FOAM

Duurzame funderingen door in situ recycling met schuimbitumentechnologie

PART V: SUSTAINABILITY ASSESSMENT OF PAVEMENTS WITH BSM

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1 Introduction

1.1 Project Description

The Tetra project HBC.2020.2094 "Sustainable base layers through in-situ recycling with foamed bitumen technology" - referred to as the "FOAM project"- has the overall objective of technically, economically, and ecologically testing and evaluating foamed bitumen technology for base layers, leading to a more sustainable base. The results are disseminated for further implementation. The project started on November 1st, 2020 and was finalised on 31 October 2022. The project was carried out by the University of Antwerp, the Belgian Road and Research Centre, and Odisee University College. The project was funded by VLAIO.

To obtain sustainable road structures, attention should not only be paid to the asphalt pavement, but the base layer also plays a decisive role. Bitumen Stabilised Material "BSM" is a material in which the granulates - in this project 100 % reclaimed asphalt - are held together by maximum 3 % foamed bitumen or bitumen emulsion. The FOAM project tested the use of BSM as a base material, investigating its structural, environmental and economic impact. The project resulted in a method for mixture design and structural road design with BSM and was demonstrated through the construction of pilot sections. These trial sections are further followed up by a monitoring campaign.

The report of the FOAM project consists of 6 reports.

- PART I: Management report FOAM project
- PART II: Market Potential for BSM in Flanders
- PART III: Mix design of BSM
- PART IV: Structural design of pavements with BSM
- PART V: Sustainability Assessment of pavements with BSM
- PART VI: Synthesis report of test sections

This report " PART V: Sustainability Assessment of pavements with BSM" describes the economic and environmental assessment of using BSM as an alternative base structure using life cycle cost analysis (LCCA) and life cycle assessment (LCA), respectively. The goal is to analyse for both test tracks how two BSM types (type A with asphalt base and type B without asphalt base) compare to more traditional pavement structures with an unbound base, cement bound base or lean asphalt base.

2 Methodology

Data from two test tracks constructed in 2021 as part of the FOAM project were selected as inputs for this research. The overall goal of the project is the technical, economic and environmental assessment of BSM so its innovative use leads to more sustainable pavement sections in Flanders. This manuscript will specifically focus on analysing the economic and environmental performance of BSM as an alternative base material in comparison with more traditional structures using LCCA and LCA, respectively. For each test track, five alternative pavement structures with varying base layers will be analysed, namely: unbound, cement bound, lean asphalt, BSM type A including the asphalt base layer, and BSM type B excluding the asphalt base layer. Note that the two test tracks were designed for different traffic loads, namely two million 100 kN equivalent single axle loads (ESALs) for the first one, and one million ESALS for the second one. An overview of the locations of the test tracks is presented in Figure 1. The first test track is clustered together with the two production plants used in this project around the centre of Belgium, whereas the second test track is more located in the northern part. The following sections describe the applied methodologies more in detail.

Figure 1 Overview of test track, material suppliers, and production plant locations

2.1 Description and design of the selected pavement sections

Figure 2 provides an overview of the considered pavement structures. In Flanders, for more traditional pavement structures, the thickness of the pavement layers can be established using standard structures. These reference structures show the layer thickness of the asphalt concrete (AC) and base layers in terms of the base type and the maximum number of 100 kN ESALs over a given design period [1], [2]. However, as BSM structures are new in Flanders, no prior information was available. Therefore, the BSM structures were designed using a mechanistic-empirical approach so their maximum number of 100 kN ESALs before failure matched with the other structures. The Rubicon stress-strain calculator was used as a multi-layer elastic analysis program to determine the stress and strain responses. Afterwards, to determine the maximum number of load repetitions, the Stellenbosch BSM transfer function was applied [3], [4].

The total AC and base thicknesses of the structures depend on the number of 100 kN ESALs and the base type, however, the AC surface thickness was kept constant for each section. Furthermore, the same AC 10 surface mixture and AC 14 base mixture were modelled for all pavement sections except for the BSM type B structure which does not contain an asphalt base course. Note that according to the Flemish design standard the minimum thickness of an entire pavement structure is linked to the frost-free depth, which is 75 cm for the first test track and 70 cm for the second test track. Hence, this depth determines the thicknesses of the subbase.

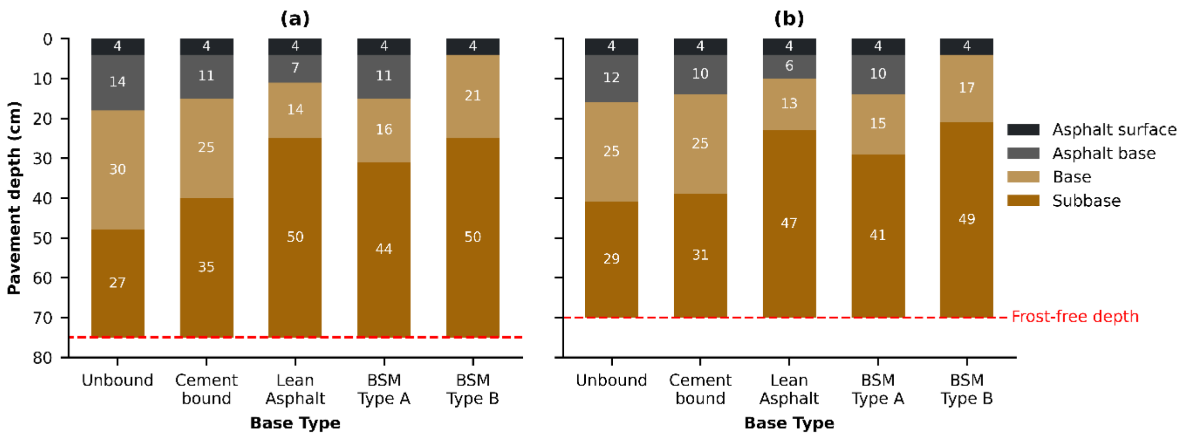

Figure 2 Pavement sections considered in the LCA and LCCA where the traffic load over 20 years does not exceed two million 100 kN ESALs for test track one (a) and one million 100 kN ESALs for test track two

Two types of construction and demolition waste (CDW) are recycled in the structures, namely recycled concrete aggregate (RCA) and reclaimed asphalt pavement (RAP). The unbound (sub)base consists of 100% RCA. According to Flemish specifications it is also possible to use RAP in unbound (sub)bases, however, it would limit the recycling rate to 30%. The aggregate mixture of the cement-bound base also consists of 100% RCA. Again, RAP could also be used in the mixture, however, at least 15% of virgin sand would have to be added to the aggregate mixture [5]. Therefore, from a recycling point of view, RCA is preferred over RAP for unbound and cement-bound mixtures. For the BSM base, the aggregate mixture consists of 100% RAP. Additionally, RAP is recycled in the lean asphalt base and the AC 14 base. Only the AC 10 surface mixture consists of 100% virgin materials. Table 1 provides the compositions of the analysed mixtures in the considered structures.

Table 1 Composition of mixtures used in evaluated structures

	AC 10 Surf	AC 14 Base	U-Base[1]	CB-Base	LA-Base	BSM-Base
Bulk density [kg/m³]	2384	2280	2150	2241	2297	2030
Crushed coarse aggregate [%][2]	54.9	48.6			19.8	
Crushed fine aggregate [%][2]	23.5	4.8				
Natural sand [%][2]	9.4	3.8			26.1	
Added filler [%][2]	6.1	1.9			0.1	
RAP [%][2]		38.1			53.2	96.7
RCA [%][2]			100	89.4		
Virgin binder [%][2]	6.2	2.8			0.8	2.1
Portland cement (CEM III/A) [%][2]				2.1		1.0
Water [%][2]				8.5		0.2[5]
Unit environmental impact [kg CO2-eq/ton][3]	45.1	31.6	0[4]	13.1	27.2	11.4 – 15.4[6]
Unit economic impact [€/ton][3]	81.7	53.4	0[4]	19.3	37.1	27.6 – 29.3[6]

[1]The same mixture is used to construct the subbase and the unbound base.
[2]Percentage by total weight of mixture.
[3]Impact of one production cycle which includes raw materials, transport to the plant, and production → cradle-to-gate impact.
[4]RAP and RCA enter the system burden free because of the end-of-waste criteria (see following sections). As the unbound mix consists of 100 % RCA and there is no further production, the cradle-to-gate impact is entirely burden free.
[5]Originally, the mixture was designed so that the water content was 5.7 % by weight of the aggregates. However, during test productions, it was noted that the RAP was too moist, so the water content needed to be reduced.
[6]As BSM is produced on site, the impact of the A2 transport phase depends on the location of the test track. Therefore, two values are given.

2.2 Environmental and economic assessment

2.2.1 Goal and scope

As mentioned before, the two test tracks have different traffic loads and can therefore not be compared with each other. Hence, two separate functional units will be considered in this research for the LCA and LCCA, namely:

- **Test track 1**: *1 m² of asphalt pavement designed according to Flemish specifications for a maximum traffic of two million ESALs over 20 years;*

- **Test track 2:** *1 m² of asphalt pavement designed according to Flemish specifications for a maximum traffic of one million ESALs over 20 years;*

Figure 3 provides an overview of the system boundaries and planning of rehabilitation intervals. The system boundaries include raw material extraction up to the recycling after the end-of-life (EOL) phase. As this research focusses on the use of RCA and RAP as secondary materials, it is important to apply correct end-of-waste (EOW) criteria. They specify when products stop being waste and become secondary materials. Hence, they provide guidance around allocating impacts to the EOL phase of the previous life cycle and the secondary material phase of the next life cycle.

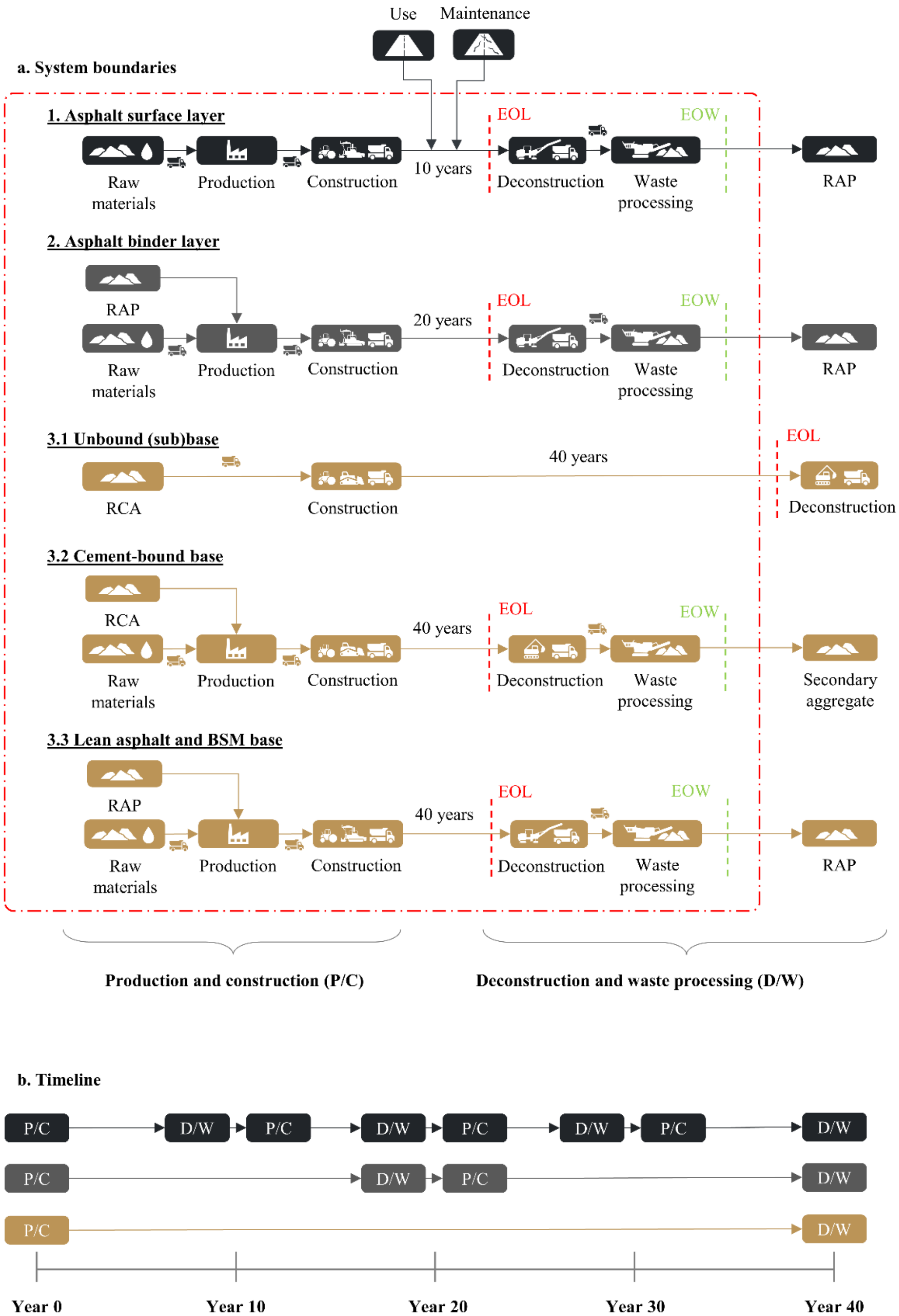

Figure 3 System boundaries of the LCA and LCCA (a) with corresponding timeline (b)

According to the Joint Research Centre of the European Commission, CDW becomes a secondary aggregate once it no longer contains any type of contaminations or dangerous substances and is processed into an aggregate with a certain quality that meets all technical standards [6]. This means all impacts up to and including the crushing and sieving of the RAP or RCA are allocated to the waste product, whereas all impacts linked to transport after the crushing and sieving are allocated to the next cycle [7]. Note that most contractors in Flanders process their RAP and RCA at their own plant using a mobile crusher, which means there is no transport of the secondary material to the plant. Therefore, RAP and RCA are both modelled as burden free material when they enter a new production cycle.

It is assumed all materials can be recycled; therefore, the system boundaries do not contain landfilling. So, for the quantities of RCA and RAP which are not recycled in a new production cycle within the system boundaries, and thus are stockpiled, a cut-off approach is used. With regards to the maintenance phase, full rehabilitation is the common practice in Flanders as opposed to smaller maintenance interventions. Hence, smaller interventions such as crack filling fall outside of the system boundaries. Furthermore, as the sections are designed for the same service life, it can be assumed that the small maintenance interventions of the asphalt layers will take place at the same time and therefore will have no effect on the final ranking of the pavement structures.

Rehabilitation intervals of 10 years, 20 years, and 40 years are assumed for the asphalt surface, asphalt base, and base layer, respectively. Note that bitumen- and cement bound bases are subjected to both permanent deformation and cracking. Hence, once they are cracked, they lose part of their bearing capacity and will need to be de- and reconstructed. However, unbound (sub)bases are only subjected to permanent deformation. In practice, once the permanent deformation is too large, the unbound base will remain in place and is covered with additional material, so the base profile is fixed. Therefore, in theory, unbound layers have an infinite service life. Hence, as indicated in Figure 3, no rehabilitation of the unbound (sub)bases is considered in this research. The total analysis period of the LCA and LCCA is 40 years as this is the most common analysis period applied in pavement projects [8].

2.2.2 Life cycle inventory (LCI)

A life cycle inventory (LCI) is used to collect, describe, and verify all necessary data. With regards to the LCA, ecoinvent 3.8 is used to link most of the environmental impacts to the LCI flows. Only for bitumen different sources will be used. Eurobitume and Asphalt Institute have issued their own LCIs which are representing the European and US bitumen sector, respectively [9], [10]. Previous research has shown that bitumen is the main environmental hotspot linked to asphalt pavements, so the selection of an LCI for bitumen can severely affect the outcome [11]. Therefore, both LCIs will be considered in the analysis and compared with each other. For the past months, prices of construction materials and energy sources were higher than normal due to current global developments. Using these prices could result in the analysis of an extreme case. However, it seems that this trend will not be reversed any time soon. Many supply chains and trading relationships have been irrevocably disrupted. So, the chances of prices returning to the levels of two or three years ago in the short term are very slim. Therefore, the decision was made to calculate with these extreme prices and consider average material and energy prices for 2022. Primary information with regards to transport distances is used and shown in Table 2. Furthermore, a detailed list with record names and unit prices is provided in

$$Q_{tot} = (1 + CL) \times \left(\sum_{i=1}^{N} m_i \times c_i \times (T_{mix}\text{-}T_0) + \sum_{i=1}^{N\text{-}1} m_i \times W_i \times c_w \times (100\text{-}T_0) + \sum_{i=1}^{N\text{-}1} m_i \times W_i \times L_v + \sum_{i=1}^{N\text{-}1} m_i \times W_i \times c_{vap} \times (T_{mix}\text{-}100) \right) \quad \textit{Eq. 1}$$

Where Q_{tot} is the required thermal production energy in MJ/ton, CL is a casing losses factor in %, N is the total number of materials used in the mixture, m_i is the mass percentage of material i by total weight of the mixture in %, c_i is the specific heat capacity coefficient of material i in KJ/kg/°C, T_{mix} is the final mixing temperature in °C, T_0 is the ambient temperature in °C, W_i is the moisture content of material i in %, c_w is the specific heat capacity coefficient of water in KJ/kg/°C, L_v is the latent heat required to evaporate water KJ/kg, and c_{vap} is the specific heat capacity coefficient of water vapor in KJ/kg/°C. Note that it is assumed only water needs to be evaporated from granular materials (including RAP) and not the bitumen, hence the total number of materials for the final three terms in the equation decreases with one.

Table 3.

Table 2 Transport distance matrix

	Concrete Plant [km]	Asphalt Plant [km]	Test Track 1 [km]	Test Track 2 [km]
Bitumen Supplier	na	51.2	57.9	38.2
Crushed Aggregate Supplier	67.9	68.0	na	na
Natural Aggregate Supplier	109.0	109.0	na	na
Filler Supplier	na	101.0	na	na
Cement Supplier	80.9	na	80.2	56.8
Concrete Plant	na	na	3.2[1]	31.4[1]
Asphalt Plant	na	na	3.3[2]	29.1[2]

[1]It is assumed RCA is crushed at the concrete plant; hence, this transport distance applies for both cement-bound mixtures to the test track as RCA to the test track.

[2] It is assumed RAP is crushed at the asphalt plant; hence, this transport distance applies for both bitumen-bound mixtures to the test track as RAP to the test track.

The BSM mixture was produced on site using a mobile cold recycling mixing plant. The total quantity of fuel used and BSM produced were monitored during the test tracks, this resulted in an average fuel consumption of 0.26 l diesel per ton BSM produced for the mobile cold recycling mixing plant. To determine the energy consumption for the cement bound base production, the following ecoinvent dataset was consulted: “Lean concrete {CH}| production, with cement CEM II/A | Cut-off, U”. Previous research has shown that thermal energy required to produce asphalt mixtures is an environmental hotspot which makes it a key input to consider [11], [12]. The energy consumption for heating materials and water evaporation can be calculated using thermodynamics laws as shown in **Fout! Verwijzingsbron niet gevonden.**. This equation was used to determine the energy consumption to produce the AC 10 surface, AC 14 base, and lean asphalt base mixture. Table 4 provides an overview of the considered parameters and shows the calculated energy consumptions for the bitumen-bound mixtures.

$$Q_{tot} = (1 + CL) \times \left(\sum_{i=1}^{N} m_i \times c_i \times (T_{mix} - T_0) + \sum_{i=1}^{N-1} m_i \times W_i \times c_w \times (100 - T_0) + \sum_{i=1}^{N-1} m_i \times W_i \times L_v + \sum_{i=1}^{N-1} m_i \times W_i \times c_{vap} \times (T_{mix} - 100) \right) \quad \text{Eq. 1}$$

Where Q_{tot} is the required thermal production energy in MJ/ton, CL is a casing losses factor in %, N is the total number of materials used in the mixture, m_i is the mass percentage of material i by total weight of the mixture in %, c_i is the specific heat capacity coefficient of material i in KJ/kg/°C, T_{mix} is the final mixing temperature in °C, T_0 is the ambient temperature in °C, W_i is the moisture content of material i in %, c_w is the specific heat capacity coefficient of water in KJ/kg/°C, L_v is the latent heat required to evaporate water KJ/kg, and c_{vap} is the specific heat capacity coefficient of water vapor in KJ/kg/°C. Note that it is assumed only water needs to be evaporated from granular materials (including RAP) and not the bitumen, hence the total number of materials for the final three terms in the equation decreases with one.

Table 3 Detailed LCI with prices and LCA record names

	Price	LCA ecoinvent record
Materials and energy		
Crushed coarse aggregate	25.01 €/ton[a]	Limestone, crushed, washed {CH}| production | Cut-off, U
Crushed fine aggregate	16.05 €/ton[a]	Limestone, crushed, washed {CH}| production | Cut-off, U
Natural sand	16.95 €/ton[a]	Sand {RoW}| sand quarry operation, extraction from river bed | Cut-off, U
Added filler	17.0 €/ton	Lime {Europe without Switzerland}| lime production, milled, loose | Cut-off, U
Virgin binder	586.10 €/ton[a]	Eurobitume – Production of 1 ton of bitumen (with infrastructure) Asphalt Institute – Asphalt binder without additives
Cement (CEM III/A)	177.16 €/ton[a]	Cement, blast furnace slag 36-65% {Europe without Switzerland}| cement production, blast furnace slag 36-65% | Cut-off, U
Water	4.74 €/m³	Tap water {Europe without Switzerland}| market for | Cut-off, U
Electricity	0.23 €/kWh[a]	Electricity, medium voltage {BE}| market for | Cut-off, U
Diesel	1.47 €/l[a]	Diesel, burned in building machine {GLO}| market for | Cut-off, U
Natural gas	0.06 €/kWh[a]	Heat, district or industrial, natural gas {Europe without Switzerland}| market for heat, district or industrial, natural gas | Cut-off, U
Transport		
Truck	0.07 €/ton·km	Transport, freight, lorry 16-32 metric ton, euro5 {RER}| market for transport, freight, lorry 16-32 metric ton, EURO5 | Cut-off, U
Equipment		
Asphalt production	12 €/ton[b]	No infrastructure, only energy consumption
Concrete production	12 €/ton[b]	No infrastructure, only energy consumption
BSM production	12 €/ton[b]	No infrastructure, only energy consumption
Paver	202.9 €/h[c]	Machine operation, diesel, >= 74.57 kW, steady-state {GLO}| machine operation, diesel, >= 74.57 kW, steady-state | Cut-off, U[d]
Grader	216.4 €/h[c]	
Soil compactor	98.4 €/h[c]	
Mobile jaw crusher	128.8 €/h[c]	
Excavator with jackhammer	156.6 €/h[c]	
Wheel loader	101.2 €/h[c]	Machine operation, diesel, >= 74.57 kW, low load {GLO}| machine operation, diesel, >= 74.57 kW, low load | Cut-off, U[d]
Tandem roller	87.8 €/h[c]	
Sweeper	105.8 €/h[c]	
Milling machine	457.3 €/h[c]	Machine operation, diesel, >= 74.57 kW, high load {GLO}| machine operation, diesel, >= 74.57 kW, high load | Cut-off, U[d]

[a]Average price for 2022 [13]–[15] (databases were validated using primary data from previous projects).

[b]Fixed cost (excluding energy) to account for depreciation, plant maintenance, certification, administrative staff, etc.

[c]Includes renting/depreciation, labor, and fuel.

[d]This dataset was chosen as its fuel consumption was the closest to the consumptions mentioned in Table 5; however, the datasets were adjusted with the calculated consumptions.

Table 4 Parameters involved in thermal energy computation

Parameter	Value	Unit	Value/Range in literature	References
Ambient temperature (T_0)	15	°C		
Mixing temperature (T_{mix})	180	°C		
Moisture content (W_i)	3	%	1 - 5	[16]–[20]
Specific heat coefficient of water (c_w)	4.19	KJ/kg/°C	4.18 – 4.20	[16], [18]–[20]
Specific heat coefficient of water vapor (c_{vap})	1.84	KJ/kg/°C	1.83 – 1.85	[16], [18]–[20]
Latent heat of vaporisation of water (L_v)	2256	KJ/kg	2250 - 2256	[16], [18]–[20]
Specific heat coefficient of aggregates (c_{agg})[1]	0.88[2]	KJ/kg/°C	0.61 - 1.19	[16]–[21]
Specific heat coefficient of RAP (c_{RAP})[3]	0.941	KJ/kg/°C	0.74	[16], [20]
Specific heat coefficient of bitumen (c_{bit})	2.093	KJ/kg/°C	2.093	[16], [18], [20]
Casing losses factor (CL)	27	%	27	[20], [22]
Thermal energy for AC 10 surface mixture ($Q_{tot,AC10}$)	298.8	MJ/ton		
Thermal energy for AC 14 base mixture ($Q_{tot,AC14}$)	298.6	MJ/ton		
Thermal energy for lean asphalt base mixture ($Q_{tot,LA}$)	297.5	MJ/ton		

[1]The same specific heat coefficient is used for filler and sand as for aggregates.

[2]This is the specific heat coefficient for limestone aggregates [21].

[3]In literature, most researchers consider the same specific heat coefficient for RAP as for aggregates, however, RAP is a mixture of bitumen and aggregates and can therefore not have the same coefficient. The coefficient is calculated using the coefficients of both aggregates and bitumen, assuming RAP consists of 95% aggregates and 5% binder.

The diesel consumption of the rest of the construction equipment is modelled using the Environmental Protection Agency's model, see Eq. 2. Load factors of 0.59 and 0.43 are used for the construction and waste processing equipment, respectively [23]. Depending on the engine type, specific fuel consumptions often range between 0.21 to 0.26 kg/kWh/h [24]; however, a specific fuel consumption of 0.25 is recommended for construction equipment when specific data is missing [25]. Table 5 provides an overview of the energy consumption of all life cycle phases.

$$FC = \frac{P \times SC \times LF}{\rho_{fuel}} \quad \text{Eq. 2}$$

Where FC is the fuel consumption in l/h, P is the power of the equipment in kW, SC is the specific fuel consumption in kg/kW/h, LF is the load factor, and ρ_{fuel} is the specific weight of diesel (0.85 kg/l).

Table 5 Overview on equipment with rates and energy consumptions

Type	Rate	Energy consumption	Engine size	Example
Production				
Asphalt plant	0.005 h/ton	See Table 4		
		Electricity: 6.1 kWh/ton		
Concrete plant	0.005 h/ton	Natural gas: 5.0 MJ/ton		
		Electricity: 5.4 kWh/ton		
Cold recycling plant	0.005 h/ton	52.0 l/h		
Wheel loaders[1]	0.005 h/ton	15.1 l/h	87 kW	Volvo L50H
Construction (bitumen- and cement-bound)				
Paver	0.013 h/ton	20.0 l/h	115 kW	Vögele SUPER 1600-3i
2 x Tandem roller	0.013 h/ton	12.8 l/h	74 kW	Hamm DV+ 90i VO-S
Construction (unbound)				
Grader	0.010 h/m³	29.2 l/h	168 kW	John Deere 622GP Grader
Wheel loader	0.002 h/m³	15.1 l/h	87 kW	Volvo L50H
Soil compactor	0.005 h/m³	20.0 l/h	115 kW	Hamm H13i
Construction (BSM)				
Paver	0.013 h/ton	20.0 l/h	115 kW	Vögele SUPER 1600-3i
Soil compactor	0.005 h/m³	20.0 l/h	115 kW	Hamm H13i
Tandem roller	0.013 h/ton	12.8 l/h	74 kW	Hamm DV+ 90i VO-S
Deconstruction (bitumen-bound)				
Milling machine	0.0005 h/m²/cm	43.4 l/h	250 kW	Wirtgen W 150 Cfi
Sweeper	0.0004 h/m²/cm	14.8 l/h	85 kW	Bucher MaxPowa V80
Deconstruction (cement bound and BSM)				
Excavator with jackhammer	0.024 h/m²	19.1 l/h	110 kW	Volvo EC160E
Wheel loader	0.011 h/m²	15.1 l/h	87 kW	Volvo L50H
Waste processing (bitumen-, cement-bound, and BSM)				
Mobile jaw crusher	0.010 h/ton	19.6 l/h	155 kW	Wirtgen MC 100i EVO
2 x Wheel loader	0.010 h/ton	15.1 l/h	87 kW	Volvo L50H

[1]For the asphalt and concrete plant two wheel loaders are considered during production whereas for the BSM production only one wheel loader is considered.

2.2.3 Life cycle impact assessment

Environmental indicators can be categorised as either midpoints or endpoints. Midpoint indicators are directly linked to physical LCI flows, such as global warming potential. Endpoint indicators are more easily to interpret because they group midpoints into more general societal themes, such as damage to human health. However, grouping the midpoints makes the result less transparent and subjective. Therefore, ISO 14040/44 [26], [27] recommends to not group midpoints into endpoints or a single score, which lowers the uncertainty of the LCA result. Previous research has shown that global warming potential (GWP) accounts for 48% to 54% of the total single score of asphalt works when using ReCiPe as LCIA method. Furthermore, GWP yielded an excellent correlation with the total environmental impact, which suggests that GWP obtained from a carbon footprint analysis may be used as a surrogate for the total impact [11]. So based on the recommendation of ISO 14040/44 and the findings from previous research, ReCiPe's GWP100 will be chosen as LCIA indicator for the environmental impact.

With regards to the economic analysis, the net present value (NPV) will be used, see Eq. 3. The NPV can calculate the total cost over the entire analysis period using a single indicator, which makes comparing results straightforward. Furthermore, it accounts for the value of time by discounting all future costs [8]. This research will consider a discount rate of 4%.

$$NPV = \sum_{n=0}^{AnP} \left(\frac{C_{RM} + C_{T,RM} + C_{WP} + C_{T,WP} + C_P + C_{T,site} + C_C + C_{DC}}{(1+d)^n} \right) \qquad Eq.\ 3$$

where NPV is the net present value in €/m², AnP is the analysis period (40 years), n is the year of cost occurrence, C_{RM} is the raw material cost in €/m², $C_{T,RM}$ is the raw material transport cost in €/m², C_{WP} is the waste processing cost in €/m², $C_{T,WP}$ is the transport cost linked to secondary materials in €/m², C_P is the production cost in €/m², $C_{T,site}$ is the transport cost to the construction site in €/m², C_C is the construction cost in €/m², C_{DC} is the deconstruction cost in €/m², and d is the discount rate (4%).

3 Results and discussion

3.1 Life cycle assessment

The results of the LCA using GWP as environmental indicator are shown in Figure 4. Overall, the same conclusions can be made for both test tracks. When comparing all structures with each other, it can be seen the cement bound structure yields the highest impact whereas the BSM type B structure yields the lowest impact. Focusing on the base layers alone, it can be seen the unbound base has the lowest impact, even though it requires the most amount of material. This explained by the EOW criteria and the fact that the unbound base consists of 100% recycled materials which results in a burden free material. However, the left part shows that the total impact of the structures is mainly determined by the asphalt surface and base layers. As the unbound structure requires the most amount of mass for the asphalt base layer, the impact of the total structure is too high to be the most environmentally friendly one.

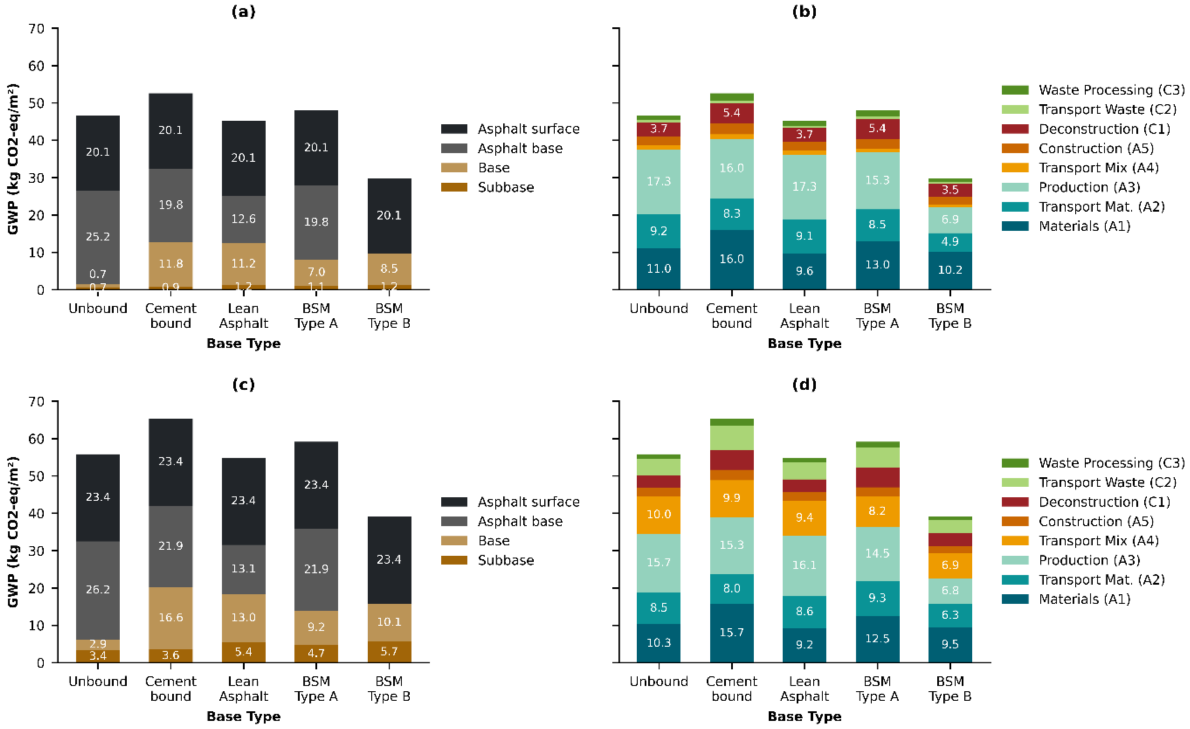

Figure 4 Results of the LCA using GWP as environmental indicator using Eurobitume's LCI where the result is shown per (a) pavement layer for TT1, (b) life cycle phase for TT1, (c) pavement layer for TT2, and (d) life cycle phase for TT2

When comparing the bound bases with each other, the most environmentally friendly one to produce depends on the test track, as shown in Table 1. For test track one, where the transport distance between the asphalt production plant and the production site of the BSM is only 3 km, the BSM base has the lowest production impact per ton. However, for test track two, the transport distance increases to 30 km which results in the cement bound having the lowest production impact per ton. For both test tracks, the lean asphalt base has the highest production impact per ton for the bound bases. When considering the functional unit of $1m^2$, thus a difference in layer thickness to account for a difference in performance, the BSM has the lowest environmental impact of all bound bases and the cement bound base has the highest impact. Note that this shows that selecting a correct functional unit is vital as it can change the overall conclusion of the analysis.

Furthermore, the BSM type A structure requires 40% more material for the asphalt base layer when equal performance is targeted with the other structures. Thus, the environmental benefit when a BSM structure type A is chosen instead of a lean asphalt structure is not enough to outweigh the environmental burden for the additional material in the asphalt base. However, choosing the BSM type B structure will eliminate the asphalt base and replace it mainly by increasing the thickness of the unbound subbase. This will reduce the impact of the BSM structure by 40%, which ultimately results in the most environmentally friendly structure.

Note that the traffic load linked to test track is two is lower compared to test track one, thus a thinner structure is required for test track two. One could expect this would also result in lower environmental impacts. However, as mentioned before, the transport between the production plants and the construction site increases, which results in a higher overall impact. This is shown by the increase in the impact for the A4 and C2 transport phase when comparing Figure 4 (b) and (d).

Figure 4 (b) and (d) also annotate the impacts for the four life cycle phases with the highest contributions to the overall impact. The material phase and the production phase are overall the main environmental hotspots; however, their mutual ranking depend on the base type. For test track one the third most important life cycle phase is the transport of the materials to the production plants, followed by the deconstruction phase. Finally, for test track two, the transport to the construction site and the transport of raw materials to the production site are the third and fourth environmental hotspot.

Figure 5 shows the comparison of the results when using the LCI of Eurobitume versus the LCI of Asphalt Institute. For the test track one, the impact for layers containing bitumen is 10% to 35% lower when using Eurobitume's LCI. For test track two, the results vary between 7% to 31%. This confirms that the selection of an LCI for bitumen can immensely affect the result. Note that both LCIs were prepared focusing on different geographies, hence part of the difference can be explained by the difference in transport, crude oil basket, use of different databases etc.

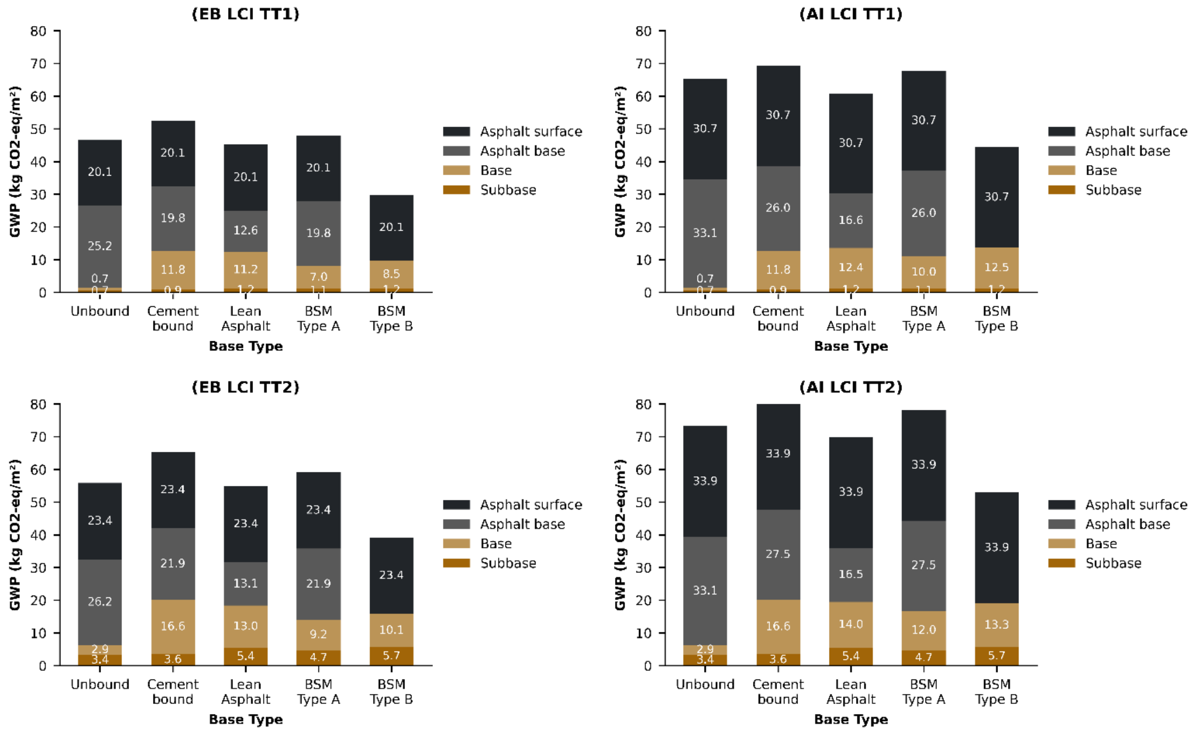

Figure 5 LCA results using GWP as environmental indicator and comparing Eurobitume's (EB) LCI with Asphalt Institute's (AI) LCI for test track one and two

However, the difference can also be partially explained by the difference in considered fugitive losses from venting and other uncontrolled releases during crude oil extraction. The LCI report of Eurobitume reports that values in literature for methane emissions from vented natural gas vary between 3,11E-4 Nm3 to 42,2 Nm3 per ton of crude oil extracted [9]. Eurobitume's LCI considers 0.28 Nm³ per ton of crude oil extracted whereas the value of the U.S. Energy Information Administration, which is used for the LCI of Asphalt Institute, is 14.2 Nm³ per ton of crude oil extracted. This difference in unintended release of methane could change the GWP impact by a factor of about two. Note, although the absolute results change based on the used LCI, the overall conclusion still stands, namely the cement bound structure yields the highest impact whereas the BSM type B structure yields the lowest impact.

3.2 Life cycle cost analysis

Figure 6 shows the results of the LCCA. Both test tracks show the same conclusions, which are comparable to the LCA. The cement-bound structure has the highest economic impact, followed by the BSM type A structure. The lean-asphalt and unbound structure show comparable impacts. The structure with the lowest impact is the BSM type B structure. Again, the unbound base layer is the layer with the lowest economic impact even though it requires most material, which results from the EOW criteria. The lean asphalt base has the highest economic production impact; however, as it requires the least amount of material in the structure, this is partly offset making it not the structure with the highest impact. Apart from the unbound base, the BSM type A base is the most economically interesting to construct when focussing on base layers. However, it requires a thicker asphalt base, resulting in a higher overall economic impact. From an economic point of view, it is better to increase the BSM thickness so that the asphalt base can be eliminated from the structure. This ultimately results in the pavement structure with lowest economic impact.

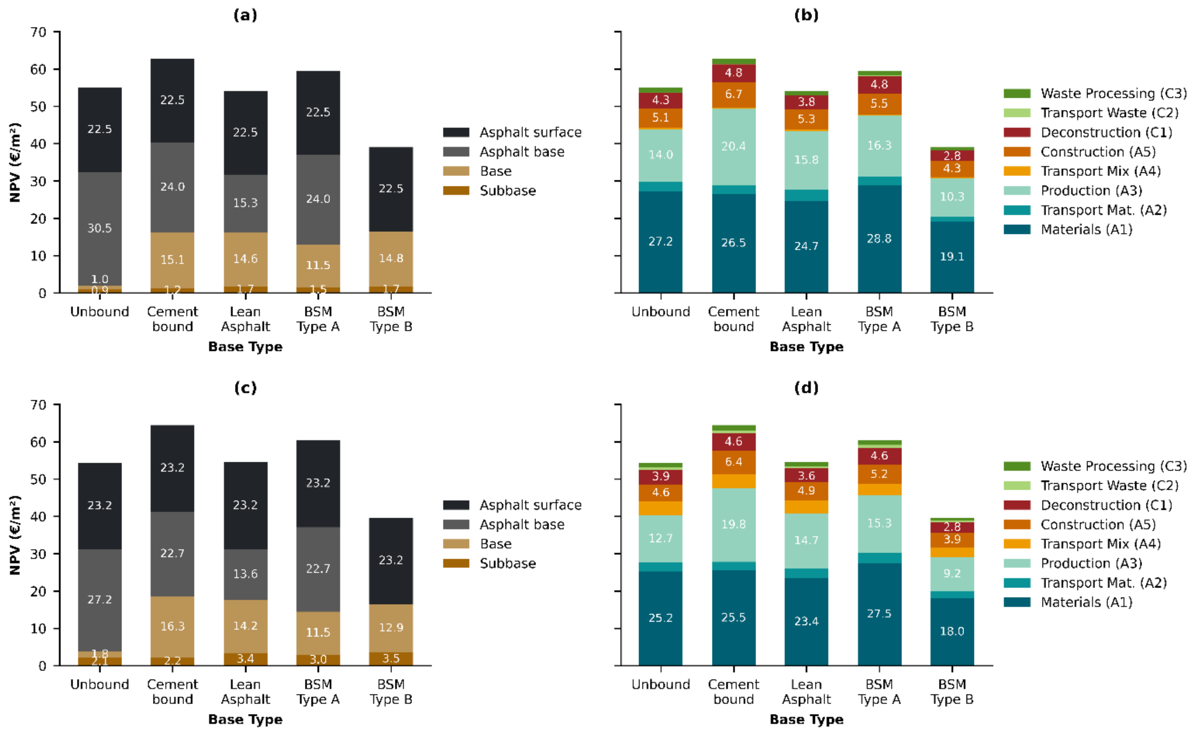

Figure 6 Results of the LCCA using NPV as economic indicator where the result is shown per (a) pavement layer for TT1, (b) life cycle phase for TT1, (c) pavement layer for TT2, and (d) life cycle phase for TT2

Furthermore, Figure 6 shows the absolute impacts for the four life cycle phases that contribute over 90% of the total impact when expressed in relative terms, namely: the material, production, construction, and deconstruction phase. Note that no transport phase is highlighted in Figure 6 whereas in Figure 4 at least one transport phase was highlighted for both test tracks during the LCA. This shows that from an economic point of view transport is less important as from an environmentally point of view.

4 Conclusion and recommendations

The goal of this report was to analyse the economic and environmental performance of BSM structures with regards to more traditional pavement structures. Overall, both test tracks and both the LCA and LCCA showed the same conclusions, namely:

- The cement-bound structure has the highest impacts, followed by the BSM type A structure.
- Lean asphalt structures and unbound structures show comparable results.
- The BSM type B structure has the lowest impact of all considered pavements structures.

The unbound base has the lowest production impact as it consists of 100% recycled materials and is modelled burden free according to the EOW criteria. However, as it requires a thick asphalt base, this effect is offset, and the structure will have a high overall impact. Depending on the transport distances, the cement bound base sometimes has the lowest economic and environmental production impact. However, the same comment applies for the cement bound structures as for the unbound structures, namely that a thicker asphalt base is needed. When comparing BSM production with lean asphalt, it is concluded that BSM has a lower production impact. Note that type A structures require a thicker asphalt base, which outweighs and counters the gains in production impact, resulting in the lean asphalt having lower overall impacts. Selecting a BSM type B structure will eliminate the asphalt base and replace it mainly by increasing the thickness of the unbound base, which has a low impact. This reduces the impact of the BSM structure by 34% to 38%, which ultimately results in the most environmentally and economically friendly structure.

So, this research concludes that the overall impact of a pavement structure is mainly determined by the asphalt layers above the base. Hence, it also shows the importance of the selection of the functional unit as the production impact per ton contradicts the impact per m^2 pavement.

Finally, the ISO 14040 standard notes that LCA is used to address potential environmental impacts but cannot be used to predict absolute or precise environmental impacts due to inherent uncertainty in modelling of environmental impacts. Furthermore, as discussed, databases are currently monitoring extreme material and energy prices due to global developments. Therefore, it is recommended to not solely rely on the deterministic results of this analysis but combine it with a detailed sensitivity and uncertainty analysis, so a more probabilistic result is obtained. A probabilistic analysis will be added in future research.

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