Delft University of Technology

Refurbishing Milled Asphalt into Pavements for Circular Infrastructure Development

Singh, Avishreshth; Varveri, Aikaterini; Berman, Daniel Gelardi; Laugesen, Jesper

DOI
10.1201/9781003402541-49

Publication date
2024

Document Version
Final published version

Published in
Bituminous Mixtures and Pavements VIII

Citation (APA)
Singh, A., Varveri, A., Berman, D. G., & Laugesen, J. (2024). Refurbishing Milled Asphalt into Pavements for Circular Infrastructure Development. In A. F. Nikolaides, & E. Manthos (Eds.), *Bituminous Mixtures and Pavements VIII* (1 ed., pp. 415-423). CRC Press. https://doi.org/10.1201/9781003402541-49

Important note
To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Copyright
Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy
Please contact us and provide details if you believe this document breaches copyrights.
We will remove access to the work immediately and investigate your claim.

This work is downloaded from Delft University of Technology.
For technical reasons the number of authors shown on this cover page is limited to a maximum of 10.

Green Open Access added to TU Delft Institutional Repository

'You share, we take care!' - Taverne project

https://www.openaccess.nl/en/you-share-we-take-care

Otherwise as indicated in the copyright section: the publisher
is the copyright holder of this work and the author uses the
Dutch legislation to make this work public.

Refurbishing milled asphalt into pavements for circular infrastructure development

A. Singh & A. Varveri
Section of Pavement Engineering, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, The Netherlands

D.G. Berman & J. Laugesen
Danish Technological Institute, Taastrup, Denmark

ABSTRACT: Refurbishing of milled asphalt into new bound layers of pavement is recognized as a sustainable maintenance practice. However, limited attention has been paid towards investigating their circularity aspects. Furthermore, evolving legislative requirements call for integration of circularity and sustainability facets. Therefore, this study presents a flexible framework that aims at assessing and integrating the environmental, economic, and circularity aspects associated with two maintenance alternatives, i.e., reconstruction of pavement with a bound base layer using bituminous materials (BSM) versus routine patch repair and resurfacing. The integration of different assessment categories was performed using a metric termed as net risk reduction gain (NRRG). The results revealed that the NRRG for BSM option was 2.5 times higher than routine maintenance over a 50 year analysis period, thereby emphasizing its higher circularity and sustainability benefits. The proposed framework is envisioned to pave way for integration of circular thinking along with sustainability considerations for pavement design and construction.

1 INTRODUCTION

Reclaimed asphalt pavement (RAP) refers to the material that is generated due to the processing of milled asphalt pavement extracted during maintenance and demolition (Yousefi et al., 2021). In general, RAP is composed of about 93-97% recycled aggregates and about 3-7% of asphalt cement. The addition of RAP as replacement of virgin aggregates results in production of mixtures that have low resistance to fatigue damage and high susceptibility to moisture induced damage (Tarsi et al., 2020). Hence, the RAP content in bituminous mixtures is typically restricted to 15-20%.

Despite these challenges, the recent technological advancements have allowed the use of high RAP contents in surface layer of bituminous pavements and also for the production of sustainable warm-mix asphalt mixtures (Tarsi et al., 2020). Researchers have suggested that use of RAP also results in lower environmental and economic aspects (Zhao et al., 2021). For instance, a study revealed that the use of 30% reclaimed binder in a bituminous mix results in higher environmental benefits and lower costs than mixes with 15% aged binder (Xiao et al., 2019). In addition, studies in Denmark and other countries across the world have shown that the incorporation of small quantity of foamed bitumen in the mixtures allows for 100% use of RAP in the bound layers of pavement (SR-Gruppen A/S, 2022; Zhao et al., 2021). Further, such pavement systems have been performing satisfactorily and cause lower environmental impacts over prolonged analysis periods. Another concept that is gaining attention is the circularity potential of pavement maintenance methods. In a cradle-to-gate study, a composite indicator that linked the environmental and circularity aspects indicated that the increasing content of RAP results in a more circular strategy (Mantalovas and Di Mino, 2020). However, this study did not capture the circularity potential over the full lifecycle as the use of high RAP content may result in premature failure, which would ultimately cause higher environmental and economic impacts.

Based on the literature, it was understood that though multiple studies have suggested that refurbishing of milled asphalt in bound layers of pavement is a sustainable strategy, limited attention has been paid to their circularity aspects. Further, there exists a vast scope to develop holistic frameworks that assist in integrating the environmental, economic, and circularity credentials. Therefore, the objective of this comparative research was to propose a simplified framework to evaluate the feasibility of two maintenance methods, namely, refurbishing milled asphalt in bound layers of pavement (BSM) and routine maintenance of patch repair and resurfacing (PRR) by integrating their sustainability and circularity credentials. It is envisioned that the current research will lay foundation for integration of circular thinking and sustainability considerations in roadway construction and maintenance.

2 METHODOLOGY FOR LIFECYCLE ASSESSMENT

This section presents the methodology adopted to integrate the environmental, economic, and circularity aspects. Further, the different key performance indicators (KPIs) that must be utilized for quantification of NRRG were elucidated.

2.1 *Goal and scope definition*

The goal of this study was to evaluate the feasibility of BSM versus routine PRR. This research involved quantification of environmental, economic, and circularity aspects, which were integrated into a single score using NRRG. The functional unit was selected as a single lane road 1000 m long and 3.5 m wide. For both scenarios, the thicknesses of surface wearing course constructed with stone matrix asphalt (SMA) and asphalt concrete binding base (ABB) layers were 0.034 m and 0.08 m, respectively. Further, the thickness of BSM base layer was 0.20 m.

In this study four different KPIs, namely, climate change-total, acidification, eutrophication-freshwater, and resource use-minerals and metals were used to report the environmental burdens as they contributed to more than 90% of the total impacts. Net present value and material circularity indicator were used as the economic and circularity KPIs, respectively. The analysis period was 50 years and the system boundary for two maintenance alternatives is presented in Figure 1. Further, the timeline for two maintenance methods were as follows: (a) BSM - reconstruction of base layer followed by resurfacing cycles once every 15 years for two cycles and last cycle being after 10 years of the second cycle, versus (b) routine PRR once in every five years on a pavement without a reconstruction of the old base layer. The mixtures for the construction of BSM and other pavement layers were prepared in an asphalt batch plant and later transported to the site.

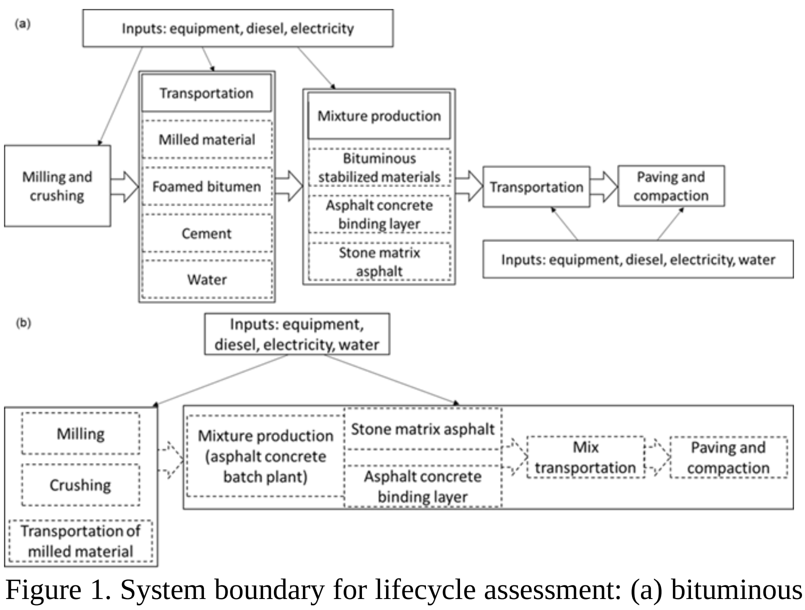

Figure 1. System boundary for lifecycle assessment: (a) bituminous stabilized materials, and (b) patch repair and resurfacing.

2.2 *Lifecycle inventory and impact assessment*

The inventory was produced by collecting data from both primary and secondary resources as discussed in the subsequent sections. The proportion of recycled materials used for the construction of BSM, ABB, and SMA layers were 94.6, 25, and 20% respectively.

2.2.1 *Environmental lifecycle assessment*

The environmental lifecycle assessment (ELCA) was performed in accordance with the International Standard Organization guidelines (ISO: 14040, 2006; ISO: 14044, 2006). The data sources included certified environmental product declarations, foreground data acquired directly from industry partners, and background modelling data provided by GaBi® and Ecoinvent® databases (GaBi Manual, 2022; Wernet et al., 2016). This data was used to model the elementary flows associated with each scenario and characterize the environmental impacts of each flow. The quality of data gathered for these cases was assessed to be between very good and fair. The inventory of all background data sets used in the modelling of BSM and PRR cases is presented in Table 1.

Table 1. Environmental lifecycle inventory.

Foreground data	Background data
Cement filler	Cement (CEM I 42.5) Portland cement
Binding coarse	Asphalt supporting layer (EN15804 A1-A3)
Wearing coarse	Stone mastic asphalt (EN15804 A1-A3)
Water	Tap water from groundwater
Hydrated lime (filler)	Calcium hydroxide ($Ca(OH)_2$); dry; slaked lime)
Road base aggregate	Gravel 2/32
Bitumen	Bitumen at refinery
Diesel	Diesel mix at filling station / at refinery
Heavy fuel oil	Heavy fuel oil at refinery (1.0wt. % S)
Running diesel equipment	Machine operation, diesel, steady state
Excavator	Excavator, 100kW, construction
Truck transport	Truck, Euro 6, 28-31t gross weight / 22t payload capacity
Ship transport	Container ship 5,000 to 200,000 dwt payload capacity, ocean going
Passenger car	Passenger car average, Euro 3-5, engine size from 1.4 l to 2.0 l

2.2.2 *Lifecycle cost assessment*

A deterministic lifecycle cost assessment (LCCA) was performed in this study using the framework specified by the Federal Highway Administration (Diependaele, 2018). The major inputs used for the construction of BSM, ABB, and SMA layers are presented in Table 2. Note that the costs associated with ABB and SMA construction include operations from milling the existing surface until road marking. The input values for estimation of road user costs were obtained from literature and International databases (CBS - Statistics Netherlands, 2018; Decò and Frangopol, 2011; Eurostat, 2022).

Table 2. Input values for construction of BSM, ABB, and SMA layers – agency costs.

Activity	Component	Data inputs
Milling operation	Milling charges per lane km	13440 Euros
Crushing operation	Crushing charges	3000 Euros per 10 h
Transportation of milled material to asphalt mix plant	Transportation charges	127.7 Euros per trip
	Vehicle payload capacity	38 t
	Density of recycled material	2350 kg/cu.m
Transportation of foamed bitumen to asphalt mix plant	Distance	300 km
	Density of foamed bitumen	1000 kg/cu.m
Mix proportions – BSM	Binder content	2.20%

	Cement filler	0.8% by volume of mix
Production and transportation – BSM mix	Water	2.5%
	Production cost of asphalt concrete	106.24 Euros/t
	Speed of laying mix	1200 m/h
	Charges for pneumatic tired roller	270 Euros/h
	Charges for static steel wheel roller	16.94 Euros/h
Construction of ABB layer	Construction charges for ABB including milling	125 Euros/t
	Binder content	5%
Construction of SMA layer	Construction charges for SMA including milling	161 Euros/t
	Binder content	7.2%
Patch and repair – ABB	Patch area per lane km	4%
	Total (length × width × thickness)	58.34 × 2.40 × 0.06 m

2.3 *Circular economy and resource efficiency*

Material Circularity Indicator (MCI) is a quantitative metric (mass-based KPI) developed by the Ellen McArthur's foundation to assess the flow of materials at product and company levels (Ellen MacArthur Foundation, 2019). MCI is assigned a score between 0 and 1, where score 1 indicates 100% restorative flow, and score 0 indicates 100% linear flow. In general, MCI is composed of:

- Utility factor (X), which is a measure of the length and intensity of the product's use in comparison with the average industry practice, and is computed using Equation 1.
- Linear flow index (LFI), which indicates the proportion of materials extracted from virgin feedstock and discarded as unrecoverable waste. It is expressed using Equation 2.
- The MCI combines these two indices and is given by Equation 3.

$$X = \frac{Length\ of\ use}{Industry\ average\ length\ of\ use} \times \frac{Functional\ use\ achieved}{Industry\ average\ functional\ use} \quad (1)$$

$$LFI = \frac{Mass\ not\ from\ reuse\ or\ recycling + Mass\ of\ unrecoverable\ wate}{2 \times Product\ mass + Factor\ for\ waste\ generated\ during\ recycling} \quad (2)$$

$$MCI = Maximum\ (0{,}1 - LFI \times \frac{0.9}{X}) \quad (3)$$

The different inputs used for the BSM and PRR scenarios are presented in Table 3. In the absence of primary information on efficiency of recycling process, the data was collected from literature that discussed about sustainability assessment of reclaimed asphalt mixtures (Mantalovas and Di Mino, 2020). Further, the industry average lifespan for the BSM, ABB, and SMA layers was considered as 15 years.

Table 3. Circularity related input values for BSM, ABB, and SMA layers.

Component	Quantity	Unit
BSM scenario		
Mass of recycled material (BSM)	1358	tonne
Mass of recycled material (ABB)	165	tonne
Mass of recycled material (ABB – patch repair)	4.94	tonne
Mass of recycled material – SMA	55.93	tonne
Efficiency of recycling process at the end of use phase	98	%
Efficiency of the recycling process to produce recycled feedstock	100	%
Patch repair and resurfacing scenario		
Mass of recycled material (ABB – patch repair)	4.94	tonne
Mass of recycled material – SMA	55.93	tonne
Efficiency of recycling process at the end of use phase	98	%
Efficiency of the recycling process to produce recycled feedstock	100	%

2.4 *Computation and integration of key performance indicators*

To rank the two maintenance alternatives, net risk reduction gain (NRRG) was selected as the metric to integrate the KPIs into a single score (see Equation (4)). Further, the values of KPIs for the different assessment categories were calculated by using a linear ranked interpolation method. It is important to mention that the metric NRRG and associated computation methodologies were developed as part of another research (Sheils and Connolly, 2023; Varveri et al., 2023) that aimed at quantifying the technical performance risks associated with different maintenance methods along with sustainability and circularity considerations. The KPI for assessing the risk is given by risk reduction index (RRI) and more details on its computation methodology can be found elsewhere (Varveri et al., 2023). Based on discussions with the maintenance agencies, it was understood that the BSM option was equally efficient in maintaining the pavement's performance characteristics as that of frequent PRR. Therefore, the computations associated with the technical performance KPI, i.e., RRI were not included for quantifying the NRRG. Furthermore, the weights for different KPIs were collected based upon their relative importance as per the recommendations of different roadway stakeholders that encompassed engineers, scientists, and policy makers.

$$NRRG_i = w_1 \times RRI_i + w_2 \times KPI_{1,i} + w_3 \times KPI_{2,i} + w_4 \times KPI_{3,i} + \cdots. \tag{4}$$

Where,
RRI = risk reduction index
$KPI_{3,4,5\ldots,i}$ = value of each KPI associated with maintenance/construction option, and
$w_{1,2,3\ldots}$ = value of weights for each KPI. Note that the sum of weights must be 1.0.

3 RESULTS AND DISCUSSIONS

3.1 *Environmental lifecycle assessment*

The ELCA results for the different environmental KPIs over the analysis period of 50 years are shown in Table 4. A single BSM treatment on 1 lane-km resulted in emissions of 106.92 kg CO_2 eq. compared to 21.05 kg CO_2 eq. for one treatment of PRR. carbon dioxide emissions for single applications each of BSM and patch repair and resurfacing. Note that these carbon emissions must not be confused with the total climate change impacts, which are expressed as carbon dioxide equivalent due to burning of fossil fuels, biogenic, and land use change over the analysis period of 50 years. Despite the higher impacts of BSM per cycle, the maintenance of asphalt pavements by PRR resulted in highest impacts for the given analysis period of 50 years, attributed to the reduced frequency of maintenance activities. In BSM scenario, the highest emissions were attributed to the production of binder layer and bitumen (for BSM base production) whose magnitudes were 38.29 kg CO_2 eq. and 24.64 kg CO_2 eq., respectively. The hotspot in PRR scenario was the construction of wearing course, which accounted for 85.60% of the total emissions attributed to the use of bitumen and cement filler.

Table 4. Environmental impact scores for BSM and patch repair and resurfacing scenarios.

Impact indicators	Units	BSM	Patch repair and resurfacing
Climate change – total	kg CO_2 eq.	170927	212419
Acidification	Mole of H+ eq.	670	719
Eutrophication, freshwater	kg P eq.	0.276	0.397
Resource use, mineral and metals	kg Sb eq.	0.029	0.036

3.2 *Lifecycle cost assessment*

A discount rate of 4% was used and the different lifecycle costs are presented in Table 5. The initial construction cost of BSM was 2.05 times higher than routine maintenance attributed to the reconstruction of base and ABB layers. However, for the analysis period of 50 years, the total lifecycle cost associated with PRR was about 1.83 times greater than BSM technology. In particular, both vehicle operation and delay costs for BSM were about 59% lower than PRR option.

Table 5. Breakdown of maintenance costs.

Maintenance alternative	Agency costs (Million Euros)	Vehicle operating costs (Million Euros)	Delay costs (Million Euros)	Total NPV (Million Euros)
BSM concept	0.37	0.52	0.31	1.20
Patch repair + resurfacing	0.18	1.27	0.75	2.20

3.3 *Circular economy and resource efficiency*

The different inputs used for the computation of MCI for BSM and PRR scenarios are presented in Tables 6 and 7, respectively. The higher MCI for BSM scenario is attributed to the lower frequency of maintenance activities during its design life, which was consequential of lesser virgin material consumption. Further, an MCI of '0' for the PRR scenario is indicative of completely linear flow majorly ascribed by the short service life of surface and intermediate layers, which call for frequent maintenance (every 5 years). As a result, higher proportions of virgin raw materials are consumed during the design life of pavement.

Table 6. Value of material circularity indicator for bituminous stabilized materials scenario.

Maintenance cycle		0	15	30	40	0	15	30	40
Component \ Material	BSM	ABB				SMA			
Mass of virgin feedstock (tonne)	77.49	493.5	14.81	14.81	14.81	223.72	223.72	223.72	223.72
Mass of finished product (tonne)	1435	658	19.74	19.74	19.74	279.65	279.65	279.65	279.65
Amount of waste going to landfill or energy recovery (tonne)	0	0	0	0	0	0	0	0	0
Waste generated at the end of recycling process (tonne)	28.70	13.16	0.39	0.39	0.39	5.59	5.59	5.59	5.59
Waste generated to produce recycled feedstock (tonne)	0	0	0	0	0	0	0	0	0
Amount of unrecoverable waste (tonne)	14.35	6.58	0.20	0.20	0.20	2.80	2.80	2.80	2.80
Product lifespan (years)	50	15	15	10	10	15	15	10	10
Industry average lifespan (years)	50	15	15	15	15	15	15	15	15
Utility	1	1	1	0.67	0.67	1	1	0.67	0.67
Linear flow index	0.52	0.38	0.38	0.38	0.38	0.41	0.41	0.41	0.41
MCI	0.97	0.66	0.66	0.48	0.48	0.63	0.63	0.45	0.45
					Average MCI_{BSM}	0.60			

Table 7. Value of material circularity indicator for patch repair and resurfacing scenario.

Component \ Material	ABB	SMA
Mass of virgin feedstock (tonne)	14.81	223.72
Mass of finished product (tonne)	19.74	279.65
Amount of waste going to landfill or energy recovery (tonne)	0	0
Waste generated at the end of recycling process (tonne)	0.39	5.59
Waste generated to produce recycled feedstock (tonne)	0	0
Amount of unrecoverable waste (tonne)	0.20	2.80
Product lifespan (years)	5	5
Industry average lifespan (years)	15	15
Utility	0.33	0.33
Linear flow index	0.38	0.41
MCI	0	0
Average $MCI_{\text{patch repair and resurfacing}}$	0	

3.4 *Computation and integration of key performance indicators*

The KPI values for the different indicators were computed in the Excel® toolkit using the methodology explained in Section 2.4 and their results are presented in Table 8. Note that a higher KPI value is indicative of more beneficial maintenance strategy and vice-versa. The weights corresponding to different KPIs are also presented in Table 8. As per the current legislations, low economic expenditure and high recyclability are the critical parameters to promote the transition of roadway sector from linear to circular economy. Therefore, NPV and MCI were assigned higher weights than other environmental KPIs.

Table 8. Key performance indicators for pavement maintenance methods and associated weights.

Key performance indicators	KPI value		Weight		NRRG	
	BSM	PRR	BSM	PRR	BSM	PRR
Climate change-total	0.53	0.25	0.15	0.15	0.08	0.04
Acidification	0.38	0.30	0.10	0.10	0.06	0.05
Eutrophication-freshwater	0.45	0.21	0.15	0.15	0.04	0.02
Resource use, minerals and metals	0.42	0.28	0.10	0.10	0.04	0.03
Net present value	0.61	0.27	0.30	0.30	0.18	0.08
Material circularity indicator	0.60	0	0.20	0.20	0.12	0
				Total NRRG	0.53	0.21

The NRRG (see Table 8) for BSM option was 2.5 times higher than the patch repair and resurfacing. The contribution of NPV to NRRG was more pronounced in BSM option as it assisted in minimizing the high expenditure associated with typical maintenance option of patch repair and resurfacing. Another major contributor to the NRRG in BSM option was MCI. However, the contribution of MCI to patch repair and resurfacing was nil attributed to its zero MCI value. Though the contribution of environmental KPIs to NRRG was high in both the maintenance methods, it was substantial for BSM option highlighting the benefit of minimizing the frequency of maintenance methods. Overall, it may be suggested that the environmental, economic, and circularity benefits associated with BSM maintenance were much lower than the typical patch repair and resurfacing.

4 CONCLUSIONS AND RECOMMENDATIONS

The objective of this research was to evaluate the feasibility of two maintenance alternatives, i.e., BSM versus routine patch repair and resurfacing using a systematic framework that integrates their sustainability and circularity aspects. The key takeaways are presented below.

- ELCA revealed that the BSM scenario performs better than patch repair and resurfacing for all environmental indicators when assessing the direct impacts related to the material and resource consumption of the maintenance processes undertaken.
- Although the BSM option was consequential of higher agency costs, the lifecycle costs were lower attributed to lower maintenance frequency than patch repair and resurfacing.
- MCI scores for the BSM and patch repair and resurfacing scenarios were 0.60 and 0, respectively. A ‘0’ score for the patch repair and resurfacing maintenance is indicative of poor material circularity and completely linear flow.
- The NRRG for the BSM option was 2.2 times higher than patch repair and resurfacing. This dictates that NRAs must transition towards the use of maintenance options similar to BSM technology, which allow the use of high recycled material proportions and results in lower environmental and economic burdens.

An important contribution of this research was the development of a simplified framework that allows selection of KPIs and associated weights based on relevance of the project, available data, and experience. The use of NRRG will allow rewarding the contractors for producing a scheme that is environment-friendly, cost effective, and used minimal raw materials. However, additional research must be conducted in the future to quantify the risks related to technical performance of maintenance methods that allow use of high recycled fractions in the mix. An integration of technical risks with the sustainability and circularity considerations will allow assessment of pavement's performance from holistic perspectives and pave way for procurement of sustainable and circular road maintenance solutions in the future.

ACKNOWLEDGMENTS

This work was part of the Circular Economy in Road COnstruction and Maintenance (CECOM) project, which was a Conference of European Directors of Roads (CEDR) project funded through the call 2020 Resource Efficiency and Circular Economy. More information about CEDR and the CERCOM project can be found in the following link: https://cedr.eu/peb-call-2020-resource-efficiency-and-circular-economy

REFERENCES

CBS - Statistics Netherlands. 2018. Trends in the Netherlands 2018 [WWW Document]. URL https://longreads.cbs.nl/trends18-eng/society/figures/traffic/ (accessed 10.22.22).

Decò, A., Frangopol, D.M. 2011. Risk assessment of highway bridges under multiple hazards. Journal of Risk Research 14, 1057–1089. https://doi.org/10.1080/13669877.2011.571789

Diependaele, M. 2018. A guide on the basic principles of Life-Cycle Cost Analysis (LCCA) of pavements. EUPAVE, Brussels, Belgium.

Ellen MacArthur Foundation. 2019. Circularity indicators - an approach to measuring circularity - methodology.

Eurostat. 2022. Passenger Mobility Statistics: Average Passenger Car Occupancy for Urban Mobility on all Days [WWW Document]. URL https://ec.europa.eu/eurostat/statistics-explained/index.php?title=File:Average_passenger_car_occupancy_for_urban_mobility_on_all_days_v2.png#file (accessed 11.11.22).

GaBi Manual. 2022. GaBi Databases & Modelling Principles. Sphera, Germany.

ISO: 14040. 2006. Environmental management — Life cycle assessment — Principles and framework. International Organization for Standardization, Geneva, Switzerland.

ISO: 14044. 2006. Environmental management — Life cycle assessment — Requirements and guidelines. International Organization for Standardization, Geneva, Switzerland.

Mantalovas, K., Di Mino, G. 2020. Integrating Circularity in the Sustainability Assessment of Asphalt Mixtures. Sustainability 12, 594. https://doi.org/10.3390/su12020594

Sheils, E., Connolly, L. 2023. Circular economy in road construction and maintenance – a risk-based analysis framework to facilitate procurement of innovative solutions. Engineers Ireland.

SR-Gruppen A/S. 2022. EPD Danmark (Environmental Product Declaration No. MD-22065-EN). Danish Technological Institute, Vejen, Denmark.

Tarsi, G., Tataranni, P., Sangiorgi, C. 2020. The Challenges of Using Reclaimed Asphalt Pavement for New Asphalt Mixtures: A Review. Materials 13, 4052. https://doi.org/10.3390/ma13184052

Varveri, A., Singh, A., Berman, D.G., Laugesen, J., Karl, A.A.W., Sheils, E., Connolly, L., Connor, A.O. 2023. CERCOM - Case studies I & II - Protocol and results (No. D4.1 and 4.2). Delft University of Technology, Delft, the Netherlands.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B. 2016. The ecoinvent database version 3 (part I): overview and methodology. Int J Life Cycle Assess 21, 1218–1230. https://doi.org/10.1007/s11367-016-1087-8

Xiao, F., Su, N., Yao, S., Amirkhanian, S., Wang, J. 2019. Performance grades, environmental and economic investigations of reclaimed asphalt pavement materials. Journal of Cleaner Production 211, 1299–1312. https://doi.org/10.1016/j.jclepro.2018.11.126

Yousefi, A., Behnood, A., Nowruzi, A., Haghshenas, H. 2021. Performance evaluation of asphalt mixtures containing warm mix asphalt (WMA) additives and reclaimed asphalt pavement (RAP). Construction and Building Materials 268, 121200. https://doi.org/10.1016/j.conbuildmat.2020.121200

Zhao, Y., Goulias, D., Peterson, D. 2021. Recycled Asphalt Pavement Materials in Transport Pavement Infrastructure: Sustainability Analysis & Metrics. Sustainability 13, 8071. https://doi.org/10.3390/su13148071