sustainability

MDPI

Article

Environmental Potentials of Asphalt Materials Applied to Urban Roads: Case Study of the City of Münster

Mayara S. Siverio Lima [1,*], Mohsen Hajibabaei [2], Sina Hesarkazzazi [2], Robert Sitzenfrei [2], Alexander Buttgereit [3], Cesar Queiroz [4], Arnold Tautschnig [1] and Florian Gschösser [1]

1 Department of Structural Engineering and Material Sciences, University of Innsbruck, 6020 Innsbruck, Austria; arnold.tautschnig@uibk.ac.at (A.T.); florian.gschoesser@uibk.ac.at (F.G.)
2 Department of Infrastructure, University of Innsbruck, 6020 Innsbruck, Austria; mohsen.hajibabaei@uibk.ac.at (M.H.); sina.hesarkazzazi@uibk.ac.at (S.H.); robert.sitzenfrei@uibk.ac.at (R.S.)
3 Department of Mobility and Civil Engineering, 48155 Münster, Germany; buttgereit@stadt-muenster.de
4 The World Bank, Washington, DC 20433, USA; queiroz.cesar@gmail.com
* Correspondence: mayara.siverio-lima@uibk.ac.at; Tel.: +43-512-507-63109

Received: 6 July 2020; Accepted: 27 July 2020; Published: 29 July 2020

check for updates

Abstract: Life cycle assessment (LCA) tools have been used by governments and city administrators to support the decision-making process toward creating a more sustainable society. Since LCA is strongly influenced by local conditions and may vary according to various factors, several institutions have launched cooperation projects to achieve sustainable development goals. In this study, we assessed the potential environmental enhancements within the production of road materials applied to the road network of Münster, Germany. We also compared traditional pavement structures used in Münster and alternative options containing asphalt mixtures with larger amounts of reclaimed asphalt pavement (RAP). Although the case study was conducted in Münster, the data collected and the results obtained in this study can be used for comparison purposes in other investigations. In the analysis, we considered all environmental impacts from raw material extraction to the finished product at the asphalt plant. Two environmental indicators were used: non-renewable cumulative energy demand (nr-CED) and global warming potential (GWP). The results show that using RAP increases the consumption of energy but potentially decreases the environmental impacts in terms of the nr-CED and GWP associated with the production of asphalt materials.

Keywords: life cycle assessment; asphalt mixtures; reclaimed asphalt pavement; environmental impact

1. Introduction

In 2015, the United Nations (UN) established a plan of action to improve the prosperity of society. Titled Agenda 2030, this plan of action comprises 17 Sustainable Development Goals (SDGs), which are political goals to ensure sustainable development on economic, social, and environmental levels, addressing global challenges related to poverty, inequality, climate, environmental degradation, and prosperity, as well as peace and justice. A sustainably built environment is one of the prerequisites for the realization of the SDGs by 2030, wherein sustainable transport infrastructures and systems form a core part of a future-oriented built environment. This is demonstrated in the detailed targets and specifications in the SDGs. For example, SDG 11—"Sustainable Cities and Communities" specifies "access to safe, affordable, accessible and sustainable transport systems for all" as a relevant SDG target [1]. Urban road systems, with their network density and high traffic loads, need to contribute to urban transport systems within the UN SDGs.

Despite the constant efforts to reduce the carbon footprint and make road constructions more sustainable, road pavements still have a large contribution to environmental impacts within the construction industry. In the UK, for example, roads consume around 25% of all materials extracted from the ground [2,3] making them a significant target to improve sustainability.

It is a common sense that primary raw materials used to build pavements are scarce and the world urgently requires a solution. The environmental impacts of using primary raw materials to compose pavements occur not only due to the extraction process but also due to the transportation since they are normally transported across long distances. On the other hand, the use of recycled materials reduces the impacts of extraction and is more likely always available, which mitigates the impacts of transportation.

The benefits of using recycled materials to compose asphalt mixtures are not only environmental but also economical. The use of RAP is more cost-effective than using primary raw materials [4]. In terms of mechanical performance, studies have shown that asphalt mixtures with RAP perform equally to regular ones [5–7].

Nevertheless, increasing the amount of RAP as the raw material used to compose asphalt mixtures is still a challenge since authorities must be convinced and regulations need to be changed.

Over the past years, a variety of studies have been conducted, analyzing the environmental sustainability of road infrastructure and specifically of road pavements by applying the life cycle assessment (LCA) methodology [8–20]. Most of these studies evaluated the environmental impacts of road pavements using a holistic approach over their entire life cycle or rather over a specific analysis period [10–12,14,18,21]. Some of these studies focused specifically on the environmental influence of maintenance strategies and policies [10–12,14,20].

An example of a holistic sustainability study of urban road infrastructure was conducted by Trigaux et al. [18], who assessed the environmental and economic impacts of roads in residential neighborhoods considering their whole life cycle (material production, pavement construction, maintenance and replacement, usage by traffic, demolition, and end of life), including supply infrastructure such as electricity supply and pipework. Gschösser [20,21] analyzed asphalt and cement concrete pavements for highways and main roads over their entire life cycle, focusing on the environmental and economic impacts of construction and maintenance processes, including material production. Both studies demonstrated the strong influence of material production processes on the overall environmental results, underlining the need to perform specific studies analyzing environmental potential within the production processes of road materials, as shown in various studies [13,16–19].

To reduce the environmental impacts of road material production, the main focus is the application of alternative raw materials and enhanced production processes. In this context, Gschösser [13], for example, assessed the potential reduction of environmental impacts within asphalt production processes with lower mixing temperatures due to the lower moisture contents of the applied aggregates and the application of foam bitumen. The partial substitution of primary raw materials (bitumen and mineral aggregates) with reclaimed asphalt pavement (RAP) and the connected environmental influence was analyzed. Farina et al. [19] performed an LCA, analyzing different types of asphalt mixtures containing recycled materials, such as crumb rubber from scrap tires, and RAP, comparing the results with standard paving materials. The literature review by Balaguera et al. [15] reported RAP, fly ash, and polymer as the most frequently applied alternative raw materials used within asphalt materials [16,17]. Balaguera et al. showed that most of the material studies focused on road materials for pavements with high traffic loads (e.g., highway pavements) and that the most frequently analyzed environmental indicators for road material LCA are non-renewable cumulative energy demand (nr-CED) and global warming potential (GWP).

The results of the analyzed LCA studies showed that the environmental performance of asphalt materials depends on numerous factors, being strongly influenced by local conditions. The City of Münster (Germany) is embracing Agenda 2030 into its strategic policies and aspires to enhance the environmental performance of its urban road network within the next few years. Therefore, the Department of Mobility and Civil Engineering of the City of Münster (Germany), together with the Münster University of Applied Sciences joined the Horizon2020 research project SAFERUP! (Sustainable, Accessible, Safe, Resilient and Smart Urban Pavements, funded by the European Union), wherein a specific environmental analysis for road pavements and materials applied within the urban road network of Münster was performed in cooperation with the University of Innsbruck (Austria). The first part of this research cooperation focused on the environmental potential within the production of road materials applied to the Münster road network.

The road network in Münster is exclusively formed of asphalt pavement. Based on the experience of the Department of Mobility and Civil Engineering of the City of Münster, we used the case study presented in this paper to examine alternative asphalt production scenarios based on the application of RAP as a raw material. The performed LCA study was based on test series and production data from a representative asphalt plant in the Münster region (one of the main asphalt suppliers of the City of Münster). The plant already produces particular asphalt mixtures containing RAP but has been encouraged (mainly by the City of Münster) to intensify the application of RAP, and to further enhance its production process from an environmental point of view. The potentials for the alternative production scenarios were determined on the pavement level, i.e., for the complete pavement structure with all its different layers and different asphalt types. Thereby, all pavement types applied in the road network in the City of Münster were analyzed.

2. Road Materials and Pavements

In our LCA study, we applied the cradle-to-gate approach considering environmental impacts and potential improvements from raw materials extraction to the finished products at the asphalt plant. Thus, construction, use, maintenance, and demolition phases were not considered in the study. The data used to characterize the evaluated road materials and pavements were provided by the Department of Mobility and Civil Engineering of the City of Münster and the analyzed asphalt plant.

2.1. Current Situation in Münster

The construction strategies applied to the urban road network of the City of Münster generally follow the German Guideline (RStO 12) entitled "Guidelines for the standardization of pavement structures of traffic areas" [22].

Depending on the traffic load, the pavement consists of three to four different layers: surface, binder (not applied to low traffic loads), base, and subbase (in this study called "unbound" because, in Münster, only unbound mineral aggregates are applied for the subbase) (Figure 1). The pavement is placed on a compacted subgrade whose thickness depends on the gradient of the road and the characteristics of the terrain. The subgrade consists of unbound mineral aggregates for all pavement variants and was not considered in this study.

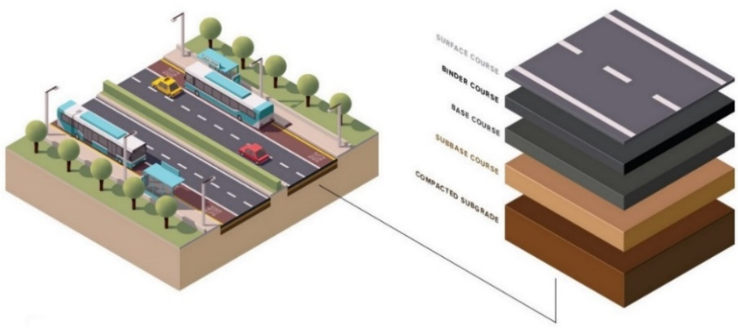

Figure 1. General pavement structure applied in Münster [23].

In Münster, three different classifications of roads are generally distinguished: main roads (MR), main access roads (MAR), and residential roads (RSDT). The Münster road network contains approximately 1200 km of roads, of which 80% are classified as residential roads, 13% as main roads, and 2–3% as main access roads. The rest is classified as private road. The pavement structure generally depends on the traffic load applied to the road section. The specifications (load class, materials, and structure) of the road pavement currently used within the Münster road network are listed in Table 1. Although the Münster road network does not contain motorways (MW), pavement for motorways was also analyzed in this study for comparisons with the other types of pavement.

Table 1. Current pavement specifications of the City of Münster.

	Load Class	Material	Thickness (cm)
Motorway	Bk 100-T	SMA 8 S	3
		AC 22 BS	9
		AC 32 TS	14
		Unbound	50
Main Roads	Bk 32-T	SMA 8 S	3
		AC 22 BS	8
		AC 32 TS	14
		Unbound	45
		OR	
	Bk 10-T1	SMA 8 S	3
		AC 22 BS	8
		AC 32 TS	10
		Unbound	45
		OR	
	Bk 10-T2	AC 8 DS	3
		AC 22 BS	8
		AC 32 TS	10
		Unbound	45
Main Access Roads	Bk 3.2-T1	SMA 8 S	3
		AC 16 BS	5
		AC 22 TS	10
		Unbound	45
		OR	
	Bk 3.2-T2	AC 8 DS	3
		AC 16 BS	5
		AC 22 TS	10
		Unbound	45
		OR	
	Bk 1.8-T	AC 8 DS	3
		AC 22 TN + 40%RAP	12
		Unbound	45
Residential Roads	Bk 1.0-T	AC 8 DN	3
		AC 22 TN + 40%RAP	10
		Unbound	45
		OR	
	Bk 0.3-T	AC 8 DN	3
		AC 22 TN + 40%RAP	8
		Unbound	39
			Surface layer
			Binder layer
			Base layer
			Unbound

The load classes (Bk, "Belastungsklasse" in German) of the pavements shown in Table 1 are based on the traffic load in terms of 10-ton axle passages (e.g., 10 to 32 million for Bk 32). The letter "T" in the load class abbreviation indicates a traditional pavement type, which is currently applied within the Münster road network. Pavement options within the load classes are distinguished as T1, T2, etc. Later on, pavement types with modified asphalt mixtures containing RAP are indicated as M1, M2, etc. The asphalt layers of the analyzed road pavements consist of stone mastic asphalt (SMA) and asphalt concrete (AC) mixtures. The nomenclature of these asphalt mixtures is explained in Figure 2. Since SMA mixtures are exclusively applied as the surface layer, the identification as "D" is not included in the specific abbreviations.

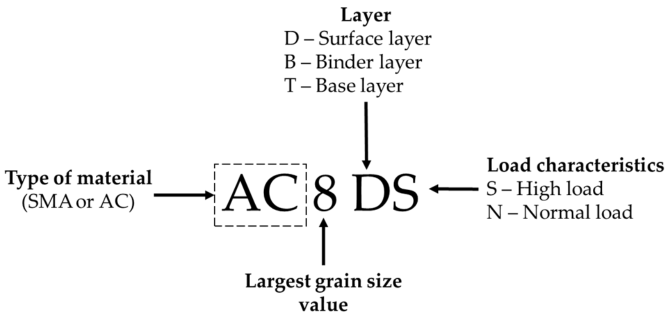

Figure 2. Nomenclature of asphalt materials [24,25].

As mentioned above, the analyzed asphalt plant was one of the main suppliers for the road network of the City of Münster and was already producing asphalt mixtures containing RAP, which were already being partially applied (e.g., AC 22 TN with 40% RAP). However, the goal of the Department of Mobility and Civil Engineering of the City of Münster is to increase the RAP content within the different asphalt mixtures to a maximum without deteriorating the technical characteristics of the specific mixtures.

2.2. Asphalt Production Scenarios

Table 2 describes the asphalt mixtures analyzed in this study. The RAP content variations were defined in cooperation with the asphalt producer, which needs to guarantee the technical equivalency of the RAP asphalt mixtures. The asphalt plant can be characterized as a batch mixing plant that applies the cold recycling method for the production of RAP asphalt mixtures, i.e., RAP is added batchwise in ambient temperature to the already heated mineral aggregates, which requires additional heat (depending on the RAP content) to further heat up the RAP for the mixing process. Table 2 lists the densities and the mixing temperatures of the produced asphalt mixtures.

Table 2. Specification of the asphalt mixtures analyzed.

	Material	Temperature (°C) Aggregates and RAP (Cold Recycling)	Mixing	Density (kg/m^3)
Surface Layer	SMA 8 S	190	170–180	2452
	AC 8 DS	190	170–180	2474
	AC 8 DS + 50% RAP	310	160–170	2489
	AC 8 DN	190	170–180	2470
Binder Layer	AC 16 BS	190	170–180	2509
	AC 16 BS + 10% RAP	210	170	2509
	AC 16 BS + 30% RAP	250	170	2508
	AC 16 BS + 50% RAP	310	160–170	2508
	AC 22 BS	190	165–180	2561
	AC 22 BS + 15% RAP	220	165–180	2561
	AC 22 BS + 30% RAP	280	165–180	2489
Base Layer	AC 22 TS	190	155–180	2537
	AC 22 TS + 10% RAP	210	155–180	2537
	AC 22 TS + 30% RAP	250	155–180	2393
	AC 22 TN + 40% RAP	290	155–180	2372
	AC 32 TS	190	170	2537
	AC 32 TS + 60% RAP	330	155–180	2383
	AC 32 TN + 60% RAP	330	155–180	2383

The analyzed asphalt plant produces about 150,000 tonnes of asphalt per year, for which almost 98% of the heating energy required is sourced from coal and the remaining 2% is from light fuel oil. The asphalt producer is able to provide an overall annual amount of coal and fuel oil consumed in its plant (2018), which allows calculating the heating energy demand per average ton of asphalt produced, as shown in Table 3.

Table 3. Energy demands for average asphalt mixture produced in the analyzed plant.

Inputs of Asphalt Production	
Electricity	16.02 MJ/t
Heat (light fuel oil)	2.84 MJ/t
Heat (coal)	277.23 MJ/t
Diesel, internal transports	8.53 MJ/t

The amount of energy necessary to heat the aggregates and to perform the mixing process varies with the percentage of RAP (Table 2), the moisture content, and the initial temperature of the raw materials, thereby significantly influencing the environmental impacts of asphalt production.

Since the production data from the asphalt plant do not allow the determination of the specific heat energy demands for the different asphalt mixtures, we decided to use Equation (1) [26], which calculates the specific thermal energy (TE) demanded to produce each asphalt mixture analyzed.

$$\mathrm{TE} = \left[\begin{array}{c} \sum_{i=0}^{M} m_i \times C_i \times (t_{mix} - t_0) + m_{bit} \times C_{bit} \times (t_{mix} - t_0) + m_{rap} \times C_{rap} \times (t_{mix} - t_0) + \\ \sum_{i=0}^{M} m_i \times W_i \times C_w \times (100 - t_0) + L_v \times \sum_{i=0}^{M} m_i \times W_i \times W_i + \sum_{i=0}^{M} m_i \times W_i \times C_{vap} \times (t_{mix} - 100) \end{array}\right] \times (1 + CL) \quad (1)$$

To perform the calculations and verify the results, a computer program (Excel, Microsoft, USA) was used. The variables and values of the parameters to be used in the applied formula are presented in Tables 4 and 5, which are based on values in the literature [26–29] as well on the specific conditions found at the asphalt plant located in Münster.

Table 4. Values of the parameters used in Equation (1).

Parameter			
C_{bit}	Specific heat coefficient of bitumen (50/70)	2.09	kJ/(kg·°C)
C_i	Specific heat coefficient of aggregates	0.86	kJ/(kg·°C)
C_w	Specific heat coefficient of water (10 °C)	4.19	kJ/(kg·°C)
C_{vap}	Specific heat coefficient of water vapor	1.83	kJ/(kg·°C)
C_{rap}	Specific heat coefficient of RAP	0.86	kJ/(kg·°C)
W_i	Water content of aggregates	3	%
L_v	Latent heat of vaporization of water	2256	kJ/kg
CL	Casing loss factor	4.5	%
t_0	Ambient temperature	12	°C
t_{mix}	Maximum temperature of aggregates & RAP	various	°C
m_{bit}	Mass of bitumen	various	kg
m_i	Mass of aggregates and filler	various	kg
m_{rap}	Mass of RAP	various	kg

Note: The Ci value is for diabase aggregates [26–29].

The bitumen used to produce the asphalt mixtures includes polymer modified bitumen (PMB) for stone mastic asphalt mixtures and 50/70 bitumen for asphalt concrete mixtures. However, in Equation (1), only an average value of the specific heat coefficient is applied for both types of bitumen based on Santos et al. [26]. The asphalt producer uses two types of rock for aggregates and filler, diabase and limestone, but for the calculation of the heat demand, only the specific heat coefficient of diabase aggregates was applied because we assumed that the major part used within the asphalt mixtures is diabase aggregates.

Table 5. Variable parameter values.

	Material	Temperature (t_{mix})	Mass, kg/ton Produced Aggregates (m_i)	Bitumen (m_{bit})	RAP (m_{rap})	Filler (m_i)
Surface Layer	SMA 8 S *	190	802	69	0	125
	AC 8 DN	190	834	61	0	105
	AC 8 DS	190	843	59	0	98
	AC 8 DS + 50% RAP	310	459	33	500	8
Binder Layer	AC 16 BS	190	896	44	0	60
	AC 16 BS + 10% RAP	210	832	38	100	30
	AC 16 BS + 30% RAP	250	640	30	300	30
	AC 16 BS + 50% RAP	310	472	20	500	8
	AC 22 BS	190	919	41	0	40
	AC 22 BS + 15% RAP	220	779	34	150	37
	AC 22 BS + 30% RAP	280	637	26	300	37
Base Layer	AC 22 TS	190	909	41	0	50
	AC 22 TS + 10% RAP	210	818	35	100	47
	AC 22 TS + 30% RAP	250	636	27	300	37
	AC 22 TN + 40% RAP	290	537	22	400	41
	AC 32 TS	190	909	41	0	50
	AC 32 TS + 60% RAP	330	372	17	600	11
	AC 32 TN + 60% RAP	330	378	11	600	11

Note: * SMA 8 S contains 4 kg of cellulose, which was not considered in the heat demand calculation.

The initial temperature of the raw materials was assumed to be the average annual temperature of the plant in Münster, which is 12 °C. This average value, however, excludes the temperature of the two coldest months (January and February) because the asphalt plant stops operations to perform necessary maintenance during this period.

In Santos et al. [26], t_{mix} is the mixing temperature of an asphalt mixture. In this paper, t_{mix} is the maximum temperature achieved, as required for the heating of the aggregates and RAP. Since the demand of heat rises with the amount of RAP, Equation (1) was used to model the specific production scenario of each asphalt mixture analyzed in this study. Although the temperature used in the formula is the one applied to heat aggregates and RAP, the formula considers the overall amount of energy required for the whole production process [26].

The casing loss factor (CL) represents the thermal energy radiated to the atmosphere and not used to heat the mixture components [29]. This parameter varies from plant to plant depending on the mixing equipment (e.g., parallel flow, double barrel, dual drum) and temperatures used to heat raw materials and to perform the mixing process. Since the asphalt producer was not able to provide an accurate value, the CL was determined by adjusting the average heat energy demand from the formula results (averaged for all asphalt mixtures analyzed) to the average heating energy provided by the producer, i.e., 280.08 MJ/ton (Table 3, coal + light fuel oil).

The electricity demand and diesel used for internal transport are the average amounts provided by the asphalt producer (Table 3) and can be found in the Tables S1–S3, where all relevant inputs and outputs used within the production process are given.

2.3. Pavement Structures

To evaluate the environmental performance of asphalt mixtures containing RAP, the pavement structures in Table 1 were compared with traditional asphalt mixtures (as shown in Table 1) and modified asphalt materials (maximum amount of RAP, Table 2) (Tables S4 and S5).

3. Life Cycle Assessment (LCA)

3.1. Goal and Scope

We aimed to identify environmental potential within the production of asphalt mixtures applied to urban pavement in Münster.

For the LCA study, we applied the cradle-to-gate approach; therefore, all life cycle phases from raw material acquisition to the finished product in the asphalt plant were analyzed (i.e., A1–A3) [25,30,31]. RAP is a secondary raw material; thus, all environmental burdens before it reaches end of waste status were not included in the analyzed system boundaries [32]. The transport from the demolition site to the recycling (= asphalt) plant and further required crushing processes were included in the RAP upstream processes. As the crushing process occurs in the asphalt plant, no further material transports are required. Figure 3 shows the system boundaries and phases considered in the analysis.

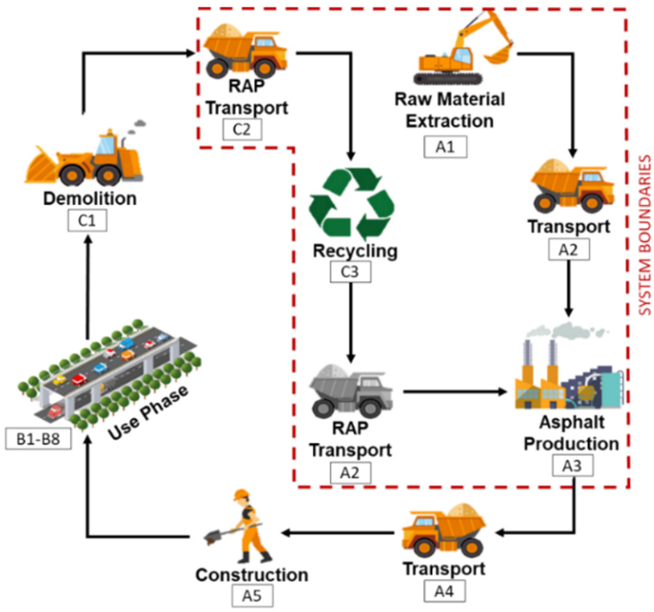

Figure 3. System boundaries in this study.

The analysis was first carried out on material level and then on pavement level. The functional unit used in this study was 1 kg of asphalt mixture produced at the asphalt plant analyzed and one square meter of road pavement.

3.2. Life Cycle Inventory (LCI)

The LCI quantifies relevant inputs and outputs of the analyzed product systems. The primary data, i.e., the data directly connected with the asphalt production (amount of raw materials, energy sources, waste outputs, etc.), were collected by questionnaires answered by the asphalt producer and the Department of Mobility and Civil Engineering of the City of Münster. The specific heat demands for the asphalt mixtures were determined using Equation (1) in Santos et al. [26]. Relevant output data, which could not be provided by the producer, were obtained from the literature [20]. Transport distances consider the location of the specific suppliers of the plant (aggregates 205 km, bitumen 112 km, and filler 205 km). The distance from the average demolition site in Münster to the asphalt plant (i.e., C2, RAP transportation) was set to 25 km. All materials are transported by a five-axle lorry that meets the EURO 6 emission standard requirements [33]. The vehicle weighs approximately 14 tons and has a maximum load capacity of 26 tons. The fuel used is biodiesel and the consumption is about 0.18 L/km when empty and 0.32 L/km when fully loaded.

All inputs and outputs were modelled using SimaPro 9.0 software [34] and the Ecoinvent 3.5 database [35]. Although the analyzed asphalt mixtures contained different types of bitumen, SimaPro provides only one average dataset for bitumen, which was used to model all asphalt mixture LCIs. The mineral aggregates were modeled with the dataset for crushed gravel. The filler applied for all asphalt mixtures was milled limestone, for which the corresponding Ecoinvent dataset was applied. The LCIs of all analyzed asphalt mixtures are listed in Tables S1–S3.

3.3. Life Cycle Impact Assessment

The Intergovernmental Panel on Climate Change (IPCC) 2013 method [36] and the Cumulative Energy Demand (CED) V1.11, based on the method published by Ecoinvent version 2.0 and expanded by Pré Consultants for raw materials and available in the SimaPro database, were used for the life cycle impact assessment. To assess the environmental impacts of asphalt production, the following impact indicators were chosen [32]: Global Warming Potential—GWP (kg CO_2 equivalent) [36] and Non-renewable Cumulative Energy Demand—Nr-CED (MJ equivalent) [34,35].

To verify the reliability of the environmental results, a Monte Carlo simulation was performed by applying the pedigree matrix method proposed by Ecoinvent [35,37]. To calculate the standard deviation for every LCI entry, the pedigree matrix was based on six factors (i.e., reliability, completeness, temporal correlation, geographical correlation, further technological correlation, and sample size). Therefore, a random value within an uncertainty range (1–5) was specified for every inventory entry as shown in Tables S1–S3.

To calculate the standard deviations, we used a lognormal uncertainty distribution with a 95% confidence interval. For each comparison, 1000 runs were calculated to form an adequate uncertainty distribution [35,37,38].

4. Results

4.1. Asphalt Materials Results

Table 6 and Figure 4 show the environmental impacts (GWP—Global Warming Potential and Nr-CED—Non-renewable Cumulative Energy Demand) associated with the production of the asphalt mixtures analyzed.

Table 6. Asphalt mixtures results.

Material		nr-CED (MJ eq/kg)	GWP (kg CO_2 eq/kg)
Surface Layer	SMA 8 S	4.21	0.07
	AC 8 DS	3.69	0.06
	AC 8 DS + 50% RAP	2.23	0.05
	AC 8 DN	3.79	0.06
Binder Layer	AC 16 BS	2.93	0.06
	AC 16 BS + 10% RAP	2.60	0.05
	AC 16 BS + 30% RAP	2.13	0.05
	AC 16 BS + 50% RAP	1.58	0.04
	AC 22 BS	2.78	0.06
	AC 22 BS + 15% RAP	2.38	0.05
	AC 22 BS + 30% RAP	1.95	0.05
Base Layer	AC 22 TS	2.78	0.06
	AC 22 TS + 10% RAP	2.45	0.05
	AC 22 TS + 30% RAP	1.98	0.05
	AC 22 TN + 40% RAP	1.71	0.05
	AC 32 TS	2.78	0.06
	AC 32 TS + 60% RAP	1.39	0.04
	AC 32 TN + 60% RAP	1.09	0.04

In general, Figure 4 shows that the production of asphalt mixtures to be applied in the surface layers has a greater environmental impact than the asphalt materials used in binder and base layers because the bitumen is responsible for a large share of gas emissions and the more bitumen in the asphalt mixture, the greater the environmental impact.

Considering the asphalt materials without RAP, the production of AC 8 DS and AC 22 BS produced fewer environmental impacts amongst the options used for surface and binder layers. For the base layers, both asphalt materials AC 22 TS and AC 32 TS generated the same impact regarding nr-CED and GWP indicators.

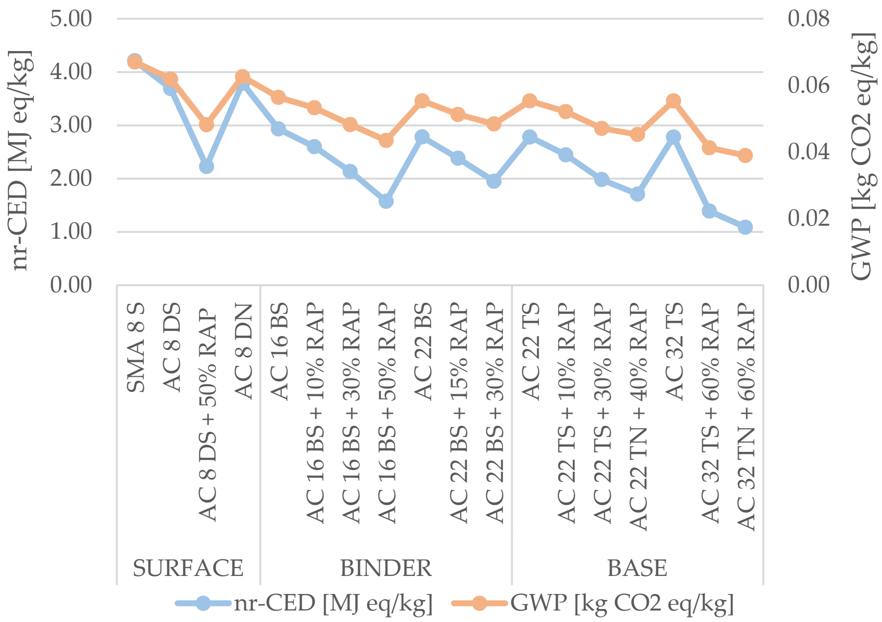

Figure 4. Results of asphalt mixtures concerning Non-renewable Cumulative Energy Demand (nr-CED) and Global Warming Potential (GWP) indicators.

Despite the greater amount of energy required by asphalt materials with RAP, due to the heating strategy used in the asphalt plant, the more RAP included, the lower the environmental burden associated with the production of asphalt mixtures per both GWP and nr-CED indicators. This occurs because the more RAP used, the fewer raw materials (e.g., aggregates and bitumen) and processes are required to produce the asphalt mixtures.

The use of higher RAP contents potentially reduces nr-CED by 47% and GWP by 25% for surface and binder layers, and approximately 61% nr-CED and 30% GWP for the base layers.

The comparison of asphalt mixtures applied to binder layers with the same amount of RAP, such as AC 16 BS and AC 22 BS with 30% RAP or within base layers, e.g., AC 32 TS and AC 32 TN with 60% RAP, indicated similar impacts concerning GWP. For nr-CED, however, the production of AC 22 BS with 30% RAP instead of AC 16 BS with 30% RAP potentially reduces the impact by 8.6%, whereas the production of AC 32 TN with 60% RAP instead of AC 32 TS with 60% RAP lowers the environmental burden by 22%.

In Figure 5, the environmental loads per nr-CED results are divided into different categories, considering the impacts of raw materials and processes caused by the mixtures during asphalt production.

As shown in Figure 5, the bitumen is mainly responsible for the environmental burden associated with the production of asphalt mixtures due to the energy and resources required for its extraction and manufacturing processes.

Asphalt mixtures with RAP require less bitumen, which automatically reduces the impact attributed to the bitumen in terms of nr-CED. However, increasing the RAP content increases the amount of heating energy required, due to the cold recycling method applied by the asphalt producer.

Transportation was the category second most affecting the nr-CED results. The higher the amount of bitumen and aggregates, the higher the transportation impact due to the distances the raw materials must be transported to the asphalt plant. As the RAP is sourced from the demolition of Münster roads, the distance for its transportation has little influence on nr-CED.

Figure 6 shows the impacts of asphalt production in terms of GWP. Figures 5 and 6 show that the use of RAP, aggregates extraction, and electricity have the least influence on the entire environmental impact caused by the production of asphalt materials.

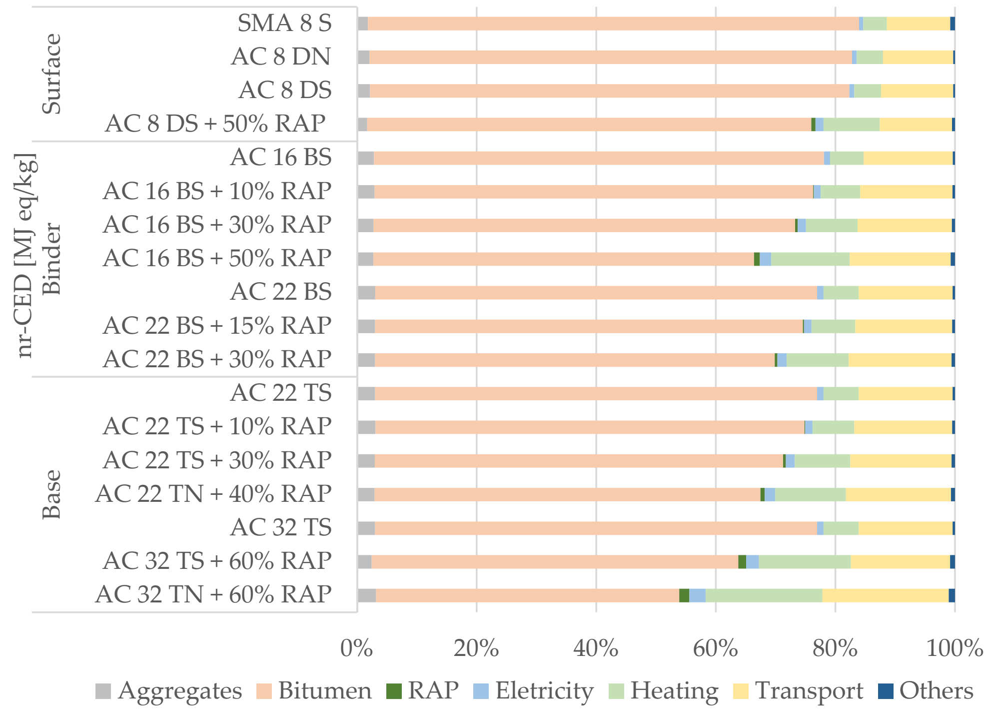

Figure 5. Nr-CED results (%). Environmental impacts of asphalt mixtures divided into different categories.

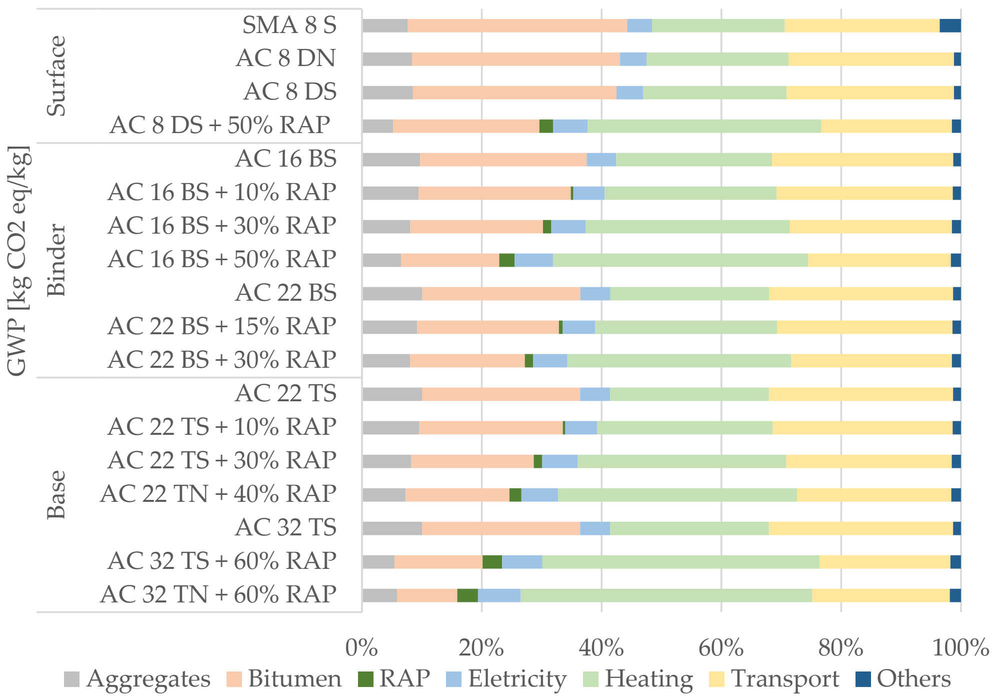

Figure 6. GWP results (%). Environmental impacts of different categories of asphalt mixtures.

Heating is responsible for a greater share of the impact for asphalt materials composed of higher percentages of RAP. For example, heating is responsible for approximately 50% of all impact generated by the production of AC 32 TS with 60% RAP and AC 32 TN with 60% RAP in terms of GWP.

In general, transportation is responsible for approximately 20% of the GWP. Bitumen and heating are responsible for 15%–30% of impact depending on the amount of RAP and bitumen used to produce the asphalt materials. Therefore, the higher the RAP content, the higher the heating and the lower the bitumen. The higher the bitumen content, the less heating required.

4.2. Pavement Structure Results

Table 7 shows the nr-CED and GWP results attributed to the traditional and modified structures. Figure 7 depicts the data in a chart.

Table 7. Pavement structures results.

Structure		nr-CED (MJ eq/m^2)	GWP (kg CO_2 eq/m^2)
MW	BK 100-T	2061.62	45.40
	BK 100-M	1333.25	37.58
MR	BK 32-T	1978.14	43.17
	BK 32-M	1272.46	35.57
	BK 10-T1	1695.82	37.56
	BK 10-M1	1139.91	31.64
	BK 10-T2	1659.78	37.22
	BK 10-M2	996.28	30.30
MAR	BK 3.2-T1	1493.62	33.29
	BK 3.2-M1	1162.27	29.50
	BK 3.2-T2	1457.58	32.95
	BK 3.2-M2	1018.64	28.16
	BK 3.2-M3	1179.68	30.32
	BK 1.8-T	1175.77	27.58
	BK 1.8-M	762.89	23.71
RSDT	BK 1.0-T	796.37	22.61
	BK 1.0-M	681.79	21.57
	BK 0.3-T	700.62	19.50

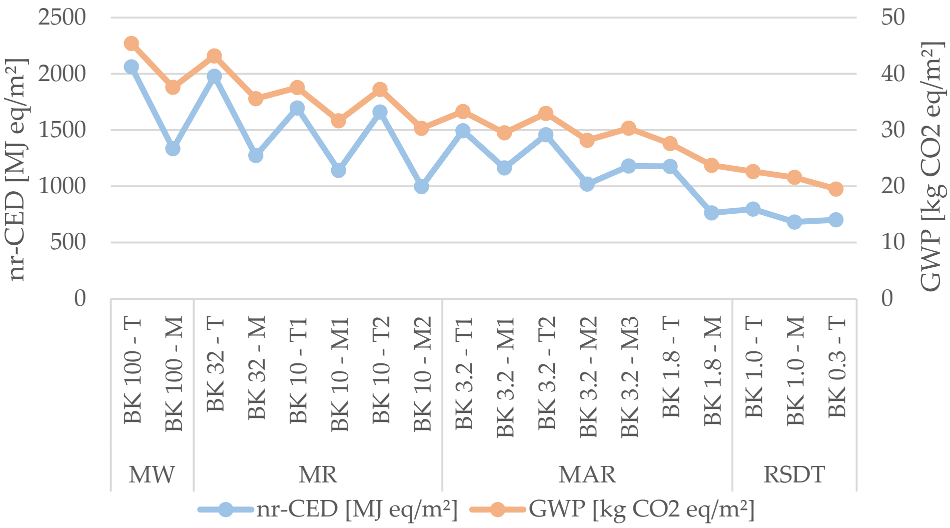

Figure 7. Nr-CED and GWP results for different pavement structure.

Figure 7 shows that the higher the traffic load designed for the road, the greater the environmental burden associated with the pavement structure. Therefore, the production of asphalt mixtures used to compose Bk 100 structures potentially have a greater impact than Bk 32, and Bk 32 should have greater impacts than Bk 10. In general, the asphalt materials used for traditional motorway structures have a 66% greater impact in terms of nr-CED than Bk 0.3 structures and around 57% more in terms of GWP due to the greater amount and quality of raw materials demanded.

The traditional structures have more of an environmental impact compared with the modified alternative. The production of asphalt materials to create modified structures instead of traditional ones can lower the nr-CED up to 42% and 19% in terms of GWP.

The environmental burden associated with the Bk 100-M is 35% lower in nr-CED and 17% lower in GWP compared with Bk 100-T. The Bk 100-M structure potentially has less of an impact than Bk 32-T and almost the same impact as Bk 32-M. Hence, even with the higher amount of road materials required to compose motorway roads, the results demonstrated that the process of choosing less impactful road materials to construct each layer can considerably decrease the overall impact associated with road pavement construction.

In the MR category, the pavement structure Bk 10-M2 had the least impact. In the MAR category, Bk 3.2-M2 produced less impact than the other options for both indicators. The alternative Bk 3.2 structures (i.e., M1 and M2) performed slightly better than the structure tested by Münster (i.e., Bk 3.2-M3), decreasing the nr-CED by 31% and GWP by 15% compared with the traditional option (i.e., Bk 3.2-T1), whereas Bk 3.2-M3 reduced the impacts per nr-CED by 21% and per GWP by 9%.

Figures 8 and 9 show the environmental burdens associated with each layer in terms of nr-CED and GWP indicators. Despite the higher thickness, the unbound layer produced less of an impact of production within all asphalt materials. As observed in Figure 5, the nr-CED results were highly influenced by bitumen. Therefore, due to the lack of bitumen, the unbound layer had a minor contribution to the impact results.

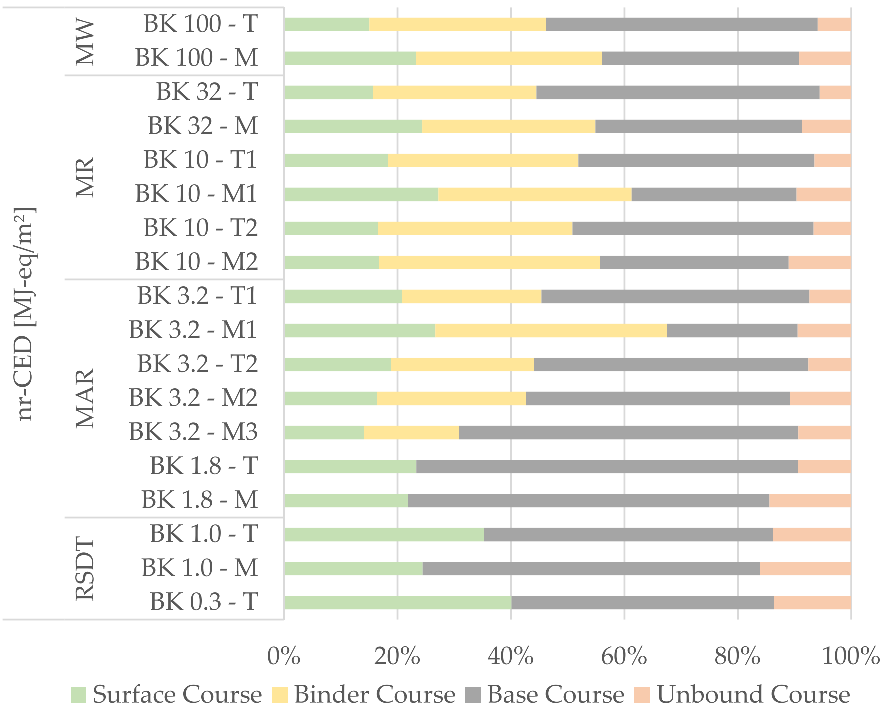

Figure 8. Nr-CED impact contribution of pavement layers.

In general, the base layer had major environmental impacts due to its thickness and raw materials used. The greater the thickness, the higher amount of raw materials and the higher the amount of bitumen, which is the road material that affects nr-CED values the most. The asphalt material modelled for base layers has a lower RAP content in comparison with the surface and binder layers, which also influenced the results since the environmental burden attributed to the surface and binder layers is directly related to the amount of RAP used to compose the asphalt mixtures.

As shown in Figure 6, transportation has a considerable influence on the impacts caused by the production process. Thus, most of the impact of the unbound layer in Figure 9 is due to its composition of 100% aggregates, sourced from outside Münster.

The impact caused by the different layers in terms of GWP (Figure 9) depends on the amount of RAP and bitumen used to produce asphalt materials. As heating considerably influenced the GWP results, the layers designed with asphalt materials and RAP are responsible for a larger share of the environmental influence than in the nr-CED results.

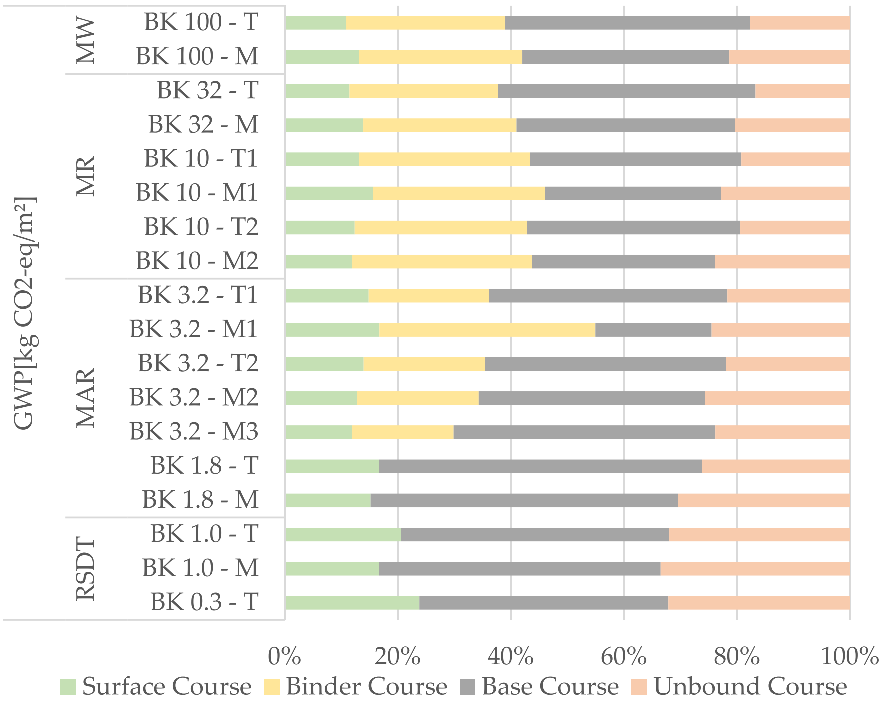

Figure 9. GWP impact contribution of pavement layers.

4.3. Monte Carlo Analysis

Figure 10 shows the probability that the environmental impacts of the traditional asphalt mixtures is higher or lower compared to asphalt mixtures with the highest content of RAP. Figure 10 also provides a comparison with asphalt materials without RAP.

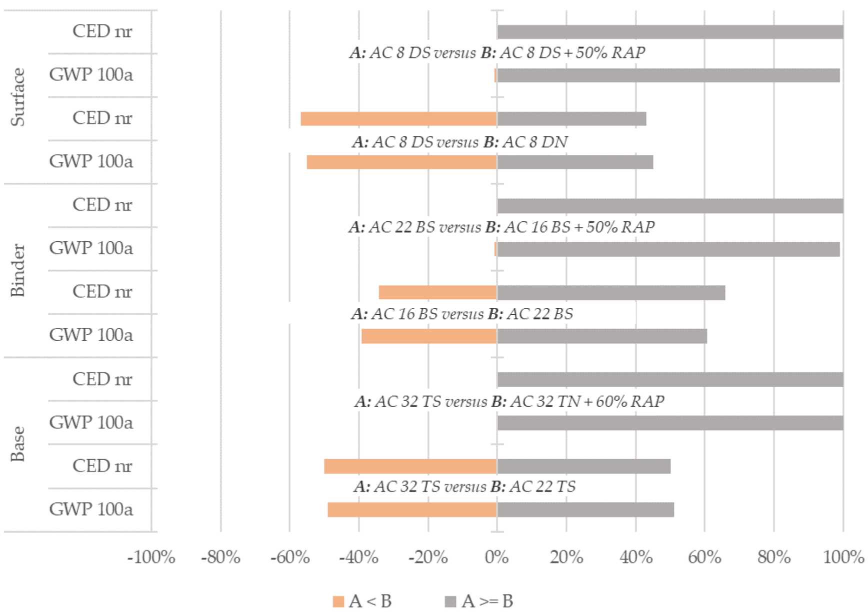

Figure 10. Monte Carlo simulation of asphalt materials.

According to Figure 10, the asphalt materials containing higher amounts of RAP have lower environmental impacts than the traditional materials. The comparison between traditional asphalt materials applied to surface and base layers showed similar performances. The AC 22 BS used within binder layers performed slightly better than AC 16 BS.

Figure 11 shows the Monte Carlo simulations applied to traditional and modified structures that potentially perform better for each group of traffic load. The results showed that pavement structures containing asphalt materials with higher amounts of RAP have a higher probability of producing less of an impact on the environment than the traditional structures used within Münster pavements.

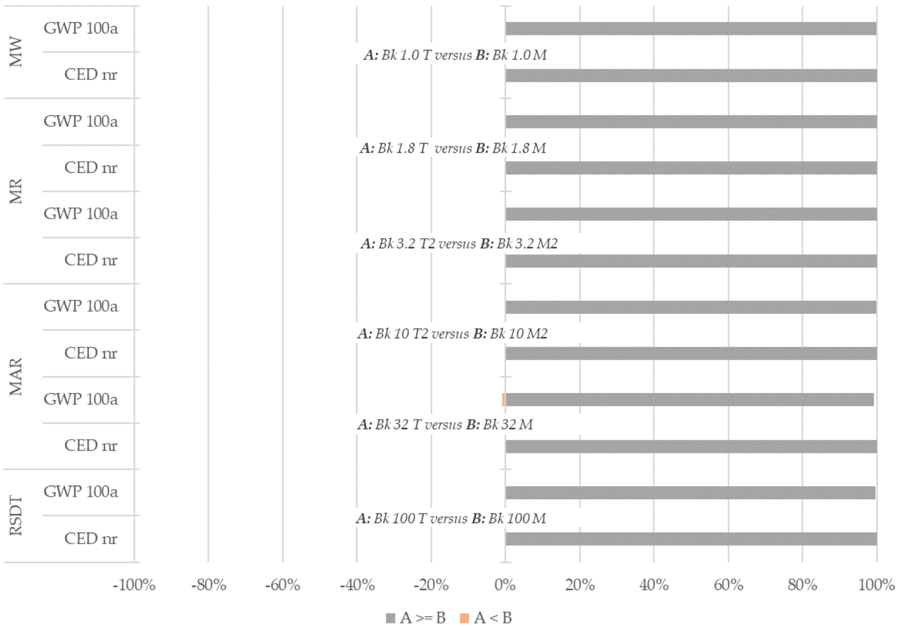

Figure 11. Monte Carlo simulation of pavement structures.

5. Conclusions and Future Works

In this study, we analyzed the environmental impacts associated with the production of asphalt mixtures applied to urban pavements in Münster and identified the benefits of using recycled materials, such as reducing the carbon footprint of road pavement constructions.

The results show that, despite the high amount of heating energy required due to the cold recycling method applied by the Munster asphalt plant, that increasing the amount of RAP reduces the environmental impacts during the production of asphalt mixtures.

The use of larger amounts of recycled raw material to compose the asphalt mixtures does not only reduce the impacts of primary raw material extraction but also the impacts caused by transportation. The transportation distances were reduced from an average of 160 km to 25 km. If we consider the average of CO_2-emission recommended by McKinnon [39,40] for road transport operations (62 g CO_2/tonne-km), the use of RAP to produce asphalt mixtures can lower the emissions by up to 217.62 kg CO_2/tonne-km.

The results additionally indicated that asphalt mixtures without RAP applied to surface (i.e., AC 8 DS and AC 8 DN) and base layers (i.e., AC 22 TS and AC 32 TS) perform similarly. Within the binder layer, the AC 22 BS has lower environmental burdens than AC 16 BS.

In general, the pavement structures designed to support lower traffic loads have minor environmental impacts due to the reduced demand for raw materials. The structures with reduced environmental impact potential are the combination of asphalt materials with the highest amount of RAP as possible. For main access roads, the structure Bk 3.2-M2 produces a lower environmental burden than the other Bk 3.2 structures; for main roads, Bk 10-M2 has a higher environmental impact.

The data used in this paper represent the reality in Münster and may not be applicable to other situations. The modified structures suggested in this study include asphalt materials that potentially have lower environmental impacts and may not be suitable for real application since local regulations must be considered in pavement design. Nevertheless, the findings provide guidance on how to apply life cycle assessment to evaluate the environmental impacts of asphalt production and can provide the basis for comparison with similar cases.

Despite all benefits presented, to calculate the total advantages of using RAP, it is necessary to evaluate the lifetime of pavements composed with asphalt mixtures with a higher content of RAP and include this variable in a future 'cradle-to-grave' analysis.

In this study, we only considered the production phase to evaluate the environment impacts of the asphalt mixtures. Therefore, to fully evaluate the sustainability of the road network in Münster, we intend to perform a cradle-to-grave and cradle-to-cradle analysis and include construction, maintenance, demolition, and end of life phases in future works.

Supplementary Materials: The following are available online at http://www.mdpi.com/2071-1050/12/15/6113/s1. Table S1: Surface layer inputs; Table S2: Binder layer inputs; Table S3: Base layer inputs; Table S4: Amount of material needed to compose traditional structures; Table S5: Amount of material needed to compose modified structures.

Author Contributions: All authors have contributed for the current paper. Data collection, writing—original draft preparation, M.S.S.L., F.G., A.B., and C.Q.; supervision, project administration, funding acquisition, A.B., C.Q., A.T., and F.G.; writing—review and editing, M.H., S.H., R.S., A.B., C.Q., A.T., and F.G. All authors have read and agreed to the published version of the manuscript.

Funding: This project has received funding from the European Union's Horizon 2020 research and innovation program under the Marie Sklodowska-Curie grant agreement no. 765057.

Acknowledgments: This study is part of the SAFERUP! Project, an innovative training network devoted to develop safe, accessible, and urban pavements. The authors appreciate the support provided by the Road Construction Department from Münster, as well as the company Oevermann (asphalt plant) for the collaboration.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. United Nations. Sustainable Development Goals. Available online: https://sustainabledevelopment.un.org/?menu=1300 (accessed on 10 March 2020).
2. Thom, N.; Dawson, A. Sustainable Road Design: Promoting Recycling and Non-Conventional Materials. *Sustainability* **2019**, *11*, 6106. [CrossRef]
3. BGS. *Construction Aggregates. Mineral Planning Factsheet*; British Geological Survey: Nottingham, UK, 2011.
4. Turk, J.; Pranjić, A.M.; Mladenovič, A.; Cotič, Z.; Jurjavčič, P. Environmental comparison of two alternative road pavement rehabilitation techniques: Cold-in-place-recycling versus traditional reconstruction. *J. Clean. Prod.* **2016**, *121*, 45–55. [CrossRef]
5. Mirhosseini, A.F.; Tahami, S.A.; Hoff, I.; Dessouky, S.; Ho, C.-H. Performance evaluation of asphalt mixtures containing high-RAP binder content and bio-oil rejuvenator. *Constr. Build. Mater.* **2019**, *227*, 116465. [CrossRef]
6. Abed, A.; Thom, N.; Presti, D.L. Design considerations of high RAP-content asphalt produced at reduced temperatures. *Mater. Struct.* **2018**, *51*, 224. [CrossRef]
7. Presti, D.L.; Carrión, A.J.d.; Airey, G.; Hajj, E. Towards 100% recycling of reclaimed asphalt in road surface courses: Binder design methodology and case studies. *J. Clean. Prod.* **2016**, *131*, 43–51. [CrossRef]
8. Reza, B.; Sadiq, R.; Hewage, K. Emergy-based life cycle assessment (Em-LCA) for sustainability appraisal of infrastructure systems: A case study on paved roads. *Clean. Technol. Environ. Policy* **2014**, *16*, 251–266. [CrossRef]
9. Petit-Boix, A.; Llorach-Massana, P.; Sanjuan-Delmás, D.; Sierra-Pérez, J.; Vinyes, E.; Gabarrell, X.; Rieradevall, J.; Sanyé-Mengual, E. Application of life cycle thinking towards sustainable cities: A review. *J. Clean. Prod.* **2017**, *166*, 939–951. [CrossRef]
10. Choi, J.-H. Strategy for reducing carbon dioxide emissions from maintenance and rehabilitation of highway pavement. *J. Clean. Prod.* **2019**, *209*, 88–100. [CrossRef]
11. Zheng, X.; Easa, S.M.; Yang, Z.; Ji, T.; Jiang, Z. Life-cycle sustainability assessment of pavement maintenance alternatives: Methodology and case study. *J. Clean. Prod.* **2019**, *213*, 659–672. [CrossRef]
12. Giustozzi, F.; Crispino, M.; Flintsch, G. Multi-attribute life cycle assessment of preventive maintenance treatments on road pavements for achieving environmental sustainability. *Int. J. Life Cycle Assess.* **2012**, *17*, 409–419. [CrossRef]

13. Gschösser, F.; Wallbaum, H.; Boesch, M.E. Life-Cycle Assessment of the Production of Swiss Road Materials. *J. Mater. Civ. Eng.* **2012**, *24*, 168–176. [CrossRef]
14. Jullien, A.; Dauvergne, M.; Cerezo, V. Environmental assessment of road construction and maintenance policies using LCA. *Transp. Res. Part D Transp. Environ.* **2014**, *29*, 56–65. [CrossRef]
15. Balaguera, A.; Carvajal, G.I.; Albertí, J.; Fullana-i-Palmer, P. Life cycle assessment of road construction alternative materials: A literature review. *Resour. Conserv. Recycl.* **2018**, *132*, 37–48. [CrossRef]
16. Chiu, C.-T.; Hsu, T.-H.; Yang, W.-F. Life cycle assessment on using recycled materials for rehabilitating asphalt pavements. *Resour. Conserv. Recycl.* **2008**, *52*, 545–556. [CrossRef]
17. Aurangzeb, Q.; Al-Qadi, I.L.; Ozer, H.; Yang, R. Hybrid life cycle assessment for asphalt mixtures with high RAP content. *Resour. Conserv. Recycl.* **2014**, *83*, 77–86. [CrossRef]
18. Trigaux, D.; Wijnants, L.; de Troyer, F.; Allacker, K. Life cycle assessment and life cycle costing of road infrastructure in residential neighbourhoods. *Int. J. Life Cycle Assess.* **2017**, *22*, 938–951. [CrossRef]
19. Farina, A.; Zanetti, M.C.; Santagata, E.; Blengini, G.A. Life cycle assessment applied to bituminous mixtures containing recycled materials: Crumb rubber and reclaimed asphalt pavement. *Resour. Conserv. Recycl.* **2017**, *117*, 204–212. [CrossRef]
20. Gschösser, F. Environmental Assessment of Road Constructions: Life Cycle Assessment of Swiss Road Pavements and Accompanying Analysis of Construction and Maintenance costs. Ph.D. Thesis, Swiss Federal Institute of Technology Zurich, Zurich, Switzerland, 2011.
21. Gschösser, F.; Wallbaum, H. Life cycle assessment of representative swiss road pavements for national roads with an accompanying life cycle cost analysis. *Environ. Sci. Technol.* **2013**, *47*, 8453–8461. [CrossRef]
22. FGSV, Richtlinien für die Standardisierung des Oberbaus von Verkehrsflächen: RStO 12 (in ger). In *Forschungsgesellschaft für Straßen- und Verkehrswesen*; FGSV Verlag GmbH: Köln, Germany, 2012; Volume 499, ISBN 978-3-86446-021-0.
23. Raja, E.W. Method Statement for Asphalt Paving Works|Asphalt Concrete|Asphalt Pavement. Available online: https://www.thecivilengineering.com/method-statement-for-asphalt-paving-works-asphalt-concrete-asphalt-pavement/ (accessed on 17 February 2020).
24. EN 13108-1. Bituminous mixtures—Material specifications—Part 1: Asphalt Concrete. 2016. Available online: https://infostore.saiglobal.com/preview/256742437874.pdf?sku=872301_SAIG_NSAI_NSAI_2074047 (accessed on 17 May 2020).
25. EN 15643-5. Sustainability of Construction Works—Sustainability Assessment of Buildings and Civil Engineering Works: Part 5—Framework for the Assessment of Sustainability Performance of Civil Engineering Works. 2016. Available online: https://infostore.saiglobal.com/preview/is/en/2017/i.s.en15643-5-2017.pdf?sku=1951532 (accessed on 17 May 2020).
26. Santos, J.; Bressi, S.; Cerezo, V.; Presti, D.L.; Dauvergne, M. Life cycle assessment of low temperature asphalt mixtures for road pavement surfaces: A comparative analysis. *Resour. Conserv. Recycl.* **2018**, *138*, 283–297. [CrossRef]
27. Waples, D.W.; Waples, J.S. A Review and Evaluation of Specific Heat Capacities of Rocks, Minerals, and Subsurface Fluids. Part 2: Fluids and Porous Rocks. *Nat. Resour. Res.* **2004**, *13*, 123–130. [CrossRef]
28. Santos, J.; Flintsch, G.; Ferreira, A. Environmental and economic assessment of pavement construction and management practices for enhancing pavement sustainability. *Resour. Conserv. Recycl.* **2017**, *116*, 15–31. [CrossRef]
29. National Academies of Sciences, Engineering, and Medicine. Field Performance of Warm Mix Asphalt Technologies. Available online: https://www.nap.edu/download/22272 (accessed on 17 May 2020).
30. ISO 14040. Environmental Management—Life Cycle Assessment—Principles and Framework. 2006. Available online: https://www.iso.org/standard/37456.html (accessed on 20 March 2020).
31. CEN-TC350. Sustainability of Construction Works—Civil Engineering Works Sustainability Assessment Methodology. 2019. Available online: https://standards.iteh.ai/catalog/tc/cen/6a14a364-e1ed-4d64-999a-c0003d282f5d/cen-tc-350-wg-6. (accessed on 10 May 2020).
32. EN 15804. Sustainability of Construction Works—Environmental Product Declarations—Core Rules for the Product Category of Construction Products. 2018. Available online: https://standards.iteh.ai/catalog/standards/cen/c98127b4-8dc2-48a4-9338-3e1366b16669/en-15804-2012a2-2019 (accessed on 5 June 2020).

33. Commission Regulation (EU) 2016/646—of Amending Regulation (EC) No 692/2008 as Regards Emissions from Light Passenger and Commercial Vehicles (Euro 6), 646/2016. Available online: https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32016R0646&from=EN (accessed on 12 May 2020).
34. PRé Consultants. SimaPro Tutorial. 2019. Available online: https://support.simapro.com/articles/Manual/SimaPro-Tutorial (accessed on 12 May 2020).
35. Ecoinvent Center. Ecoinvent Database. 2010. Available online: https://www.ecoinvent.org/ (accessed on 12 May 2020).
36. Intergovernmental Panel on Climate Change, IPCC. Available online: http://www.ipcc.ch/ (accessed on 1 July 2020).
37. Frischknecht, R.; Jungbluth, N.; Althaus, H.J.; Hischier, R.; Doka, G.; Dones, R.; Heck, T.; Hellweg, S.; Wernet, G.; Nemecek, T.; et al. Ecoinvent 2 Overview and Methodology. *Ecoinvent Rep. No1* **2007**, *1*, 1–77.
38. Hajibabaei, M.; Hesarkazzazi, S.; Lima, M.; Gschösser, F.; Sitzenfrei, R. Environmental assessment of construction and renovation of water distribution networks considering uncertainty analysis. *Urban Water J.* **2020**, *41*, 1–12. [CrossRef]
39. Cefic: Conseil Européen des Fédérations de l'Industrie Chimique. Guidelines for Measuring and Managing CO_2 Emission from Freight Transport Operations. 2011. Available online: https://www.ecta.com/resources/Documents/Best%20Practices%20Guidelines/guideline_for_measuring_and_managing_co2.pdf (accessed on 17 May 2020).
40. McKinnon, A.C.; Piecyk, M. Measuring and Managing CO_2 Emissions in European Chemical Transport. 2010. Available online: https://cefic.org/app/uploads/2018/12/MeasuringAndManagingCO2EmissionOfEuropeanTransport-McKinnon-24.01.2011-REPORT_TRANSPORT_AND_LOGISTICS.pdf (accessed on 17 May 2020).