion (4%) and water (3.1%).</td></tr>
<tr><td>Analysis period</td><td colspan="4"><u>Republic of San Marino</u>: 20 years
<u>Germany</u>: 50 years</td></tr>
<tr><td>Country dependent maintenance strategy</td><td colspan="3">Republic of San Marino</td><td>Germany:</td></tr>
<tr><td rowspan="5"></td><td>year</td><td>procedure</td><td>year</td><td>procedure</td></tr>
<tr><td>y 7,5</td><td>Crack repair with bitumen emulsion</td><td>y 12,5</td><td>milling surface course / paving surface course / production new HMA</td></tr>
<tr><td>y 10</td><td>milling surface course / paving surface / production new HMA</td><td>y 25</td><td>milling surface+binder course / paving surface+binder course / production new HMA</td></tr>
<tr><td>y 20</td><td>milling surface course + binder course / paving surface course + binder course / production new HMA and CRAB</td><td>y37,5</td><td>milling surface course / paving surface course / production new HMA</td></tr>
<tr><td>-</td><td>-</td><td>Y 50</td><td>full rehabilitation of all bounded layers _ new HMA + CRAB in- situ recycling</td></tr>
<tr><td colspan="2">Typical compaction schedule and equipment
Republic of San Marino (as provided by partners)</td><td colspan="3">Asphalt and CRAB Paving:
Vogele Super 1803-3i paver,4 h paving, fuel consumption (l/h): 11,25
Asphalt Compaction:
Steel-wheeled roller CAT, 4m to 1 h compaction, fuel consumption (l/h): 3,75
CRAB Compaction: Pneumatic-tired HAMM GRW180i 50l/8h
Asphalt reclaiming:
Cold milling machine Wirtgen W200i, fuel consumption (l/h) : 25</td></tr>
<tr><td colspan="2">Germany (as provided by partners)</td><td colspan="3">Recycler: 0,0788 l/m^2
Padfoot Compactor: 0,0077 l/m^2
Vobratory Compactor: 0,0077 l/m^2
Tandem roller: 0,0077 l/m^2
Static roller: 0,007 l/m^2</td></tr>
</table>

3.2.2. Summary of results

This study aimed at understanding if road pavements with CRAB are more environmentally friendly than conventional ones, considering all the life cycle in a cradle-to-grave scenario (A1-C3) and considering both in-situ recycling and in-plant recycling.

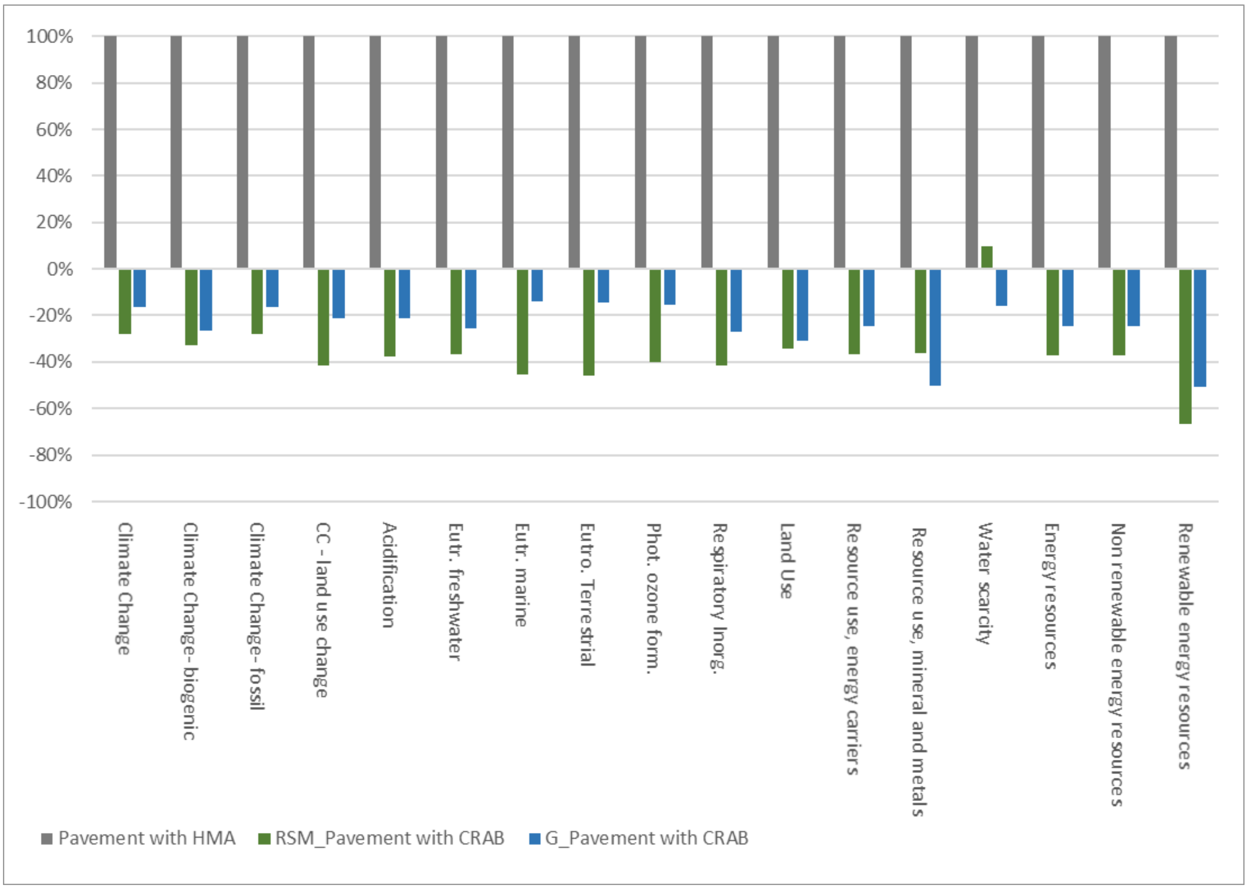


Figure 19 - Comparison between Pavements with HMA and Pavements with CRAB

As a result:

The research shows that regardless of the whole Life Cycle, the environmental performance of **the investigated pavements with CRABs are between 15% and 60% lower than a pavement with HMA depending on the impact category**. Only the impact category “water scarcity” seems to be negatively affected when using CRABs (at least for the case study in Republic of San Marino). This can be explained by the fact that

- CRABs are produced at ambient temperatures, hence, they need less energy than a conventional HMA.
- Furthermore, CRABs contain a much higher amount of RA, a component with 0% of embodied environmental impacts.
- Also, CRABs paving practices requires lower amounts of materials to be transported at the manufacturing/paving site, which in turns corresponds to a significant lower number of trips, hence an overall reduced impact of the transport phase (A2 and A2-B3).

- **The previous findings seem to be valid independently on the case studies**, hence for both in-situ recycling and in-plant recycling.

- The overall **environmental impact of pavement with CRABs remains lower than a base/binder with HMA, regardless of the fact that the use of CRABs implies a variation in the pavement design,** with an increase in the base/binder layers
- The hotspot analysis showed that **the most impactful stages is the Use phase (maintenance over 1 RSL)**. Specifically in all case study (with both HMA and CRABs) and for each life cycle stages, the recorded impact ranged between:
  - Production: 30-45%
  - Installation/Construction: 0-11%
  - Use (Maintenance over 1 RSL): 49-82%
  - End-of-life: 0-4%%
- From a tailored sensitivity analyses it was found that **also for road pavement with CRABs the increase of transport distances produces an almost linear increase of the environmental impacts**.

3.3. LCA of innovative paving activities with "FIBRA" technologies

In the present section, it is presented a summary of the main results and conclusions of the LCA that compares two asphalt pavement sections implemented in the Netherlands as part of the scaling up and long-term monitoring activities proposed by the FIBRA project. As already mentioned, this LCA is carried out following the PavementLCM Framework and Guidelines. The complete report can be found in the annex.

3.3.1. Case study

As already mentioned, as part of the FIBRA project, a pilot section including 2 different surface layers were built for their long-term performance evaluation. These road sections are located in the A73 motorway (the Netherlands) with an AADT of 50000 vehicles. Both road sections include three asphalt layers: a 2L-PA8, an AC16 binder and an AC22 base, and only differs in the asphalt mixture placed in the surface layer:

- **Alternative 1 (PMB):** a conventional 2L-PA8 mixture with PMB (styrelf 65/105-80 A AP) produced at a temperature of 185ºC.
- **Alternative 2 (FIBRA):** a Fibre-reinforced 2L-PA with penetration grade bitumen (70/100) and 0.15% of polyacrylonitrile fibres. This mixture was produced at 165ºC.

<u>Production and construction methods:</u>

In the Netherland, a 2L-PA8 is a mixture with a maximum grain size of 8mm that is widely used on the primary road network. This mixture is designed with 25mm thickness and design air voids of 23%. Compared with a traditional single layer, this mixture has a smaller grain size and slightly higher air voids. Commonly an SBS PMB is used in this PA8.

The composition, density and thickness of the different asphalt layers in alternative 1 and alternative 2 are shown in Table 11 and

Table 12.

Table 11. Asphalt layers' composition in Alternative 1

	2L ZOAB 8 Top layer PA8-PMB	2L ZOAB 8 Bottom layer PA16	AC 16 bin/base 30/45 60% RAP	AC 22 bin/base 30/45 60% RAP
PEN bitumen (%)	0	5.2	1.51	1.48
PMB bitumen (%)	5.3	0	0	0
Aggregate (%)	89.1	90.3	38.01	37.92
Filler (%)	5.6	4.2	0.29	0.29
Cellulose Fibre (%)	0	0.3	0	0
RAP (%)	0	0	60.19	60.31
Density (ton/m^3)	1.90	1.90	2.482	2.497
Thickness (m)	0.025	0.045	0.06	0.16

Table 12. Asphalt layers' composition in Alternative 2

	2L ZOAB 8 Top layer PA8-FIBRA	2L ZOAB 8 Bottom layer PA16	AC 16 bin/base 30/45 60% RAP	AC 22 bin/base 30/45 60% RAP
PEN bitumen (%)	5.3	5.2	1.51	1.48
Aggregate (%)	88.9	90.3	38.01	37.92
Filler (%)	5.6	4.2	0.29	0.29
Cellulose Fibre (%)	0.15	0.3	0	0
PAN fibre (%)	0.15	0	0	0
RAP (%)	0	0	60.19	60.31
Density (ton/m^3)	1.90	1.90	2.482	2.497
Thickness (m)	0.025	0.045	0.06	0.16

On the other hand, during the production of the asphalt mixtures and the construction of the road sections, the following observations from the builders were considered in the LCA:

- The two mixes were designed with same aggregate type (Bestone), gradation and bitumen content (5.3%). The only difference between them is the type of bitumen and fibres if any.
- Regarding the fibre-reinforced mixture, a Polyacrylonitrile fibres with a length of 3.2mm was used at an application rate of 0.15% (w/wmixture). In addition, 0.15% cellulose fibre is added to the mixture to prevent binder drainage.
- The two mixtures for the A73 test sections were produced in the BAM asphalt plant BAC in Helmond. During the production of the mixtures, it was observed that the production temperature of the mixture with PMB is approximately 20ºC higher than that of the fibre-reinforced mixture.
- The two types of 2L-PA8 mixtures were constructed with a thickness of 25mm on top of a 45mm of standard 2L-PA16. The installation temperature of the FRAM was 10-20ºC lower than that of the control mixture with PMB.
- The compaction of the two sections was done using the same equipment and following the same standard procedures. No differences between compaction behaviour were observed.
- All mixtures were homogeneous without cluster.

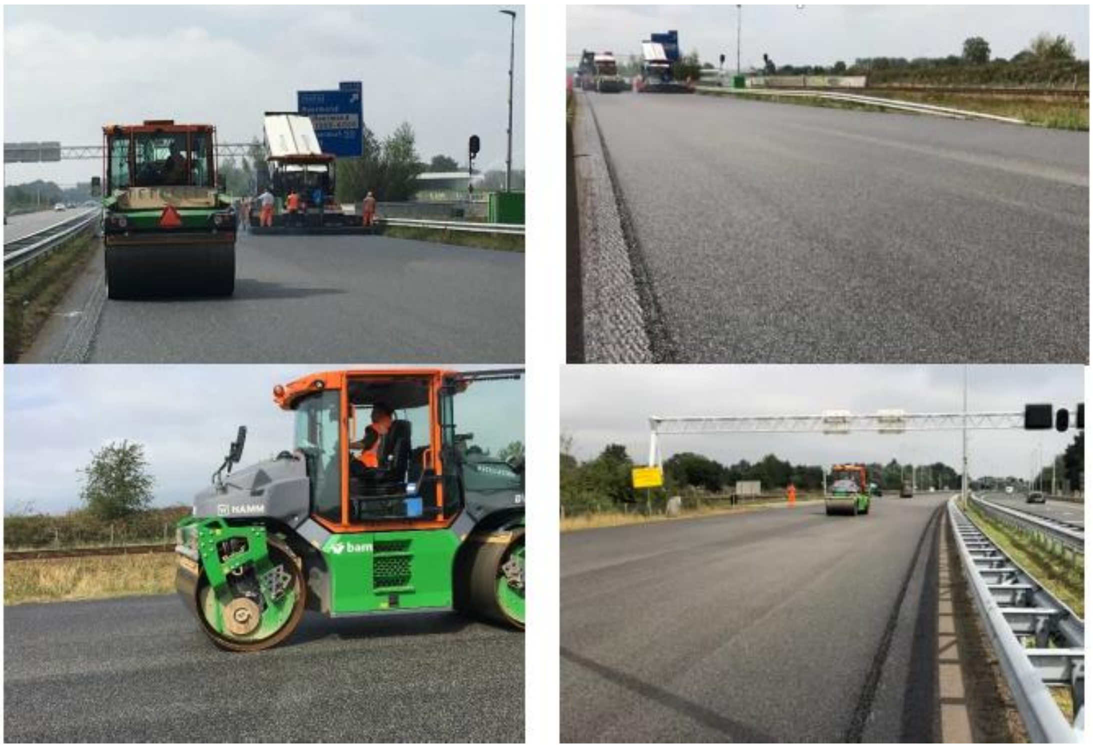


Figure 20. Laying and compaction process of FIBRA mixtures

<u>Transportation distances</u>

The transportation distances used in this LCA are shown in

Table 13. Transportation distances

Material	Distance (km)
Pen bitumen (from supplier to asphalt plant)	115
PMB bitumen (from supplier to asphalt plant)	530
Aggregates (from supplier to asphalt plant)	150
Filler (from supplier to asphalt plant)	150
Cellulose (from supplier to asphalt plant)	100
PAN fibre (from supplier to asphalt plant)	150
HMA (asphalt plant to A73 worksite)	40
RAP (A73 worksite to recovery centre)	40

Maintenance strategy

An analysis period of 26 years has been chosen. The specifications for the design of Asphalt pavements issued by Rijkswaterstaat in 2016[1] indicates an expected service life for a 2LPA with PMB of 9 years on the right slow lane and 13 years on the left lane. Given these figures, the standard maintenance protocol that is proposed in this analysis is to mill and overlay (M&O) the top PA8 layer in the right lane after 9 years and M&O the complete 2LPA system of both the left and right lanes in year 13. Afterwards, at year 22, the top layer of the left lane is M&O again and in year 26 the complete asphalt system (surface, binder and base course) is removed (Figure 38).

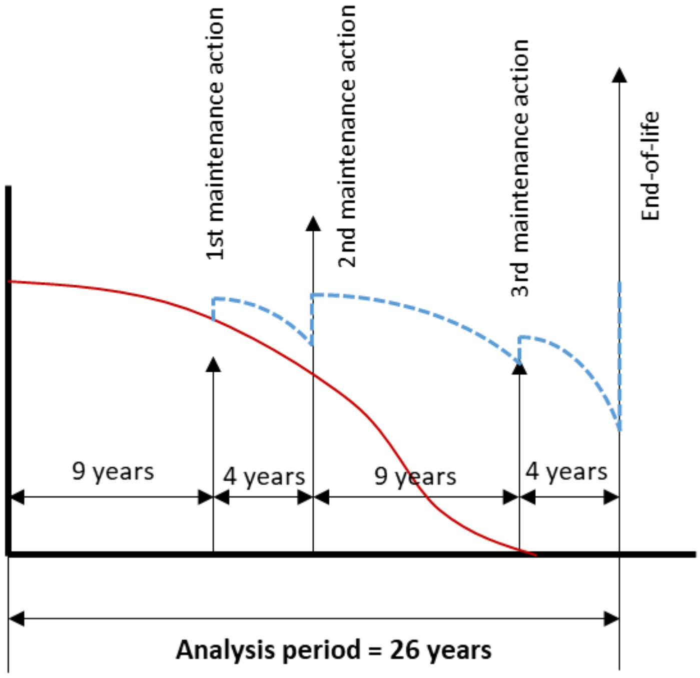


Figure 21. Schedule for maintenance works

3.3.2. Summary of results

In this study, following the guideline proposed by PavementLCM SA framework, the environmental impact of using fibres to reinforce asphalt mixtures has been evaluated and compared to the impact of using polymer modified bitumen. To do so, a cradle-to-grave life cycle assessment has been carried out. According to the PavementLCM guidelines, after the life cycle assessment and to further evaluate the overall robustness of the LCA, the interpretation phase has included a hotspot, a sensitivity and an uncertainty analysis.

In Figure 32 the comparative life cycle impact assessment of alternative 1 (PMB) and alternative 2 (FIBRA) is shown. Based on the results, **very small differences in the environmental impact of the two alternatives have been found**, with only one significant difference in the "water use" category impact, apparently due to the higher water consumption during the PMB production compared to the penetration grade bitumen.

[1] Specificaties ontwerp Asfatverhardingen Dienst Grote Projecten en onderhoud, Juli 2016

From the hot spot analysis, it can be said that the most impactful stage in the life cycle of the road systems here considered is the production phase (A1-A3). Concerning the most contributing processes, bitumen production, materials transportation and hot mix asphalt production are those with the highest contribution for both alternatives.

Finally, the Monte-Carlo simulation carried out as part of the uncertainty analysis, confirmed the main conclusion of the study consisting in that both alternatives present very similar environmental impact if the same durability is considered for both mixtures.

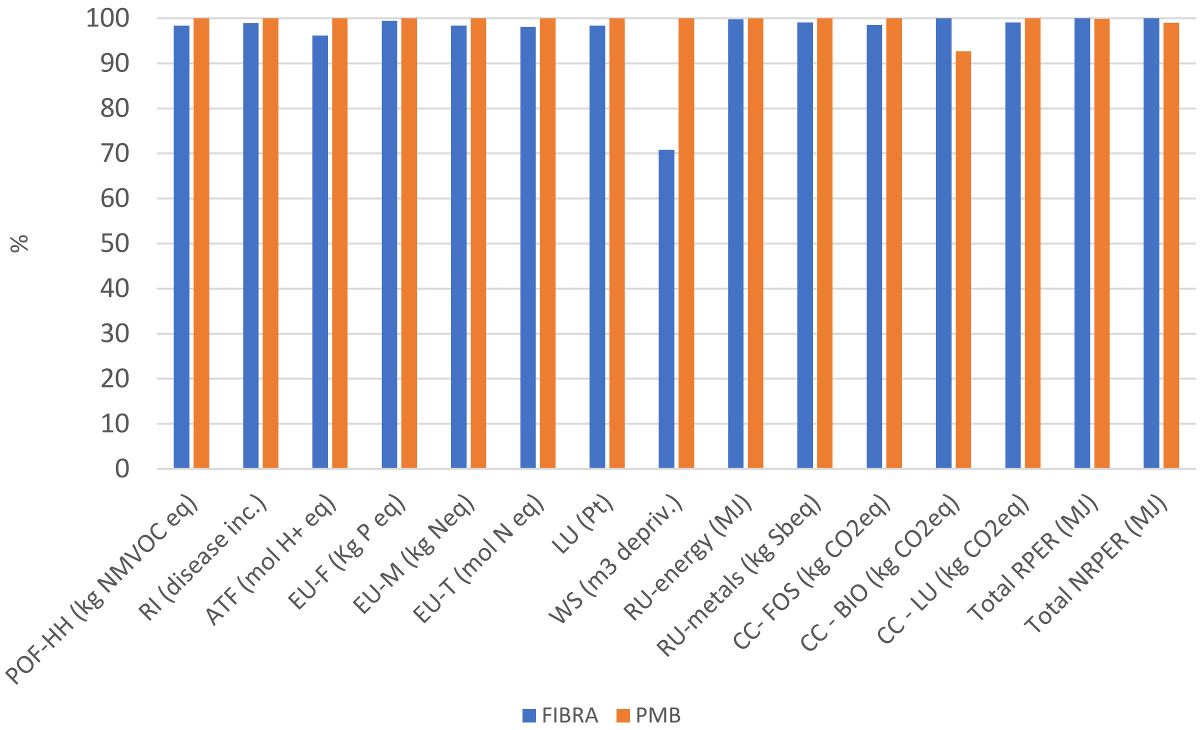


Figure 22. Comparative life cycle impact assessment of Alternative 1 and 2

3.4. Conclusions and recommendations from the harmonised LCA

Innovative paving activities with "CRABforOERE" technologies

- The research shows that, regardless of the cold recycled paving technology (in-situ recycling vs in-plant recycling), the environmental impact of 1 m^2 of road pavement with CRABs, expressed with 16 different indicators, is on average **between 15% and 60% lower** of a conventional road pavement with hot mix asphalt.
- ***This is true for both innovative paving practices*** despite the fact that pavement with CRAB requires an increase of thickness
- The hotspot analysis showed that ***the most impactful stages is the use phase*** (maintenance over 1 RSL). Specifically, for all case studies (with both HMA and CRABs) and for each life cycle stage, the recorded impact ranged between:
  - Production: 30-45%
  - Installation/Construction: 0-11%
  - Use (Maintenance over 1 RSL): 49-82%
  - End-of-life: 0-4%%
- In general, ***increasing the durability of pavement components is certainly the most important step to improve the environmental impact of road pavements.*** This is regardless of paving practices and mainly due to the repeated supply of materials for the planned maintenance strategies.
- ***The obtained results are for road pavement designed with CRABs as technology for the binder/base layers while keeping hot mix asphalt for surface and binder courses.*** Hence, the overall impact of the innovative road paving activities, over the analysis period (1 RSL), are still influenced by the significant amount of hot mix asphalt still used within the maintenance strategy with cold recycling for binder/base layers.

Innovative paving activities with "FIBRA" technologies

- Based on the results obtained, and assuming the same durability for both alternatives, the use of polymer modified bitumen or the use of fibre-reinforcement to improve the durability of asphalt mixtures in the wearing course result in a very similar environmental impact. The uncertainty analysis confirms the results.
- In both case studies, bitumen production, materials transportation and the hot mix asphalt production are the processes with the highest contribution.

These results can be used by NRAs for further sustainability assessment exercises and/or in databases providing the life cycle environmental impact of road pavement materials and activities. The authors hope this report can contribute to raise the importance for asphalt contractors to assess sustainability performance of their products at the design stage and to assist road authorities/decision makers moving towards prescribing eco-design as a mandatory practice within the industry.

4. Final Conference "Research Programme Call 2017 New Materials"

On 5th October 2021, the final conference of the "New materials and techniques" programme was held. About 46 participants attended this online conference organised by FFG that addressed the achievements and findings of the PavementLCM, CRAB for OERE and FIBRA project. The attendees were representatives of National Road Authorities (30), including 10 members of the CEDR PEB, invited industry and research representatives (4) and members of the three projects consortia (12) and attended from Austria, Belgium, Denmark, Estonia, Finland, France, Germany, Hungary, Italy, Netherlands, Norway, Spain, Sweden, Switzerland and United Kingdom.

4.1. Conference outline

The conference was opened by Dr. Dietrich Leihs, programme manager at FFG and the welcome speech was carried out by Steve Phillips, Secretary-General CEDR. Following, after an introduction to the CEDR Transnational Research Programme Call 2017 given by Mr. Oliver Ripke (BASt), an overview of the three projects was provided by each project coordinator. Thus, Prof. Davide Lo Presti, Dr. Konrad Mollenhauer and Prof. Daniel Castro, coordinators of PavementLCM, CRAB for OERE and FIBRA projects respectively, presented the results and achievements on behalf of their project partners.

After the presentations introducing the projects, three individual breakout sessions, one per project, were created to promote the discussion on the presented outcomes and on their future implementation by the National Road Authorities focusing on next steps and main issues.

Next, the conference gave the opportunity for a group discussion in the plenary, where the project coordinators summarized main findings from the breakout sessions.

Finally, concluding remarks were made by Mr. Peter Schmitz, German's CEDR's Executive Board member, who highlights the life cycle approach of the three projects as the right way to address road research today and also the potential of the projects from CEDR 2017 Call to contribute to reach CO_2 targets in the road sector.

4.2. Breakout sessions

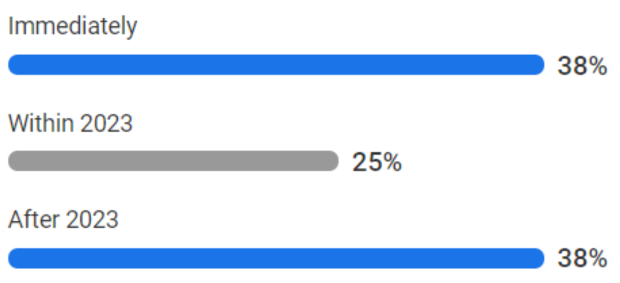
As mentioned before, three breakout sessions were organized during the final conference. Thus, after the project presentations, the participants were asked to choose, depending on their interest, among three virtual rooms moderated by each project coordinator. The breakout sessions aimed to further discuss about the projects outcomes and their potential implementation options and issues. In the plenary session, moderated by Dr. Dietrich Leihs, each project coordinator summarized the main finding and outcomes coming from these breakout sessions.

4.2.1. Breakout session 1: PavementLCM

The breakout session 1 was attended by 18 representatives from National Road Authorities (BASt, BMVI, Asfinag, Danish Road Directorate, SPW, AWV, Estonian Transport Agency, Finnish Transport Infrastructure Agency, Hungarian National Road Inc., TNO, Swedish Transport Administration). The discussion about PAVEMENTLCM started with a more detailed presentation of the Framework and the Package produced by the project. The discussion then developed around the following questions, answers and conclusions

1) **When do you think the PLCM framework could be implemented? Immediately, within 2023 or after 2023?**

Mixed answers point at the difference between ambitions (immediately please!) and practical drawbacks. Explanation of one person why after 2023: for next couple of years carbon is the most important, most likely other sustainability aspects will have to wait a few years.

	Conclusions: *Mixed answers point at the difference between ambitions (immediately please!) and practical drawbacks. Explanation of one person why after 2023: for next couple of years carbon is the most important, most likely other sustainability aspects will have to wait a few years.*

2) **Are you aware of alternative approaches to EPDs?**

Not really. Someone mentioned CWA17089, but not sure if it is used anywhere. Sweden uses a different tool (IKA), which is LCA based but just a slightly different framework and accounts only for CO2. This is a good to hear, because we did not find any other ways of sustainability communicating either so this confirms that the developed framework is the right way to go. Adoption of CWA has been considered but is outdated; only some parts of this approach have been adopted in the PLCM framework.

• I have hear but do not remember the alternative approach... • Sweden use an alternative way while implementing EPD:s. • Only the CWA method (?), that is different in scope, covering noise, rolling resistance etc. • No • no • No	Conclusions: *Most of the audience is aware of this and some of them start to take action towards including them, e.g. by accounting for future service life, maintenance and risks; or by calculation impact per m2 and per average year (divide total impact by expected life time*

3) **Are you aware of the importance of durability in Sustainability Assessment?**

Most of the audience is aware of this and some of them start to take action towards including them, e.g. by accounting for future service life, maintenance and risks; or by calculation impact per m2 and per average year (divide total impact by expected life time)

• Very much. Account for future service life, maintenance needs and risks. • Interesting question, as usually mostly the talk is about using recycled materials and forgetting that building durable construction gives more results • Yes, probably the most important and the most difficult to assess/include • yes and we tend to go more to kg CO2/m2/year	• Indeed • Very much. • Yes! • Yes! Conclusions: *Most of the audience is aware of this and some of them start to take action towards including them, e.g. by accounting for future service life, maintenance and risks; or by calculation impact per m2 and per average year (divide total impact by expected life time)*

4) **What are your ambitions in terms of implementing Sustainability Assessment (SA) in the short term (2023) and in the long term (2030)?**

Mixed answers: most people do hope to have implemented it throughout the whole organization on the long term, but on the short term they first need to have more discussion about it, to let it grow within the organization. Some countries are already a bit further, have LCA and LCC already implemented; their next goal is to have economic, social and environmental impacts aligned in a multicriteria approach.

• Sweden short term: For design and procuremnt. EPD for envoronmental SA. LCC type design. Long term: align environmental, social and economic SA. Better tailored decision making elements in process run by the NRA. • yes, we allready implemented and also will monitor the achieved reduction • Short term, to initiate with ambition. Long term, to have it as a key part of all activities, phases, etc. • I want to see it to be applied for long term but as early as possible • As mentioned before, it is likely to be carbon first by 2023 and then supplemented with further indicators later • personally I think it should be done, but at first our NRA should grow in understanding. We have started discussions about it at least	Conclusions: *Mixed answers: most people do hope to have implemented it throughout the whole organization on the long term, but on the short term they first need to have more discussion about it, to let it grow within the organization. Some countries are already a bit further, have LCA and LCC already implemented; their next goal is to have economic, social and environmental impacts aligned in a multicriteria approach*

5) **Is the content of the package comprehensive and exhaustive? Please explain why.**
Multiple suggestions about durability and reference service life.

• The use of a "harmonized" dtabase is important • I have not looked over the package, it is very good for a start, - the legal part might be good to be added. Maybe also the differences in local conditions concerning available resources and climate • Great job. The next step I would suggest to better synthesize the service life considerations in the durability part with EPD approach. • Yes, it is comprehensive but we still need to tackle the RSL question and durability in more detail	Conclusions: *Most of the audience is aware of this and some of them start to take action towards including them, e.g. by accounting for future service life, maintenance and risks; or by calculation impact per m2 and per average year (divide total impact by expected life time)*

6) **Should we harmonise approaches over CEDR members? Please explain why**

Since we are a common market, it would be great to have some alignment. But on details, every nation should be able to follow their own approach

• Yes, of course the details and climate and other things are different - we are in common market (wider than EU), as products market is allready harmonised and EPD and other standards also • It's a good idea but a huge challenge. Working together to tackle the issues is important however. • Common market aspects yes. For NRA decision making, not necessary. We have so many decisions in our process that we need to support. • yes with some flexibility	Conclusions: *Since we are a common market, it would be great to have some alignment. But on details, every nation should be able to follow their own approach.*

4.2.2. Breakout session 2: CRABforOERE

The breakout session 2 was attended by eight representatives from National Road Authorities (BASt, BMVI, Asfinag, Danish Road Directorate). The discussion about CRABforOERE scope, methodology and results were started by raising a question during the overall conference from a representative of German Ferderal Ministry for Transport, Dr. Schmitz, for what reason conventional asphalt base layers should be applied if there are CRAB available. The position of project partners was, that indeed – after a time required for the industry to adopt the required techniques – CRAB can be applied in future.

The discussion was initiated by the question, why the application of CRAB pavements is far behind HMA applications in many European countries. Following topics were discussed in detail:

- Lack of experience:
    - Both, road administration and companies are not familiar with this type of materials which results in low motivation for their application. Pettinari (DRD) reports of his experience when comparing Italian and Danish situation, that universities play a vital role in research, develop and implement new technologies. He invites European university representatives to actively contact road administrations and road industry to apply new ideas in road construction.
- Concern for low durability of CRM:
    - Kalantari comments discussion about the presumably reduced durability of CRM compared to HMA based on the reduced strength and stiffness properties. However, by properly designing the pavement for CRM, durable structures can be obtained.
    - Especially for mechanical-empirical pavement design, adopted transfer functions are required.
- Concern about materials homogeneity:
- Kalantari raises concern about the homogeneity of CRM, when produced in mobile plants or in-situ based on experience from some test roads, where single lorry batches could be identified by FWD measurements and performance of core samples.
- Experience from Italy shows, that in case of central plant production, the same material homogeneity will be reached as experienced for HMA. Only the added binders will change,

but dosing procedures are the same as well as the paving machinery. The same level of quality control shall be applied.

- Concern of downgrading the reclaimed asphalt:
  - Schmitz (BMVI) raises concern, that even in hot recycling, a high proportion of RA used in base layers are originally recovered from higher quality surface and binder layers. This downcycling will also concern the use of these RAs in CRM.
  - The starting point of the project was to identify a possible use of RA which could not be applied in high-quality hot recycling (e. g. because of severe ageing) but was stockpiled for a specific time duration. In CRM, the RA takes the role of a high-quality pre-coated aggregate.
- High costs:
  - So far, especially bitumen emulsion is a cost factor for reduced application in some countries (e. g. Germany), whereas in others the prices are similar to these of pure bitumen (e. g. Italy). Obviously, the market volume seems to affect the prices.
  - Ripke (BASt) added that the actual construction costs will change considerably after introduction of environmental cost transfer (e. g. CO2-pricing).
- High technology level:
  - Ripke mentioned, that the procedures for bitumen emulsion selection seems to make the quality control for CRAB more complicated compared to HMA. Gaudefroy confirms, that the need for formulating the bitumen emulsion to the individual aggregate and RA properties makes the applications difficult for small and medium-sized construction companies. Mollenhauer remarks, that by adding cement already at low proportions, the need to individually optimise the bitumen emulsion to the actual mix granulate is reduced, as the cement predominates the emulsion breaking process. This could be confirmed by the very similar results obtained for CRAB mixtures where Emulsions produced in Italy and Germany were applied.
- Lack of experimental methods and/or interpretation experience
  - Kalantari (BASt) raises the need to identify and define suitable laboratory test methods and loading parameters in order to be able to compare the results obtained in various countries. This is important as the mechanical properties of CRM are different compared to HMA. Gaudefroy also mentioned the need of adopting test procedures, which were designed for HMA testing, e.g. by applying reduced loads and even introduce additional test procedures. He results of the mxi design study show, that the national specification procedure result in different quality levels of the materials. Especially for promoting the application in less-experienced countries, a harmonised approach for mix design would help the introduction of the procedures.
- Low confidence in material performance in cold and moist climate and/or high traffic loading
  - Pettinari raises concern about the applicability of CRAB in northern moist and cool climate conditions, where the materials curing is slower compared to the results experienced in Italian demonstration section. However, several CRAB structures from Sweden, UK, Germany and also France show that CRM also works in moist regions – even without addition of cement.

- Despite most experience with cold recycled materials was gained for low and medium trafficked pavements, even highly-trafficked motorway structures were assessed within the project and no indications for short service life could be identified.

After discussing these possible constraints, some future research aspects were proposed:

Kalantari asks about experience about experience with different test procedures for assessment of stiffness and fatigue as there is concern about the application of indirect tensile test procedure. Reason is the difficulty to define stress levels for testing. In Italy, good experience was made by conducting cyclic direct tension-compression tests for obtaining real complex modulus data and of cyclic uniaxial compression tests as a faster test procedure applicable for control testing. In France experiences were obtained by 2-point-bending tests which is only applicable for fully-cured specimens. In fresher state, triaxial tests are applicable and – as a more simple procedure – oedometric cyclic tests at fully-supported specimens were successfully applied.

Further the question was raised, if CRM can be applied in binder layers in order to transfer cracking from a deteriorated base layer to surfacing. Actually, in San Marino, CRM with slightly adopted properties (e. g, latex-modified emulsion) was applied in the demonstration sections.

4.2.3. Breakout session 3: FIBRA

In breakout session 3, representatives from four National Road Authorities (Norwegian Public Roads Administration, the Dutch Ministry of Infrastructure and Water Management, Flemish Road Agency and Swiss Federal Road Office) attended the group discussing together with FIBRA partners (from BAM infra, SINTEF, TUB and University of Cantabria). To open the discussing, Mr. Daniel Castro, presented a summary of main outcomes from the FIBRA project and the potential application of fibre-reinforced asphalt mixtures by National Road Authorities.

In the presentation, the fibre-reinforced asphalt mixture are compared with the most conventional alternatives in terms of their mechanical performance and their economic and environmental impact. For the dense asphalt concrete type of mixture (AC), fibre reinforcement improves the rutting resistance and the abrasion by studded tires comparing to conventional AC mixtures with penetration grade bitumen while the differences in the environmental and economic impact remain low. However, comparing to AC mixtures with polymer modified bitumen, the fibre-reinforced asphalt mixtures do not achieve their fatigue and low temperature thermal cracking resistance. As for the open porous asphalt mixtures (PA), the particle loss in the fibre reinforced mixtures is greatly enhanced compared to the PA mixtures with penetration grade bitumen. On the other hand, the fibre reinforcement neither reach the performance of the mixture with polymer modified bitumen, especially in terms of the resistance to thermal cracking.

It was also highlighted that the impact of fibre-reinforcement on the asphalt mixtures in terms of service life increase is still unknown. Although the improvement in the most typical mechanical properties is well documented in the project, how this improvement will affect the service life of the road surface is difficult to correlate. However, it is expected that the long-term monitoring of the demonstrators placed at Norway and the Netherlands will shed light on this.

After the summary of the main findings, several questions were put on the table:

- Which other issues about fibre-reinforcement need to be further answered?
- Based on the results, is the technology interesting for NRAs?
- Which are the possible obstacles for further implementation (i.e. technical specifications or requirements)?

Main comments concerning the findings of the project and their future implementation were the following:

- The Flemish Road Agency representative showed surprise that fatigue resistance of the AC was not improved. The agency usually receives suggestions from companies fostering the use of fibres with the aim of reducing layer thickness thanks to the fatigue resistance improvement. In the FIBRA project, at the laboratory level, the fatigue resistance of the AC mixture with penetration grade bitumen was not significantly improved when fibres were added. These results were obtained both using EU and USA standards. It should be noted that the aging impact on the mechanical performance is not addressed. More information will be obtained from the long-term monitoring of the two pilot-sections implemented in Norway and the Netherlands.
- The representative from BAM infra remarked that in the case of PA mixtures, in previous experiences in the Netherlands, in which BAM and RWS were involved, a pilot section built also incorporating fibres currently outperforms the control PA mixture with PMB. On the other hand, using fibre reinforcement with penetration grade bitumen makes possible to go for low temperature applications, opening the door for more sustainable applications for asphalts.
- The representative form the Norwegian public roads administration indicated that in Norway very strict requirements exist, especially in highways, due to their weather conditions, the maintenance and operation and the common use of studded tires during the winter season. In this moment, several SMA and AC recipes using PMB are working well. However, in the last years they are now forced to look on long-term perspective when choosing different solutions (i.e. EPD), being therefore the recyclability potential of the mixtures an important point.
- For the further implementation in Norway, the representative from the Norwegian public roads administration indicates the need to discuss with their contractors, in a more local regional level, issues such as if the selected fibres are the best for their mixtures or if there is enough availability in the market for the Norwegian industry. FIBRA partners confirmed that the priority in the selection of the fibres was the availability at EU level and that in addition to the possibility of testing other local fibres also different dosages and lengths can be further explored.
- Regarding Norwegian design guides, there are not problems for the implementation because their specifications are opened to innovative materials as long as a good technical performance in terms of durability is confirmed and the mixtures do not cause harm to the environment in the short and long-term. In coming years, the long-term monitoring of the pilot sections implemented in Norway will provide interesting information about the durability of the technology compared to the control sections.
- Concerning the Netherlands situation, sustainable purchasing is embedded in the project so the long-term mixture environmental performance (considering the pavement life cycle) should be ensured beforehand.

5. Conclusions

The main objective of the “New materials & techniques” programme, to ease and foster the implementation of existing research results related to the efficient use of resources as well as to the efficient use of alternative solutions to optimize pavement durability could be reached by the three funded projects.

Within Pavement LCM, tools, guidelines, datasets, roadmaps and recommendations were provided, which will allow road agencies to implement life cycle management practices on basis of the most recent international standards. These procedures were demonstrated on two groups of innovative materials aiming at improving the life-cycle impact by increasing energy and resource efficiency and by increasing the durability pf the pavement infrastructure. Pavement LCM further designed a platform, which will allow the interactive transfer of knowledge on best practices on sustainability assessment and Life Cycle Management to generate reliable durability data for green asphalt.

For implementation of cold recycled asphalt base layers (CRAB) in flexible pavements, CRABforOERE project proposed procedures for mixture and pavement design based on the diverting international experience. The assessment of 17 existing structures with CRAB layers allowed the verification of the proposed design systems as well showed, that these structures will result in comparable maintenance demands to conventional pavements with hot mixed asphalt layers. The conducted LCA showed, that the environmental impact of pavements can be substantially reduced by the application of CRAB.

In FIBRA project the functioning, usability, benefits, sustainability and cost-efficiency of fibre-reinforced asphalt could be proven both for dense and open graded mixtures. The mechanical properties will be improved for conventional asphalt mixtures (with penetration grade bitumen) but, in general, not reach the performance level of the asphalt mixtures with PMB. Thus, FRAC mixes present an excellent rutting resistance, and FRPA mixes show a better resistance to ravelling and water sensitivity compared to AC and PA mixes with penetration grade bitumen, indicating a possible positive effect on the long-term performance of the road surface. These mixtures can be applied to the road surface of any traffic category road and comply with the technical requirement of the most demanding traffic categories.

The results of the three projects were intensively discussed within a workshop, where open questions from practitioners from European Road Authorities could be solved.

ANNEX A

LIFE CYCLE ASSESSMENT OF INNOVATIVE PAVING TECHNIQUES

1. Life Cycle Assessment of innovative paving activities with "CRABforOERE" technologies

This LCA was performed to understand the environmental benefits of pavements with CRAB, a technology which uses a high quantity of Reclaimed Asphalt (RA) and is produced at ambient temperature, when compared with a pavement realized with a conventional Hot Mix Asphalt (HMA). Two case studies were analysed, representative of two different production techniques: in-situ recycling and in-plant recycling.

Here below the case studies are detailed and the LCA explained step by step.

1.1 Case Studies

The presented case studies have been selected as representative of two different manufacturing processes of CRAB materials as well as for the subsequent installation and maintenance strategy of road pavement components. The two case studies are real projects recently carried out at the Republic of San Marino and in Germany. Hence, they differ in terms of geographical location, pavement structure, traffic level and above all, construction methods: in-plant recycling for San Marino and in-situ recycling for Germany.

The table below summarizes the main information directly collected from contractors and/or project partners. As it can be seen in both cases the project consists of a major maintenance activity that includes the use of a cold mix asphalt (CRAB), in place of conventional hot asphalt mixtures, for binder layers (San Marino) or for base layers. (Germany).

Table 14 - Main information of Case Studies

Pavement course	In-Plant recycling: Republic of San Marino		In-Situ recycling: Germany	
	original	*with CRABs*	*original*	*with CRABs*
Section Width	4m		12,5m	
Section Length	80m		150m	
Wearing	Asphalt (HMA – AC12) 40 mm		Asphalt (HMA-SMA8) 40 mm	
Binder	Asphalt (HMA-AC12) 70 mm	CRAB 100 mm	Asphalt (AC16) 80 mm	Asphalt (AC16) 65 mm
Base	-	Recycled materials treated with cement 150 mm	Asphalt (AC32) 220 mm	Asphalt (AC32TS) 120 mm
Sub-Base	-	-	-	CRAB 200 mm

- **In-plant recycling case study: Republic of San Marino**

<u>Location</u>: The case study consists of a repaving operation on a two-lane dual carriageway road section part of Via XXV Marzo. According to the available data, the pavement can be divided into subsections, which differ in terms of materials, distresses and type of interventions. The average daily traffic used for the design of the pavement is 4.000 vehicles per day.

Figure 23- Republic of San Marino Site Location

<u>Production and Construction methods:</u>

- In-plant recycled CRAB materials are produced within the asphalt plant facilities of Cooperativa Braccianti and then transferred to the site. Regarding the construction procedure, at first, the reclaimed asphalt was produced by milling the existing pavement and transferred to stockpiling facilities, then the CRAB is produced at the plant, transported and fed into a paver followed by a roller. It's installed over a tack coat made of bitumen emulsions and mineral filler.
- Conventional asphalt mixtures are manufactured at the asphalt plant of Cooperativa Braccianti and then installed by using mineral filler and bitumen emulsion as a tack coat over the binder layer and then a paver and a roller will complete the construction.

The design formula of the materials used in the "in-plant recycling" case study (San Marino) are provided in Table 15.

Table 15 – Republic of San Marino asphalt pavement composition

PAVEMENT MATERIALS – Republic of San Marino case study	
Mix specifications for all mixes used on the project. These should include (at the very least) aggregate type and content, asphalt content and any modifiers used in the mix.	**Asphalt Concrete- modified bitumen (Surface)** - Aggregate 90.5% - Filler 4% - Total binder content: 5.5% - Type of binder: Bitumen - No added fibres, additive or modifiers **CRAB mix (Binder)** - Aggregate 89.5% (84.5% Reclaimed Asphalt) - Filler 4% - Total binder content: 4.5% - Type of binder: Bitumen emulsion - Cement: 2% - This binder substituted the conventional mix, assumed to be the same of surface. **Cement treated material (Base)** - Aggregate 97% - Total binder content: 3% - Type of binder: Cement

	- No added fibres, additive or modifiers

Transport distances: locations of interest for the different phases from material sourcing to pavement installation are shown in Figure 24.

- Conventional
  - Refinery (bitumen, modified binder and bitumen emulsion): Bologna, Italy - 125 km
  - - Fine and Coarse Aggregate Quarry: Forlì, Italy (fine) – 65 km / Castel Viscardo, Italy (coarse) - 235 km
  - Filler Quarry: Serra San Quirico, Ancona, Italy - 150 km
  - Asphalt manufacturing and paving equipment storage: Cooperativa Braccianti Riminesi in San Leo, Rimini, Italy – 15 km
- CRABs
  - Refinery (bitumen emulsion): Bologna, Italy – 125 km
  - Fine Aggregate Quarry: Ravenna, Italy – 65 km
  - Filler Quarry: Gubbio, Italy – 145 km
  - Additives storage: Moselice, Padova, Italy – 210 km
  - Asphalt plant, RA processing and Stockpile (asphalt manufacturing and paving equipment storage): Cooperativa Braccianti Riminesi in San Leo, Rimini, Italy – 15 km

Figure 24 – Republic of San Marino- Locations of interest

Selected subsection and maintainance activity:

A conventional pavement, with hot mix asphalt layers, is partially substituted, according to the scheme in Figure 4. The selected subsection 2 showed a series of interconnecting cracks caused by repeated traffic loading, high-severity level of the fatigue cracking, combined with a localised depression due to the settlement of the foundation. The maintenance of subsection 2 (Figure 4) requires the milling of 29 cm of the old pavement, laying and compaction of 15 cm of cement treated recycled materials, spreading of the prime coat (bituminous emulsion with dosage of 1.00 kg/m2 of residual bitumen and saturation with mineral filler), laying and compaction of 10 cm of cold recycled mixture, spreading of the tack coat (bituminous emulsion with dosage of 0.45 kg/m2 of residual bitumen and saturation with mineral filler) and laying and compaction of 4 cm of asphalt concrete (maintenance work code: P-4c)

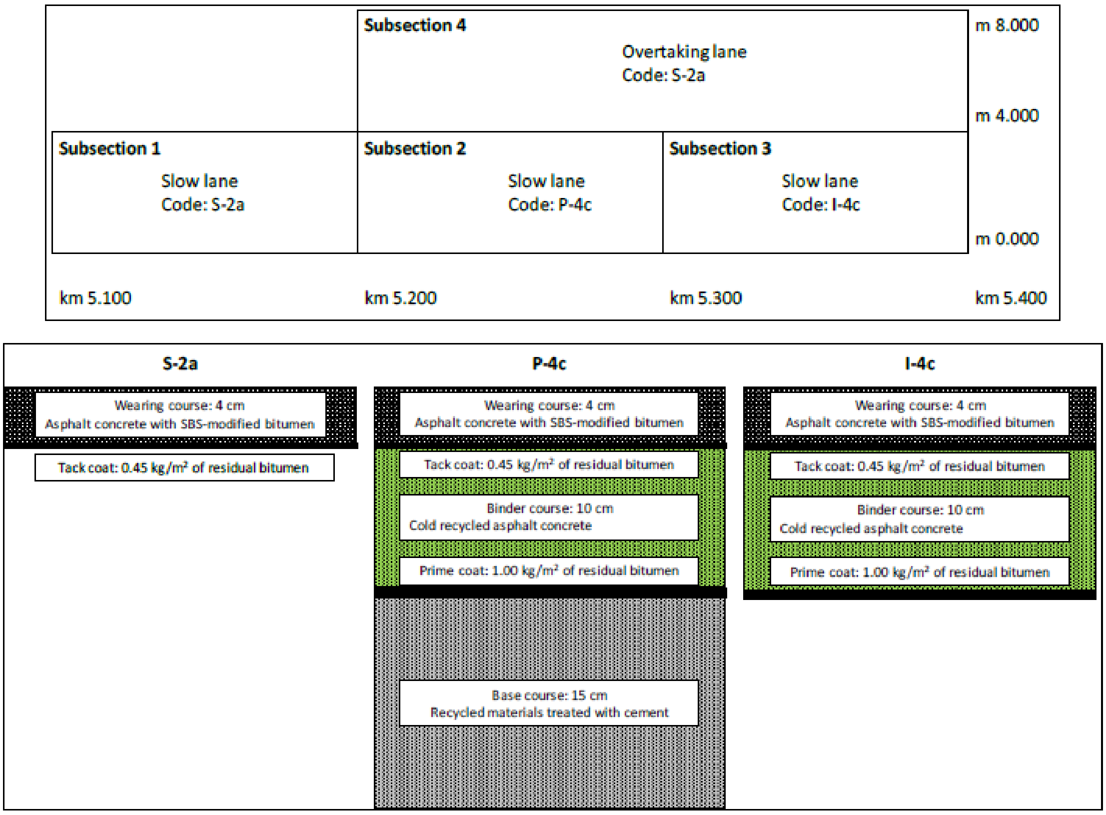


Figure 25- Scheme of the working sections and maintenance methods

- ## In-situ recycling case study: Germany

Location: The case study consists of a repaving operation on section of 150 m x 12.5 m, which is part of E44 in Trier.

Manufacturing and Construction method:

- In-situ recycled CRAB materials are manufactured on-site, hence allowing to minimize the transport for the reclaimed asphalt milled directly from the site. At first the reclaimed asphalt is milled, then there is a levelling with a grader, tack coat is added with a spreader, then a recycler (mix paver, water tank and bitumen tank) manufactures the CRAB with the addition of bitumen emulsion and cement and lays down the crab material which is then compacted with a roller.

- Conventional asphalt mixtures are manufactured at the Asphalt Plant in Trier and then installed by using bitumen emulsion as a tack coat over the binder layer and then a paver and a roller will complete the construction.

The design formula of the materials used in the “in-site recycling” case study (Germany) are provided in *Table 16*.

Table 16 - Germany asphalt pavement composition

PAVEMENT MATERIALS – Germany case study	
Mix specifications for all mixes used on the project. These should include (at the very least) aggregate type and content, asphalt content and any modifiers used in the mix.	**SMA 8 S (Surface)** - Aggregate: 83% - Filler 10% - Total binder content: 7% - Type of binder: Bitumen - No added fibers, additive or modifiers **AC16BS (binder)** - Aggregate 90.5% - Filler 5% - Total binder content: 4.5% - Type of binder: Bitumen - No added fibers, additive or modifiers **CRAB_G (Cold Asphalt Base)** - Reclaimed Asphalt 93.6% - Total binder content: 4% - Type of binder: Bitumen emulsion - Additive (cement): 4 % This CRAB substituted the conventional **base (AC32TS)** - Aggregate 89.5% - Filler 7% - Total binder content: 3.5% - Type of binder: Bitumen - No added fibers, additive or modifiers

Transport distances: locations of interest for the different phases from material sourcing to pavement installation are shown in Figures 6:

- Refinery (bitumen emulsion): Bonn, Germany – 163 km
- Aggregate Quarry: Neumagen-Dhron, Germany – 94 km
- Filler Quarry: Neumagen-Dhron, Germany – 94 km
- Additives Storage: Allmendingen, Germany – 392 km
- Asphalt plant (asphalt manufacturing and paving equipment storage): Basalt-Actien-Gesellschaft, Trier, Germany – 2.9 km

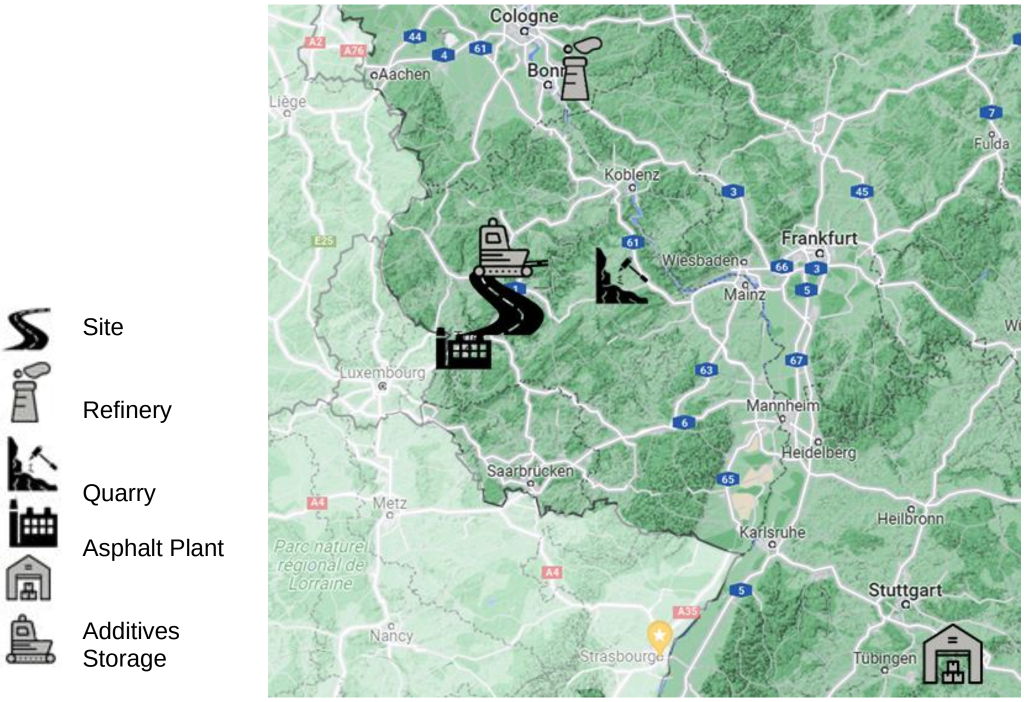


Figure 26 - Germany - Locations of interest

<u>Selected subsection and maintenance activity:</u> For this case study the sub-section III was selected having a total width of 12.50m (currently divided in 4 lanes). According to German design the rehabilitation of this section would have had a pavement structure made of asphalt concrete with 4cm SMA8 over 8cm AC16 and 22cm AC32TS. The same design method suggests using a solution with CRAB material with bitumen emulsion and the following pavement design: 4cm of wearing course (SMA8), 8 cm of binder (AC16 made), 12cm of base (AC32) and finally 20cm of CRAB materials.

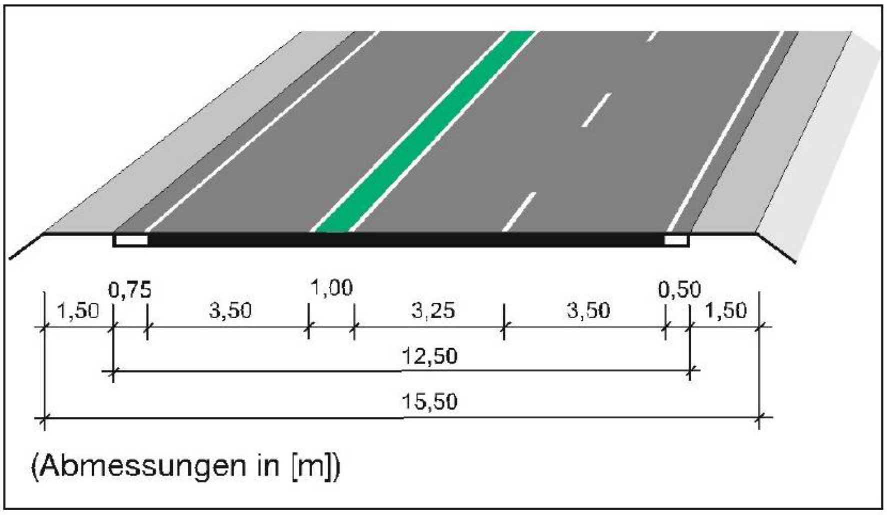


Figure 27 - German subsections

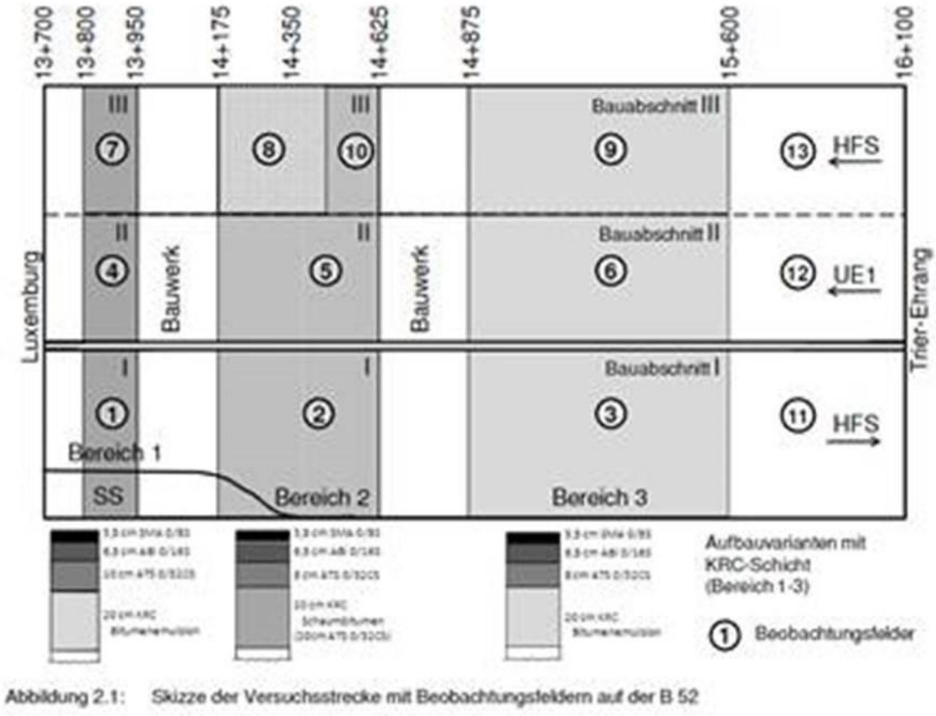


Figure 28 - German Maintenance

The described case studies were analyzed in terms of environmental impacts in a cradle-to-gate approach.

- **Selected maintenance strategies and general assumptions**

The C4O technologies have been used to demonstrate the improvement in terms of environmental emissions, compared with conventional mixtures.

In order to account these benefits, a similar maintenance strategy has been defined for both case studies, consisting of milling and paving surface course, complemented with interventions on binder course and on base course too (this one at the end of 50 years).

This will consider as common assumption that the road pavement foundation and sublayers will not deteriorate and the asphalt will only last for its full estimated lifetime with no under/over performance.

Table 17 - Maintenance information

	Maintenance information
Maintenance Treatment	- Surface treatments with periodic inlay of wearing course and occasional inlay of binder and base course. - Maintenance is undertaken in one carriageway (two lane), or one lane at a time, with the traffic diverted onto the other carriage/lane.

Materials for maintenance strategies	• Republic of San Marino: Current asphalt mixture used for binder course will be compared with a C4O mix technology (90%RA, 10%sand). • Germany: Current asphalt mixture used for base will be compared with the C4O mix composed of RA, Cement (4%), Bitumen Emulsion (4%) and water (3.1%).			
Analysis period	• Republic of San Marino: 20 years • Germany: 50 years			
Country dependent maintenance strategy	Republic of San Marino		*Germany:*	
	year	*procedure*	*year*	*procedure*
	y 7,5	Crack repair with bitumen emulsion	y 12,5	milling surface course / paving surface course / production new HMA
	y 10	milling surface course / paving surface / production new HMA	y 25	milling surface+binder course / paving surface+binder course / production new HMA
	y 20	milling surface course + binder course / paving surface course + binder course / production new HMA and CRAB	y37,5	milling surface course / paving surface course / production new HMA
	-	-	Y 50	full rehabilitation of all bounded layers _ new HMA + CRAB in- situ recycling

Typical compaction schedule and equipment • Republic of San Marino *(as provided by partners)*	• Asphalt and CRAB Paving: Vogele Super 1803-3i paver,4 h paving, fuel consumption (l/h): 11,25 • Asphalt Compaction:

	Steel-wheeled roller CAT, 4m to 1 h compaction, fuel consumption (l/h): 3,75 • CRAB Compaction: Pneumatic-tired HAMM GRW180i 50l/8h • Asphalt reclaiming: Cold milling machine Wirtgen W200i, fuel consumption (l/h) : 25
• Germany *(as provided by partners)*	• Recycler: 0,0788 l/m^2 • Padfoot Compactor: 0,0077 l/m^2 • Vobratory Compactor: 0,0077 l/m^2 • Tandem roller: 0,0077 l/m^2 • Static roller: 0,007 l/m^2

1.2 Results of Comparative LCA of Pavement Activities for road pavement with CRABforOERE technologies

This exercise was carried out concerning the area of pavement activities, assessing the environmental impacts related to the C4O pavements, as can been seen if.

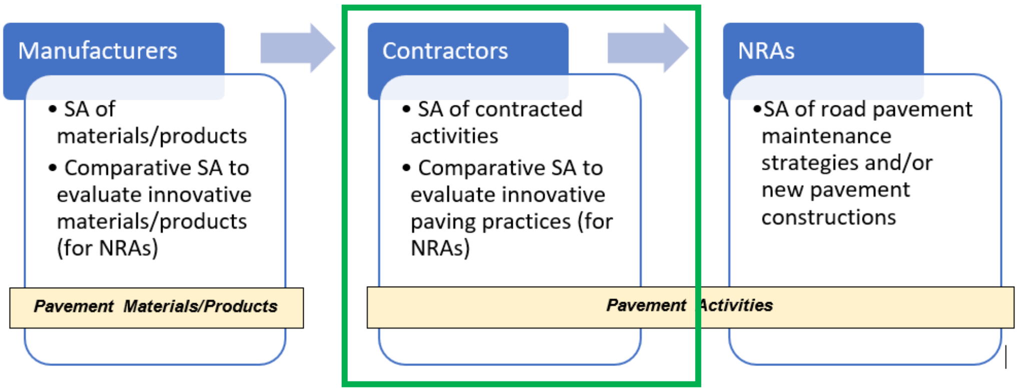


Figure 29 - Selection of LCA exercise according to the PAVEMENTLCM framework (pavementlcm.eu)

- **LCA phase 1: Goal and Scope Definition**

The aim of this study is to calculate the environmental impacts of different pavement designs during their reference service life (RSL). The pavements investigated are composed of conventional hot asphalt mixtures and/or cold asphalt mixtures (Crab4Oere mixtures). These mixtures are produced with different manufacturing processes: in-situ recycling for the German case study, in-plant recycling for the one produced in San Marino. The results of the study can be compared to understand how less impactful the use of cold asphalt mixture technologies (comparative LCA) is.

The intended applications of the study are:

- The understanding of the environmental benefits related to cold asphalt recycling;

- The understanding of the pros and the cons of using the C4O technologies when compared to currently used construction methods
- The support of more sustainable decision-making processes of asphalt mixture producers

The study is part of Crab4Oere project, funded by the CEDR within the call 2017 "New Materials" and it is directed to the scientific community (National Road Authority, Academics, etc.) to provide evidence of results the environmental impact of cold recycled asphalt mixtures used for pavement maintenance. The outcomes could also be used for further sustainability assessment extended to pavement activities, as indicated within the PavementLCM framework.

- **Description of the object under study**

In Crab4Oere project, as mentioned before, two case studies were taken into account.

Both in San Marino and in Germany the comparison was made between the HMA pavements and CRAB pavements.

The considered sections include three layers for German case study, two layers (surface + binder courses) for San Marino.

Details of the two pavements with CRAB are provided to be compared with conventional hot asphalt mixtures to be used for binder and base course. Here are the details of each case study:

- German Case Study – in-situ recycling CRAB

In this case study, a conventional pavement (Pavement with HMA), realized with three layers of HMA, is compared with one (Pavement with CRAB) whose base course was substituted with CRAB. The two structures changes also in terms of layers thickness.

- San Marino Case Study- in-plant recycling CRAB

The environmental impacts of the conventional pavement (RSM_Pavement with HMA), realized with HMA, is compared to another pavement (RSM_Pavement with CRAB), whose binder course was substituted with a CRAB mixture.

- **Functional unit and System Boundaries**

In both cases, the chosen functional unit (f.u.) is the exact weight of the road pavement to be built as required at project-level (as suggested in PavementLCM Guidelines).

It follows that:

- Concerning San Marino, the f.u. is given by the total weight of CRABs and HMA mixtures needed for the subsection 2 which is 320 m2 big.

	Pavement with HMA		**Pavement with CRAB**	
	m^3	tons	m^3	tons
Surface course AC12	13	30	13	30
Binder course AC12	25.6	60	-	-
Binder course CRAB	-	-	32	75

- Concerning Germany, the f.u. is given by the total weight of CRABs and HMA mixtures needed for the considered section which is 1780 m2 big.

Pavement with HMA		**Pavement with CRAB**	
m^3	tons	m^3	tons

Surface course SMA8S	75	184	66	160
Binder course AC16	150	375	122	305
Base Course AC32TS	413	1047	150	381
Base course CRAB	-	-	375	863

A cradle-to-grave analysis was performed, according to the stages identified in the EN 15643-5. This kind of analysis covers the modules A, B, C and D, even if not all the B stages were taken into account.

- **System boundaries**

In this research, the physical boundaries include:

- For Germany, the full pavement, with all the layers;
- For Republic of San Marino, only the surface and binder courses.

- **Analysis period**

The analysis period covers one Reference Service Life of the two pavements system considered. In particular, for Republic of San Marino, it is defined in 20 years, when the surface and binder courses are removed, after a refurbishment of only surface course in year 10.

Instead, in Germany the analysis period is defined in 50 years, when the complete asphalt system (from surface course to base) is removed. During this period, two refurbishments of wearing course (y 12,5 and 37,5) and one of both wearing and binder courses (y 25) are planned to be done.

- **Cut-off rules**

In order to simplify inventory activities, standard EN 15804 allows a cut-off threshold of 99% of the mass of the input flows, provided that substances that are very toxic, toxic, harmful or hazardous to the environment and are intentionally introduced into the manufacturing of the assessed products should be taken into consideration (EAPA, 2016). Therefore, according to EAPA, the following criteria are applied:

1. In case of insufficient input data or data gaps for a unit process, the cut-off criteria shall be 1% of the total (renewable and non-renewable) primary energy usage and 1% of the total mass input of that unit process. The total sum of neglected input flows shall not exceed 5% of energy usage and mass. This applies particularly to material and energy flows known to have the potential to cause significant emissions into air and water or soil during the life cycle of the product; it also applies to processes that are known to be resource intensive.

2. Materials that are less than 1% of the total mass input but are considered environmentally relevant include additives and polymers. There might be data gaps in their publicly available life cycle inventories, but these materials should be included when publicly available data exists.

During the development of this LCA and according to the goal and scope definition of the study, no cut-off rules were applied in order to consider all materials' influence. All data was available and produced when necessary.

- **Allocation procedures**

For the allocation the only aspect taken under consideration was the effect of Reclaimed Asphalt. RA is considered to bring zero emission into the considered system boundaries (EAPA, 2016). Hence, the considered emissions will be only those related to operational procedures for RA treatment, such as those crushing and screening and eventual transport to the asphalt plant.

- **Impact categories**

The aim of an LCA is the quantification of environmental impacts all along the life cycle of a product, according to the chosen system boundaries. In order to interpret the collected inputs, they are translated into outputs/environmental impact categories thanks to a series of characterization factors. Characterization factors indicate the environmental impact per unit of stressor (e.g. per kg of resource used or emission released). Impacts are calculated during the third part of LCA, so in the Life Cycle Impact Assessment (LCIA) with a specific methodology called EF2.0, developed by the European Commission in 2018. It is recommended by PavementLCM Guidelines to consider other two indicators (Energy Use and Secondary Materials Consumption), which are directly provided by the Life Cycle Inventory.

The list of all indicators is provided in the introduction of third paragraph of this deliverable.

- **Data requirements and data quality**

The data quality requirements were considered following EN 15804 (2012). Primary data was obtained by sending questionnaires about materials, processes and transportation to the different partners of the consortium involved in this stage.

When primary data was not available, secondary data was used from recognized databases (such as GaBi) or collected from literature. The source of all data is detailed

in the LCI section, results of the quality data assessment are shown in below. As mentioned in ISO14040:2006, data have to comply with some requirements and in the next steps a rating score can be assigned, according to their quality with a specific table presented in LCI phase.

- **Assumptions and limitations of the study**

The following assumptions are declared:

  - No asphalt plant stack emissions were considered.
  - When used, RA stockpile and processing are considered to be located at the asphalt plant, therefore, transport distance of RA is zero.
  - Ancillary materials in the asphalt plant or on the workzone (A3, A5 and C1).
  - In the RAP treatment (A1), only energy consumption during crushing and sieving is included. No data is available concerning diesel consumption for materials movement inside the plant.
  - No data is available concerning the waste and/or over consumption of energy and materials generated during the production at the asphalt plant
  - Material waste and energy over-consumption during installation or dismantling of pavement components is assumed zero,
  - Reclaimed asphalt obtained from the milling process is assumed to be 100% recyclable.

- **LCA phase 2: Life Cycle Inventory**

The source of data collection can be divided into two categories: primary and secondary, according to the information provided by the partners and those taken from the software database. Partners have been interviewed in order to have details on materials, asphalt pavement structure, mix design recipes, transport distances and current manufacturing and installation practices. When there was a lack of information, needed data were taken from GaBi Database.

- **Data Collection**

When possible, primary data were used, if available because provided by the partners. Otherwise, they have been taken from the Professional Database of GaBi ts by Thinkstep, a company of Sphera (Thinkstep, 2019).

- **Production stage A1-A3**

This stage includes the quantification of all the materials used and energy consumed from the extraction of raw materials to the production of asphalt mixtures, considering also the consumptions linked to the transport to the plant.

Table 18 - Asphalt mixtures components by weight (as inputted in LCA software)

	GERMANY				REPUBLIC OF SAN MARINO	
	SMA8S	AC16BS	AC32TS	CRAB_G	AC12	CRAB_RSM
Fine Aggregates	250 kg	275 kg	295 kg	-	505 kg	50 kg
Coarse Aggregates	580 kg	630 kg	600 kg	-	400 kg	-
Reclaimed Asphalt	-	-	-	936 kg	-	845 kg
Cement	-	-	-	40 kg	-	20kg
Bitumen	70 kg	45 kg	35 kg	-	55 kg	-
Bitumen emulsion	-	-	-	40 kg	-	45 kg
Filler	100 kg	50 kg	70 kg	-	40 kg	40 kg
Water	-		-	31 kg	-	29 kg

Table 19 - A1 + A2- - Raw material acquisition + Transport (as inputted in LCA software)

	Distances in Germany (km)	Distances in Republic of San Marino (km)
Fine Aggregates	28 km	65 km
Coarse Aggregates	28 km	235 km
Reclaimed Asphalt	0 km	0 km
Cement	392 km	210 km
Binder	163 km	125 km
Filler	28 km	150 km
Water	0 km	0 km

Table 20 - A3 – Production (as inputted in LCA software)

	GERMANY		REPUBLIC OF SAN MARINO	
	SMA8S-AC16BS-AC32TS	CRAB	AC12	CRAB
Electricity	3,33 kWh/t		6,75 kWh/t	0,65 kWh/t
Natural Gas	-		10 m3	
Water	0,55 kWh/t		-	
Diesel	-	0,16 kg	0.042 kg	0,17 kg
Heating oil	116 kWh/t		-	

- **Construction stage (A4-A5)**

It includes all the data linked to the transportations of materials/components from the asphalt plant to the site and the energy required for the installation of pavement (paving, rolling).

Table 21. Distances from the asphalt plant to the worksite (as inputted in LCA software)

	Germany	Rep. of San Marino
Transportation	Distance (Km)	Distance (Km)
Asphalt plant to site	2,9	15

- **Use stage (B3 – B4)**

The impacts of this stage involve those related to the milling and overlay (M&O) of the wearing course. Processes included in the M&O operation are milling of the deteriorated asphalt layer, the transportation to the recovery centre, the production of the materials (A1, A2 and A3), their transportation to the roadwork (A4) and the construction of the new layer (A5). The sources for the LCI of the materials and processes considered in this stage are shown in from Table 22 to Table 27.

Table 22. LCI Sources for the use stage

B3	Crack Repair	Gabi Database: EU:28- Propane mix at refinery
B4	Milling process	Primary data obtained from partners
	Diesel combustion in milling machine	Gabi Database: EU:28- Diesel mix at refinery
	Truck transportation (RAP)	Gabi Database: Transport, freight, lorry, 16-32 ton, EURO 5
	Overlay process	Same as in A1 to A5

Table 23. Distances for the use stage

Transportation	Distance (Km)
Raw materials and asphalt mixtures (overlay process)	Same as A2 and A4
RAP transportation from worksite to recovery centre	Germany: 2,9 km- Republic of San Marino: 15 km

Table 24. Mass (ton) of HMA involved in each activity. For Germany case study

	Process	SMA8S Surface	AC16 Binder	AC32TS Bse
Initial construction	Production & construction	184	375	1047
Maintenance (year 12,5 + 37,5)	Milling	368	0	0
	Production & construction	368	0	0
Maintenance	Milling	184	375	0

(year 25)	Production & construction	184	375	0
End-of-life (year 50)	Milling	184	375	1047

Table 25. Mass (ton) of HMA and CRAB involved in each activity. For Germany case study

	Process	SMA8S Surface	AC16 Binder	AC32TS Base	CRAB
Initial construction	Production & construction	160	305	381	863
Maintenance (year 12,5 + 37,5)	Milling	320	0	0	0
	Production & construction	320	0	0	0
Maintenance (year 25)	Milling	160	305	0	0
	Production & construction	160	305	0	0
End-of-life (year 50)	Milling	160	305	381	863

Table 26. Mass (ton) of HMA involved in each activity. For Republic of San Marino case study

	Process	AC12 Surface	AC12 Binder
Initial construction	Production & construction	30	60
Maintenance (year 12,5 + 37,5)	Milling	30	0
	Production & construction	30	0
Maintenance (year 25)	Milling	30	60
	Production & construction	30	60
End-of-life (year 50)	Milling	30	60

Table 27. Mass (ton) of HMA and CRAB involved in each activity. For Republic of San Marino case study

	Process	AC12 Surface	CRAB Binder
Initial construction	Production & construction	30	75
Maintenance (year 12,5 + 37,5)	Milling	30	0
	Production & construction	30	0
Maintenance (year 25)	Milling	30	75

	Production & construction	30	75
End-of-life (year 50)	Milling	30	75

- **End-of-Life stage (C1-C3)**

End-of-Life stage involves the milling of the three asphalt layers from the road (C1) and the transportation of the RAP to the recovery centre (C2). The data for the processes here involved are already described in B4 (milling and RAP transportation).

- **Data Calculation**

All the collected data was introduced in GaBi ts software, in order to create the plans containing all the processes the model is composed of.

- **Data Quality**

The Data Quality Assessment was performed according to JRC (2016). It consists of attributing a score, related to some quality indicators, to each data (both primary and secondary) used in the LCA. As a result, the average data quality rating was judged satisfactory, being comprised between good and very good.

Table 28 - Assessment of Data Quality

Data	Type	Source	Technological Representativ.	Geographical Representativ.	Temporal correl.	Completeness	Methodological Appropriateness and Consistency	Avarage
EU-28: Crushed rock 16-32 mm	Secondary	GaBi	1	2	1	2	2	1.6
EU-28: Crushed sand grain 0-2 mm	Secondary	GaBi	1	2	1	2	2	1.6
EU-28: Bitumen at refinery	Secondary	GaBi	2	2	1	2	2	1.8
EU-28: Limestone	Secondary	GaBi	2	2	1	2	2	1.8
EU-28: Bitumen emulsion	Secondary	GaBi	3	2	1	2	2	2
EU-28: Cement (CEM II)	Secondary	GaBi	2	2	1	2	2	1.8
Reclaimed Asphalt (RA)	Secondary	GaBi	2	2	2	2	1	1.8
EU-28: Water	Secondary	GaBi	2	2	1	2	2	1.8
EU-28: Diesel mix at filling station	Secondary	GaBi	2	2	1	2	2	1.8
Gas Consumption in Asphalt Plant	Primary	Material Producer	2	2	1	2	1	1.6
EU-28: Electricity Grid mix	Secondary	GaBi	2	2	1	2	2	1.8
Other resources use consumption : EU-28: Oil	Primary	Material Producer	2	2	2	2	1	1.8
Transport Distances	Primary	Real Distances related to the specific case study	1	1	1	1	2	1.2
Transport Mean	Secondary	GaBi Database	2	2	1	2	1	1.6
EU-28: Propane	Secondary	GaBi Database	2	2	1	2	2	1.8
Total Avarage								1.72

- **LCA Phase 3: Life Cycle Impact Assessment**

The third LCA step aims to assess a product system and better understand its environmental burden. The results are shown in the tables below and contain the comparison between the pavements with hot and cold mixtures.

Once selected the impact categories and the linked indicators, the results of the environmental assessment have been defined and reported below from *Table 29* to *Table 33*.

Table 29 - Republic of San Marino - LCIA Results for Pavement with CRAB

	ENVIRONMENTAL LIFE CYCLE IMPACT with CRAB				
	A1-A3	A4-A5	B	C	TOTAL
Climate Change [kg CO2 eq.]	4.35E+03	1.39E+02	7.05E+03	1.29E+02	1.17E+04
Climate Change -biogenic [kg CO2 eq.]	7.28E+00	2.65E-01	1.43E+01	2.66E-01	2.21E+01
Climate Change -fossil [kg CO2 eq.]	4.33E+03	1.36E+02	7.01E+03	1.26E+02	1.16E+04
Climate Change -land use change [kg CO2 eq.]	1.04E+01	2.59E+00	2.38E+01	2.62E+00	3.94E+01
Acidification [Mole of H+ eq.]	1.50E+01	4.64E-01	2.34E+01	4.26E-01	3.93E+01
Eutrophication freshwater [kg P eq.]	7.56E-03	8.18E-04	1.52E-02	8.28E-04	2.44E-02
Eutrophication marine [kg N eq.]	4.41E+00	2.00E-01	7.78E+00	1.80E-01	1.26E+01
Eutrophication terrestrial [Mole of N eq.]	4.84E+01	2.23E+00	8.55E+01	2.02E+00	1.38E+02
Photochemical ozone formation - human health [kg NMVOC eq.]	1.25E+01	4.00E-01	2.03E+01	2.39E-06	3.32E+01
Respiratory inorganics [Deaths]	1.45E-04	2.67E-06	2.60E-04	3.65E-01	3.65E-01
Land Use [Pt]	1.95E+04	1.99E+03	3.82E+04	2.02E+03	6.17E+04
Resource use, energy carriers [MJ]	1.83E+05	2.26E+03	2.86E+05	2.29E+03	4.73E+05
Resource use, mineral and metals [kg Sb eq.]	6.71E-04	1.35E-05	1.22E-03	1.19E-05	1.92E-03
Water scarcity [m³ world equiv.]	4.89E+02	3.78E+00	4.80E+02	3.70E+00	9.77E+02
Energy use (mJ)	4.42E+03	5.46E+01	7.08E+03	5.42E+01	1.16E+04
- Non renewable	4.42E+03	5.46E+01	7.08E+03	5.42E+01	1.16E+04
- Renewable	7.42E-18	0.00E+00	3.33E-17	0.00E+00	4.07E-17
Secondary Materials Consumption (kg)	7.50E+04	0.00E+00	7.50E+04	0.00E+00	1.50E+05

Table 30 - Republic of San Marino - LCIA Results for Pavement with HMA.

	ENVIRONMENTAL LIFE CYCLE IMPACT with HMA				
	A1-A3	A4-A5	B	C	TOTAL
Climate Change [kg CO2 eq.]	6.10E+03	1.19E+02	8.24E+03	1.11E+02	1.46E+04
Climate Change -biogenic [kg CO2 eq.]	1.10E+01	2.17E-01	1.51E+01	2.28E-01	2.65E+01

Climate Change -fossil [kg CO2 eq.]	6.07E+03	1.17E+02	8.19E+03	1.08E+02	1.45E+04
Climate Change -land use change [kg CO2 eq.]	2.01E+01	2.11E+00	3.01E+01	2.25E+00	5.46E+01
Acidification [Mole of H+ eq.]	2.44E+01	3.96E-01	3.27E+01	3.65E-01	5.79E+01
Eutrophication freshwater [kg P eq.]	1.25E-02	6.68E-04	1.77E-02	7.10E-04	3.16E-02
Eutrophication marine [kg N eq.]	8.29E+00	1.72E-01	1.12E+01	1.55E-01	1.98E+01
Eutrophication terrestrial [Mole of N eq.]	9.13E+01	1.92E+00	1.24E+02	1.73E+00	2.19E+02
Photochemical ozone formation - human health [kg NMVOC eq.]	2.12E+01	3.43E-01	2.84E+01	2.05E-06	4.99E+01
Respiratory inorganics [Deaths]	2.52E-04	2.27E-06	3.35E-04	3.13E-01	3.14E-01
Land Use [Pt]	3.10E+04	1.63E+03	4.38E+04	1.73E+03	7.81E+04
Resource use, energy carriers [MJ]	2.91E+05	1.85E+03	3.85E+05	1.96E+03	6.80E+05
Resource use, mineral and metals [kg Sb eq.]	1.06E-03	1.11E-05	1.43E-03	1.02E-05	2.51E-03
Water scarcity [m³ world equiv.]	4.46E+02	3.09E+00	5.60E+02	3.17E+00	1.01E+03
Energy use (mJ)	7.05E+03	4.46E+01	9.31E+03	4.65E+01	1.65E+04
- Non renewable	7.05E+03	4.46E+01	9.31E+03	4.65E+01	1.65E+04
- Renewable	2.22E-17	0.00E+00	2.96E-17	0.00E+00	5.18E-17
Secondary Materials Consumption (kg)	6.10E+03	1.19E+02	8.24E+03	1.11E+02	1.46E+04

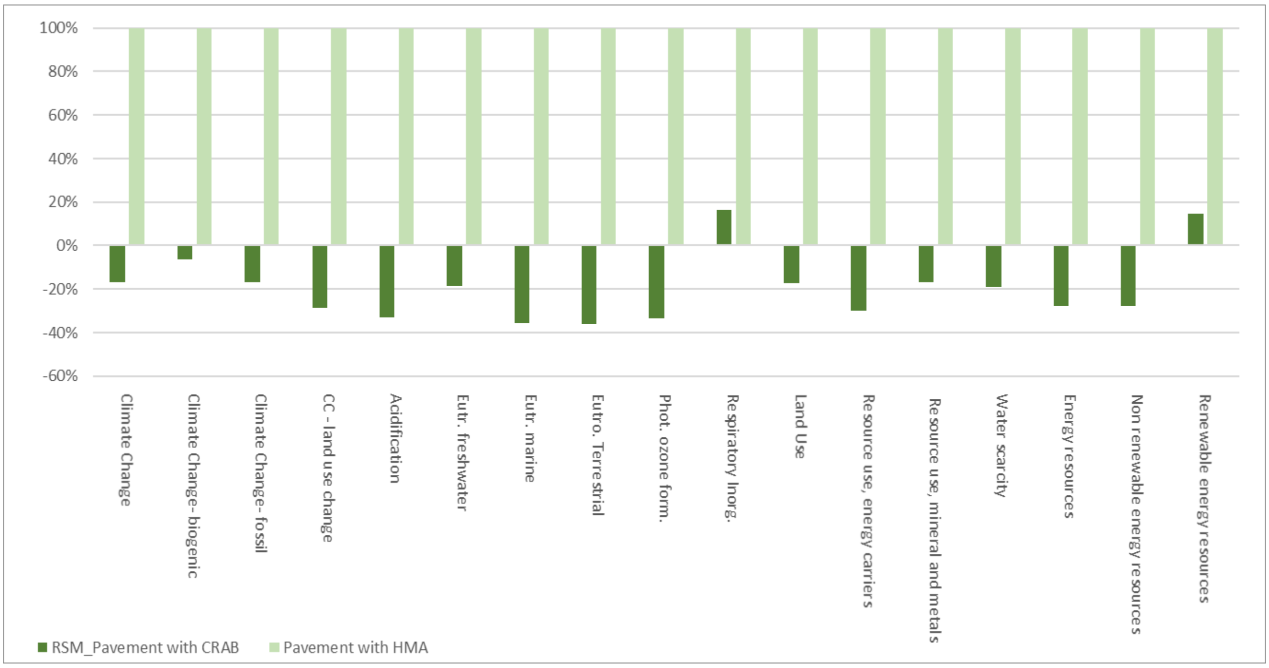


Figure 30 - Comparison between Pavement with HMA and Pavement with CRAB in the Republic of San Marino

Table 31 - Germany - LCIA Results for Pavement with CRAB

	GERMANY_ENVIRONMENTAL LIFE CYCLE IMPACT with CRAB				
	A1-A3	A4-A5	B	C	TOTAL
Climate Change [kg CO2 eq.]	9.78E+04	3.04E+02	1.66E+05	2.70E+02	2.64E+05
Climate Change -biogenic [kg CO2 eq.]	141.4	1.60E+00	2.93E+02	1.83E+00	4.38E+02
Climate Change -fossil [kg CO2 eq.]	9.75E+04	3.00E+02	1.65E+05	2.65E+02	2.63E+05
Climate Change -land use change [kg CO2 eq.]	173.67	2.33E+00	3.63E+02	2.66E+00	5.42E+02
Acidification [Mole of H+ eq.]	277	1.00E+00	4.41E+02	9.12E-01	7.20E+02
Eutrophication freshwater [kg P eq.]	0.14415	1.85E-03	2.91E-01	2.10E-03	4.39E-01
Eutrophication marine [kg N eq.]	65.104	3.96E-01	1.10E+02	3.32E-01	1.76E+02
Eutrophication terrestrial [Mole of N eq.]	715.4	4.60E+00	1.21E+03	3.93E+00	1.93E+03
Photochemical ozone formation - human health [kg NMVOC eq.]	209.167	8.33E-01	3.40E+02	7.36E-01	5.51E+02
Respiratory inorganics [Deaths]	0.0032597	1.03E-05	5.74E-03	1.06E-05	9.02E-03
Land Use [Pt]	4.06E+05	6.07E+03	8.11E+05	6.91E+03	1.23E+06
Resource use, energy carriers [MJ]	3.23E+06	7.67E+03	5.68E+06	8.74E+03	8.93E+06
Resource use, mineral and metals [kg Sb eq.]	0.6799488	5.12E-05	1.12E+00	5.84E-05	1.80E+00
Water scarcity [m³ world equiv.]	8575.76	4.24E+00	1.06E+04	4.83E+00	1.92E+04
Energy use (mJ)	7.96E+04	1.82E+02	142188.3706	2.07E+02	2.22E+05
- Non renewable	7.96E+04	1.82E+02	142188.3706	2.07E+02	2.22E+05
- Renewable	8.86E-08	0.00E+00	1.46E-07	0.00E+00	2.34E-07
Secondary Materials Consumption (kg)	834+E03	0	834+E03	0	0

Table 32 - Germany - LCIA Results for Pavement with HMA

	GERMANY_ENVIRONMENTAL LIFE CYCLE IMPACT with HMA				
	A1-A3	A4-A5	B	C	TOTAL
Climate Change [kg CO2 eq.]	1.17E+05	4.82E+02	1.89E+05	5.08E+02	3.07E+05
Climate Change -biogenic [kg CO2 eq.]	192.74	2.26E+00	3.38E+02	3.44E+00	5.36E+02
Climate Change -fossil [kg CO2 eq.]	1.17E+05	4.77E+02	1.88E+05	4.99E+02	3.05E+05
Climate Change -land use change [kg CO2 eq.]	219.72	3.28E+00	4.70E+02	5.01E+00	6.98E+02
Acidification [Mole of H+ eq.]	351.43	1.57E+00	5.55E+02	1.72E+00	9.10E+02
Eutrophication freshwater [kg P eq.]	0.1934	2.60E-03	3.57E-01	3.96E-03	5.57E-01
Eutrophication marine [kg N eq.]	75.659	6.41E-01	1.30E+02	6.26E-01	2.07E+02
Eutrophication terrestrial [Mole of N eq.]	834.61	7.39E+00	1.44E+03	7.41E+00	2.29E+03

Photochemical ozone formation - human health [kg NMVOC eq.]	246.68	1.32E+00	4.10E+02	1.39E+00	6.59E+02
Respiratory inorganics [Deaths]	0.0044647	1.53E-05	7.47E-03	1.99E-05	1.20E-02
Land Use [Pt]	5.87E+05	8.54E+03	1.02E+06	1.30E+04	1.63E+06
Resource use, energy carriers [MJ]	4.30E+06	1.08E+04	7.16E+06	1.65E+04	1.15E+07
Resource use, mineral and metals [kg Sb eq.]	1.3699279	7.21E-05	1.74E+00	1.10E-04	3.11E+00
Water scarcity [m³ world equiv.]	10194.03	5.97E+00	1.37E+04	9.10E+00	2.39E+04
Energy use (mJ)	1.06E+05	2.56E+02	1.77E+05	3.90E+02	2.83E+05
- Non renewable	1.06E+05	2.56E+02	1.77E+05	3.90E+02	2.83E+05
- Renewable	1.80E-07	0.00E+00	2.27E-07	0.00E+00	4.07E-07
Secondary Materials Consumption (kg)	0	0	0	0	0

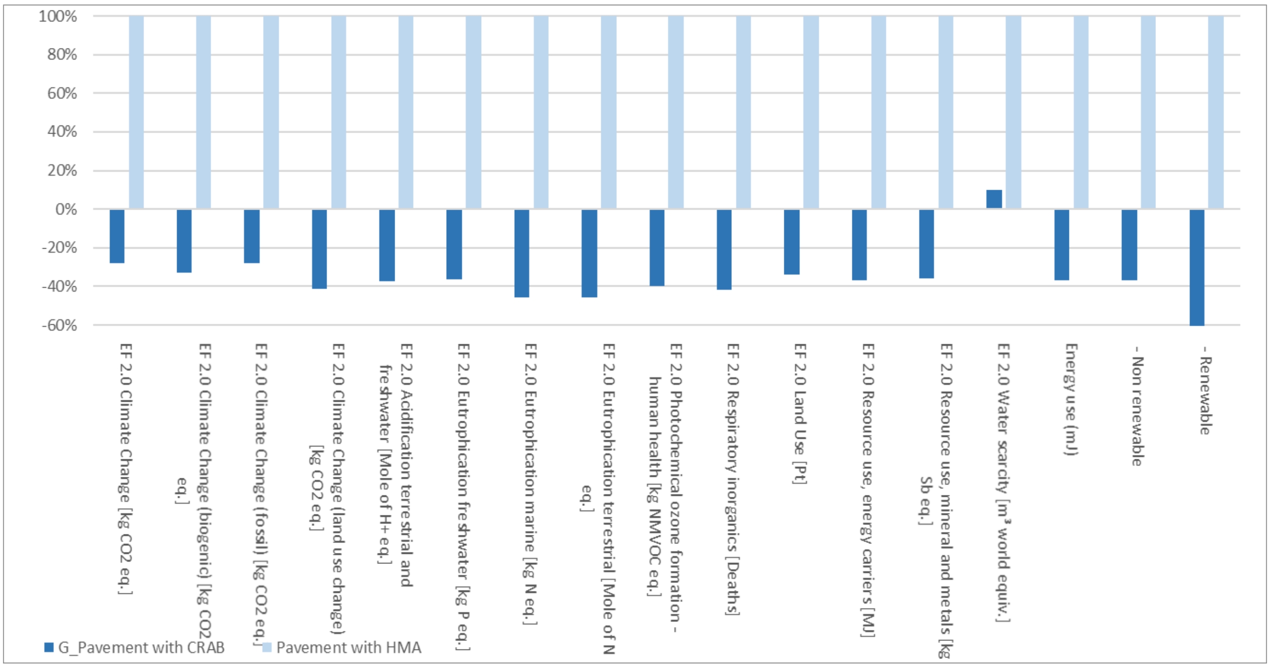


Figure 31 - Comparison between Conventional Base and CRAB base in Germany

- **Optional steps**

Standards identify some optional steps in order to deepen the results obtained.

- **Normalization and weighting**

1. Normalization in terms of dimensions
A normalization was proposed in this research. All the impacts, firstly calculated at project level, with the specific weight of materials needed, are normalized at 1 m2 of pavement, included the physical boundaries.

Table 33 – Republic of San Marino - LCIA Results for Pavement with CRAB

	REPUBLIC OF SAN MARINO_ENVIRONMENTAL LIFE CYCLE IMPACT 1 M² ROAD PAVEMENT WITH CRAB as binder course				
	A1-A3	A4-A5	B	C	TOTAL
Climate Change [kg CO2 eq.]	1.36E+01	4.34E-01	2.20E+01	4.03E-01	3.65E+01
Climate Change -biogenic [kg CO2 eq.]	2.27E-02	8.28E-04	4.47E-02	8.31E-04	6.91E-02
Climate Change -fossil [kg CO2 eq.]	1.35E+01	4.25E-01	2.19E+01	3.94E-01	3.63E+01
Climate Change -land use change [kg CO2 eq.]	3.25E-02	8.09E-03	7.44E-02	8.19E-03	1.23E-01
Acidification [Mole of H+ eq.]	4.70E-02	1.45E-03	7.31E-02	1.33E-03	1.23E-01
Eutrophication freshwater [kg P eq.]	2.36E-05	2.56E-06	4.75E-05	2.59E-06	7.63E-05
Eutrophication marine [kg N eq.]	1.38E-02	6.25E-04	2.43E-02	5.63E-04	3.93E-02
Eutrophication terrestrial [Mole of N eq.]	1.51E-01	6.97E-03	2.67E-01	6.31E-03	4.32E-01
Photochemical ozone formation - human health [kg NMVOC eq.]	3.91E-02	1.25E-03	6.34E-02	7.47E-09	1.04E-01
Respiratory inorganics [Deaths]	4.54E-07	8.34E-09	8.13E-07	1.14E-03	1.14E-03
Land Use [Pt]	6.10E+01	6.22E+00	1.19E+02	6.31E+00	1.93E+02
Resource use, energy carriers [MJ]	5.71E+02	7.06E+00	8.94E+02	7.16E+00	1.48E+03
Resource use, mineral and metals [kg Sb eq.]	2.10E-06	4.22E-08	3.81E-06	3.72E-08	5.99E-06
Water scarcity [m³ world equiv.]	1.53E+00	1.18E-02	1.50E+00	1.16E-02	3.05E+00
Energy use (mJ)	1.38E+01	1.71E-01	2.21E+01	1.69E-01	3.62E+01
- Non renewable	1.38E+01	1.71E-01	2.21E+01	1.69E-01	3.62E+01
- Renewable	2.32E-20	0.00E+00	1.04E-19	0.00E+00	1.27E-19
Secondary Materials Consumption (kg)	7.50E+04	0.00E+00	7.50E+04	0.00E+00	1.50E+05

Table 34 – Republic of San Marino - LCIA Results for Pavement with HMA

	REPUBLIC OF SAN MARINO_ENVIRONMENTAL LIFE CYCLE IMPACT 1 m² ROAD PAVEMENT with HMA				
	A1-A3	A4-A5	B	C	TOTAL
Climate Change [kg CO2 eq.]	1.91E+01	3.72E-01	2.58E+01	3.47E-01	4.55E+01
Climate Change -biogenic [kg CO2 eq.]	3.43E-02	6.78E-04	4.72E-02	7.13E-04	8.29E-02
Climate Change -fossil [kg CO2 eq.]	1.90E+01	3.66E-01	2.56E+01	3.38E-01	4.53E+01
Climate Change -land use change [kg CO2 eq.]	6.28E-02	6.59E-03	9.41E-02	7.03E-03	1.70E-01
Acidification [Mole of H+ eq.]	7.63E-02	1.24E-03	1.02E-01	1.14E-03	1.81E-01
Eutrophication freshwater [kg P eq.]	3.92E-05	2.09E-06	5.53E-05	2.22E-06	9.88E-05
Eutrophication marine [kg N eq.]	2.59E-02	5.38E-04	3.50E-02	4.84E-04	6.19E-02
Eutrophication terrestrial [Mole of N eq.]	2.85E-01	6.00E-03	3.88E-01	5.41E-03	6.84E-01

Photochemical ozone formation - human health [kg NMVOC eq.]	6.61E-02	1.07E-03	8.88E-02	6.41E-09	1.56E-01
Respiratory inorganics [Deaths]	7.87E-07	7.09E-09	1.05E-06	9.78E-04	9.80E-04
Land Use [Pt]	9.68E+01	5.09E+00	1.37E+02	5.41E+00	2.44E+02
Resource use, energy carriers [MJ]	9.10E+02	5.78E+00	1.20E+03	6.13E+00	2.12E+03
Resource use, mineral and metals [kg Sb eq.]	3.31E-06	3.47E-08	4.47E-06	3.19E-08	7.84E-06
Water scarcity [m³ world equiv.]	1.39E+00	9.66E-03	1.75E+00	9.91E-03	3.16E+00
Energy use (mJ)	2.20E+01	1.39E-01	2.91E+01	1.45E-01	5.14E+01
- Non renewable	2.20E+01	1.39E-01	2.91E+01	1.45E-01	5.14E+01
- Renewable	6.94E-20	0.00E+00	9.25E-20	0.00E+00	1.62E-19
Secondary Materials Consumption (kg)	0	0	0	0	0

Table 35 - Germany - LCIA Results for Pavement with HMA

	GERMANY - ENVIRONMENTAL LIFE CYCLE IMPACT 1 m² ROAD PAVEMENT with HMA				
	A1-A3	A4-A5	B	C	TOTAL
Climate Change [kg CO2 eq.]	5.22E+01	1.62E-01	8.85E+01	1.44E-01	1.41E+02
Climate Change -biogenic [kg CO2 eq.]	7.54E-02	8.53E-04	1.56E-01	9.76E-04	2.34E-01
Climate Change -fossil [kg CO2 eq.]	5.20E+01	1.60E-01	8.80E+01	1.41E-01	1.40E+02
Climate Change -land use change [kg CO2 eq.]	9.26E-02	1.24E-03	1.94E-01	1.42E-03	2.89E-01
Acidification [Mole of H+ eq.]	1.48E-01	5.33E-04	2.35E-01	4.86E-04	3.84E-01
Eutrophication freshwater [kg P eq.]	7.69E-05	9.87E-07	1.55E-04	1.12E-06	2.34E-04
Eutrophication marine [kg N eq.]	3.47E-02	2.11E-04	5.87E-02	1.77E-04	9.38E-02
Eutrophication terrestrial [Mole of N eq.]	3.82E-01	2.45E-03	6.45E-01	2.10E-03	1.03E+00
Photochemical ozone formation - human health [kg NMVOC eq.]	1.12E-01	4.44E-04	1.81E-01	3.93E-04	2.94E-01
Respiratory inorganics [Deaths]	1.74E-06	5.49E-09	3.06E-06	5.65E-09	4.81E-06
Land Use [Pt]	2.16E+02	3.24E+00	4.33E+02	3.69E+00	6.56E+02
Resource use, energy carriers [MJ]	1.72E+03	4.09E+00	3.03E+03	4.66E+00	4.76E+03
Resource use, mineral and metals [kg Sb eq.]	3.63E-04	2.73E-08	5.97E-04	3.11E-08	9.60E-04
Water scarcity [m³ world equiv.]	4.57E+00	2.26E-03	5.65E+00	2.58E-03	1.02E+01
Energy use (mJ)	4.25E+01	9.70E-02	7.58E+01	1.11E-01	1.19E+02
- Non renewable	4.25E+01	9.70E-02	7.58E+01	1.11E-01	1.19E+02
- Renewable	4.73E-11	0.00E+00	7.78E-11	0.00E+00	1.25E-10
Secondary Materials Consumption (kg)	0	0	0	0	0

Table 36 - Germany - LCIA Results for Pavement with CRAB

	GERMANY - ENVIRONMENTAL LIFE CYCLE IMPACT 1m² ROAD PAVEMENT with CRAB as base course				
	A1-A3	A4-A5	B	C	TOTAL
Climate Change [kg CO2 eq.]	6.21E+01	2.57E-01	1.01E+02	2.71E-01	1.63E+02
Climate Change -biogenic [kg CO2 eq.]	1.03E-01	1.21E-03	1.80E-01	1.83E-03	2.86E-01
Climate Change -fossil [kg CO2 eq.]	6.21E+01	2.54E-01	1.00E+02	2.66E-01	1.63E+02
Climate Change -land use change [kg CO2 eq.]	1.17E-01	1.75E-03	2.51E-01	2.67E-03	3.72E-01
Acidification [Mole of H+ eq.]	1.87E-01	8.37E-04	2.96E-01	9.17E-04	4.85E-01
Eutrophication freshwater [kg P eq.]	1.03E-04	1.39E-06	1.90E-04	2.11E-06	2.97E-04
Eutrophication marine [kg N eq.]	4.04E-02	3.42E-04	6.93E-02	3.34E-04	1.10E-01
Eutrophication terrestrial [Mole of N eq.]	4.45E-01	3.94E-03	7.68E-01	3.95E-03	1.22E+00
Photochemical ozone formation - human health [kg NMVOC eq.]	1.32E-01	7.04E-04	2.19E-01	7.41E-04	3.52E-01
Respiratory inorganics [Deaths]	2.38E-06	8.16E-09	3.98E-06	1.06E-08	6.38E-06
Land Use [Pt]	3.13E+02	4.55E+00	5.44E+02	6.93E+00	8.69E+02
Resource use, energy carriers [MJ]	2.29E+03	5.76E+00	3.82E+03	8.80E+00	6.13E+03
Resource use, mineral and metals [kg Sb eq.]	7.31E-04	3.85E-08	9.28E-04	5.87E-08	1.66E-03
Water scarcity [m³ world equiv.]	5.44E+00	3.18E-03	7.31E+00	4.85E-03	1.28E+01
Energy use (mJ)	5.64E+01	1.37E-01	9.44E+01	2.08E-01	1.51E+02
- Non renewable	5.64E+01	1.37E-01	9.44E+01	2.08E-01	1.51E+02
- Renewable	9.60E-11	0.00E+00	1.21E-10	0.00E+00	2.17E-10
Secondary Materials Consumption (kg)	834+E03	0	834+E03	0	0

2. <u>Normalization and weighting according EF2.0 Methodology</u>

   In order to further understand the results obtained, the EF2.0 Methodology was used also to apply the provided way for weighting and normalizing the impacts. EF 2.0 with tox category for weighting and EF 2.0 Global Equivalent normalization, aimed at describing and quantitatively assessing the level of pressure to the environment at the global scale, were used. This exercise was useful to understand, in the next step, the most relevant impact categories.

   - **Grouping**

   No grouping was undertaken.

- **LCA Phase 4: Interpretation of results**

In this section, the results of LCI and LCIA are summarized and discussed as a basis for further conclusions and recommendations in accordance with the goal and scope definition of the study.

- **Identification of significant issues**

The table below shows the percentage change of the value of each impact category indicator of the C4O technologies with respect to the conventional pavement.

Table 37 - Comparison of Pavements with Conventional mix and CRABs

	Pavement with HMA	RSM_Pavement with CRAB	G_Pavement with CRAB
Climate Change [kg CO2 eq.]	100%	-17%	-16%
Climate Change -biogenic [kg CO2 eq.]	100%	-6%	-27%
Climate Change -fossil [kg CO2 eq.]	100%	-17%	-16%
Climate Change -land use change [kg CO2 eq.]	100%	-29%	-21%
Acidification [Mole of H+ eq.]	100%	-33%	-21%
Eutrophication freshwater [kg P eq.]	100%	-18%	-26%
Eutrophication marine [kg N eq.]	100%	-35%	-14%
Eutrophication terrestrial [Mole of N eq.]	100%	-36%	-14%
Photochemical ozone formation - human health [kg NMVOC eq.]	100%	-34%	-15%
Respiratory inorganics [Deaths]	100%	17%	-27%
Land Use [Pt]	100%	-17%	-31%
Resource use, energy carriers [MJ]	100%	-30%	-25%
Resource use, mineral and metals [kg Sb eq.]	100%	-17%	-50%
Water scarcity [m³ world equiv.]	100%	-19%	-16%
Energy use (mJ)	100%	-28%	-25%
- Non renewable	100%	-28%	-25%
- Renewable	100%	14%	-51%

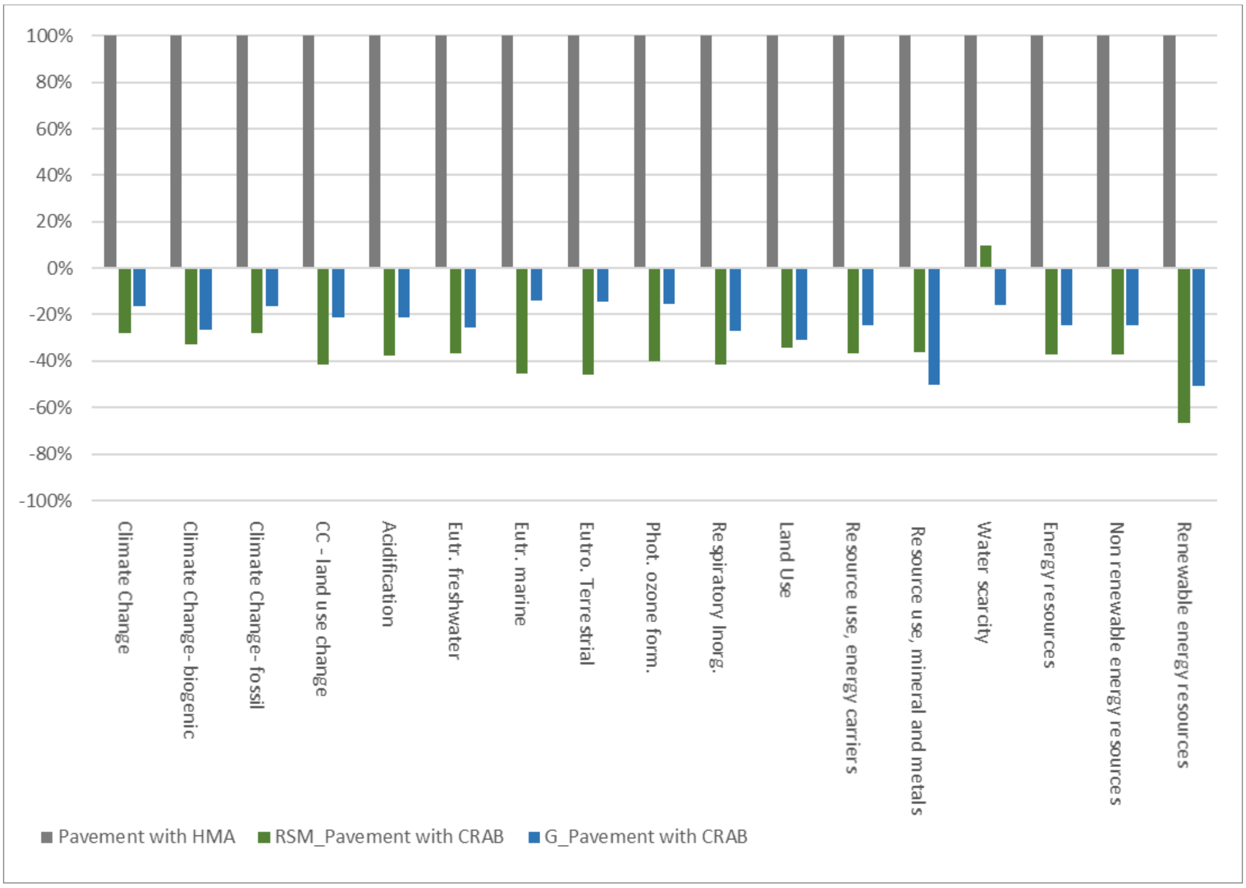


Figure 32 - Comparison between Pavements with HMA and Pavements with CRAB

Paying attention to the Table 37 and Figure 32, it is possible to underline that:

- In both cases, Pavements with CRAB are more environmentally performant than the pavements with conventional hot mix, in any environmental impact category, except for San Marino Case Study, for which Water scarcity and renewable energy resources increase. These results are mainly due to the fact that CRAB materials have got a very high quantity of reclaimed asphalt sourced from nearby and/or on-site location. Furthermore, in Germany, pavement with CRAB is composed of layer thinner than the conventional one, which means a reduction in terms of tons of HMA needed.
- For Germany, the highest decreases in terms of impacts can be seen on the Resource use, minerals and metals (-50%), Land use (-31%), on Respiratory Inorganics and Climate Change- biogenic (both -27%), Eutrophication freshwater (-26%), Energy Use and Resource Use- Energy carriers (both -25%).
- For Republic of San Marino, the highest decreases in terms of impacts can be seen on Eutrophication terrestrial (-36%), Photochemical Ozone Formation (-34%), Eutrophication marine (-35%), Acidification (-33%), Resource Use- Energy carriers (-30%).
- Furthermore, German Pavement with CRAB contains a higher quantity per ton of reclaimed asphalt than the Republic of San Marino, because of one ton of German CRAB contains 936 kg, while 845 kg are contained in one ton of CRAB_RSM.

- **Hotspot analysis**

According to the JRC Report (2018), hotspots in LCA are defined as those life cycle stages, processes and elementary flows cumulatively contributing at least 50% to any impact category. They become relevant when they cumulatively contribute almost to 80%.

The hotspot analysis was performed to know:

- the most relevant Life Cycle stage: all life cycle stages contributing cumulatively more than 80% to any impact category.
- Most relevant processes: all processes contributing cumulatively more than 80% to any impact category.
- Most relevant impact categories based on the normalized and weighted results. All impact categories cumulatively contributing to 80% of the total impact.

The life cycle stages included in the cradle-to-grave system under analysis are 1) Production (A1-A3), 2) Installation (A4-A5) and 3) Use (B3-B4) and 4) End-of-life (C1-C3). The analysis was performed for the pavements with both HMA and CRAB.

Firstly, the most contributing Life Cycle Stages were studied. In all the four analyses, as shown in Table 38, Table 39, Table 40 and

Table *41* , it's evident that the most impactful stages are the Production (A1-A3) and the Use (B): B is always a hotspot, that summed up with A1-A3 become relevant.

It can be explained because B phase, as standards require, contains the impacts linked to the production and installation of those materials needed for maintenance/refurbishment.

It can be stated that:

- On average, for Republic of San Marino Case Study, the production of Pavement with CRAB is less impactful than that one with HMA (33% vs 39%), as supposed. In fact, CRABs mixtures are manufactured at law temperatures during the mixing process, that's why the impacts linked to the production are reduced. Furthermore, the specific case study implies the production of one layer with conventional way and another in cold, while in Germany three layers are made of HMA, while just one is in CRAB. In fact, analyzing the average of impacts linked to A1-A3 of both German case study, the difference between the two pavements is almost trifiling (38% HMA, 36% CRAB).
- In San Marino, B always represents a hotspot (>56%), except for water scarcity in Pavement with CRAB and for Respiratory Inorganics for both pavements.
- Furthermore, A4-A5 is particularly linked with Climate Change- land use change, due to the use of diesel and fossil fuels.
- In Germany, A4-A5 and C1-C3 give a null contribution to the overall impact: they are influent compared with the burdens due to production and maintenance. Furthermore, the distance from plant/stockpile and site is almost irrelevant (2,9 km) and CRABs is produced in-situ, so a huge quantity of milled asphalt is not transported to stockpile, hence also these burdens are avoided.

Table 38 - Hotspot Analysis Conventional Pavement in Republic of San Marino

	ENVIRONMENTAL LIFE CYCLE IMPACT 1m² ROAD PAVEMENT with HMA			
	A1-A3	A4-A5	B	C
Climate Change [kg CO2 eq.]	42%	1%	57%	1%
Climate Change -biogenic [kg CO2 eq.]	41%	1%	57%	1%
Climate Change -fossil [kg CO2 eq.]	42%	1%	57%	1%
Climate Change -land use change [kg CO2 eq.]	37%	7%	55%	4%
Acidification [Mole of H+ eq.]	42%	1%	57%	1%
Eutrophication freshwater [kg P eq.]	40%	4%	56%	2%
Eutrophication marine [kg N eq.]	42%	2%	57%	1%
Eutrophication terrestrial [Mole of N eq.]	42%	2%	57%	1%
Photochemical ozone formation - human health [kg NMVOC eq.]	42%	1%	57%	0%
Land Use [Pt]	40%	4%	56%	2%
Resource use, energy carriers [MJ]	43%	0%	57%	0%
Resource use, mineral and metals [kg Sb eq.]	42%	1%	57%	0%
Water scarcity [m³ world equiv.]	44%	1%	55%	0%
Energy use (mJ)	43%	0%	57%	0%
- Non renewable	43%	0%	57%	0%
- Renewable	43%	0%	57%	0%
Secondary Materials Consumption (kg)	42%	1%	57%	1%

Table 39 - Hotspot Analysis Pavement with CRAB in RSM

	ENVIRONMENTAL LIFE CYCLE IMPACT 1 m² ROAD PAVEMENT with CRAB			
	A1-A3	A4-A5	B	C
Climate Change [kg CO2 eq.]	37%	2%	60%	1%
Climate Change -biogenic [kg CO2 eq.]	33%	2%	65%	1%
Climate Change -fossil [kg CO2 eq.]	37%	2%	60%	1%
Climate Change -land use change [kg CO2 eq.]	26%	11%	60%	7%
Acidification [Mole of H+ eq.]	38%	2%	60%	1%
Eutrophication freshwater [kg P eq.]	31%	5%	62%	3%
Eutrophication marine [kg N eq.]	35%	3%	62%	1%

Eutrophication terrestrial [Mole of N eq.]	35%	3%	62%	1%
Photochemical ozone formation - human health [kg NMVOC eq.]	38%	2%	61%	0%
Land Use [Pt]	32%	5%	62%	3%
Resource use, energy carriers [MJ]	39%	1%	60%	0%
Resource use, mineral and metals [kg Sb eq.]	35%	1%	64%	1%
Water scarcity [m³ world equiv.]	50%	1%	49%	0%
Energy use (mJ)	38%	1%	61%	0%
- Non renewable	38%	1%	61%	0%
- Renewable	18%	0%	82%	0%
Secondary Materials Consumption (kg)	37%	2%	60%	1%

Table 40 - Hotspot Analysis Pavement with HMA in Germany

	ENVIRONMENTAL LIFE CYCLE IMPACT 1m² ROAD PAVEMENT with HMA			
	A1-A3	A4-A5	B	C
Climate Change [kg CO2 eq.]	38%	0%	62%	0%
Climate Change -biogenic [kg CO2 eq.]	36%	0%	63%	1%
Climate Change -fossil [kg CO2 eq.]	38%	0%	62%	0%
Climate Change -land use change [kg CO2 eq.]	31%	0%	67%	1%
Acidification [Mole of H+ eq.]	39%	0%	61%	0%
Eutrophication freshwater [kg P eq.]	35%	0%	64%	1%
Eutrophication marine [kg N eq.]	37%	0%	63%	0%
Eutrophication terrestrial [Mole of N eq.]	36%	0%	63%	0%
Photochemical ozone formation - human health [kg NMVOC eq.]	37%	0%	62%	0%
Respiratory inorganics [Deaths]	37%	0%	62%	0%
Land Use [Pt]	36%	1%	63%	1%
Resource use, energy carriers [MJ]	37%	0%	62%	0%
Resource use, mineral and metals [kg Sb eq.]	44%	0%	56%	0%
Water scarcity [m³ world equiv.]	43%	0%	57%	0%
Energy use (mJ)	37%	0%	62%	0%
- Non renewable	37%	0%	62%	0%
- Renewable	44%	0%	56%	0%
Secondary Materials Consumption (kg)	38%	0%	62%	0%

Table 41 - Hotspot Analysis Pavement with CRAB in Germany

	ENVIRONMENTAL LIFE CYCLE IMPACT 1m² ROAD PAVEMENT with CRAB			
	A1-A3	A4-A5	B	C
Climate Change [kg CO2 eq.]	37%	0%	63%	0%
Climate Change -biogenic [kg CO2 eq.]	32%	0%	67%	0%
Climate Change -fossil [kg CO2 eq.]	37%	0%	63%	0%
Climate Change -land use change [kg CO2 eq.]	32%	0%	67%	0%
Acidification [Mole of H+ eq.]	38%	0%	61%	0%
Eutrophication freshwater [kg P eq.]	33%	0%	66%	0%
Eutrophication marine [kg N eq.]	37%	0%	63%	0%
Eutrophication terrestrial [Mole of N eq.]	37%	0%	63%	0%
Photochemical ozone formation - human health [kg NMVOC eq.]	38%	0%	62%	0%
Respiratory inorganics [Deaths]	36%	0%	64%	0%
Land Use [Pt]	33%	0%	66%	1%
Resource use, energy carriers [MJ]	36%	0%	64%	0%
Resource use, mineral and metals [kg Sb eq.]	38%	0%	62%	0%
Water scarcity [m³ world equiv.]	45%	0%	55%	0%
Energy use (mJ)	36%	0%	64%	0%
- Non renewable	36%	0%	64%	0%
- Renewable	37%	0%	63%	0%
Secondary Materials Consumption (kg)	32%	0%	67%	0%

Secondly, the hotspot analysis was performed to understand the most relevant impact categories.
It can be stated that:

- In all the four case studies, the most relevant impact categories are Resource use, mineral and fossil (around 37%) and Climate Change- land use change (around 22%). As showed in the previous hotspot analysis, the highest burdens are linked to the Production and Use stage and, hence, with the extraction of raw materials and production of asphalt mixtures (considered both in A1-A3 and in B for refurbishment of layers).

- **Sensitivity Analysis**

In order to understand how much the impacts are influenced by choices and parameters and in response to question three, a sensitivity analysis was performed about the contribution of transport distances (A4). To understand how much the increase of distances from the asphalt plant to the site contributes to the emissions, three scenarios were created. The distances considered are 50km, 100km and 200km.

For both case studies, Pavements at project level were compared with those ones whose distances were assumed as above for all the components to be transported. Both in Germany and in Republic of San Marino, as distances increase, also impacts become bigger, even if the increase of emissions incidence for CRAB pavement is lower than for HMA pavements. In fact:

- in San Marino, the variation range changes on average from 4% to 22% for CRAB Pavement and from 8% to 41% for HMA Pavement. Some impact categories are mostly affected, such as Climate Change- land use change (86% in CRAB Pavement and 172% in HMA Pavement), Eutrophication freshwater (45% in CRAB Pavement and 21% in HMA Pavement) and Land use (45% for CRAB Pavement and 80% for HMA Pavement).
- In Germany, the variation range changes on average from 4% to 16% for CRAB Pavement and from 5% to 22% for HMA Pavement. Some impact categories are mostly affected, such as Eutrophication terrestrial (45% in CRAB Pavement and 28% in HMA Pavement), Resource Use- Energy Carriers (33% in CRAB Pavement and 7% in HMA Pavement), Eutrophication marine (27% in CRAB Pavement and 44% in HMA Pavement), Eutrophication freshwater (27% in CRAB Pavement and 38% in HMA Pavement) and Climate Change- land use change (24% in CRAB Pavement and 33% in HMA Pavement).
- From this it was deduced that transport doesn't affect in a huge way the impacts: even if the distances increase, any impact category becomes a hotspot (contribution >50%) or relevant (contribution >80%), except for Pavement with CRAB in Republic of San Marino, where Climate Change- land use change, Eutrophication freshwater and Land Use become hotspot or relevant ad the distance increase at 100 km or 200 km. Climate Change- land use change becomes relevant (86%) for Pavement with HMA in San Marino when distance from site to plant increases at 200 km.
- Otherwise, it can be stated that HMA pavement in Germany is more affected by the increase of distances than the pavement with CRAB. In fact, for the first one the range goes from 4% to 16%, while for the second one from 5% to 22%. In Republic of San Marino, CRABs pavement seems to be more influenced than the Pavement with HMA. In fact, the range when a cold mixture is used goes from 8% to 41%, while when the conventional mixtures are used the range goes from 4% to 22%. It can be explained in relationship to the tons of CRAB to be transported for the binder course, which are more than the ones necessary for the layer constructed with a conventional mix.

In conclusion:

- Figure 33, Figure 34, Figure 35, it can be stated that the environmental impacts in both case studies are directly dependent on transport distances. In particular, most of the impact categories increase their values whenever transport distances increase.
- German Pavement with CRAB is the one with the lower impacts linked to the increase of distances. This is due to the use of in-situ recycling technique for CRAB, which implies a reduction in terms of emission linked to the transport of RAP from the plant to the site.
- On the contrary, Pavement with CRAB in Republic of San Marino is more influenced by the increase of transport distances because it is needed a higher quantity of

mixtures for a cold binder than for a HMA one: a major amount of materials needs to be transported at the site, which in turns corresponds to a significant higher number of trips.

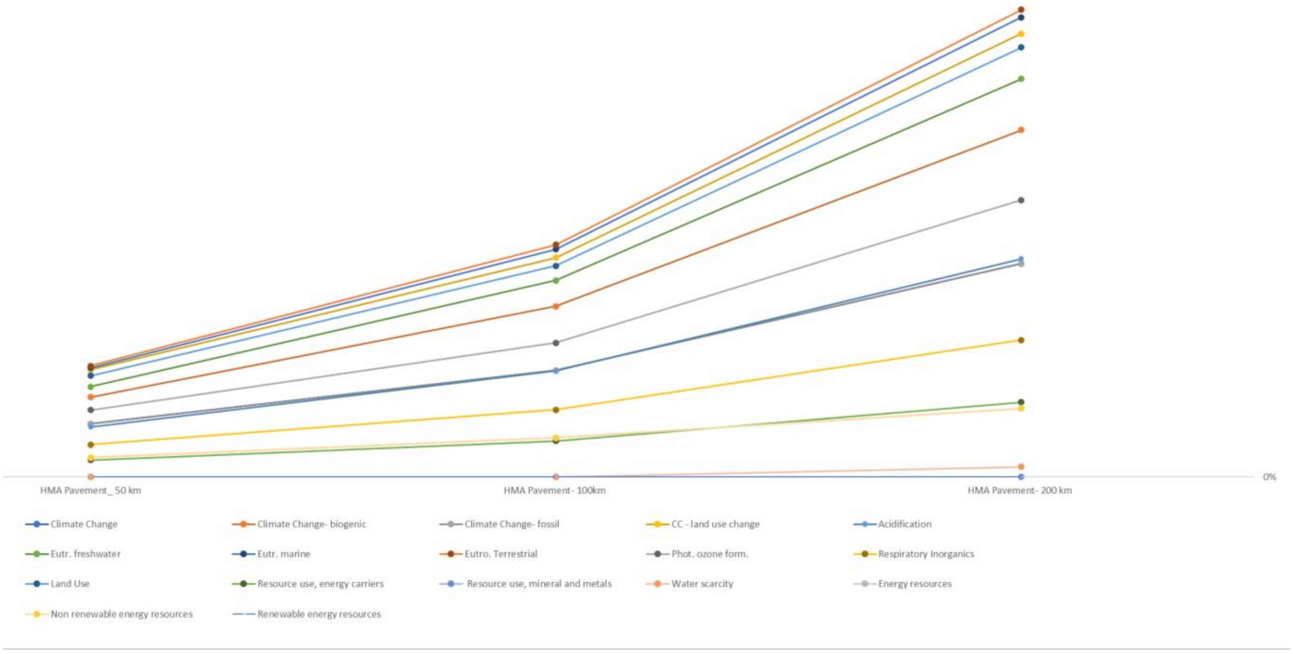


Figure 33 - How distances affect Pavement with HMA in Germany

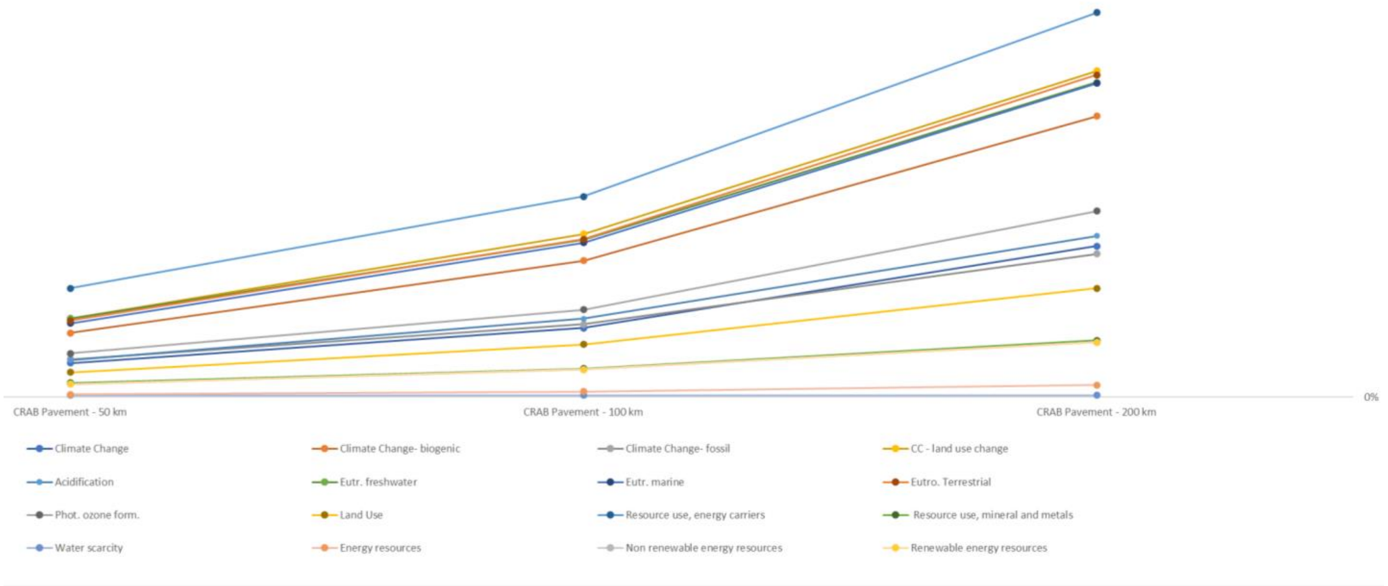


Figure 34 - How distances affect Pavement with CRAB in Germany

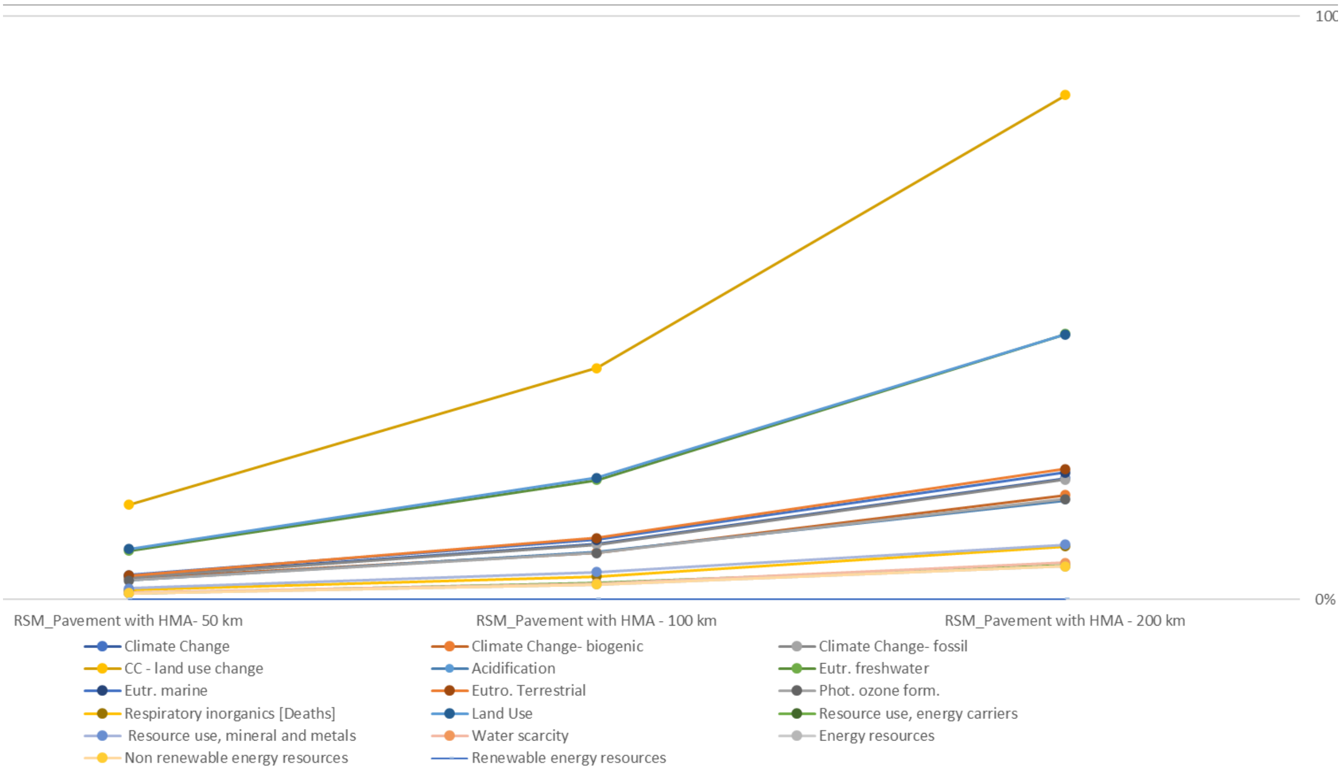


Figure 35 - How distances affect Pavement with HMA in Republic of San Marino

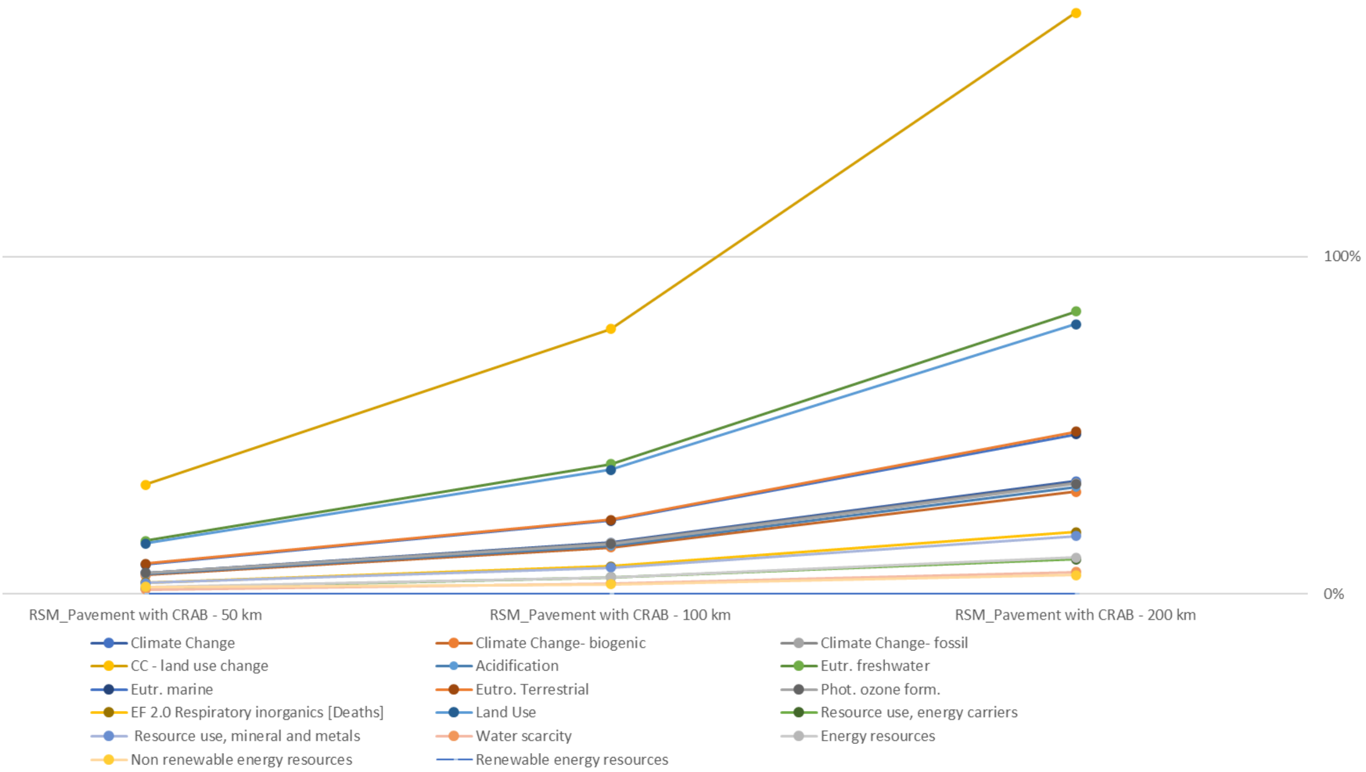


Figure 36- How distances affect Pavement with CRAB in Republic of San Marino

- **Sensitivity Check with Uncertainty Analysis**

  No sensitivity analysis was performed.

- **Consistency Check**

  The consistency check is done to investigate whether the assumptions, methods and data have been applied consistently throughout the LCI/LCA study.

  First of all, the consistency with Goal and Scope is assured. In fact, for instance, we can state that the functional unit, the impact categories chosen following the Pavement LCM Guidelines and system boundaries are all consistent with what stated in Goal and Scope.

  Secondly, the consistency with the LCI phase is assured too thanks to the data provided by the partners and specific for the case studies and responding to the requirements (see data quality). All the data were uploaded in GaBi database to perform the assessment.

  Thirdly, concerning the consistency for LCIA phase, the methodology and impact categories used are the same of those defined in Goal and Scope Definition. Furthermore, all the processes were included.

- **Completeness Check**

  According to ISO 14040, it is important to ensure that all relevant information and data needed for the interpretation are complete and available. As stated in the Goal & Definition phase, any cut-off rule was applied.

  In detail, it can be stated that:

  - all the LCI unit process coverage and system modeling are complete. In fact, the model is exactly created in GaBi ts according to the chosen system boundaries. No process was excluded;
  - Intermediate and elementary flow coverage are complete. The model is created with GaBi ts and all the unit processes contain the linked elementary flows;
  - Life Cycle Impact Assessment phase is complete. In fact, the following evaluations were done:
    - the selected impact categories are those one suggested by PavementLCM Framework, which is based on the actual suggestions by JRC and they cover the set of most relevant impacts potentially occurring;
    - Completeness of the model's elementary flows recorded in the inventory is assured and no significant elementary flows are excluded in the impacts calculation, as checked in GaBi database.

- **Conclusions, limitations and recommendations**

  This study aimed at understanding if road pavements with CRAB are more environmentally friendly than conventional ones, considering all the life cycle in a cradle-to-grave scenario (A1-C3) and considering both in-situ recycling and in-plant recycling.

  In order to carry out the analysis, two case studies were built and presented in the previous sections. These differ in terms of mix design and mix production of materials used, location, section dimensions and maintenance strategy.

  The case studies were built with the collaboration of several stakeholders and data from literature, and show how the use of cold technology is more environmental friendly. The results were calculated by using GaBi software and the EF2.0 methodology and following the Guidelines for Sustainability Assessment provided by PavementLCM Project.

As a result:

- The research shows that regardless of the whole Life Cycle, the environmental performance of **the investigated pavements with CRABs are between 15% and 60% lower than a pavement with HMA depending on the impact category**. Only the impact category "water scarcity" seems to be negatively affected when using CRABs (at least for the case study in Republic of San Marino). This can be explained by the fact that
  - CRABs are produced at ambient temperatures, hence, they need less energy than a conventional HMA.
  - Furthermore, CRABs contain a much higher amount of RA, a component with 0% of embodied environmental impacts.
  - Also, CRABs paving practices requires lower amounts of materials to be transported at the manufacturing/paving site, which in turns corresponds to a significant lower number of trips, hence an overall reduced impact of the transport phase (A2 and A2-B3).
- **The previous findings seem to be valid independently on the case studies**, hence for both in-situ recycling and in-plant recycling.
- The overall **environmental impact of pavement with CRABs remains lower than a base/binder with HMA, regardless of the fact that the use of CRABs implies a variation in the pavement design,** with an increase in the base/binder layers
- The hotspot analysis showed that **the most impactful stages is the Use phase (maintenance over 1 RSL)**. Specifically in all case study (with both HMA and CRABs) and for each life cycle stages, the recorded impact ranged between:
  - Production: 30-45%
  - Installation/Construction: 0-11%
  - Use (Maintenance over 1 RSL): 49-82%
  - End-of-life: 0-4%%
- From a tailored sensitivity analyses it was found that **also for road pavement with CRABs the increase of transport distances produces an almost linear increase of the environmental impacts**.

In general, appreciable emissions savings (at least 20%) can be observed for both case studies using CRABs. Hence, Pavements with CRAB are less impactful than pavements with HMA regardless of the manufacturing process and maintenance strategy

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2. Life Cycle Assessment of innovative paving activities with "FIBRA" technologies

2.1 Case study

The SYRAF report is part of the CEDR 2017 Call "New Materials" and one of each objectives is the performance of the Life Cycle Assessment of the solutions studied in FIBRA and CRAB4OERE following the common guide proposed by the project PavementLCM. In the present section, a LCA comparing two asphalt pavement sections implemented in the Netherlands as part of the scaling up and long-term monitoring activities proposed by the FIBRA project is presented.

Thus, as already mentioned, as part of the FIBRA project, BAM and its NRA, Rijkwaterstaat (RWS) built on August 2020 a test section in the A73 motorway. The pilot section included, among others, the following mixtures:

- A conventional 2L-PA8 mixture with PMB (styrelf 65/105-80 A AP) produced at a temperature of 185ºC.
- A Fibre-reinforced 2L-PA with penetration grade bitumen (70/100) and 0.15% of polyacrilonitrile fibres. This mixture was produced at 165ºC.

In the Netherland, a 2L-PA8 is a mixture with a maximum grain size of 8mm that is widely used on the primary road network. This mixture is designed with 25mm thickness and design air voids of 23%. Compared with a traditional single layer, this mixture has a smaller grain size and slightly higher air voids. Commonly an SBS PMB is used in this PA8.

During the production of the asphalt mixtures and the construction of the road sections, the following observations from the builders were considered in the LCA:

- The two mixes were designed with same aggregate type (Bestone), gradation and bitumen content (5.3%). The only difference between them is the type of bitumen and fibres if any.
- Regarding the fibre-reinforced mixture, a Polyacrylonitrile fibres with a length of 3.2mm was used at an application rate of 0.15% (w/wmixture). In addition, 0.15% cellulose fibre is added to the mixture to prevent binder drainage.
- The two mixtures for the A73 test sections were produced in the BAM asphalt plant BAC in Helmond. During the production of the mixtures, it was observed that the production temperature of the mixture with PMB is approximately 20ºC higher than that of the fibre-reinforced mixture.
- The two types of 2L-PA8 mixtures were constructed with a thickness of 25mm on top of a 45mm of standard 2L-PA16. The installation temperature of the FRAM was 10-20ºC lower than that of the control mixture with PMB.
- The compaction of the two sections was done using the same equipment and following the same standard procedures. No differences between compaction behaviour were observed.
- All mixtures were homogeneous without cluster.

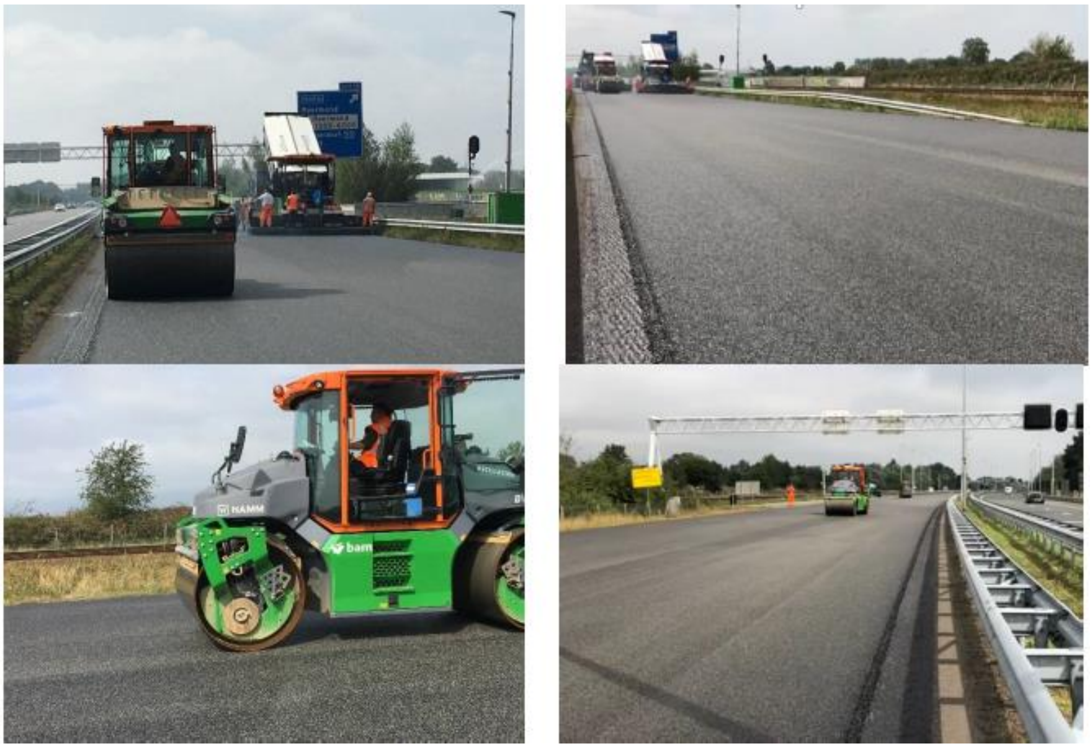

Figure 37. Laying and compaction process of FIBRA mixtures

- **LCA Phase 1: Goal and scope definition**

The goal of this study is to evaluate the feasibility from the environmental point of view of using fibres to extend the service life of asphalt mixtures. This is done by comparing the environmental impacts that a road section with a FRAM in the surface layer produced with the ones generated by a more traditional road section using a polymer modified bitumen in the surface layer. The study is carried out from the whole life cycle perspective (cradle-to-grave analysis).

The intended application of the results is to assist NRAs in the decision making concerning the use of fibre-reinforced asphalt mixtures to increase the service life of road pavements.

This study is part of the SYRAF project, funded by the CEDR under 2017 call "New Materials and Techniques" and is carried out following the PavementLCM framework. It is aimed at informing NRAs, road constructors and HMA providers about the comparative environmental performance of two competing technologies, Fibre-Reinforcement (FR) and Polymer modified bitumen (PmB).

- **Description of the object under study**

In the FIBRA project, a pilot section including 2 different surface layers were built for their long-term performance evaluation. These road sections are located in the A73 motorway (the Netherlands) with an AADT of 50000 vehicles. Both road sections include three asphalt layers: a 2L-PA8, an AC16 binder and an AC22 base. In alternative 1 (Table 42), the top layer in the 2L-PA8 uses a PmB. In alternative 2 (

Table 43), the top layer in the 2L-PA uses a 70/100 penetration grade bitumen and PAN fibres.

Table 42. Asphalt layers' composition in Alternative 1

	ALTERNATIVE 1			
	2L ZOAB 8 – Top layer PA8-PMB	2L ZOAB 8 Bottom layer PA16	AC 16 bin/base 30/45 60% RAP	AC 22 bin/base 30/45 60% RAP
PEN bitumen (%)	0	5.2	1.51	1.48
PMB bitumen (%)	5.3		0	0
Aggregate (%)	89.1	90.3	38.01	37.92
Filler (%)	5.6	4.2	0.29	0.29
Cellulose Fibre (%)	0	0.3	0	0
PAN fibre (%)	0	0	0	0
RAP (%)	0	0	60.19	60.31
Density (ton/m^3)	1.90	1.90	2.482	2.497
Thickness (m)	0.025	0.045	0.06	0.16

Table 43. Asphalt layers' composition in Alternative 2

	ALTERNATIVE 2			
	2L ZOAB 8 – Top layer PA8-PMB	2L ZOAB 8 Bottom layer PA16	AC 16 bin/base 30/45 60% RAP	AC 22 bin/base 30/45 60% RAP
PEN bitumen (%)	5.3	5.2	1.51	1.48
PMB bitumen (%)	0		0	0
Aggregate (%)	88.9	90.3	38.01	37.92
Filler (%)	5.6	4.2	0.29	0.29
Cellulose Fibre (%)	0.15	0.3	0	0
PAN fibre (%)	0.15	0	0	0
RAP (%)	0	0	60.19	60.31
Density (ton/m^3)	1.90	1.90	2.482	2.497
Thickness (m)	0.025	0.045	0.06	0.16

- **Functional unit and system boundaries**

The functional unit is defined as a 1m^2 of a one-way road pavement section of the A78 motorway in the Netherlands, where only the three asphalt layers are considered. The project analysis period is 26 years, beginning in 2020 with the construction of the three asphalt layers. The annual average daily traffic is 50,000 vehicles of which 20% are trucks. The asphalt pavement complies with noise suppression and type tests according to the Dutch technical requirements. The required service life of the asphalt pavement is 26 years.

A cradle-to-grave analysis is done mostly based on the stages defined in the standard UNE-EN-15804:2012+A2:2020. According to EN-15804:2012+A2:2019, the cradle-to-grave analysis cover the modules A, B, C and D. However, not all the stages B1 to B7 or C1-C4 have been considered in the study. Energy use for general management (i.e. office, laboratory) is excluded from the system boundaries.

- **Analysis period**

An analysis period of 26 years has been chosen. The specifications for the design of Asphalt pavements issued by Rijkswaterstaat in 20162 indicates an expected service life for a 2LPA with PMB of 9 years on the right slow lane and 13 years on the left lane. Given these figures, the standard maintenance protocol that is proposed in this analysis is to mill and overlay (M&O) the top PA8 layer in the right lane after 9 years and M&O the complete 2LPA system of both the left and right lanes in year 13. Afterwards, at year 22, the top layer of the left lane is M&O again and in year 26 the complete asphalt system (surface, binder and base course) is removed (Figure 38).

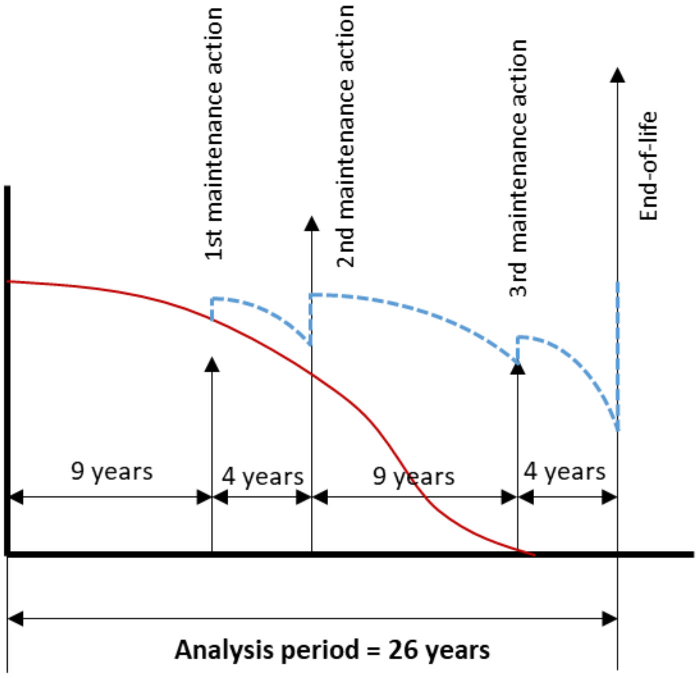

Figure 38. Schedule for maintenance works

- **Cut-off rules**

In the case of data gaps for a unit process, the cut-off criteria is 1% of renewable and non-renewable primary energy usage and 1% of the total mass input of that unit process.

- **Allocation procedure**

No allocation is needed in the processes corresponding to the asphalt plant or the road construction. However, along the LCI of the different processes involved in this LCA (i.e. bitumen

[2] Specificaties ontwerp Asfatverhardingen Dienst Grote Projecten en onderhoud, Juli 2016

production, diesel production, etc.), specific allocation procedures were applied by their creators (i.e. Eurobitume, ELCD, USLCI, etc.). From those processes available in the Ecoinvent database, the cut-off system model is used.

Concerning the allocation for recycling, the impacts associated with the processes involved in preparing the recycled materials for use in the asphalt mixture are considered part of the system boundary (i.e. crushing and screening of RAP to become RA). Regarding the RAP leaving the system, only transportation of the material to the recycling process is included.

- **Choice of indicators and characterization method**

The indicators have been chosen in agreement to the PavementLCM guidelines, as specified in Paragraph 3 of this deliverable. In this guideline, the EF Life Cycle Impact Assessment method is recommended with the addition of Energy Use and Secondary Materials indicators proposed in CWA17089.

- **Data requirements and Data Quality**

Different data sources have been used in this work. The asphalt mixtures recipes, densities and thicknesses, the energy consumption during the construction of the road sections and all the transportation distances were provided by the contractor (primary data). On the other hand, secondary data from professional databases were used for the rest of processes (see Table 44 to

Table ***49***). Finally, consumptions at the asphalt plant were estimated through a theoretical model. A data quality assessment is done using a pedigree matrix (Table 53).

- **Assumptions and limitations of the study**

Not included in the analysis:

  - B2 (common maintenance works) and B3 (repair) are not included in the analysis due to the difficulties to estimate the number of actions within the road service life. It is assumed that these works will be similar in the two alternatives.
  - B1 is not included. The particulate emissions related to surface wear are not included due to the lack of harmonized and accurate test methods for their measurement.
  - Possible consequences on traffic flow in B3, B4 and C1 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.

Concerning the life cycle inventory (LCI), the following data gaps/assumptions are declared:

  - Water consumed during the laying, compaction or milling process (A5, C1).
  - Ancillary materials in the asphalt plant or on the workzone (A3, A5 and C1).
  - In the RAP treatment (A1), only energy consumption during crushing and sieving is included. No data is available concerning diesel consumption for materials movement inside the plant.
  - No data is available concerning the waste generated during the production at the asphalt plant.

- Waste production during construction or dismantling processes is assumed zero, except for the asphalt or the RAP that are assumed 100% recyclable.
- Same dataset is used for both coarse and fine aggregates. A specific fraction of fine and coarse aggregates is used in the Ecoinvent dataset to create the process LCI.

Other limitations due to methodological choices:

The Environmental footprint 2.0 assessment method is used for the impact assessment. To explore the influence of this choice, other assessment methods will be applied in the sensitivity analysis.

Two asphalt mixtures used in one of the case studies of the FIBRA project were selected for this study (one FRAM and one polymer-modified asphalt mixture). This choice presents two limitations. The first one is that, in this case study, a 2-layer Porous Asphalt mixture (2LPA) is used and the fibre is only added to the top layer, with only 25mm thickness. This will have an impact on the cradle-to-gate analysis. The second one is that cellulose fibres were added to the FRAM. The use of these fibres is a common practice in the Netherlands when porous asphalt mixtures are used but its use is not generalized in other countries, and it is not used in other type of mixtures (i.e. asphalt concrete). To evaluate the impact of this on the LCA, the 2LPA surface will be substituted by a conventional 1-layer porous asphalt (PA) of 50mm thickness and no cellulose fibres are added to this mixture.

- **LCA Phase 2: Life Cycle inventory**

- **Data Collection**

- **Production stage (A1 to 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, cellulose fibres, polyacrylonitrile fibres) and their transportation to the asphalt plant as well as the manufacturing of the different asphalt mixtures. The processing of the secondary materials (i.e. RAP) is also included in this stage.

The formulas, thickness and density of the asphalt mixtures that are being studied are shown in Table 42 and
Table *43*. The sources for the LCI of the materials and processes considered in this stage are shown in Table 44.

Table 44. LCI Sources for the production stage

A1	Aggregates	Ecoinvent 3.8: Gravel production, crushed (RoW)
	Filler	Ecoinvent 3.8: Lime production, milled, loose
	Penetration grade bitumen	Eurobitume LCI, 2020
	Polymer modified bitumen	Eurobitume LCI, 2020 + Eurobitume LCI, 2012 (SBS + PmB milled process)
	Cellulose fibre	Ecoinvent 3.8: Cellulose fibre production (RoW)
	Polyacrylonitrile fibre	ELCD database
	RAP processing	UNPG, 2011c (UNPG , 2011)

A2	Truck transportation	Ecoinvent 3.8: Transport, freight, lorry, 16-32 ton, EURO 6 (RER)
A3	Asphalt mixture manufacturing	Thermodynamic model adapted from Peinado et al. (2011). Specific temperature data from Construction company were used for the calculation of energy consumption.
	Natural gas combustion	Ecoinvent 3.8: heat production, natural gas, at industrial furnace low-NOx >100kW (Europe without Switzerland)
	Electricity grid mix	Ecoinvent 3.8: Market group for electricity, low voltage (RER)
	Diesel combustion in building equipment	Ecoinvent 3.8: machine operation, diesel >= 18.64 kW and < 74.57 kW, low load factor
	PAH emissions to air during asphalt mixture production	The German Bitumen Forum 2016

The transportation distances corresponding to A2 stage are presented in *Table **45***.

Table 45. Distances to calculate transportation impact in module A2

Transportation of raw materials to the asphalt plant	Distance (Km)
Pen bitumen	115
PMB bitumen	530
Aggregates	150
Filler	150
Cellulose	100
PAN fibre	150

- **Construction stage (A4 to A5)**

The construction stage includes the transportation of the asphalt mixtures from the asphalt plant to the roadwork (A4) in addition to their paving and compaction operations (A5).

The sources for the LCI of the materials and processes considered in this stage are shown in Table 46 and

Table ***47***.

Table 46. LCI Sources for the construction stage

A2/A4	Truck transportation	Ecoinvent 3.8: Transport, freight, lorry, 16-32 ton, EURO 6 (RER)
A5	Energy consumption during laying and compaction (MJ)	Primary data from construction company (22,4MJ/ton of installed asphalt)
A5	Diesel combustion in paver and roller	Ecoinvent 3.8: machine operation, diesel >= 74.57 kW, high load factor

Table 47. Distances from the asphalt plant to the worksite

Transportation	Distance (Km)
Asphalt plant to A73	40

- **Use stage (B4)**

The impacts of this stage involve those related to the milling and overlay (M&O) of the wearing course. Processes included in the M&O operation are milling of the deteriorated asphalt layer, the transportation to the recovery centre, the production of the materials (A1, A2 and A3), their transportation to the roadwork (A4) and the construction of the new layer (A5). The sources for the LCI of the materials and processes considered in this stage are shown in Table 48 and

Table ***49***.

Table 48. LCI Sources for the use stage

B4	Milling process	Primary data obtained from a previous (Lizasoain-Arteaga, et al., 2019).
	Diesel combustion in milling machine	Ecoinvent 3.8: machine operation, diesel >= 74.57 kW, high load factor
	Truck transportation (RAP)	Ecoinvent 3.8: Transport, freight, lorry, 16-32 ton, EURO 6 (RER)
	Overlay process	Same as in A1 to A5

Table 49. Distances for the use stage

Transportation	Distance (Km)
Raw materials and asphalt mixtures (overlay process)	Same as A2 and A4
RAP transportation from worksite to recovery centre	40

- **End-of-Life stage (C1 & C2)**

End-of-Life stage involves the milling of the three asphalt layers from the road (C1) and the transportation of the RAP to the recovery centre (C2). The data for the processes here involved are already described in B4 (milling and RAP transportation).

- **Data Calculation**

Based on the selected functional unit, the mass of the of the raw materials (

Table ***51*** and

Table ***52***) that are needed to produce the asphalt mixtures and the mass of the different asphalt mixtures (Table 50) to be produced and installed in 1m^2 of the road pavement are calculated for the 26 years analysis period.

Table 50. Mass (ton) of HMA involved in each activity (for 1m2 asphalt pavement during its LC). For both alternatives in study

	Process	2L-PA Top layer	2L-PA Bottom layer	AC16 Binder	AC22 Base
Initial construction	Production & construction	4,88E-02	9,45E-02	1,47E-01	3,92E-01
Maintenance (year 9)	Milling	2,44E-02	0,00E+00	0,00E+00	0,00E+00

	Production & construction	2,44E-02	0,00E+00	0,00E+00	0,00E+00
Maintenance (year 13)	Milling	4,88E-02	9,45E-02	0,00E+00	0,00E+00
	Production & construction	4,88E-02	9,45E-02	0,00E+00	0,00E+00
Maintenance (year 22)	Milling	2,44E-02	0,00E+00	0,00E+00	0,00E+00
	Production & construction	2,44E-02	0,00E+00	0,00E+00	0,00E+00
End-of-life (year 26)	Milling	4,88E-02	9,45E-02	1,47E-01	3,92E-01

Table 51. Mass (ton) of raw materials involved in each activity (for 1m2 asphalt pavement during its LC). Polymer modified asphalt mixture

	PEN bitumen	PMB	Cellulose fibre	Filler	Aggregates	RAP
Initial construction	1,29E-02	2,58E-03	2,84E-04	8,30E-03	3,33E-01	3,25E-01
Maintenance year 9	0,00E+00	1,29E-03	0,00E+00	1,37E-03	2,17E-02	0,00E+00
Maintenance year 13	4,91E-03	2,58E-03	2,84E-04	6,74E-03	1,29E-01	0,00E+00
Maintenance year 22	0,00E+00	1,29E-03	0,00E+00	1,37E-03	2,17E-02	0,00E+00

Table 52. Mass (ton) of raw materials involved in each activity (for 1m2 asphalt pavement during its LC). Fibre-reinforced asphalt mixture.

	PEN bitumen	PMB	Cellulose fibre	Filler	Aggregates	RAP
Initial construction	1,55E-02	3,57E-04	8,30E-03	3,33E-01	7,31E-05	3,25E-01
Maintenance year 9	1,29E-03	3,66E-05	1,37E-03	2,17E-02	3,66E-05	0,00E+00
Maintenance year 13	7,50E-03	3,57E-04	6,74E-03	1,29E-01	7,31E-05	0,00E+00
Maintenance year 22	1,29E-03	3,66E-05	1,37E-03	2,17E-02	3,66E-05	0,00E+00

- **Data Quality**

The quality of the data is evaluated through a pedigree matrix. The Pedigree matrix is composed on five data quality indicators (reliability, geographical representativeness, temporal correlation, completeness and technological correlation). The data quality is then assessed scoring these indicators with a value from 1 to 5 being number 1 the highest quality and 5 the lowest.

For the datasets coming from Ecoinvent database, the pedigree matrix is already available for each data point on the unit process level. These data is used to estimate the uncertainty and calculating the cumulative uncertainty of the LCIs through Monte-Carlo simulation. In *Table **53***, and only for informative purposes, an estimated average representing the general data quality of each of the Ecoinvent processes used in this study is included.

For the rest of datasets, coming from primary data or from sources different from Ecoinvent, the data quality has been evaluated by completing the pedigree matrix based on the information provided by the source.

Table 53. Data Quality assessment through the Pedigree Matrix.

PROCESS	SOURCE	TYPE	Reliability	Completeness	Temporal correlation	Geographical representativeness	Technological representativeness	Comments
PEN bitumen	Eurobitume 2019	Second.	3	2	1	2	2	Eurobitume provides a pedigree matrix assessment for each foreground data. The uncertainty of each data is used in the uncertainty analysis in section o
SBS	Eurobitume 2012	Second.	5	3	5	4	5	Eco-profile of SBS. The international Institute of Synthetic Rubber Producers, I. Boustead & D.L. Cooper, July 1998
High shear milling	Eurobitume 2012	Second.	2	2	3	1	2	Data from plant (average energy consumption)
filler	Ecoinvent 3.7.1	Second.	1	3	4	2	4	Ecoinvent provides a pedigree matrix assessment for each flow. This matrix is later used in the uncertainty analysis by simapro. Here an estimated average is included.
Aggregates	Ecoinvent 3.7.1	Second.	1	3	3	2	2	Ecoinvent provides a pedigree matrix assessment for each flow. This matrix is later used in the uncertainty analysis by simapro. Here an estimated average is included.
Cellulose fibres	Ecoinvent 3.7.1	Second.	1	4	4	4	4	Ecoinvent provides a pedigree matrix assessment for each flow. This matrix is later used in the uncertainty analysis by simapro. Here an estimated average is included.
Polyacrylonitrile fibres	ELCD	Second.	2	2	5	2	2	Good overall data quality. The inventory is mainly based on industry data and completed with secondary data.
RAP processing	literature	Second.	2	2	2	2	2	Inventory created from 7 different recycling facilities including classification, crushing and screening. Representative of France national production.
Truck transportation	Ecoinvent 3.7.1	Second.	1	2	5	1	2	Ecoinvent provides a pedigree matrix assessment for each flow. This matrix is later used in the uncertainty analysis by simapro. Here an estimated average is included.

Gas consumption at plant	Model	Second.	3	3	3	2	3	Model. Different conditions have been simulated (i.e. moisture, heat losses, air/fuel excess). Average and SD data is included.
electricity consumption at plant	Literature	Second.	4	5	5	5	5	Literature (estimation)
Diesel consumption at plant	Literature	Second.	4	5	5	5	5	Literature (estimation)
Direct emissions to air (PAH)	Literature	Second.	2	3	5	4	4	Literature. Includes material handling, load-out and emissions prior to departure to the job site
laying and compaction	Constructor	Prim.	2	2	1	1	2	Average consumption during the experimental pilot section building
Milling	Constructor	Prim.	2	2	2	2	2	Average consumption
Electricity mix	Ecoinvent 3.7.1	Second.	1	2	5	4	3	Ecoinvent provides a pedigree matrix assessment for each flow. This matrix is later used in the uncertainty analysis by simapro. Here an estimated average is included.
Heat, Gas	Ecoinvent 3.7.1	Second.	1	1	5	2	1	Ecoinvent provides a pedigree matrix assessment for each flow. This matrix is later used in the uncertainty analysis by simapro. Here an estimated average is included.
Energy, diesel Paver, roller, milling	Ecoinvent 3.7.1	Second.	1	1	3	3	1	Ecoinvent provides a pedigree matrix assessment for each flow. This matrix is later used in the uncertainty analysis by simapro. Here an estimated average is included.
Energy, diesel Internal transport at plant	Ecoinvent 3.7.1	Second.	1	1	3	3	1	Ecoinvent provides a pedigree matrix assessment for each flow. This matrix is later used in the uncertainty analysis by simapro. Here an estimated average is included.

- **LCA Phase 3: Life Cycle Impact Assessment**

Results presented in Table 54 and

Table 55 quantify the cradle-to-grave environmental impacts of the two alternative asphalt pavements 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 Figure 39, the comparative life cycle impact assessment is shown.

Table 54. LCIA results for alternative 1 (PMB)

	ENVIRONMENTAL LIFE CYCLE IMPACT 1m^2 ROAD PAVEMENT				
	A1-A3	A4-A5	B	C	TOTAL
POF-HH (kg NMVOC eq)	9,0E-02	1,6E-02	5,5E-02	1,4E-02	1,8E-01
RI (disease inc.)	2,9E-06	3,8E-07	1,3E-06	3,4E-07	4,9E-06
ATF (mol H+ eq)	1,1E-01	1,8E-02	7,0E-02	1,6E-02	2,1E-01
EU-F (Kg P eq)	4,7E-03	3,4E-04	1,9E-03	3,3E-04	7,3E-03
EU-M (kg Neq)	2,6E-02	4,3E-03	1,5E-02	3,6E-03	4,9E-02
EU-T (mol N eq)	2,8E-01	4,7E-02	1,7E-01	4,0E-02	5,3E-01

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LU (Pt)	2,1E+02	7,0E+01	1,5E+02	7,0E+01	5,0E+02
WS (m3 depriv.)	3,5E+00	2,3E-01	3,2E+00	2,1E-01	7,1E+00
RU-energy (MJ)	1,2E+03	9,6E+01	7,1E+02	7,9E+01	2,1E+03
RU-metals (kg Sbeq)	8,8E-05	1,7E-05	5,1E-05	1,7E-05	1,7E-04
CC- FOS (kg CO2eq)	3,5E+01	5,8E+00	1,8E+01	5,3E+00	6,4E+01
CC - BIO (kg CO2eq)	3,3E-02	1,7E-03	1,7E-02	1,6E-03	5,4E-02
CC - LU (kg CO2eq)	1,2E-02	1,6E-03	5,7E-03	1,6E-03	2,1E-02
Total use of renewable primary energy resources (MJ)	3,6E+01	1,2E+00	1,4E+01	1,2E+00	5,3E+01
Total use of non-renewable primary energy resources (MJ)	1,3E+03	1,0E+02	7,4E+02	8,6E+01	2,2E+03
Use of secondary materials (ton)	3,3E-01	0,0E+00	2,8E-04	0,0E+00	3,3E-01

Table 55. LCIA results for alternative 2 (FIBRE)

	ENVIRONMENTAL LIFE CYCLE IMPACT 1m^2 ROAD PAVEMENT				
	A1-A3	A4-A5	B	C	TOTAL
POF-HH (kg NMVOC eq)	8,9E-02	1,6E-02	5,4E-02	1,4E-02	1,7E-01
RI (disease inc.)	2,9E-06	3,8E-07	1,3E-06	3,4E-07	4,9E-06
ATF (mol H+ eq)	1,1E-01	1,8E-02	6,4E-02	1,6E-02	2,0E-01
EU-F (Kg P eq)	4,7E-03	3,4E-04	1,9E-03	3,3E-04	7,3E-03
EU-M (kg Neq)	2,5E-02	4,3E-03	1,5E-02	3,6E-03	4,8E-02
EU-T (mol N eq)	2,7E-01	4,7E-02	1,6E-01	4,0E-02	5,2E-01
LU (Pt)	2,1E+02	7,0E+01	1,5E+02	7,0E+01	4,9E+02
WS (m3 depriv.)	2,8E+00	2,3E-01	1,8E+00	2,1E-01	5,0E+00
RU-energy (MJ)	1,2E+03	9,6E+01	7,1E+02	7,9E+01	2,1E+03
RU-metals (kg Sbeq)	8,7E-05	1,7E-05	5,0E-05	1,7E-05	1,7E-04
CC- FOS (kg CO2eq)	3,4E+01	5,8E+00	1,7E+01	5,3E+00	6,3E+01
CC - BIO (kg CO2eq)	3,5E-02	1,7E-03	2,0E-02	1,6E-03	5,8E-02
CC - LU (kg CO2eq)	1,2E-02	1,6E-03	5,5E-03	1,6E-03	2,1E-02
Total use of renewable primary energy resources (MJ)	3,6E+01	1,2E+00	1,4E+01	1,2E+00	5,3E+01
Total use of non-renewable primary energy resources (MJ)	1,3E+03	1,0E+02	7,5E+02	8,6E+01	2,2E+03
Use of secondary materials (ton)	3,3E-01	0,0E+00	4,3E-04	0,0E+00	3,3E-01

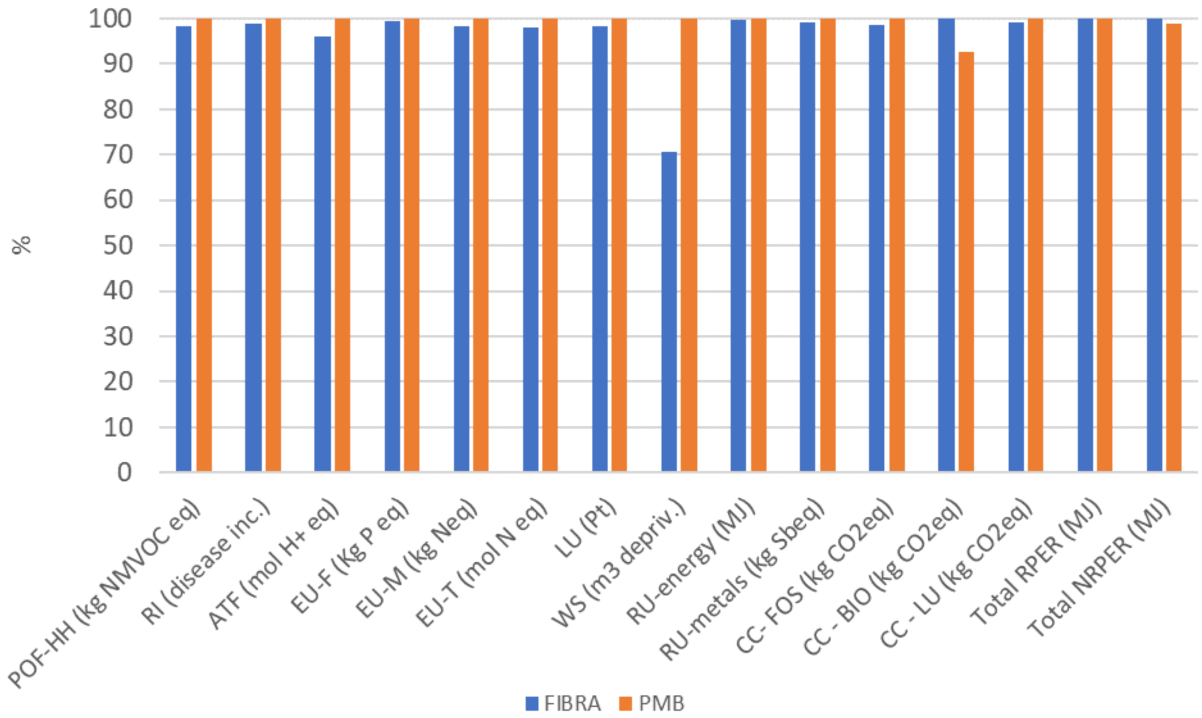

Figure 39. Comparative life cycle impact assessment of Alternative 1 and 2

- **Optional steps**
    - **Normalization and weighting**

In *Table 56* and *Figure 40* normalization and weighting according to the EF method 2.0 have been applied to previous results.

Table 56. LCIA normalized and weighted results for alternative 1 and 2.

	Alternative 1: PMB				**Alternative 2: FIBRA**			
	A1-A3	A4-A5	B	C	A1-A3	A4-A5	B	C
POF-HH (mPt)	1,1E-01	2,1E-02	7,0E-02	1,8E-02	1,1E-01	2,1E-02	6,7E-02	1,8E-02
RI (mPt)	4,3E-01	5,6E-02	2,0E-01	5,1E-02	4,3E-01	5,6E-02	1,9E-01	5,1E-02
ATF (mPt)	1,3E-01	2,1E-02	8,4E-02	1,9E-02	1,3E-01	2,1E-02	7,7E-02	1,9E-02
EU-F(mPt)	5,5E-02	4,0E-03	2,2E-02	3,8E-03	5,5E-02	4,0E-03	2,2E-02	3,8E-03
EU-M(mPt)	2,8E-02	4,7E-03	1,7E-02	4,0E-03	2,8E-02	4,7E-03	1,6E-02	4,0E-03
EU-T (mPt)	6,2E-02	1,0E-02	3,7E-02	8,8E-03	6,1E-02	1,0E-02	3,6E-02	8,8E-03
LU (mPt)	1,3E-02	4,4E-03	9,5E-03	4,4E-03	1,3E-02	4,4E-03	9,2E-03	4,4E-03
WS(mPt)	2,7E-02	1,8E-03	2,5E-02	1,7E-03	2,2E-02	1,8E-03	1,4E-02	1,7E-03
RU-energy (mPt)	1,7E+00	1,3E-01	9,7E-01	1,1E-01	1,7E+00	1,3E-01	9,7E-01	1,1E-01
RU-metals (mPt)	1,2E-01	2,3E-02	7,1E-02	2,3E-02	1,2E-01	2,3E-02	6,9E-02	2,3E-02
CC- FOS (mPt)	9,9E-01	1,7E-01	5,1E-01	1,5E-01	9,8E-01	1,7E-01	4,9E-01	1,5E-01

TOTAL (mPt)	3,63	0,44	2,01	0,39	3,61	0,44	1,96	0,39
LCA index (mPt)	6,48				6,41			

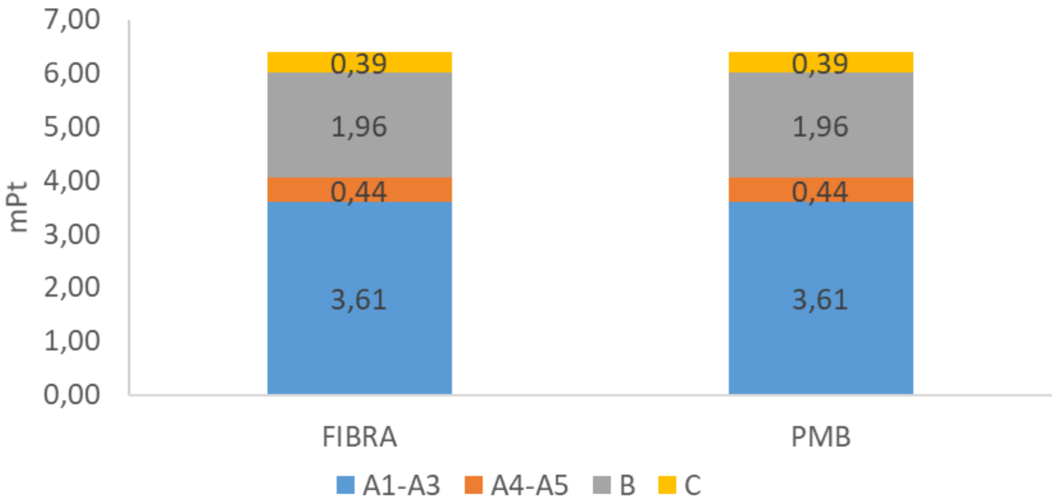

Figure 40. LCIA normalized and weighted results for alternative 1 and 2.

- **LCA Phase 4: Interpretation of results**

- **Hot Spot Analysis**

A hot spot analysis has been done for the LCA to identify the following items:

- Most relevant life cycle stages: all life cycle stages contributing cumulatively more than 80% to any impact category.
- Most relevant processes: all processes contributing cumulatively more than 80% to any impact category.
- Hotspots, considered as all life cycle stages, processes and elementary flows cumulatively contributing at least 50% to any impact category.
- Most relevant impact categories based on the normalized and weighted results. All impact categories cumulatively contributing to 80% of the total impact.
- According to the results, the most relevant life cycle stages (Table 57 and Table 58) are the same for both alternatives and include phase A1-A3 and phase B4. Concerning hot spots, the production phase (A1-A3) is the most impactful life cycle stages in almost all category impacts.
- On the other hand, the most relevant processes are shown in Table 59 and Table 60 for both alternatives. Similar results are obtained in both cases. Bitumen, cellulose and aggregates production, transportation and asphalt mix production are the 6 most relevant processes according to the definition mentioned above. Regarding hotspots, the processes with the highest contribution are bitumen production, transportation and hot mix asphalt production for the PMB alternative and the same for the FIBRA alternative including the cellulose production.

- If the most relevant impact categories are considered (Table 61), the most relevant processes in both cases are reduced to the bitumen and aggregates production, transportation and the asphalt production and the hot spots to bitumen production, transportation and asphalt mix production. Regarding the most relevant life cycle stages and hot spots, in alternative 1 (PMB), the most relevant stages would remain unaltered. The hot spots would be reduced to raw materials production and transportation both at the production stage (A1 to A3) and the use stage (B4).

Table 57. Alternative 1 (PMB): Most relevant life cycle stages contributing cumulatively at least 80% to each category impact (pink) and hotspots (red), including those contributing at least 50%.

	A1-A3	A4-A5	B4	C
POF-HH (kg NMVOC eq)	51,0	9,4	31,5	8,1
RI (disease inc.)	58,8	7,7	26,6	7,0
ATF (mol H+ eq)	51,7	8,3	32,8	7,3
EU-F (Kg P eq)	64,8	4,7	26,0	4,5
EU-M (kg Neq)	52,3	8,8	31,5	7,4
EU-T (mol N eq)	52,1	8,8	31,7	7,4
LU (Pt)	42,3	13,9	30,0	13,8
WS (m3 depriv.)	48,8	3,3	45,0	3,0
RU-energy (MJ)	57,7	4,6	33,9	3,8
RU-metals (kg Sbeq)	51,0	9,8	29,5	9,7
CC- FOS (kg CO2eq)	54,5	9,1	28,0	8,4
CC - BIO (kg CO2eq)	62,1	3,2	31,6	3,1
CC - LU (kg CO2eq)	58,0	7,7	26,8	7,5
Total use of renewable primary energy resources (MJ)	69,2	1,9	27,0	1,9
Total use of non-renewable primary energy resources (MJ)	57,5	4,7	33,8	3,9
Use of secondary materials (MJ)	99,9	0,0	0,1	0,0

Table 58. Alternative 2 (FIBRE): Most relevant life cycle stages contributing cumulatively at least 80% to each category impact (pink) and hotspots (red), including life cycle stages contributing at least 50%.

	A1-A3	A4-A5	B4	C
POF-HH (kg NMVOC eq)	51,3	9,5	30,9	8,2
RI (disease inc.)	59,0	7,7	26,2	7,0
ATF (mol H+ eq)	52,4	8,6	31,4	7,6
EU-F (Kg P eq)	65,0	4,7	25,7	4,5
EU-M (kg Neq)	52,6	8,9	30,9	7,6

EU-T (mol N eq)	52,5	8,9	31,0	7,6
LU (Pt)	42,4	14,1	29,4	14,1
WS (m3 depriv.)	55,2	4,6	36,0	4,2
RU-energy (MJ)	57,8	4,6	33,9	3,8
RU-metals (kg Sbeq)	51,2	9,9	29,1	9,8
CC- FOS (kg CO2eq)	54,8	9,3	27,4	8,5
CC - BIO (kg CO2eq)	60,0	3,0	34,2	2,8
CC - LU (kg CO2eq)	58,2	7,8	26,5	7,6
Total use of renewable primary energy resources (MJ)	69,1	1,9	27,0	1,9
Total use of non-renewable primary energy resources (MJ)	57,2	4,7	34,2	3,9
Use of secondary materials (MJ)	99,9	0,0	0,1	0,0

Table 59. Alternative 1: Most relevant processes (pink), contributing cumulatively more than 80% to any impact category and hotspots (red), including those processes contributing at least 50%.

	PEN production	PMB production	Cellulose production	Filler production	Aggregate production	RAP processing	Transportation	Asphalt mix production	Laying and compaction	Asphalt layer Milling	Tack coat production & application
POF-HH	17,8	10,6	0,3	1,1	7,5	2,7	33,9	19,7	2,5	3,8	0,1
RI	3,4	2,7	0,3	0,5	6,0	1,2	31,9	50,0	1,6	2,4	0,0
ATF	17,7	13,2	0,4	1,5	6,9	1,7	32,5	21,2	1,9	2,8	0,1
EU-F	0,0	0,0	0,5	3,8	7,0	0,6	23,5	63,5	0,5	0,7	0,0
EU-M	17,1	11,0	0,3	1,4	8,9	3,1	29,3	21,9	2,7	4,1	0,1
EU-T	17,1	11,0	0,3	1,5	10,8	3,1	29,1	20,2	2,7	4,1	0,1
LU	0,0	0,0	0,1	0,8	14,2	0,2	77,6	6,7	0,2	0,3	0,0
WS	12,0	37,5	0,4	10,5	7,5	0,2	15,5	15,4	0,3	0,5	0,1
RU-e	38,7	17,5	0,1	0,3	1,3	0,5	18,3	21,3	0,7	1,1	0,2
RU-m	0,0	0,0	0,9	1,0	21,0	-0,9	53,7	23,6	0,3	0,4	0,0
CC- F	5,8	4,2	0,1	0,6	2,8	1,3	39,2	41,6	1,7	2,6	0,0

CC - B	0,0	0,0	22,0	2,6	10,7	0,1	15,9	47,8	0,3	0,5	0,0
CC - L	0,0	0,0	0,3	2,6	7,2	0,7	40,7	47,4	0,4	0,6	0,0

Table 60. Alternative 2: Most relevant processes (pink), contributing cumulatively more than 80% to any impact category and hotspots (red), including those processes contributing at least 50%.

	PEN production	Cellulose production	Filler production	Aggregate production	PAN production	RAP processing	Transportation	Asphalt mix production	Laying and compaction	Asphalt layer Milling	Tack coat production & application
POF-HH	25,9	0,4	1,1	7,7	2,2	2,7	33,7	19,7	2,6	3,9	0,1
RI	4,9	0,4	0,6	6,1	0,7	1,2	31,5	50,0	1,6	2,4	0,0
ATF	26,4	0,6	1,6	7,2	2,6	1,8	33,1	21,2	2,0	2,9	0,1
EU-F	0,0	0,7	3,9	7,1	0,0	0,6	23,1	63,5	0,5	0,7	0,0
EU-M	24,9	0,5	1,4	9,1	2,8	3,1	29,2	21,9	2,8	4,2	0,1
EU-T	25,0	0,5	1,5	11,0	2,6	3,1	29,0	20,2	2,8	4,2	0,1
LU	0,0	0,2	0,8	14,4	0,0	0,2	77,2	6,7	0,2	0,3	0,0
WS	24,4	0,8	14,8	10,6	4,7	0,3	21,5	15,4	0,4	0,7	0,1
RU-e	55,6	0,1	0,3	1,3	1,3	0,5	17,9	21,3	0,7	1,1	0,2
RU-m	0,0	1,2	1,0	21,2	0,0	-0,9	53,1	23,6	0,3	0,4	0,0
CC- F	8,5	0,2	0,6	2,8	2,0	1,3	38,9	41,6	1,8	2,7	0,0
CC - B	0,0	28,3	2,4	9,9	0,0	0,1	14,4	47,8	0,3	0,5	0,0
CC - L	0,0	0,4	2,6	7,3	0,0	0,7	40,2	47,4	0,4	0,6	0,0

Table 61. Most relevant impact categories (after normalization and weighting). Alternative 1 (left) and alternative 2 (right).

	Most relevant impact categories Alternative 1			
	A1-A3	A4-A5	B	C
POF-HH	3,1	4,7	3,5	4,6
RI	11,9	12,7	9,7	13,0
ATF	3,6	4,7	4,1	4,7
EU-F	1,5	0,9	1,1	1,0
EU-M	0,8	1,1	0,8	1,0

	Most relevant impact categories Alternative 2			
	A1-A3	A4-A5	B	C
POF-HH	3,1	4,7	3,4	4,6
RI	11,9	12,7	9,7	13,0
ATF	3,6	4,7	3,9	4,7
EU-F	1,5	0,9	1,1	1,0
EU-M	0,8	1,1	0,8	1,0

EU-T	1,7	2,3	1,9	2,2
LU	0,4	1,0	0,5	1,1
WS	0,8	0,4	1,3	0,4
RU-energy	45,6	29,4	48,3	27,5
RU-metals	3,4	5,3	3,5	5,9
CC-F	27,3	37,4	25,3	38,6

EU-T	1,7	2,3	1,8	2,2
LU	0,4	1,0	0,5	1,1
WS	0,6	0,4	0,7	0,4
RU-energy	45,9	29,4	49,4	27,5
RU-metals	3,4	5,3	3,5	5,9
CC-F	27,2	37,4	25,0	38,6

- **Sensitivity Analysis**

Taking into account the hotspot analysis, cellulose production is considered a hotspot process in the life cycle impact assessment of the porous asphalt road pavement. As the use of cellulose and the two-layer Porous Asphalt are not as extended in Europe as they are in the Netherlands, a sensitivity analysis is carried out to evaluate the impact of this previous decision. To do so, instead of a two-layer Porous Asphalt, a one-layer porous asphalt (1L-PA) will be considered. This 1L-PA does not contain cellulose and its total thickness is 50mm. The results are shown in Figure 41. Although a very slightly higher difference between alternative 1 and 2 is observed, these differences are in most category impacts lower than 5%.

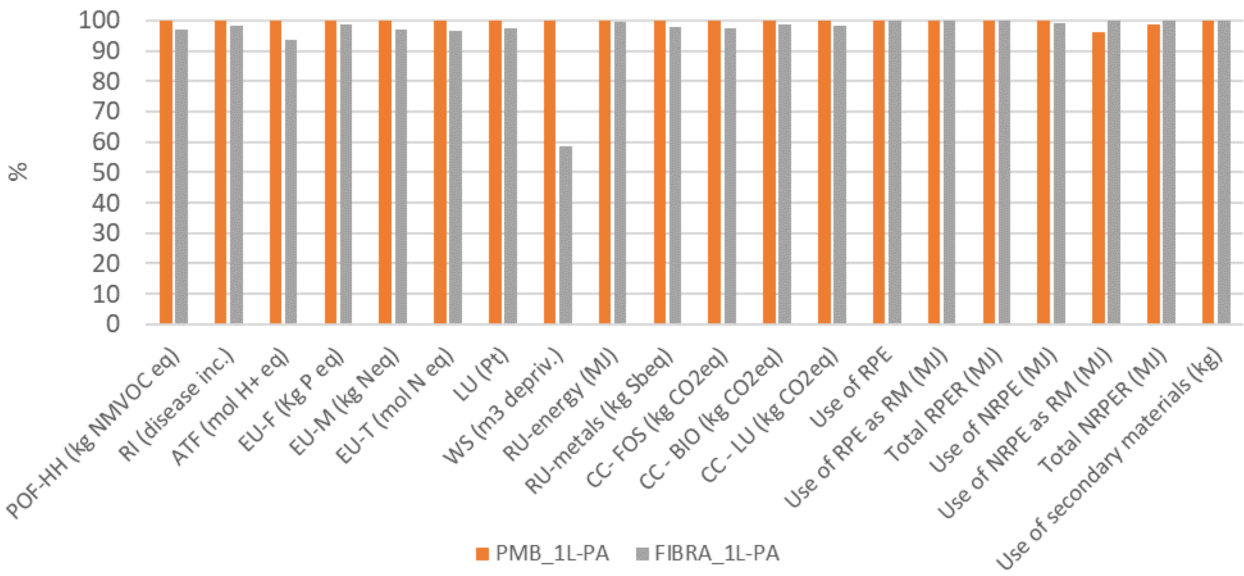

Figure 41. Comparative life cycle impact assessment of Alternative 1 and 2 considering a 1L-PA instead of a 2L-PA.

To evaluate the effect in the results of the selection of E.F v2.0 as the impact assessment method, a sensitivity analysis is done by choosing the ReCiPe end point impact assessment method. The results are shown in *Figure **42***. Similar results are obtained in most category impacts.

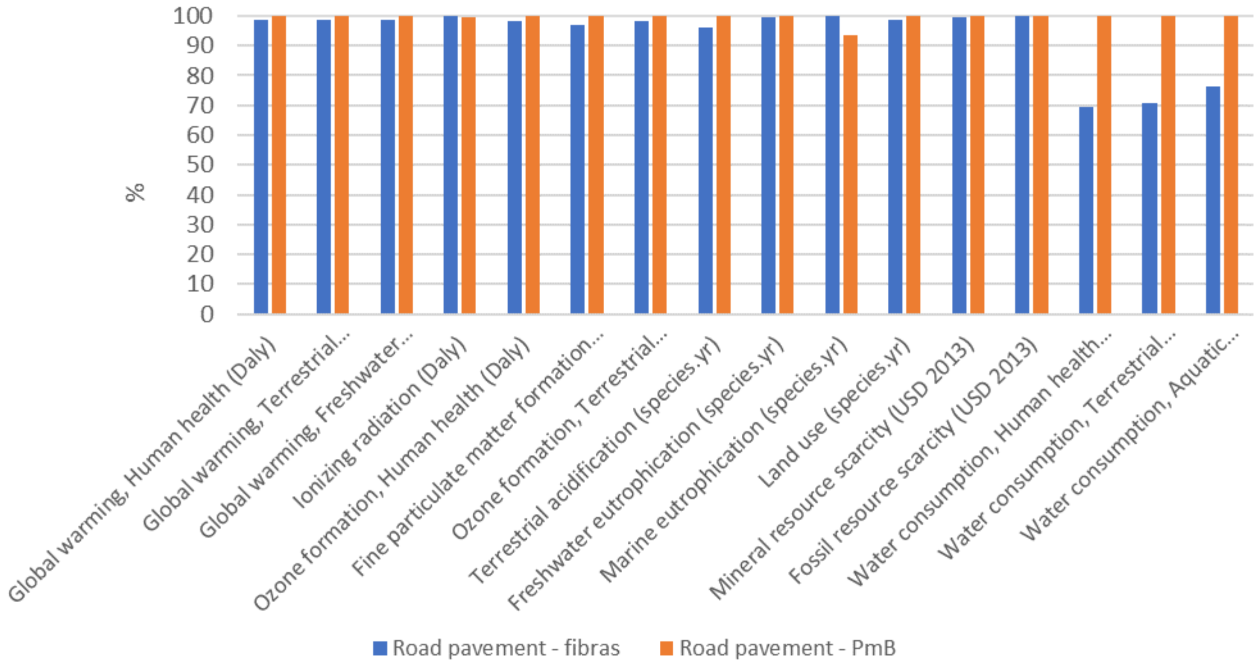

Figure 42. Comparative life cycle impact assessment of Alternative 1 and 2 with ReCiPe 2016 end-point impact assessment method

- **Uncertainty Analysis**

Ecoinvent database includes uncertainty data in all the datasets following a semi-quantitative approach based on the use of a pedigree matrix[3]. Two uncertainty parameters are used in this approach:

- The **basic uncertainty** relates to uncertainties coming from measurements or other specific variabilities of the process or activity. This factor can be calculated from statistical information of available real data. When not enough data is available to obtain statistical variability, Ecoinvent provides a table with basic uncertainty factors[4].
- The **additional uncertainty** that is the uncertainty due to the use of imperfect data. To obtain this factor, a pedigree matrix is applied to evaluate the data. The Pedigree matrix is composed on five data quality indicators (reliability, geographical representativeness, temporal correlation, completeness and technological correlation). The data quality is then assessed scoring these indicators with a value from 1 to 5 being number 1 the highest quality and 5 the lowest.

The scores obtained through the pedigree matrix are converted to uncertainty factors using the conversion tables include in the Ecoinvent data quality guideline[3]. The additional uncertainty factors and the basic factors are combined[2] to obtain a total uncertainty.

In this work, for those datasets coming from primary data or from sources different from Ecoinvent, the same approach has been considered. The basic uncertainty factor for all the flows and

[3]. Muller, S.; Lesage, P; Ciroth, A.; Muter, C.; Weidema, B.P.; Samson, R.; The application of the pedigree approach to the distributions foreseen in Ecoinvent v3. Int. J. Life Cycle Assess (2016)1:1327-1337.

[4] Weidema, B.P; Bauer, C.; Hischier, R.; Mutel, C.; Nemecek, T.; Reinhard, J.; Vadenbo, C.O.; Wernet, G.; Overview and methodology. Data quality guideline for the Ecoinvent database version 3. 2013

exchanges comprising the dataset has been estimated based on the figures proposed by Ecoinvent, except for the gas consumption in the asphalt plant where statistical data was available. Concerning the additional uncertainty, the figures of the pedigree matrix in *Table **53*** are used for all the intermediate and elementary exchanges and then converted to uncertainty factors using the conversion tables mentioned before. Finally, both basic and additional uncertainty factors are compiled to obtain the total uncertainty factor, which is input in Simapro.

With these uncertainties estimated for each data point on the unit process level, the cumulative uncertainty of the LCIs is calculated via Monte-Carlo simulation. It should be noted that he uncertainty analysis has been carried out only for the category impacts considered by EF method 2.0. This method is included in Simapro so the Monte-Carlo simulation can be done. Energy Use and Secondary Materials indicators proposed in CWA17089 are not considered.
Two different analyses have been done. In the first analysis, the individual uncertainty in the LCA index (after normalization and weighting) has been calculated for both alternatives (*Figure **43***). As expected, the result for both alternatives is similar. In the second analysis, the two alternatives are compared using the same variation in the data. It should be noted that in both alternatives almost all the raw materials and processes are common so a correlation in the uncertainty can be applied in Simapro. In *Figure **44***, it is shown how many times (from 1000 series repetitions) alternative 1 scored lower than alternative 2 on the different indicators. In most impact categories, the alternative incorporating PMB present a higher environmental impact than when fibres are used. However, the differences are not significant.

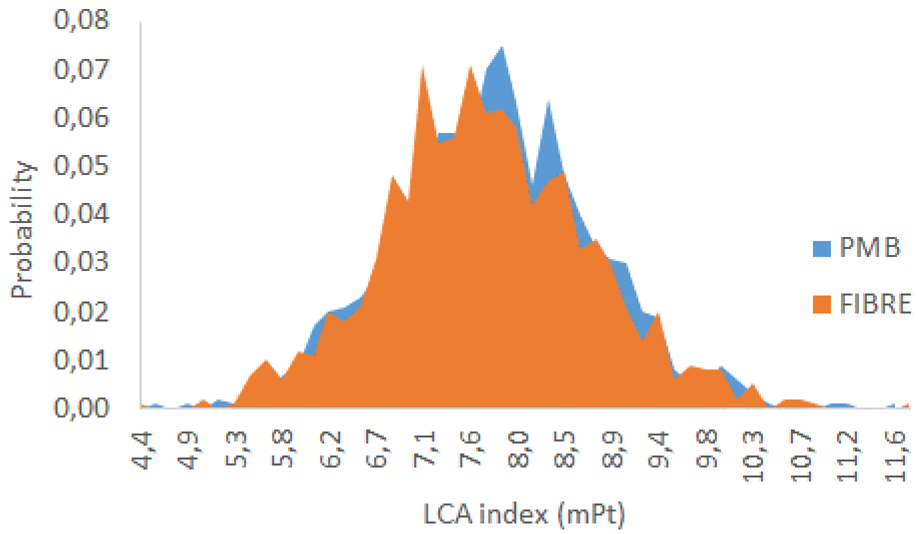

Figure 43. Distribution of the LCA index obtained after Monte-Carlo simulation for alternative 1 and 2.

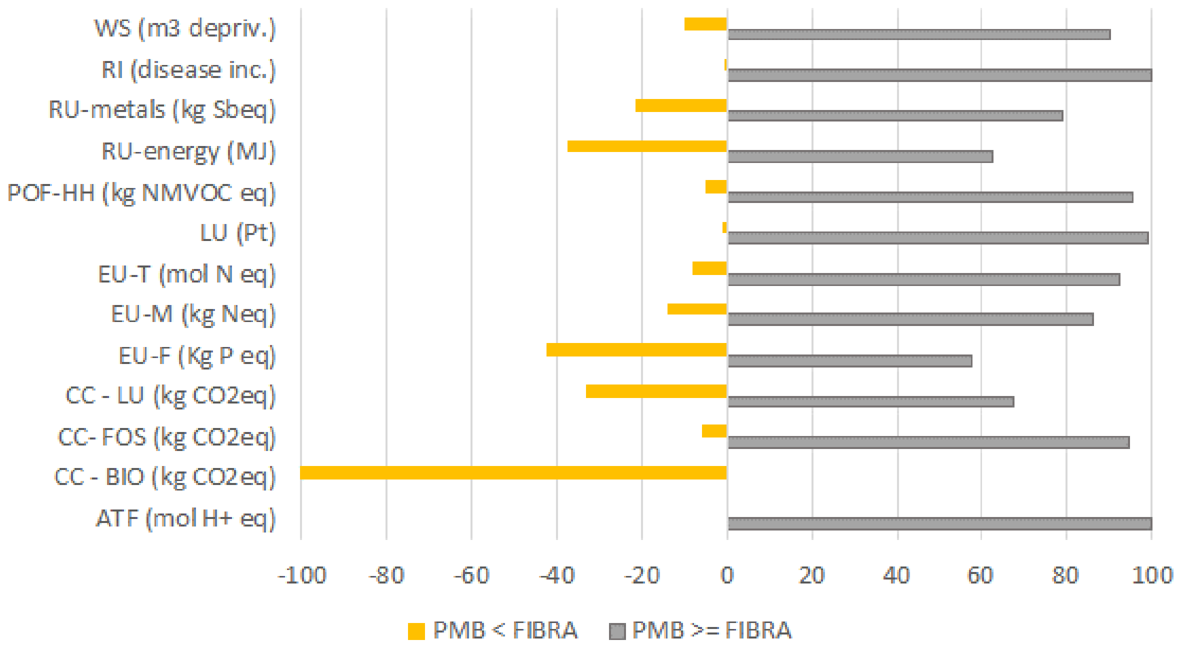

Figure 44. Comparative Monte-Carlo showing the percentage of the samples where PMB<FIBRA and PAM>=FIBRA.

- **Completeness, sensitiveness and consistency checks**

Consistency Check

The consistency check is done to investigate whether the assumptions, methods and data have been applied consistently throughout the LCI/LCA study.

- The functional unit and the system boundaries defined are consistent with the goal and scope of the study. The impact categories used are those defined in the goal and scope definition and in agreement with the PavementLCM guideline.
- The selected datasets from Ecoinvent and other assumptions made during the LCI are consistent with the allocation procedures defined at the goal and scope definitions. The data quality has also been assessed and included in the uncertainty analysis to take into account possible lack of quality or uncertainties in the data.
- Concerning the LCIA phase, the methodology and impact categories used are the same of those defined in the goal and scope definition.

Completeness Check

Based on the limitation already stated in the goal and scope definition section and on the hot spot analysis it can be stated that the completeness of the LCI is sufficient for reaching conclusions in accordance with the goal and scope definition.

Sensitivity Check with Uncertainty Analysis

The reliability of the final results and of the conclusions of this study has been checked through two different assessments. Firstly, through a sensitivity analysis by evaluating the effect on the results of changing some methodological choices and secondly, through an uncertainty analysis taking into account the uncertainty in the data.

- **Conclusions, limitations and recommendations**

In this study, following the guidelines proposed by PavementLCM SA framework, the environmental impact of using fibres to reinforce asphalt mixtures has been evaluated and compared to the impact of using polymer modified bitumen. To do so, a cradle-to-grave life cycle assessment has been carried out.

According to the PavementLCM guidelines, after the life cycle assessment and to further evaluate the overall robustness of the LCA, the interpretation phase has included a hotspot, a sensitivity and an uncertainty analysis.

Based on the obtained results, the following conclusions are drawn:

- Very small differences in the environmental impact of the two alternatives has been found.
- The most impactful stages in the life cycle of the road systems here considered are the production phase (A1-A3), with a contribution higher than 50% in almost all category impacts.
- The most impactful processes in both road systems are bitumen production, transportation and the asphalt mixture production.
- Uncertainty has been included in all processes that have turned to be the most impactful in the hot spot analysis. The Monte-Carlo simulation carried out confirmed the main conclusion of the study consisting of that both alternatives present very similar environmental impact.

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Conference of European Directors of Roads (CEDR)
Ave d'Auderghem 22-28
1040 Brussels, Belgium

Tel: +32 2771 2478
Email: information@cedr.eu
Website: http://www.cedr.eu

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