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CONSIDERING THE BENEFITS OF ASPHALT MODIFICATION USING A NEW TECHNICAL LIFE CYCLE ASSESSMENT FRAMEWORK

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Abstract. Asphalt mixtures properties can be enhanced by modifying it with additives. Even though the immediate benefits of using 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. To investigate this, a newly developed open technical life cycle assessment (LCA) framework was used to determine production energy and emission limits for the asphalt additives. The LCA framework is coupled to a calibrated mechanics based computational framework that predicts the in-time pavement performance. Limits for production energy of wax and polymers were determined for the hypothetical case studies to show how LCA tools 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. From the detailed case-studies, it was concluded that better understanding of materials will lead to enhanced pavement design and could help in the overall reduction of energy usage and emissions.

Keywords: life cycle assessment, asphalt binder additives, bitumen healing, calibrated mechanics based pavement design model, polymer, wax.

Introduction

By binding the aggregate skeleton together, bitumen provides the necessary stiffness and strength in asphalt mixtures to transfer the traffic loads. In addition to its strength, asphalt pavements also offer a damping ability due to the visco-elastic nature of the bitumen. As such, asphalt mixtures are uniquely qualified for providing an optimal driving comfort as well as flexible maintenance actions. Due to the depleting crude oil sources, asphalt binder prices have been increased rapidly in the past years and its overall supply is diminishing as refineries are modifying and proposing methods to convert their heavy crudes to fuels. For this reason, on the one hand, it is important to optimize the lifetime and rheological properties of the binder to postpone distresses like cracking and rutting that diminish the lifetime of the asphalt pavements. On the other hand, it is important to start exploring novel materials that are suitable for pavement construction, yet do not depend on the diminishing fossil resources. The first can partly be achieved by modification of the bitumen using additives such as polymers and waxes. The second can be achieved by imbedding alternative materials, such as biomass based materials or reclaimed materials.

Larger distances for the materials transportation, consume the most process energy in a roads life cycle (Butt *et al.* 2014). However, for shorter transport distances, asphalt production comes at the top of the energy chain. It has been shown in several studies that the asphalt mixing phase is the most energy intensive process (Huang *et al*. 2009; Zapata, Gambatese 2005; Butt *et al.* 2014). To date, the pavement industry is investigating how to lower the energy use and emissions, for example by converting from hot mix asphalt (HMA) to cold mix asphalt technology. But there has not been any major paradigm shift in the industries so far. Additives are added in the asphalt mixes for number of reasons that include lowering mixing and compacting temperatures, improving adhesion and increasing resistance against cracking and rutting. Polymer modification is known to have the potential to enhance the binder properties such that it becomes more resistant to higher and lower temperatures (Carpenter, VanDam 1987; Lewandowski 1994; Lu *et al.* 1999; Von Quintus *et al.* 2007). On the other hand, working temperatures of polymer modified asphalt are much higher as compared to conventional HMA which means more energy will be consumed to mix and compact it. Working at higher temperatures also needs expertise and it becomes quite unpleasant for the workers. Therefore, waxes are sometimes added to reduce the viscosity of bitumen so it can be processed at lower temperatures (Hurley, Prowell 2006; Soenen *et al.* 2008; Edwards *et al.* 2010). It is popular today in the asphalt industry to use

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waxes to produce warm mix asphalt (WMA). 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 addition to this, it is not a common practice to report the energy consumption and emissions for the production of additives used in the asphalt industry. Therefore, to date, very little data is available for the production phase of additives, causing a gap in the 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 was recently developed which is able to calculate the energy consumption and Green House Gas (GHG) emissions during the production phase of any material based on the electricity and fuel usage (Butt *et al.* 2014).

Due to the environmental and mechanical loading during its service life, asphalt pavements develop internal micro-damage which can lead to visible meso-scale damage and significantly degrade its long-term 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. Several researchers are working and developing models for better understanding and prediction of healing behavior of the binders (Kim, Little 1989; Little *et al.* 1999; Bhasin *et al.* 2011; Darabi *et al.* 2012; Tan *et al.* 2012). 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.* 2011). 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, the question could arise as to the long-term benefit of adding waxes to bitumen, especially considering the other connotation of increased risk of low temperature cracking when waxes are involved.

It is therefore of increasing importance to be able to objectively measure and quantify the potential benefit of additives on the long term performance predictions of pavements due to enhanced knowledge of the mechanical performance, such as discussed earlier. Considering also the important task that our infrastructure has to contribute to enhancing our society's sustainability, being able to judge the durability and environmentally friendliness linked to the long-term performance, having tools available that can assess pavements on a life cycle basis are of crucial importance.

Due to the depletion of resources and concerns of the climatic change, Life Cycle Assessment (LCA) for different products, systems and activities have increased in popularity among researchers for the past years. 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 propose different alternatives for different phases in a life cycle of the system. There have been studies that quantify the energy and emissions at different road phases during the roads life time (Häkkinen, Mäkelä 1996; Horvath, Hendrickson 1998; Stripple 2001; Park *et al.* 2003). However, not much has been published in the road LCA studies that quantify energy and emissions of using different road additives. Also currently LCA has not yet been used in the road projects to put constraints when considering environmental aspects. This could partly be explained due to the lack of a technical tool that accurately represents all the aspects of the pavement sector. From a historical perspective, one could say that LCA application to engineering fields is still relatively new and lacks uniform guidelines (Du, Karoumi 2012). Another reason could be that some of the available tools are linked to rather simplified pavement prediction response models that reduce the accurateness of the LCA outcome. There is thus a need to develop LCA tools that more closely follow the aspects of design, construction and maintenance of a road. The above stated arguments were the reason for the authors to develop an improved open technical LCA framework specialized to the road project level (Butt *et al.* 2014). The framework is closely linked to an in-house developed calibrated mechanics based framework to assess the long-term mechanical performance as well as assist in the overall design. This new system is therefore allowing for an integrated holistic approach, taking into account the non-linear environmental-mechanical performance of the pavement as well as allowing for detailed calculations of the environmental impacts.

This paper is presenting some of the details of the LCA framework and demonstrates its use for two case studies associated with the use of additives. The first case study that is presented is associated with a hypothetical self-healing capability of bitumen and the use of Montan wax followed by the second case study on polymer modification for crack resistance. Both cases are referring to the use of additives in asphalt pavement to optimize its lifetime, since this presents a strong argument for how LCA can be used. In addition to presenting the technical LCA framework, the paper also aims at demonstrating the importance of analyzing the long-term benefits of such modification by including the energy and GHG emissions that are associated with their production and calculating the limits for production energies of the additives that can assist manufacturers to modify their production procedures and help road-authorities in setting "green" limits.

1. Principles and boundaries of the new technical life cycle assessment framework

Life cycle assessment 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, Tillman 2004). Ideally, it includes all the processes from the cradle to the grave of a product. Studying the different effects and the impacts on the environment during the different phases of a road's lifetime enables the development of the effective measures to reduce the resource use and the environmental loads.

A LCA framework for asphalt roads was recently developed by Butt *et al.* (2014) that consider the energy consumption and GHG emissions produced in the lifetime of the road (Fig. 1). The LCA framework takes the resulting design from the pavement design model as an input and processes it to quantify the energy, raw materials and emissions for the construction, maintenance and the end of life of the asphalt pavement. Certain system boundaries were assumed in the development of the framework. First of all, the study is limited to a project level. Thus, the road location is assumed to have been pre-determined and the land area use for some other purpose doesn't apply. This boundary has been imposed to focus the use of this LCA on the optimization of the pavements, rather than the optimization of land use. Furthermore, the thickness of the asphalt layer was assumed to be constant along the length of the road, and fuel and electric energies were accumulated separately. This latter assumption was necessary as electricity is a secondary energy source, which could only be added to the total energy if the electricity production energy and efficiency are known. The raw materials considered for the framework are bitumen, aggregates and additives. The fuel consumption of the traffic and related emissions has not been considered as the study was limited to the project only. However, at the network level, it becomes highly relevant to consider the energy and emissions from traffic for decision support in LCA.

2. Pavement design

A calibrated mechanics based design tool is used to get the design thicknesses for both case studies. 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 was developed. In this approach, each mix is 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 micro-cracks 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. Case studies

In this paper, the LCA framework is demonstrated via two case studies, Case Study A and B, to quantify the energy and GHG emissions during the life time of the pavement. The pavement has been designed for 20 years using the calibrated mechanics based pavement design procedure described above for both case studies. The wearing course was assumed to be 50 mm thick above the structural course. The thickness for the structural course changes with the change of pavement design thickness depending on what material properties were taken as an input for the system. Energy consumption data for the asphalt production was acquired from Skanska, one of the larger Swedish contractors. Energy consumption data per tonne of material, electricity mix, fuel and emissions used by Stripple (2001) were used for the analysis. In the following, first the two Case studies are described, after which the results of the analyses and the outcomes and limitations are discussed in detail.

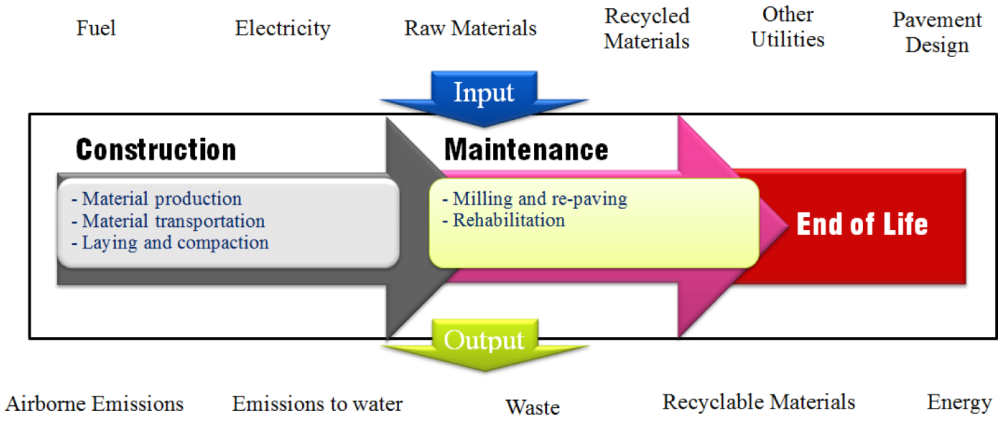

Fig. 1. Life cycle assessment framework for asphalt roads

3.1. Case Study A

The base layer of the pavement analyzed in Case A is 80 mm thick over a 420 mm granular sub-base layer. The wearing course consists of a densely graded asphalt mixture (ABT 11) with a maximum aggregate size of 11 mm. The asphalt concrete structural layer is assumed to be an asphalt-bound base mixture (AG 22) with a maximum aggregate size of 22 mm. For the Case Study A (Butt *et al.* 2012a), three different variants are considered in which the bitumen phase is slight varied. The consequences of these variations are then calculated using the LCA framework:

- The first variant (named Case A1) is based on bitumen with an unknown healing capacity, which can therefore not be accounted for in the design;
- The second variant (named Case A2) is based on the assumption that the same bitumen as in case A1 is used, but now the intrinsic healing mechanism is known and can be accounted for without the need for any additional modification. This healing capacity is assumed to give a "free" 10% increase of the pavement lifetime when compared to the case A1;
- The third variant (named Case A3) is based on the modification of the bitumen with respect to case A1 by adding 4% Montan wax to the bitumen. It is thereby assumed that the modification gives the same effect as of case A2 but the bitumen does not have natural healing tendency. This gave the pavement an added 10% increase of the lifetime, similar to case A2.

The added benefits in terms of reduced energy and GHG emissions based on bitumen with intrinsic healing capacity can then be quantified by comparing case A1 and case A2. The comparison between case A1 and case A3 enables balancing the pros and cons of extra energy and emissions due to the wax modification of the bitumen with the added lifetime benefits.

The design lifetime of the case A1 pavement is 20 years. An added lifetime of 10% would thus indicate an extra 2 years of remaining pavement life, leading to a functional lifetime of 22 years as for case A2 and A3. Considering the current warranty system in the EU, in which pavements are designed for a given lifetime and any unexpected damages will result in penalties for the contractor during this period; the extra lifetime is here incorporated into the design life by keeping the 20 years as the maximum service life. Thus, a pavement supposed to have a service life of 20 years could in fact be designed for 18 years (i.e. 90% of the service life) when the healing capacity gives an added lifetime of 10%. All three cases are assumed to be exposed to 7.5 million Equivalent Single Axle Loads (ESAL's). The asphalt mix design is 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 has a binder content of 6% and 94% aggregates. In Cases A1 and A2, the binder has a PG 58-22 (binder 70/100) whereas in case A3, 4% Montan wax by weight of bitumen is added which results in PG 64-22.

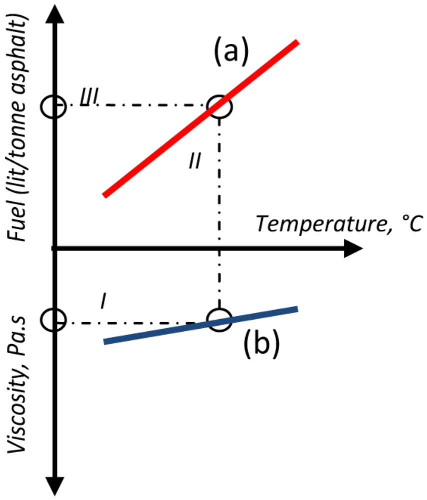

Fig. 2. Fuel reduction based on reduction in viscosity due to wax modification of the binder (Butt *et al.* 2012a)

The functional unit defined for this case study is the construction of 1 km long and 3.5 m wide asphalt pavement for the nominal design life. Asphalt production data for the electricity and heating oil is 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 is assumed to be 100 km, whereas the transfer of the asphalt mixtures to the construction site is taken as 50 km. The aggregate quarry site and the asphalt mix plant are hereby assumed to be closely located, 5 km from each other. Data for the wax production is missing in the current literatures so a method was developed to estimate it (Butt *et al.* 2012a). The fuel versus asphalt mixing temperature curve was deducted from the relationship developed by D'Angelo *et al.* (2008), Figure 2a. A reduction in the mixing temperature due to the addition of wax in the bitumen was calculated based on the rotational viscosity data taken from Das *et al.* (2012), Figure 2b. By combining these two functions, a direct relationship between the binder viscosity and the fuel consumption was established (Fig. 2). Reduction in the fuel consumption when preparing wax modified asphalt mixtures can easily be estimated. By using this method, the addition of 4% Montan wax resulted in a PG grade change from PG 58-22 to PG 64-22, and a reduction of almost 6 °C in average mixing temperature was found. From Figure 2, the reduction in temperature was used to determine an estimated reduction in fuel usage for the production of wax modified asphalt mixture, which was determined to be 0.6 liter per tonne asphalt produced. As a result, 6.2 liters fuel was used per tonne wax modified asphalt production in the asphalt plant.

3.2. Case Study B

The design of the pavement section used in Case B (Butt *et al.* 2012b) is based on the work by Almqvist (2011). The base layer is 178 mm thick whereas the sub-base 1.0 m lying on top of the bedrock. The design is done for a mean temperature of 5 °C which corresponds to the Swedish climate zone 3. The design ESALs are assumed to be 1 million.

It was observed from the literature that a small percentage of polymer not only provides resistance against cracking but also allows reduction of the asphalt layer thicknesses. For example, it has been observed that Styrene-Butadiene-Styrene (SBS) polymer enhances the properties of the asphalt mixtures against rutting and cracking (Romeo *et al.* 2010; Ping, Xiao 2011). This decrease in thickness itself saves energy and reduces emissions associated with the material reduction, but the polymer production and transportation emissions should then be included to allow for a calculation of the real saving of the resources, energy or emissions. The following three variants are analyzed in this case study:

- The first variant (named Case B1) is based on an asphalt mixture with no polymer modification;
- The second variant (named Case B2) is based on a modification of the asphalt with respect to case B1 by adding 3.5% SBS polymer to the bitumen. It was observed from IDT results of 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. This result is assumed in this Case.
- The third variant (named Case B3) is 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 is thereby assumed that the modification gives an increase in the $DCSE_{lim}$ of almost 100%. Though this seems rather extreme, new materials are being developed to be used in the road industry and there may be materials in the future that will give much improved road performance and better designs. So this assumption is based on a parametric study to show the potential of the developed LCA framework as well as point out the missing information to date.

The thicknesses of the asphalt layers according to the pavement design are shown in Table 1. It is hereby assumed that both the wearing and the structural course contain the same asphalt mix design of 5.2% binder content and 94.8% aggregates. The construction site and the bitumen and aggregates storage sites are 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 and compacting temperatures (around 200 °C) when compared to unmodified asphalt mixture (around 170 °C). It is thereby assumed that an increase of 17% in the fuel consumption was required for the polymer modification of the asphalt mixture. The functional unit (FU) defined for the study was the construction of 1 km of asphalt pavement for a nominal design life. Lane width was selected to be 4 m wide.

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

4. Results

Based on all the assumptions and available data, the open technical LCA framework was used to calculate the energy consumption and emissions for the variants of both case studies. The limits of the energy use and emissions for the production of wax and polymer upon which the additives would still lead to a positive LCA effect are also calculated. This can help the producers of such additives to consider the energy and emissions values for optimizing and improving their production techniques. It is however, important for the additive producers to report the production energies of the additives in order to understand the real benefit of using such additives in a life cycle perspective of the roads. As mentioned earlier, a simplified way, based on mass-energy flow system can be used to define the production systems and quantify the energy and emissions.

4.1. Results from Case Study A

Tables 2 and 3 summarize the results of the LCA analysis. 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 $CO_{2\text{-eq}}$ values (in tonnes) for wax production and transportation. For case A2, the accounted 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 $CO_{2\text{-eq}}$ emissions per functional unit when comparing to case A1. When comparing case A3 with case A1, almost 53 GJ (or 7.2%) energy and 4 tonnes $CO_{2\text{-eq}}$ (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 1. Asphalt pavement layer thicknesses for different cases (B)

Cases	Description	Assumed 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

Table 2. Process energy for Case Study A per FU for different stages in the construction of the asphalt pavement

Energy Consumed	Item	Energy Consumed per ton of material (MJ/tonne)	CASE A1				CASE A2				CASE A3			
			Total Energy consumed (GJ)	∑ Energy (GJ)	ETE (GJ)	% Energy consumed	Total Energy consumed (GJ)	∑ Energy (GJ)	ETE (GJ)	% Energy consumed%	Total Energy consumed (GJ)	∑ Energy (GJ)	ETE (GJ)	% Energy consumed
Electricity	Bitumen Production	252.	15.78	85.60	190.89	4.87%	15.33	82.97	185.02	4.88%	14.72	82.36	183.66	4.89%
	Wax Production	–	–			–	–			–	***a***			–
	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%
Fuel	Bitumen Production	1060	66.36	532.18	532.18	9.18%	64.48	516.16	516.16	9.20%	61.91	487.10	487.10	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%
	Wax transported* to the asphalt plant (0 km)		–			–	–			–	***c***			–
	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 transport wax in GJ.

Table 3. Greenhouse Gases (GHGs) for Case Study A per FU produced during different processes in the construction of the asphalt pavement

Emissions to air (tonnes/FU)	CASE A1			CASE A2			CASE A3		
	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′′′*
$\sum$	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 4 shows the limits of the wax production and transportation energies. According to the case studies, the bitumen modification is beneficial from an energy point of view if the total sum of the energy and GHG emissions spent on wax production and transportation are less than 53 GJ and 4 tonnes $CO_{2\text{-eq}}$ when comparing to the case of non-healing bitumen. When compared to the bitumen with intrinsic healing capacity, i.e. case A2, the total energy and GHG emissions spent on the wax should be less than 30 GJ and 3 tonnes $CO_{2\text{-eq}}$ to be beneficial.

4.2. Results from Case Study B

The results of the LCA analysis are summarized in Table 5 and Table 6. 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 $CO_{2\text{-eq}}$ values (in tonnes) for the polymer production and transportation. For case B2, SBS polymer modification of the asphalt led to an increase of 50% $DCSE_{\text{lim}}$ 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 $DCSE_{\text{lim}}$ to 100% which lead to a decrease of 64% w.r.t. case 1 and a further decrease of almost 50% w.r.t. case B2. From Table 5, 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 6, it can be seen that the total $CO_{2\text{-eq}}$ reduces from 55 to 47 to 34 tonnes, respectively. These values, however, still do not include the

Table 4. Beneficial bitumen modification boundaries w.r.t. energy and emissions allocation for Case Study A comparison

		Comparision	
Energy spent on wax (GJ/FU)		Case A3 vs Case A1	Case A3 vs Case A2
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 2 and *d*, *e* from Table 3.

Table 5. Process energy for Case Study B per FU for different stages in the construction of the asphalt pavement

Energy Consumed	Item	Energy Consumed per ton of material (MJ/ton)	Case B1				Case B2				Case B3			
			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) consumed	% 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 transport SBS in GJ.

i Electric energy required to transport unknown polymer in GJ.

j Fuel energy required to produce unknown polymer in GJ.

k Transport fuel energy required to transport unknown polymer in GJ.

Table 6. Greenhouse Gases (GHGs) for Case study B per FU produced during different processes in the construction of the asphalt pavement

Emissions to air (tonnes)	CASE B1			CASE B2			CASE B3		
	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′′*
$\sum$	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*		

production energy and emissions of the polymers. For this reason, in the following the thresholds are determined for these.

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 are determined for the polymer production and transportation based on the study's cases results (Table 7).

It was determined that for a polymer modification that increases 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 $CO_{2\text{-eq}}$/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 $CO_{2\text{-eq}}$ to be beneficial per FU.

Conclusions and recommendations

From the parametric case studies, it can be concluded that better understanding of the binder provides basis for better pavement design optimization, hence reducing the energy consumption and emissions. Limits in terms of energy and emissions for the production of the wax and polymers were also found which, when applied to additional cases, 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

Table 7. 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

and emissions are lower in comparison to the unmodified asphalt when considering the life cycle of a road. In the case of polymers, it's a question in itself whether polymer modification is environmental beneficial when compared to the performance benefits. This could be addressed using the LCA framework by comparing the polymer modified and unmodified asphalt pavements designed for the same life span with a condition of having production data of the polymer used.

From the case studies, asphalt production was identified as the most energy intensive process (Tables 2 and 5) and it also emitted most GHG emissions (Tables 3 and 6). Therefore, 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. Wax may be lowering the mixing and compacting temperatures on one hand but there might be quite an amount of energy utilized or emissions produced during its production, ending up as a loss in the overall system. 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. The developed LCA tool could become imbedded inside the 'normal' pavement design, procurement, built and maintain routine and thus provide a useful tool for material suppliers, contractors as well as road authorities to assess the sustainability of various choices.

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