KTH Architecture and the Built Environment

Life Cycle Assessment of Asphalt Pavements including the Feedstock Energy and Asphalt Additives

Licentiate Thesis

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Abstract:

Roads are assets to the society and an integral component in the development of a nation’s infrastructure. To build and maintain roads; considerable amounts of materials are required which consume quite an amount of electrical and thermal energy for production, processing and laying. The resources (materials and the sources of energy) should be utilized efficiently to avoid wastes and higher costs in terms of the currency and the environment.

In order to enable quantification of the potential environmental impacts due to the construction, maintenance and disposal of roads, an open life cycle assessment (LCA) framework for asphalt pavements was developed. Emphasis was given on the calculation and allocation of energy used for the binder and the additives. Asphalt mixtures properties can be enhanced against rutting and cracking by modifying the binder with additives. Even though the immediate benefits of using additives such as polymers and waxes to modify the binder properties are rather well documented, the effects of such modification over the lifetime of a road are seldom considered. A method for calculating energy allocation in additives was suggested. The different choices regarding both the framework design and the case specific system boundaries were done in cooperation with the asphalt industry and the construction companies in order to increase the relevance and the quality of the assessment.

Case-studies were performed to demonstrate the use of the LCA framework. The suggested LCA framework was demonstrated in a limited case study (A) of a typical Swedish asphalt pavement. Sensitivity analyses were also done to show the effect and the importance of the transport distances and the use of efficiently produced electricity mix. It was concluded that the asphalt production and materials transportation were the two most energy consuming processes that also emit the most GreenHouse Gases (GHG’s). The GHG’s, however, are largely depending on the fuel type and the electricity mix. It was also concluded that when progressing from LCA to its corresponding life cycle cost (LCC) the feedstock energy of the binder becomes highly relevant as the cost of the binder will be reflected in its alternative value as fuel. LCA studies can help to develop the long term perspective, linking performance to minimizing the overall energy consumption, use of resources and emissions. To demonstrate this, the newly developed open LCA framework was used for an unmodified and polymer modified asphalt pavement (Case study B). It was shown how polymer modification for improved performance affects the energy consumption and emissions during the life cycle of a road. From the case study (C) it was concluded that using bitumen with self-healing capacity can lead to a significant reduction in the GHG emissions and the energy usage. Furthermore, it was concluded that better understanding of the binder would lead to better optimized pavement design and thereby to reduced energy consumption and emissions. Production energy limits for the wax and polymer were determined which can assist the additives manufacturers to modify their production procedures and help road authorities in setting ‘green’ limits to get a real benefit from the additives over the lifetime of a road.

Keywords: Life Cycle Assessment; feedstock energy; asphalt binder additives; mass-energy flows; bitumen healing; wax; polymer

Preface

The work presented in this licentiate thesis has been carried out at KTH, Royal Institute of Technology, at the division of Highway and Railway Engineering.

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I would specially like to thank and give my high regards to my supervisor, Professor Björn Birgission and co-supervisor, Dr. Susanna Toller, for their guidance during this process. What I have achieved, wouldn't have been possible without their time and supervision. I am deeply indebted to Prof. Niki Kringos whose suggestions and encouragement helped me do even more than I planned for.

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Special thanks to my mom, grandma, sister and brother for always being with me.

In the end, I want to thank my wife, Amna Ali Butt, for her love and belief in me, and my family in Pakistan and abroad for their moral support.

I could go on and on thanking a lot more people but, honestly, thanks a lot everyone for your love and support.

Ali Azhar Butt

علی اظہر بٹ

Stockholm, Oct'12

Dedication

Allhamdullilah……

In the name of Allah, The most Gracious, The most Merciful.

"O my Lord! Open for me my chest (grant me self-confidence, contentment and boldness). And ease my task for me; And loose the knot from my tongue. That they understand my speech." (Surah Taha, verses 25-28)

I would like to dedicate my work to my parents specially my dad, Azhar Mahmood Butt (late), who will be proud of me somewhere in the other world.

I surely love and miss you dad!!!

Publications

This Licentiate thesis is based on the following publications:

Journal:

I. Butt, A.A., Mirzadeh, I., Toller, S. and Birgisson, B. (2012), "Life Cycle Assessment Framework for asphalt pavements; Methods to calculate and allocate energy of binder and additives", *International Journal of Pavement Engineering*, DOI:10.1080/10298436.2012.718348.

II. Butt, A.A., Birgisson, B. and Kringos, N. (2013), "Considering the benefits of asphalt modification using a new technical LCA framework", submitted for a special edition of *International Journal of Road Materials and Pavement Design* in 5th EATA conference, 3-5 June, Braunschweig, Germany.

Conference:

III. Butt, A.A., Birgisson, B. and Kringos, N. (2012), "Optimizing the Highway Lifetime by Improving the Self Healing Capacity of Asphalt", *Procedia - Social and Behavioral Sciences*, Fourth Transport Research Arena, Vol. 48, 23-26 April, Athens, Greece, p. 2190-2200.

Other relevant publications:

i. Butt, A.A., Tasdemir, Y. and Edwards, Y. (2009), "Environmental friendly wax modified mastic asphalt", *II International Conference on Environmentally Friendly Roads*, ENVIROAD, 15-16 Oct, Warsaw, Poland.

ii. Edwards, Y., Tasdemir, Y. and Butt, A.A. (2010), "Energy saving and environmental friendly wax concept for polymer modified mastic asphalt", *Materials and Structures*, Vol. 43, supplement 1, p. 123-131.

iii. Butt, A.A., Jelagin, D., Tasdemir, Y. and Birgisson, B. (2010), "The Effect of Wax Modification on the Performance of Mastic Asphalt", *International Journal of Pavement Research and Technology*, Vol. 3, No. 2, p. 86-95.

iv. Mirzadeh, I., Butt, A.A., Toller, S. and Birgisson, B. (2012), "Life Cycle Cost Analysis Based on Time and Energy Entities for Asphalt Pavements", under review in *International Journal of Pavement Engineering*.

v. Mirzadeh, I., Butt, A.A., Toller, S. and Birgisson, B. (2012), "A Life Cycle Cost Approach based on the Calibrated Mechanistic Asphalt Pavement Design Model", *European Pavement and Asset Management Conference,* EPAM, 5–7 Sep, Malmö, Sweden.

vi. Butt, A.A., Mirzadeh, I., Toller, S. and Birgisson, B. (2012), "Bitumen Feedstock Energy and Electricity production in Pavement LCA", *ISAP 2012 International Symposium on Heavy Duty Asphalt Pavements and Bridge Deck Pavements*, 23-25 May, Nanjing, China.

vii. Butt, A.A., Jelagin, D., Birgisson, B. and Kringos, N. (2012), "Using Life Cycle Assessment to Optimize Pavement Crack-Mitigation", *Scarpas et al. (Eds.), 7th RILEM International Conference on Cracking in Pavements*, Vol. 1, 20-22 June, Delft, Netherlands, p. 299-306.

Contents

1.0 Introduction

Roads are assets to the society and an integral component in the development of a nation's infrastructure. Sweden has a road network consisting of streets, state and municipal roads, and private roads which sums up to be about 0.6 million km, according to Swedish National Road Administration. To build and maintain roads; considerable amounts of materials including bitumen, aggregates and additives are required which consume quite an amount of electrical and thermal energy for production, processing and laying. All these materials and the source of energies are the resources which are part of the nature. These resources shouldn't be wasted rather utilized efficiently to avoid wastes and higher costs in terms of currency and the environment. Hence, environmental tools are required which can help to determine and improve the efficient use of such resources.

Life cycle thinking is becoming popular in different fields of research as it is being recognized that resource depletion and the emissions of different potentially harmful substances are often a result from the activities in different life cycle stages of a product´s life. Life Cycle Assessment (LCA) is a versatile tool to investigate the environmental aspect of a product, a service, a process or an activity by identifying and quantifying related input and output flows utilized by the system and its delivered functional output in a life cycle perspective (Baumann *et al.,* 2003). Ideally, it includes all the processes associated to a product from its 'cradle-raw material extraction' to its 'grave-disposal'. LCA studies can help to determine and minimize the energy consumption, use of resources and emissions to the environment by giving a better understanding of the systems. LCAs can also purpose different alternatives for different phases of a life cycle of the system if we have different design alternatives. Unfortunately, LCA has not yet been adopted by the industry or the road authorities as part of the procurement and material selection procedure. This could partly be explained by the lack of a technical tool that accurately represents all the aspects of the pavement sector and is able to make close predictions of the in-time pavement response. This system should be transparent and black boxes should be avoided in the system.

The potential energy embedded in the resource which is not used as energy source may be referred to as feedstock energy. Bitumen has a high energy content of 40.2 MJ/kg (Garg *et al.,* 2006) but using bitumen as a fuel results in very high emissions (Faber, 2002; Herold, 2003) and high energy costs. Aggregate on the other hand is considered to have no feedstock energy. It has also been reported in number of previous studies that bitumen has a low expended energy (energy used throughout the production of a material) of approximately 0.4 to 6 MJ/kg (Zapata *et al.,* 2005). There are authors who include the feedstock energy of the bitumen but the procedure to calculate it and the theories behind the decision to include it are seldom explicitly described. So far the source being referred regarding the feedstock energy of the bitumen is Garg *et al.* (2006) and (VTT). A general approach to calculate the feedstock energy in bitumen seems to be missing.

The pros and cons of using polymers and waxes to modify the binder properties are well documented. The long-term effect of this modification over the entire life time of the pavement is, however, very seldom considered. In fact, it is not a common practice to report the energy consumption and emissions for the production of the additives used in the asphalt industry. Therefore to date, very little data is available for the production phase of the additives, causing a gap in knowledge of the long-term benefit from the additives from a life cycle perspective. Considering the importance of such information, a mass-energy flow framework is needed which is able to calculate the energy consumption and emissions during the production phase of any material based on the electricity and fuel usage.

1.1 Research Aims

The objective of this study is to enable the improvements of the asphalt pavement LCAs by describing methods to consider feedstock energies and the asphalt additives. The work focuses on asphalt pavement and not the whole road network. A general framework for LCA of the asphalt pavement was suggested and the methods to calculate the feedstock energy, and quantify the mass and energy flows of the additives like waxes and polymers, were developed. The use of the LCA framework and developed calculation methods was demonstrated in three case studies;

- The first case study (A) demonstrates the use of LCA framework for a typical Swedish asphalt pavement followed by two sensitivity analysis (SA).
    - The first SA demonstrates how the transportation distances affect the overall LCA results.
    - The second SA considers the importance of efficient electricity production and its use.
- The second case study (B) focuses on the polymer modification for increased crack resistance.
- The third case study (C) focuses on the self-healing capability of bitumen and the use of Montan wax.

In addition to enable improved LCAs of pavements, a goal was also to increase the knowledge on the long-term benefits of asphalt modification by including the energy and emissions that are associated with their production, and calculating the limits for the production energies of the additives. These limits can assist the manufacturers to modify their production procedures and help road-authorities in setting the 'green' limits.

1.2 Thesis Outline

The thesis has been divided into two sections. The first section describes the LCA framework for the asphalt pavements. It also suggests a method to estimate feedstock energy of bitumen and a method to allocate energy in a production phase of the additives (*Paper I*). The second section consists of three case studies which show the broad spectra in which the LCA framework could be used followed by SA (*Paper I, Paper II*, *Paper III*).

SECTION 1

2.0 Description of Life Cycle Assessment Framework (Paper I)

The life cycle of a road can be divided into several stages; Extraction of the raw materials, processing the construction materials, transportation, construction, operation, maintenance, demolition, recycling and waste treatment. Several researchers are studying the effects on the environment due to construction, maintenance and disposal of roads (Birgisdóttir, 2005; Huang *et al.*, 2009; Santero *et al.*, 2010a; 2010b; Stripple, 2001; Zhang *et al.*, 2008;). Such research enables effective measures to be identified to reduce the resource use and the environmental loads from the roads, for example by suggesting changes in the technical procedure or the choice of materials. There are number of softwares and models developed like Federal Highway Administration's (FHWA) RealCost, Caltrans' Cal B/C and FHWA's IMPACTS but most look at the life cycle cost (LCC) analysis or neglect the pavements life cycle perspective (Santero *et al.*, 2010a). On the other hand, several previous LCA´s of roads have mostly been focused on comparing asphalt and concrete pavements (Santero *et al.*, 2010a; 2010b).

In this thesis, construction, maintenance and end of life of a flexible pavement (asphalt road) were considered for the development of the LCA framework. The functional unit defines the function of the system and for this study; it includes the length, lane width, nominal design life and residual material at the end of life of the pavement. The use phase is however important to consider at the network level when decisions of constructing a road, bridge or a tunnel are being made. On the other hand, if the fuel usage and emissions from the traffic are included in a life cycle study at a project level, it will over shadow all the other phases in a road's life cycle. The LCA framework developed in this study focuses on a project level, therefore the use phase was not considered. Material transport, construction and maintenance equipment, and machinery are present at each unit process in the road system and each unit process is based on the design considerations.

2.1 System Boundaries

Figure 1 shows the LCA framework for the asphalt pavement. For the development of the framework, use of the materials was taken as the starting point and end of life of the pavement to be the end point. The input includes the resources and utilities whereas the output is the environmental impacts as shown in Figure 1. The energy consumption and emissions produced in the asphalt production and handling of the asphalt mixtures and their components were considered.

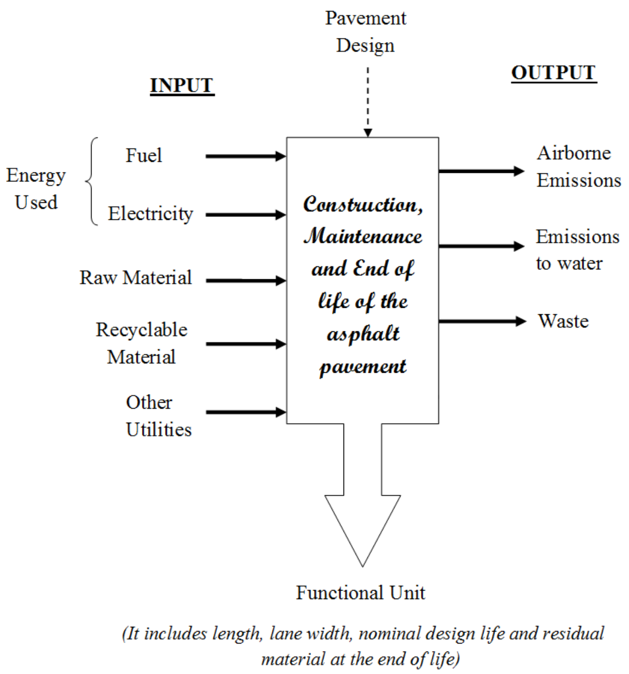

Figure 1. The asphalt pavement LCA framework showing the input-output flows in the system

In the system definition, certain boundaries were assumed in the development of the framework. The study was limited to the project level, hence land area uses for some other purpose and use phase were not considered in the LCA framework. It was assumed that the road location was already known. Furthermore, the thickness of the base and sub-base layers was assumed to be constant along the length of the road. The raw materials considered for the framework were bitumen, aggregate and additives. Anything that did not end up as an output in the system, but still was utilized in the process, was referred to as "other utilities" in the framework.

Fuel and electric energies were accumulated separately. This procedure was necessary because electricity is a secondary energy source which could only be added to the fuel energy if the electricity production energy and efficiency are known i.e. if electricity and fuel energy are to be cumulated to get equivalent thermal energy (ETE), conversion factors are needed to be known.

2.2 Feedstock Energy Calculation

The asphalt components are not consumed during the pavements life and therefore, it may be argued that feedstock energy should not be included in a life cycle study of the asphalt pavements. It could be considered as borrowed from the nature. According to Oers *et al.* (2002), a certain functional element from a natural resource which can be recycled and has an economical reserve is considered as borrowed. The feedstock energy consideration becomes important only when the asphalt is combusted to extract energy. The asphalt mixture is placed on the ground in form of a pavement and once the asphalt pavement serves its function during its design life, it could be recycled, reused, or else buried in the ground as the subgrade. The feedstock energy remains unused as the asphalt materials, although relocated, are placed back into the nature in form of the asphalt mixture. When progressing from a LCA to its corresponding LCC, however the feedstock energy contents of the binder becomes highly relevant as the cost of the binder will be reflected in its alternative value as fuel. Therefore, it may be argued that the energy used within the asphalt materials should be reported although it is not consumed. What is missing in the literature is the method to calculate the feedstock energy in the asphalt pavements.

Bitumen performance and properties as a binder could be investigated in the laboratory study which then is used as the inputs in the road design procedures. The main component of HFO is the residual oil i.e. the heaviest or the bottom product that comes out from a crude oil refinery if bitumen is not being produced. Energy contents of HFO and that of the bitumen are basically the same if they are of the same density. Considering this fact, HFO equivalence can be used to find the energy value for the bitumen. There are good correlations available between density and energy contents for HFO (Notes on Heavy Fuel Oil, 1984). Hence, if the sulphur content and the density of the bitumen is obtained from the laboratory tests, the Higher Heating Value (HHV, includes condensation of water in the flue gases) or Lower Heating Value (LHV, all combustion products leave the system as gases except ashes) could be read from Figure 2. Normally, LHV is closest to the actual energy yield in most of the cases (NPC, 2007). This heating value may therefore be seen as the feedstock energy which is the inherent energy.

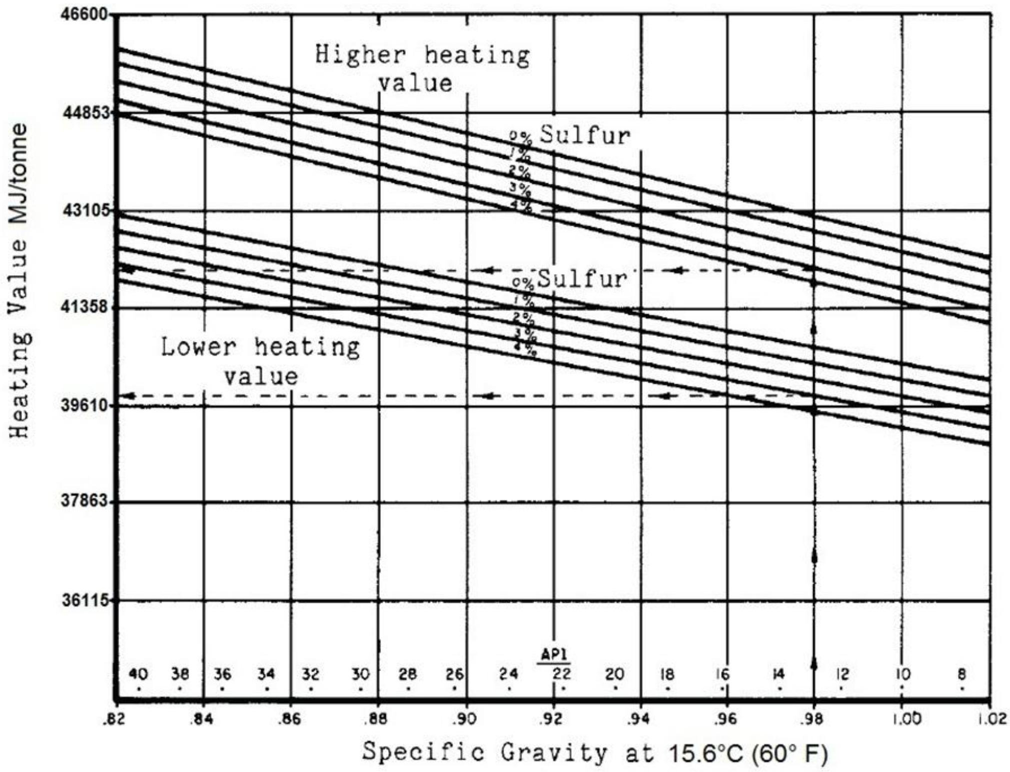

Figure 2. Heating Values relative to gravity and sulphur content (Notes on Heavy Fuel Oil, 1984) (Heating values converted to MJ/tonnes)

2.3 Method to calculate mass-energy flows

There are claims that certain additives reduce the mixing temperatures of the asphalt mixtures without having a negative impact on the mixture properties. Waxes are one of the additives which have been tested in number of studies and some have proved to fulfill the claim. However, it is not a common practice to report the energy consumption and emissions for the production of such additives used in the asphalt industry. Thus, the real gain in terms of saving energy and reducing emissions is unknown in a life cycle perspective of a road. Therefore, a framework to calculate the mass and energy consumption is developed (Figure 3) that could be used in the LCA framework to quantify the energy consumed and emissions emitted during the production phase of such additives. There are different terms used; P for process, B for by-product, Y for yield, E for electricity and H for heating.

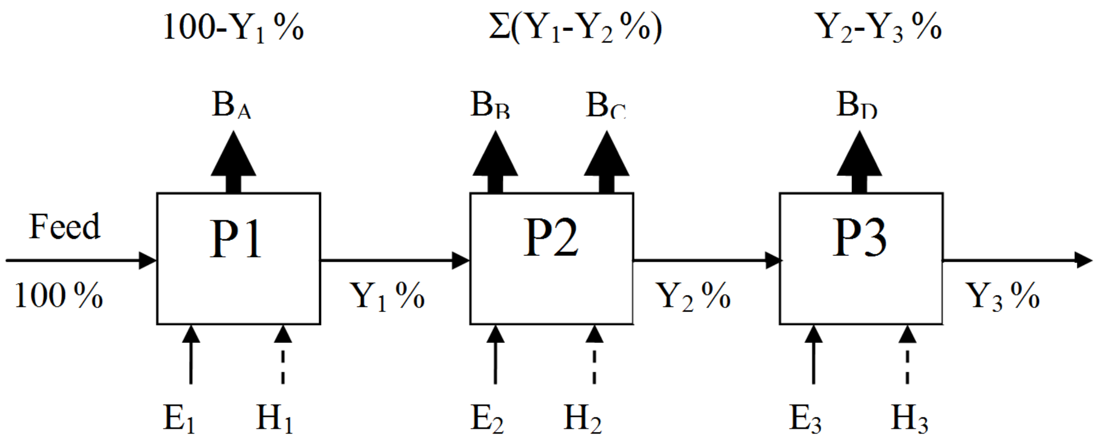

Figure 3. Framework to calculate mass balance and energy consumption of a process

In Sweden, resources like fossil fuels, nuclear and hydro power, wind and biofuel are used to produce an electricity mix. The mix varies every year resulting in a different ETE value for every electricity mix produced. The conversion factor to get ETE consumed is denoted as 'X' in the formulas depending on what electricity mix is being used.

If a 100% feed enters the process then equations will be as under;

ETE consumed per tonne product = $$100.\frac{X.E_1 + H_1}{Y_1} \qquad (1)$$

ETE by-product calculation per tonne product = $$100.\frac{X.E_1 + H_1}{100 - Y_1} \qquad (2)$$

Mass-distributed ETE = $$\left(X.E_1 + H_1\right).\frac{Y_1}{100} \text{ and } \left(X.E_1 + H_1\right).\frac{(100\text{-}Y_1)}{100} \qquad (3)$$

Equations (1) and (2) are the result of typical economic calculations whereas Equation (3) takes no position to allocation. Being faced with LCA data from product sheets it is not always clear which distribution principles have been used. Standards normally recommend allocation to mass but this is no universal solution. The equation to choose has to be based on the questions asked. As an example one can also look at different scenarios in a process. If the final yield (Y3) is the required product (wax); the energy flow accumulates and may be allocated to the final product only. This way the by-product (Y2-Y3) could be considered having no energy allocation.

SECTION 2

3.0 Case studies

Three case studies are presented in this section;

i. *Case study A:* The suggested LCA framework for the asphalt pavement applied on a theoretical case in which a typical Swedish asphalt pavement was assumed to be constructed as part of Norra länken in Stockholm, Sweden.
   a. SA-1 on the transport distances
   b. SA-2 on efficient electricity production and its use

ii. *Case study B:* The suggested LCA framework for the asphalt pavement was applied on three cases; unmodified asphalt, bitumen with known intrinsic healing potential and bitumen with 3% Montan wax.

iii. *Case study C:* The suggested LCA framework for the asphalt pavement was applied on three cases; unmodified asphalt, bitumen with 3.5% Styrene Butadiene Styrene (SBS) polymer and bitumen with 3.5% unknown polymer that gives 100% better performance when compared with unmodified case.

For all the case studies, the energy, fuel and electricity were calculated as MJ/FU whereas emissions and materials as tonne/FU.

3.1 Case study A *(Paper I)*

3.1.1 Goal and scope

The suggested framework for the asphalt pavement was applied on a theoretical case in which a typical Swedish asphalt pavement was assumed to be constructed as part of Norra länken in Stockholm, Sweden. The functional unit (FU) for the case study A was defined as the construction of 1 km flexible pavement per lane for the nominal design life.

3.1.2 Inventory analysis

The asphalt pavement design was based on the design life of 18 years for the Equivalent Single Axle Load (ESAL's) of 7.5 million and a reliability of 85%. As a result, the thickness of the asphalt pavement was 0.165 m and the width of the lane was 3.5 m. The density of asphalt was assumed to be 2.4 tonne/m^3. The asphalt mix design was assumed to consist of 4.5% bitumen and 95.5% aggregate by weight of the asphalt. Additives were not considered in this case. For determining the feedstock energy of the binder, 70/100 bitumen with sulphur content of 3% and specific gravity of 1.02 at 15.6°C (60°F) was considered.

The feedstock energy of the bitumen was determined using Figure 2. The material energy and emission data set for bitumen and aggregate can be read from Table 1 and 2 respectively. For the impact assessment only GreenHouse Gases (GHGs) were considered and their contribution to the environmental impact category of the climate change. Swedish electricity mix was calculated based on the data from IEA (2008) whereas the raw material data and GHGs were calculated from Baumann *et al.* (2003) (Table 3).

Table 1. Energy data used for bitumen and aggregate

Material	Type	Energy per tonne of material (MJ/tonne)	
Bitumen[1]	70/100	39213	
		Electricity used per tonne of material (MJ/tonne)	**Fuel used per tonne of material (MJ/tonne)**
Bitumen[2]	70/100	252	1060
Aggregate[2]	crushed	21.19	16.99

[1] Feedstock energy calculated based on (Notes on Heavy Fuel Oil, 1984) (Figure 2)
[2] Expended energy (Stripple, 2001)

Table 2. Emissions to air in grams per tonne of bitumen and aggregates produced

Emissions to Air (g/tonne of material)	Bitumen[1]	Aggregate
CO_2	173000	1537
N_2O	0.106	0.058
CH_4	0.035	0.529

[1] Emissions from bitumen were assumed to be the same as reported by Stripple (2001)

Table 3. Swedish electricity mix, calculated based on IEA (2008), and corresponding resource consumption and GHGs calculated based on Baumann *et al.* (2003).

		Resources consumed									Emissions to air		
Electricity produced	**Swedish Mix**	**Cu in ore**	**oil**	**Lignite**	**Limestone**	**Natural gas**	**Hard coal**	**U in ore**	**Water**	**Wood**	**CO_2**	**N_2O**	**CH_4**
1 TJ	%	**Kg**	**Kg**	**Kg**	**Kg**	**Nm^3**	**Kg**	**Kg**	**Kg**	**Kg**	**Kg**	**Kg**	**Kg**
Hard Coal	1.49	0.0638	38.43	29.05	32.92	28.27	2726	0.002	159396	19.66	4109.04	0.0267	14.95
Oil	0.58	0.0243	425.35	7.16	2.51	35.25	8.67	0.0005	112302	0.166	1334.71	0.0322	1.786
Fuel Gas	0.40	0.0176	5.06	1.07	0.80	237.58	48.63	7.36E-05	2443.64	0.418	988.03	0.006	1.502
Nuclear	42.6	0.9624	104.76	101.35	69.41	176.72	536.55	3.3411	1077365	9.113	1535.14	0.341	4.369
Biofuel	6.04	0.0268	167.84	7.62	5.18	17.23	17.71	0.0005	3977	10517	670.66	1.02	1.024
Hydro	46.1	0.0267	34.51	30.17	302.17	10.89	135.62	0.0021	5397.3	1.361	482.07	0.0069	1.103
Wind	1.33	0.5508	8.91	3.11	10.04	5.03	20.35	0.0002	618	0.209	60.90	0.001	0.203
										Summa:	**9181**	**1.431**	**24.94**

The emissions from waste combustion (1.44%) were assumed to be equal as biofuel

The main processes considered for the case study were the emissions and the energy used during the transportation of the materials, the asphalt mixing, paving and compaction. The data for the processes listed above can be read from Tables 4-7.

Table 4. Asphalt mixing process

Material	Type	Energy per tonne of asphalt (MJ/tonne)
Asphalt[1]	Hot mix	39213
Electricity/Heat [2]	**Units**	**Amount Per tonne of asphalt**
Swedish Mix	kWh/tonne	8.3
Eldningsolja 1	liter/tonne	6.8
Emissions to air[3]	**Units**	**Amount per tonne of asphalt**
CO_2	g	19392
N_2O	g	0.430
CH_4	g	0.757

[1] Feedstock energy (feedstock energy of bitumen + aggregate)
[2] Data from NCC (Jonas Ekblad)
[3] It has been assumed that the emissions from the production and combustion of Eldningsolja 1 are same as diesel.

Table 5. Data set for the paver and the compactor (Stripple, 2001)

Paving/Rolling	Units	Paver (Dynapac F16)	Compactor (Dynapac CC421)
Energy	MJ/m^2	0.5940	0.7988
Speed	m/hr	240	4000
Effective capacity	m^2/hr	1300	791
Paving time (efficiency)	min/hr	50	50
Number of Passes		1	6

Table 6. Transportation of materials by distribution trucks with 14 tonnes load capacity including weight of the vehicle

Transport Material	From	To	Distance[4] (km)	Material quantity (tonne)	Tonne-Kilometer (tkm)
Binder	Refinery[2]	Mixing plant[1]	100	63	12474
Aggregate	Quarry site[1]	Mixing plant	5	1324	13236
Asphalt	Mixing plant	Construction site[3]	50	1386	138600

[1] Arlanda: Aggregate Quarry Site and Asphalt Mixing Plant
[2] Nynäshamn: Bitumen Refinery
[3] Norra Länken: Road Construction Site
[4] Distance will double as loaded trucks will roll to the required site and unloaded when coming back

Table 7. Emissions from vehicles, paver and compactor (Stripple, 2001)

Emissions to air	Units	Amount per MJ energy used (g/MJ)
CO_2	g	79
N_2O	g	0.0016
CH_4	g	0.00005

3.1.3 Impact assessment and interpretation

Assuming the conversion factor as 1, the feedstock energy of the bitumen (2408 GJ) was almost 30 times higher than the expended energy (82 GJ) to produce it (Table 8). The production energy of aggregate was 51 GJ. As no additives were considered and aggregates do not have any feedstock energy, the feedstock energy of the asphalt was the same as for the bitumen. The asphalt production in the plant was the most energy consuming process both regarding the electricity and the fuel consumption due to the fact that the asphalt requires heating of the materials before mixing. High temperatures usually are required to dry the aggregates, melt the bitumen and additives, for the mixing and the storage of the asphalt mixtures.

Table 8. Results of the case study A

Feedstocks Energy (TJ)	Bitumen	2.4	
	Aggregate	0	
	Asphalt	2.4	
	Item	**Energy consumed per tonne of material (MJ/tonne)**	**Total Energy (GJ/FU)**
Electricity Consumption	Bitumen Production	252	15.72
	Aggregate Production	21.19	28.05
	Asphalt Production	29.88	41.41
Fuel Consumption	Bitumen Production	1060	66.11
	Aggregate Production	16.99	22.49
	Asphalt Production	242	335.41
	Transport bitumen to the asphalt plant		10.63
	Transport aggregate to the asphalt plant		11.28
	Transport asphalt to the construction site		118.15
	Laying Asphalt		3.86
	Compacting Asphalt		2.27

The second highest energy intensive process was the transportation of the materials as considerable amount of diesel was burned to transport the asphalt. Due to the localization assumption done in the case study, a relatively low amount of energy was used for transporting the asphalt and aggregates. Paving and compaction, on the other hand, do not require much energy, but this depends on what system boundaries have been defined. If the production energy of the equipment used to pave and compact the road are considered, the results might be quite different than what can be seen.

Regarding GHGs, almost 51 tonnes of CO_2, 0.9 kg of N_2O and 2 kg of CH_4 were produced per functional unit (Table 9). Using the data of 100-year GWP (Solomon *et al.,* 2007), these emissions correspond to almost 52 tonnes CO_2-eq in terms of global warming contribution. The asphalt production was the most important process regarding these emissions whereas transporting materials and bitumen production were also relatively important.

Table 9. Total emissions to air from different processes of road construction in tonnes/FU

Emissions to air	CO_2	N_2O	CH_4
Bitumen production	10.79	6.61E-06	2.20E-06
Aggregate production	2.03	7.61E-05	7.01E-04
Asphalt production	26.88	5.96E-04	1.05E-03
Paving	0.31	6.18E-06	1.93E-07
Compacting	0.18	3.64E-06	1.14E-07
Transportation	11.06	2.24E-04	7.00E-06
Σ (tonnes)	51.25	9.13E-04	1.76E-03

3.1.4 Sensitivity Analysis (SA) (Paper I)

Sensitivity analyses were done regarding the transport distances and the electricity production mix. The different choices regarding both the framework design and the case specific system boundaries were done in cooperation with the asphalt industry and the construction companies in order to increase the relevance and the quality of the assessment.

SA-1 on transport distances

According to the SA-1, change in the transport distances largely affected the energy consumption of the system (Tables 10 and 11). The asphalt mix usually consists of about 92-96% of aggregate (by weight) which means that the aggregate quarry site and the asphalt plant should not be very far from each other or else, one of the most energy consuming process will be transportation of aggregates to the asphalt plant. With an increase of the distance of 95 km between aggregate quarry site and asphalt plant, the fuel energy increased from 11 GJ/FU to 226 GJ/FU. Similarly, the distance between the construction site and the asphalt plant will also alter the results by large. Increasing the distance between the asphalt mixing plant and the construction site also resulted in an increase of the transportation energy from 118 GJ/FU to 177GJ/FU. Thus, in case of the SA, the transportation energy consumption became much higher than the asphalt production energy bringing the transportation energy to be the highest on the energy consumption chain.

Table 10. Transportation of materials by distribution trucks with 14 tonnes load capacity including weight of the vehicle

Transport Material	From	To	Distance[1] (km)	Material quantity (tonne)	Tonne-Kilometer (tkm)
Binder	Refinery	Mixing plant	150	63	18711
Aggregate	Quarry site	Mixing plant	100	1324	264726
Asphalt	Mixing plant	Construction site	75	1386	207900

[1] Distance will double as loaded trucks will roll to the required site and unloaded while coming back

Table 11. SA-1 by changing transportation distances

	Item	Total Energy consumption (GJ/FU)
Fuel Consumption	Transport bitumen to the asphalt plant	15.95
	Transport aggregate to the asphalt plant	225.66
	Transport asphalt to the construction site	177.22

SA-2 on efficient electricity production and its use

According to the SA-2 of the electricity production assumptions, the production may have a large impact on the results. The electricity is used for heating in most of the asphalt plants in the countries where the electricity is cheap. In terms of the costs, this might be low but in terms of the excess use of resources to produce the electricity; there may be more environmental impacts which are being neglected in most of the cases. It is commonly assumed that the consumption of electricity is environmental friendly due to 'no emissions'. In a life cycle perspective, however, the production of electricity should also be included and due to different possibilities for the electricity production, there can be a large variation regarding its environmental burdens (Butt *et al.,* 2012b). The SA was done by comparing the process energy at an asphalt plant which used Swedish electricity mix from 2008 (IEA), and the asphalt plant which produced the electricity from an electricity generator running on diesel. The efficiency of the generator was around 33%. Hence, 3 MJ of diesel energy was used to produce 1 MJ of electricity resulting in the excess amount of emissions. Almost 26 times more emissions per tonne of asphalt produced were reported when the electricity used in the asphalt plant was generated using a diesel generator (Table 12). It is going to be even worse if the heating in an asphalt plant is also carried out using the electricity produced inefficiently rather than fuel.

Table 12. CO_2 emissions from Swedish electricity mix and a power plant run on diesel

Emissions to air from asphalt production (g/tonne asphalt)	CO_2
Electricity mix	274
Electricity generator	7082

3.2 Case study B *(Paper II)*

For this case study, a calibrated mechanics based design tool was used to get the design thicknesses. The model has been calibrated for Swedish conditions (Gullberg *et al.,* 2012). The analysis and design framework presented by Gullberg *et al.* (2012) is an extension of the earlier work by Birgisson *et al.* (2006), in which a framework for a pavement design against fracture based on the principles of viscoelastic fracture mechanics has been reported. In this approach, each mix was evaluated based on its dissipated creep strain energy limit ($DCSE_{lim}$), which is a measure of how much damage mixture can tolerate before a non-healable macro-crack forms. Hence, $DCSE_{lim}$ acts as a threshold between healable microcracks and non-healable macro-cracks. This is a threshold that has proven to be fundamental and independent of the mode of loading (Zhang *et al.,* 2001).

3.2.1 Goal and scope

The suggested framework for the asphalt pavement was applied on three cases using polymer as an additive. The functional unit (FU) for the case study was defined as the construction of 1 km flexible pavement per lane for the nominal design life.

– Case B1 was based on the asphalt with no polymer modification;

– Case B2 was based on the modification of the bitumen with respect to case B1 by adding 3.5% SBS polymer to the bitumen. It was observed from the IDT testing of the asphalt mixtures that the $DCSE_{lim}$ changed from 3.57 (for unmodified asphalt mixture) to 5.34 kJ/m^3 (for 3.5% SBS modified asphalt mixture) (Romeo *et al.,* 2010). Hence, an increase in $DCSE_{lim}$ of almost 50% was achieved.

–Case B3 was based on the modification of the bitumen with respect to case B1 by adding 3.5% of some unknown additive (polymer) to the bitumen. It was thereby assumed that the modification gave an increase in the $DCSE_{lim}$ of almost 100%.

The comparison of case B1 with case B2 and B3 gave insight into the added benefits in terms of reduced energy and GHG emissions when polymer was added to the asphalt against crack resistance.

3.2.2 Inventory analysis

The design of the pavement section used in Case B (Butt *et al.,* 2012a) was based on the work by Almqvist (2011). The base layer was 178 mm thick whereas the sub-base 1.0 m lying on top of the bedrock. The design was done for a mean temperature of 5 °C which corresponds to the Swedish climate zone 3. The design ESALs were assumed to be 1 million. The thicknesses of asphalt layers according to the pavement design are presented in Table 13. It was hereby assumed that both the wearing and the structural course contained the same asphalt mix design of 5.2% binder content and 94.8% aggregates. The construction site and the bitumen and aggregates storage sites were considered to be 25, 75 and 35 km from the asphalt plant, respectively. The polymer modification makes the asphalt mixture more viscous resulting in an increase in the mixing (around 200°C) temperatures when compared to unmodified asphalt mixture (around 170°C). It was thereby assumed that an increase of 17% in the fuel consumption was required for the polymer modification of the asphalt mixture.

Table 13. Asphalt pavement layer thicknesses for different cases

Cases	Description	Increase in $DCSE_{lim}$ (%)	Structural Course Thickness (mm)	Total asphalt pavement Thickness (mm)
B1	Unmodified asphalt	0	100	150
B2	3.5% SBS modified asphalt	50	69	119
B3	3.5% unknown polymer modified asphalt	100	36	86

It was observed from the literatures that a small percentage of polymer not only provides resistance against rutting and cracking (Romeo *et al.,* 2010; Ping *et al.,* 2011) but also allows reduction of the asphalt layer thicknesses. This decrease in thickness itself saves energy and reduces emissions, but polymer's production and transportation cannot be neglected as then, the real saving of the resources, energy or emissions can be reported in a life cycle perspective.

3.2.3 Impact assessment and interpretation

The results of the LCA analysis are summarized in Table 14 and Table 15. Parameters *f, g, h* are the unknown energy values (in GJ) for the SBS whereas *i, j, k* are energy values (in GJ) for the unknown polymer which are associated with the electric, fuel and transportation energies, respectively. Parameters *l, m, n* and *o* are CO_2-eq values (in tonnes) for the polymer production and transportation. For case B2, SBS polymer modification of the asphalt led to an increase of 50% $DCSE_{lim}$ which resulted in a decrease of the structural course by 31% assuming the same service life of the pavement. For the calculation of case B3, it was assumed that 3.5% of an unknown polymer was added in the asphalt which would increase the $DCSE_{lim}$ to 100% which led to a decrease of 50% w.r.t. case B2 and a further decrease of almost 64% w.r.t. case B1. From Table 14, it can be seen that the total used energy therefore reduces from 830 GJ (case B1) to 700 GJ (case B2) to 508 GJ (case B3). From Table 15, it can be seen that the total CO_2-eq reduces from 55 to 47 to 34 tonnes, respectively. These values, however, still do not include the production energy and emissions of the polymers. For this reason, the thresholds were determined for the production of such additives in Table 16.

Table 14. Process energy for case Study B per FU for different stages in the construction of the asphalt pavement

			Case B1				Case B2				Case B3			
Energy Consumed	**Item**	**Energy Consumed per ton of material (MJ/ton)**	**Total Energy consumed (GJ)**	**Σ Energy (GJ)**	**ETE (GJ)**	**% Energy consumed**	**Total Energy consumed (GJ)**	**Σ Energy (GJ)**	**ETE (GJ)**	**% Energy consumed**	**Total Energy consumed (GJ)**	**Σ Energy (GJ)**	**ETE (GJ)**	**% Energy consumed**
Electricity	Bitumen Production	252.	18.87	99	220	5.07%	14.45	78	173	4.60%	10.44	56	125	4.58%
	Polymer Production	-	-			-	***f***			-	***i***			-
	Aggregate Production	21.19	28.93			7.78%	22.95			7.31%	16.58			7.28%
	Asphalt Production	35.28	50.80			13.66%	40.30			12.83%	29.13			12.79%
Fuel	Bitumen Production	1060.	79.37	610	610	9.57%	60.77	527	527	8.68%	43.91	383	383	8.65%
	Polymer Production	-	-			-	***g***			-	***j***			-
	Aggregate Production	16.99	23.19			2.80%	18.40			2.63%	13.30			2.62%
	Asphalt Production	242/(281 for case B2-B3)	348.48			42.01%	321.18			45.86%	232.11			45.70%
	Bitumen transported* to the asphalt plant		9.57			1.15%	7.33			1.05%	5.30			1.04%
	Polymer transported* to the asphalt plant		-			-	***h***			-	***k***			-
	Aggregate transported* to the asphalt plant		81.46			9.82%	64.62			9.23%	46.70			9.20%
	Asphalt transported* to the construction site		61.37			7.40%	48.69			6.95%	35.19			6.93%
	Laying Asphalt		3.86			0.47%	3.86			0.55%	3.86			0.76%
	Compacting Asphalt		2.27			0.27%	2.27			0.32%	2.27			0.45%
	Total Process Energy =				**830**				**700 + (2.23 x *f*) + *g* + *h***				**508 + (2.23 x *i*) + *j* + *k***	

ETE (Equivalent Thermal Energy) factor for electricity is 2.23 MJ

* Transportation distances were doubled in the calculation as loaded trucks are empty on return.

f Electric energy required to produce SBS in GJ.

g Fuel energy required to produce SBS in GJ.

h Transportation fuel energy required to produce SBS in GJ.

i Electric energy required to produce unknown polymer in GJ.

j Fuel energy required to produce unknown polymer in GJ.

k Transportation fuel energy required to produce unknown polymer in GJ.

Table 15. GHGs for case study B per FU produced during different processes in the construction of the asphalt pavement

	CASE B1			CASE B2			CASE B3		
Emissions to air (tonnes)	**CO_2**	**N_2O**	**CH_4**	**CO_2**	**N_2O**	**CH_4**	**CO_2**	**N_2O**	**CH_4**
Bitumen production	12.95	7.94E-06	2.64E-06	9.92	6.08E-06	2.02E-06	7.17	4.39E-06	1.46E-06
Polymer production	-	-	-	***l'***	***l''***	***l'''***	***n'***	***n''***	***n'''***
Aggregate production	1.94	4.93E-05	5.21E-06	1.54	3.91E-05	4.13E-06	1.11	2.82E-05	2.99E-06
Asphalt production	27.72	5.79E-04	2.45E-05	25.53	5.31E-04	2.17E-05	18.45	3.84E-04	1.57E-05
Paving	0.31	6.18E-06	1.93E-07	0.31	6.18E-06	1.93E-07	0.31	6.18E-06	1.93E-07
Compacting	0.18	3.64E-06	1.14E-07	0.18	3.64E-06	1.14E-07	0.18	3.64E-06	1.14E-07
Transportation	12.04	2.44E-04	7.62E-06	9.53	1.93E-04	6.03E-06	6.89	1.39E-04	4.36E-06
Polymer transportation	-	-	-	***m'***	***m''***	***m'''***	***o'***	***o''***	***o'''***
Σ	55.14	8.90E-04	4.03E-05	47.00	7.79E-04	3.42E-05	34.10	5.66E-04	2.48E-05
CO_2-eq		**55.41**			**47.23 + *l* + *m***			**34.27 + *n* + *o***	

Polymer production and transportation

The polymers production and transportation energies were not included in case B2 and B3, which should be considered to make an objective judgment of the long term effect of the modification. For this reason, in the following, the thresholds of the energy and emission limits were determined for the polymer production and transportation based on the study's cases results (Table 16).

Table 16. Beneficial bitumen modification boundaries w.r.t. energy and emissions allocation for case study B

Energy spent on polymer	**(GJ/FU)**	**Case B1 Vs Case B2**	**Case B1 Vs Case B3**
ETE Electricity used/FU	***f, i***	<40.5	<103
Fuel consumption/FU	***g, j***	<78	<195
Transportation Energy/FU	***h, k***	<9.5	<24
Total Polymer Energy/FU		**<129**	**<322**
GHGs Emissions (tonnes)			
Polymer production/FU	***l, n***	<8	<20.5
Polymer Transportation/FU	***m, o***	<0.3	<0.7
Total Process Emissions		**<8.3**	**<21.2**

It was determined that for a polymer modification that increased the $DCSE_{lim}$ to 100%, the total sum of the energy and GHG emissions spent on polymer production and transportation should be less than 322 GJ/FU and 21 tonnes CO_2-eq/FU when comparing with the unmodified asphalt case for the modification to be beneficial from an energy and emissions point of view. When compared to the SBS polymer modified asphalt, i.e. case B2, the total energy and GHG emissions spent on the SBS should be less than 129 GJ and 8 tonnes CO_2-eq to be beneficial per FU.

3.3 Case study C *(Paper II and Paper III)*

Due to the environmental and mechanical loading during the service life, the asphalt pavements develop micro-damages which can lead to visible meso-scale damage that can significantly degrade its performance. Asphalt mixtures have, however, a known tendency to be able to heal a certain portion of this micro-damage, enabling sometimes a reduction in this mechanical degradation. Unfortunately, very little fundamental understanding of this healing behavior is currently available. In an earlier investigation, a hypothesis was developed that the healing capability of the bitumen is related to a wax-induced phase separation process (Kringos *et al.,* 2012). In this, bitumen from different crude sources were investigated under an Atomic Force Microscope (AFM) for their phase behavior. In the proposed model, the interfaces between the various phases in the bitumen are noted as the potential weakened zones, which upon phase movement could lead to a damage memory loss, resulting in the noted healing behavior as observed on meso-scale. Considering that, this model has suggested that waxes could play a significant role in the asphalt healing potential. This can have an impact on the overall road's life cycle. For the case study, the hypothesis was made that the benefit of having self-healing bitumen in the pavement would lead to a lighter pavement design for the same service life time of a pavement.

3.3.1 Goal and scope

The suggested framework for the asphalt pavement was applied on the three cases. The FU defined for this case study was the construction of a 1 km long and 3.5 m wide asphalt pavement for the stated design life.

- Case C1 was based on bitumen that was assumed to have no healing capacity;
- Case C2 was based on the assumption that the bitumen had in fact known capability for an intrinsic healing mechanism, without the need for any additional modification. This healing capacity was giving a 'free' 10% increase of the pavement lifetime with comparison to the 'non-healing' case C1;
- Case C3 was based on modification of the bitumen with respect to case C1 by adding 4% Montan wax to the bitumen. This was giving the pavement an added 10% increase of the lifetime; similar to case C2, but in this case the bitumen did not have a natural healing tendency and had to be modified.

The comparison between cases C1 and C2 would give insight into the added benefits in terms of reduced energy and GHG emissions when the used bitumen has an intrinsic healing capacity. Here the assumption was made that exactly the same bitumen was used in both cases. The comparison between cases C1 and C3 would enable balancing the pro's and con's of extra energy and emissions due to modifying the bitumen with the added lifetime benefits.

3.3.2 Inventory analysis

The selected pavement profile and materials were based on a commonly built Swedish pavement structure that is designed to have a service life time of 20 years. The pavement consisted of a 50 mm thick wearing course, binder course (different for different cases depending on the design) above a 80 mm base course and a 420 mm granular sub-base layer. The wearing course was made with a densely graded asphalt mixture (ABT 11) with a maximum aggregate size of 11 mm whereas the binder course (AG 22) according to the design was 105 mm for case C2 and C3, and 110 mm for case C1 with a maximum aggregate size of 22 mm. All three cases were assumed to be exposed to 7.5 million ESAL's and the asphalt mix design was kept the same for all three cases, in which the AG 22 binder course had a binder content of 4.5% and 95.5% aggregates and the ABT 11 wearing course had a binder content of 6% and 94% of aggregates. In cases C1 and C2, the binder had a PG 58-22 (binder 70/100) whereas in case C3, 4% Montan wax by weight of bitumen was added to create the healing capacity as predicted by the healing model. Binder modification with wax, in addition to enhancing the healing capacity, also changed its viscosity. In this case, the wax modification changed the binder to a PG 64-22. Asphalt production data for the electricity and heating oil was determined to be 9.8 kWh and 6.8 liter per tonne of produced asphalt, respectively. The distance to transfer the bitumen to the asphalt mix plant was assumed to be

100 km, whereas the transfer of the asphalt mixtures to the construction site was taken as 50 km. The aggregate quarry site and the asphalt mix plant were hereby assumed to be at the same location, 5 km from each other.

3.3.3 Impact assessment and interpretation

Table 17 and 18 summarize the results of the LCA analyses. Parameters *a, b* and *c* are the unknown energy values (in GJ) which are associated with the electric, fuel and transportation energies for the wax, respectively. Parameters *d* and *e* are CO_2-eq values (in tonnes) for wax production and transportation. For case C2, the better understanding of the healing capability of the binder resulted in an increase of 10% predicted life time which led to 22 GJ (or 3%) less energy consumption and almost 1.5 tonnes (or 3%) less CO_2-eq emissions per functional unit when compared to case C1. When comparing case C3 with case C1, almost 53 GJ (or 7.2%) energy and 4 tonnes CO_2-eq (or 8.2%) were saved, without taking the production and transportation energy of the wax into account. In a life cycle perspective, however, it is important that these should in fact be part of the calculations.

Table 17. Process energy for case study C per FU for different stages in the construction of the asphalt pavement

			CASE C1				CASE C2				CASE C3			
Energy Consumed	**Item**	**Energy Consumed per ton of material (MJ/tonne)**	**Total Energy consumed (GJ)**	**Σ Energy (GJ)**	**ETE (GJ)**	**% Energy consumed**	**Total Energy consumed (GJ)**	**Σ Energy (GJ)**	**ETE (GJ)**	**% Energy consumed**	**Total Energy consumed (GJ)**	**Σ Energy (GJ)**	**ETE (GJ)**	**% Energy consumed**
	Bitumen Production	252.	15.78			4.87%	15.33			4.88%	14.72			4.89%
Electricity	Wax Production	-	-	85.60	190.89	-	-	82.97	185.02	-	***a***	82.36	183.66	-
	Aggregate Production	21.19	25.37			7.83%	24.58			7.82%	24.58			8.17%
	Asphalt Production	35.28	44.45			13.71%	43.06			13.70%	43.06			14.32%
	Bitumen Production	1060.	66.36			9.18%	64.48			9.20%	61.91			9.23%
	Wax Production	-	-			-	-			-	***b***			-
	Aggregate Production	16.99	20.34			2.81%	19.70			2.81%	19.70			2.94%
	Asphalt Production	242/221(MW)	304.92			42.17%	295.39			42.13%	269.33			40.15%
	Bitumen transported* to the asphalt plant (100 km)		10.67			1.48%	10.37			1.48%	9.96			1.48%
Fuel	Wax transported* to the asphalt plant (0 km)		-	532.18	532.18	-	-	516.16	516.16	-	***c***	487.10	487.10	-
	Aggregate transported* to the asphalt plant (5 km)		10.21			1.41%	9.89			1.41%	9.89			1.47%
	Asphalt transported* to the construction site (50 km)		107.41			14.85%	104.05			14.84%	104.05			15.51%
	Laying Asphalt		7.72			1.07%	7.72			1.10%	7.72			1.15%
	Compacting Asphalt		4.55			0.63%	4.55			0.65%	4.55			0.68%
	Total Process Energy (GJ) =				**723.08**				**701.18**				**670.75 + 2.23*a + b + c**	

ETE (Equivalent Thermal Energy) factor for electricity is 2.23 MJ

* Tranportation distances were doubled in the calculation as loaded trucks will reach the site and empty will return.

a Electric energy required to produce wax in GJ.

b Fuel energy required to produce wax in GJ.

c Transportation fuel energy required to produce wax in GJ.

Table 18. GHGs for case study C per FU produced during different processes in the construction of the asphalt pavement

	CASE C1			CASE C2			CASE C3		
Emissions to air (tonnes/FU)	CO_2	N_2O	CH_4	CO_2	N_2O	CH_4	CO_2	N_2O	CH_4
Bitumen production	10.83	6.64E-06	2.21E-06	10.52	6.45E-06	2.15E-06	10.10	6.19E-06	2.06E-06
Wax production	-	-	-	-	-	-	***d'***	***d''***	***d'''***
Aggregate Production	1.70	4.32E-05	4.57E-06	1.65	4.18E-05	4.43E-06	1.65	4.18E-05	4.43E-06
Asphalt Production	24.26	5.07E-04	2.15E-05	23.50	4.91E-04	2.08E-05	21.44	4.49E-04	1.95E-05
Paving	0.61	1.24E-05	3.86E-07	0.61	1.24E-05	3.86E-07	0.61	1.24E-05	3.86E-07
Compacting	0.36	7.28E-06	2.27E-07	0.36	7.28E-06	2.27E-07	0.36	7.28E-06	2.27E-07
Transportation	10.13	2.05E-04	6.41E-06	9.82	1.99E-04	6.22E-06	9.79	1.98E-04	6.19E-06
Wax Transportation	-	-	-	-	-	-	***e'***	***e''***	***e'''***
Σ	47.90	7.81E-04	3.53E-05	46.46	7.58E-04	3.42E-05	43.95	7.15E-04	3.28E-05
CO_2-eq	**48.13**			**46.69**			**44.17 + *d* + *e***		

d is CO_2-eq from the wax production/FU
e is CO_2-eq from the wax transportation/FU

Wax production and transportation

Table 19 shows the limits of the wax production and transportation energies. According to the case studies, the bitumen modification was beneficial from an energy point of view if the total sum of the energy and GHG emissions spent on wax production and transportation were less than 53 GJ and 4 tonnes CO_2-eq when compared to the case of non-healing bitumen. When compared to the bitumen with intrinsic healing capacity, i.e. case C2, the total energy and GHG emissions spent on the wax should be less than 30 GJ and 1.5 tonnes CO_2-eq to be beneficial.

Table 19. Beneficial bitumen modification boundaries w.r.t. energy and emissions allocation for case study C

		Comparison	
Energy spent on wax (GJ/FU)		**Case C3 vs Case C1**	**Case C3 vs Case C2**
ETE Electricity used	***a***	<16.4	<9.5
Fuel consumption	***b***	<30.9	<17.98
Transportation Energy	***c***	<4.97	<2.89
Total Wax Energy		**<52**	**<30**
GHGs Emissions (tonnes/FU)			
Wax production	***d***	<3.72	<2.37
Wax Transportation	***e***	<0.24	<0.15
Total Process Emissions		**<3.96**	**<2.52**

a, b, c parameters from Table 17 and ***d, e*** from Table 18

4. Conclusions

In this work, an open LCA framework is suggested for quantifying energy and environmental loads during construction, maintenance and end of life phases of a given asphalt pavement. A method to calculate feedstock energy of bitumen is developed and a method to quantify mass-energy flows of additives is described. If the production data of additives is available, an energy-mass flow of any asphalt additive can be calculated based on the method suggested. Such calculations for waxes and polymers should be valuable in order to determine the life cycle benefits from using such additives. However, this would require information on electricity and fuel usage. Regarding feedstock energy in the binder, it is highly relevant for the LCC as the cost of the binder will be reflected in its alternative value as fuel. For LCAs, however, it is suggested to be of a limited importance although it may be used to quantify the resource energy.

From the case studies, it could be concluded that asphalt production is a highly energy consuming process. Hence, the use of additives should be further studied in order to determine their potential to decrease energy use through lowering the mixing temperatures. Transportation of the materials plays a very important role in terms of energy consumption and emissions. It is favourable to have quarry site, asphalt production plant and the construction site not far from each other to avoid excess energy use and fuel combustion emissions. It is also highly favourable to use electricity that has been produced in an efficient way.

From the case studies, it can be concluded that better understanding of the binder provides bases for better pavement design optimization, hence reducing the energy consumption and emissions. A limit in terms of energy and emissions for the production of the wax and polymers was also found which could help the additive producers to improve their manufacturing processes making them efficient enough to be beneficial from a pavement life cycle point of view. In other words: positive effects obtained due to the use of additives are only beneficial when the energy and emissions are lower in comparison to the unmodified asphalt when considering the life cycle of a road. Hence, the binder self-healing capability and the use of additives like polymers and waxes should be further studied in order to determine the benefits which could be achieved in terms of the resource consumption, energy and emissions by lowering the energy utilization in the asphalt mix plant. This would also help the road authorities in setting 'green' limits to get a real benefit from the additives over the lifetime of a road.

It is not possible to make the infrastructure sector more environmentally conscious unless we have a tool that takes all the associated aspects into consideration. Otherwise, new technologies that, for example, may reduce CO_2 emissions on one end and may reduce the pavement sustainability on the other, thus resulting in an overall situation that is not beneficial from an environmental perspective.

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