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LIFE CYCLE ASSESSMENT OF BITUMINOUS PAVEMENTS PRODUCED AT VARIOUS TEMPERATURES IN THE BELGIUM CONTEXT

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Abstract
Bituminous mixture is the premier material for road construction in Belgium. Innovative technologies to improve energy efficiency of pavement constructions are necessary. Warm mix asphalt may provide significant energy savings to the asphalt industry, but the environmental impact of the total life cycle has to be investigated. The use of additives may counteract the reduced environmental impact due to energy savings. This paper presents the results of an environmental impact assessment of four wearing course test sections. Using life cycle assessment, hot mix asphalt is compared to a cold asphalt mix with emulsion and warm mix asphalt with two types of additives: a synthetic zeolite and an organic Fischer-Tropsch wax. Neither hot nor warm mix asphalt could be preferred based on the results of this study, because the additive has a major influence on the environmental results. It was seen that the production of bitumen, the transport and energy in order to generate heat mainly contribute to the total environmental impact. The results from the sensitivity analyses show that the total environmental impact of the life of the pavement can vary significantly based on the choice of the specific data source and service life.

Keywords: life cycle assessment (LCA); warm mix asphalt (WMA); hot mix asphalt (HMA); additives; sensitivity analysis; contribution analysis

1 INTRODUCTION

Infrastructure plays a vital role in the society in order to move people and goods. Roads in particular offer service without fixed departure times or limited service offers and is therefore experienced as freedom. Furthermore roads are the crucial connection between e.g., other transport services (airports, railway stations, bus stops), services, health facilities etc. (International Road Research Board 2013).
Since all installations with a net heat excess of 20 MW or more are subjected to the Kyoto Protocol and hence the European Union emissions trading system (EU ETS), 13 of the 20 Flemish asphalt plants have to monitor and report on their CO_2-emissions. Each year these companies have to hand in emission allowances in accordance with the emitted quantity (Departement Leefmilieu Natuur en Energie 2014; European Union 2013b). It is important to note that the EU ETS only accounts for the emissions due to fuel consumption by particular companies. Hereby the reduction of the asphalt production temperature is encouraged by the EU ETS.
In various recent developments, researchers succeeded to reduce the production temperature of asphalt mixtures from 150 °C - 190 °C for hot mix asphalt (HMA) to 100 °C - 150 °C for warm mix asphalt (WMA) (Leyssens et al. 2013). As described by (Rubio et al. 2012), roughly three technologies to produce warm mix asphalt could be distinguished: i) adding organic additives (e.g., Fischer-Tropsch wax); ii) adding chemical additives (e.g., emulsifiers); iii) adding small amounts of water, either by water-containing technologies (e.g., a synthetic zeolite additive) or by water-based technologies (e.g., directly injecting water into the hot binder).
For the bitumen and asphalt industry, additional key drivers to decrease the production temperature of asphalt are related to less fumes and emissions, which lead to better working conditions and more safe working situations.
Cold asphalt is another technique sometimes used in Flanders, mainly for maintenance projects. A bitumen emulsion (fluid at ambient temperature) is the binder of the cold asphalt mixture.

Despite these promising ideas, an assessment of the environmental impact of these technologies applied in practice is necessary. The aim of the presented study was to perform a life cycle assessment (LCA) of bituminous road pavements with asphalt mixtures produced at various temperatures. This paper focussed on the methodology, difficulties and challenges of conducting an LCA study on bituminous pavements. The main results and findings are discussed as well.

In the following chapter, the applied methodology is elaborated including the different stages of an LCA as defined in the LCA standard (ISO 14040 (International Organization for Standardization n.d.)): goal, scope, life cycle inventory and life cycle impact assessment. In the next section, the results will be presented, including a comparison of four different cases, contribution analysis and sensitivity analysis. In the final section, the conclusions and recommendations are described.

2 METHODOLOGICAL FRAMEWORK

The LCA methodology was chosen as the most adapted method for the current case study that takes the entire life cycle into account, from resource extraction, maintenance operations and including end-of-life of the pavement.
A full, in depth life cycle assessment was chosen as the most appropriate LCA methodology. This type of analysis offers the possibility to express the contribution to the environmental impact in terms of percentage for various processes and materials i.e., the contribution of the warm mix to the environmental impact of the total life cycle. This is not possible in a comparative LCA, where identical processes are omitted from analysis and only the differences are to be compared.

Difficulties in bituminous pavement life cycle assessment are related to the complexity of the asphalt sector and the variability in numerous related parameters. In Belgium, as in most other countries, multiple types of asphalt mixtures are applied, with differences in public and private works, differences in different layers etc. Furthermore there is a significant variability in raw material resources, in transport method (ship, truck, and train) and distance, energy type, manufacturing principles etc. Differences are observed from one asphalt work to the other, from one asphalt plant to the other, and from one country to another. This results in a large variability in calculated and measured data, and makes it difficult to apply average data. The deviation from possible “generic” or “average” data will be large. Hence, in the current case study, most quantitative data are case specific and therefore the results from LCA-calculations are only representative for the current situation.

A number of software tools have been developed to analyse the environmental impact of road pavements. Some of these tools are based on the life cycle assessment method and allow including processes from different phases in the life cycle of a road pavement, e.g. asphalt production, road construction, maintenance and end-of-life. On the other hand, the simplified tools to assess the environmental impact of road pavements are often limited to a single impact (i.e. global warming potential). These single issue LCA approaches may take a life cycle perspective but focus on one impact category only.
It is recognized internationally (European Union 2013a), that the assessment of CO_2-equivalents or in general any single metric (e.g. carbon footprint, water footprint) is limited and does not reveal the full picture of the effect on the environment. The LCA approach applied in this study includes multiple environmental issues.
The SimaPro software version 8.0, developed by PRé-consultants BV in the Netherlands, was used to elaborate the analysis.

2.1 Goal and scope definition

A common pitfall when trying to implement an LCA is the lack of a clear purpose and intended application of an LCA (Goedkoop, Oele, et al. 2013). Furthermore, in order to perform an LCA, a product, service, or system life cycle has to be modelled. It is important to realize that a model is a simplification of a complex reality and as with all simplifications this means that the reality will be distorted in some way. The challenge is to develop the model in such a way that the simplifications and distortions do not influence the results too much. The best way to deal with both problems is to carefully define the goal and scope of the LCA study.

2.1.1 Goal

Defining the goal includes a description of both the application and intended audiences and the reasons for carrying out the study (International Organization for Standardization n.d.; Goedkoop, Oele, et al. 2013).
The goal of this research was to analyse, on the basis of a specific example, the differences in environmental impact when different bituminous binders or manufacturing methods are used for road pavement construction. The focus is on the environmental impact of a reduction in asphalt production temperatures. Besides, the aim of this study is to determine the processes which significantly contribute to the environmental impact and to evaluate the influence of the most important assumptions on the results. A second goal is to evaluate a more complete environmental impact instead of limiting the study to CO_2 footprint.
The intended audiences are other researchers but also road engineers and the road agency which might yield to the implementation of the main findings into their policy.

2.1.2 Scope

The scope of the study consists of the most important methodological choices, assumptions and limitations; e.g. functional unit and reference flow, system boundaries, thresholds for inclusion of inputs and outputs and type of allocation (International Organization for Standardization n.d.; Goedkoop, Oele, et al. 2013).

Product system

The environmental impact of four wearing courses of pavement sections made of hot mix asphalt (HMA), warm mix asphalt (WMA) and cold asphalt are compared in the current case study. The HMA is a dense grade mixture and serves as the control or reference pavement. The WMA is based on the recipe of the reference mixture. Two different types of additives are used to facilitate warm mixing: Fischer-Tropsch wax and a synthetic zeolite. An emulsion is used for the cold asphalt. All materials used for the asphalt production are virgin, non-recycled materials because recycling in wearing courses is not allowed according to the Flemish road standard SB250 version 3.1. The case study is based on a real construction case, except for the cold mix asphalt, which is added to the study as a theoretical case, with a maximum temperature reduction. The field case is located in Assenede in Belgium on a single carriageway with one lane for each direction (a two-lane road). It is a quiet road with sometimes heavy agricultural traffic and a speed limit of 70 km/h.

Functional unit

(Jullien et al. 2014) mentioned that the functional unit can be described in four various ways in the road LCA practice. The preferred way for the current study is the definition of the functional unit by their geometry, service life, and levels of traffic supported (also stated by (Vidal et al. 2013)). (Araújo et al. 2014) clarified that the length and width of the road should be the same for all alternatives in order to be able to compare them. (Araújo et al. 2014) also stated: “The pavement thickness can vary and is determined (by conventional pavement design methods) so that all analysed solutions are capable of carrying the same design traffic in a similar service life”.
The functional unit used for this study is a wearing course section of 300 m in length and 6 m in width over a 48 years’ service life. The functional unit represents pavement structures of the same length and width and hence meet the same performance requirements; and the functional unit represents pavement structures on the same road with the same traffic intensity (which is unknown for this road) and hence meets equal technical requirements.

WMA is recently introduced in the Flemish road industry. The quality of the mixture and therefore the service life and rolling resistance of the pavement are not yet investigated in practice. At the design stage, the same thickness was applied to all test sections.

System boundary

The system boundaries for the baseline scenario for the four cases (reference, wax, zeolites and emulsion) are described in this section.
This work primarily focuses on the analysis of the material production, road construction and maintenance phases considering the selection of green construction techniques at the design stage (analogue to study (Celauro et al. 2015)).
The period of analysis includes the entire life cycle of the pavement material from raw material extraction to final disposal, thus a “cradle-to-grave” life cycle analysis is considered. The system boundaries include all the significant life cycle phases covering the production and transportation of materials, their placement in the road structure, the maintenance of the construction and the situation after the use of the construction.
Following processes are beyond the scope of the study:

- preparation of the work site (including earthwork etc.);
- construction of sub base, base and binder courses;
- leaching, lighting of the road, impact from traffic, albedo, etc.;
- land use impact due to the presence of the road;
- overhead impacts e.g. from offices;
- traffic congestion during road works.

The importance of the users phase for pavement life cycle assessment is known (Araújo et al. 2014), but not included in this study. The decision to omit the users phase arises from the consideration that user phase impacts (due to e.g., rolling resistance or retroflection) are assumed to be the same, due to lack of research in practice.

Hence, only a few differences among the four cases were investigated.

- The mixture composition of the reference mixture is adapted for the other mixtures. In the WMA mixtures a fraction of bitumen is replaced by the wax additive, or a fraction of filler is replaced by the zeolite additive. In the cold asphalt mixture an emulsion is used instead of bitumen.
- The target production temperature is 160 °C for the HMA control mixture; and 130 °C for the WMA mixtures. In case of the emulsion, only the bitumen, before emulsification, was heated.
- The roller passes for the compaction of the pavement were measured in practice. 14 roller passes were needed for the pavement with the wax mixture compared to 9 roller passes for all other mixtures.

The life cycle assessment in this case study takes ecological aspects into account. The social and economic factors are important as well for decision-making in civil engineering, but are beyond the scope of the current study.

Assumptions

Besides the observations in practice, some assumptions have been made for the LCA calculations of the baseline scenario to deal with the lack of proper information. The assumptions are varied in sensitivity analyses, to compare alternative scenarios with the baseline scenario.

- It was assumed that the pavement (all bound courses) would remain in service for 48 years, what is the analysis period. The unbound layers of pavement structures usually remain in situ at the end of the structural pavement life.
- The default service life is 14 years for the wearing course and 24 years for the base course. This yields 3 maintenance interventions for the wearing course during the analysis period of 48 years. [reference: interview with senior adviser at Agency for Roads and Traffic]
- Based on internal laboratory test results for rut resistance and similar conclusions in literature (Zhang 2010; Hill 2011), it was assumed that the service life of the wearing course with FT wax is prolonged with 5 years. Hereby 3 maintenance interventions would be needed during 60 years, what is converted to 2.5 maintenance interventions during the analysis period of 48 years.
- In this case study, the wearing course is milled at end-of-life and the released materials are transported to a stockpile for reuse or deposited to a landfill. Based on figures from EATA (European Asphalt Pavement Association 2013) for the Belgian situation, a 60% reuse and 40% landfill rate was applied.
- The landfill scenario takes into account the transport of the material from work site to sanitary landfill (a distance of 100 km was assumed) and the environmental impact related to the deposited asphalt material (predefined in Ecoinvent).

- The reuse scenario takes into account the transport of the material from the work site to the stockpile on the asphalt plant (a distance of 35 km in this case) and the impact associated with processing the material from waste to material ready for reuse (breaking, sieving).

2.2 Life cycle inventory

Both quantitative and environmental data are necessary to develop a life cycle inventory. The inventory for this case study was build up by combining information from literature or existing databases (generic data) and specific data for the investigated case. The three test sections were constructed in actual practice in 2009 and some useful quantitative information was collected in a case description. This includes the following information useful for the LCA:

- origin and moisture content of the raw materials,
- recipe of the three asphalt mixtures,
- fuel type for heating the drum in the asphalt plant,
- mixing temperatures,
- transport distance asphalt plant to work site and
- number of roller passes for the compaction of the pavement.

Table 1 illustrates the data sources for the quantification of processes which are not specified in the case description. The fuel consumption for drying and heating aggregates was calculated based on the moisture content and the temperature of aggregates, the production temperature, the flue gas temperature and the specific heat capacities as defined by (OCW 2002).
Information on diffuse emissions during road construction for HMA were taken from study (Jullien et al. 2006) and reduced by 30% for WMA, based on findings from (Finset 2012). It is important to note that other values were found in other sources in the literature. Study (Read & Whiteoak 2003) states: “the amount of fume generated doubles for each 10 to 12 °C”.

Table 1: Data sources for the quantification of parameters in the case study

Process	Source
Energy consumption for the storage of bitumen	(Wayman et al. 2012)
Electrical energy consumption for engines at the asphalt plant (sieving, dosing, conveyor belt,…)	(Leyssens et al. 2013)
Fuel consumption for processing of reclaimed asphalt pavement	(Wayman et al. 2012)
Fuel consumption for milling existing pavement	(Wayman et al. 2012)
Fuel consumption for tack coating, paving, compaction	(Stripple 2001)
Bitumen consumption for tack coating	(Stripple 2001; Vlaamse overheid n.d.)
Rate of laying asphalt courses	(ECRPD 2010)
Emissions VOC and PAH during road construction	(Jullien et al. 2006; Finset 2012)

Environmental data were taken from the Swiss Ecoinvent database version 2.2 for all raw materials and processes, except for the bitumen and the Fischer-Tropsch wax. The Ecoinvent database is widely accepted as one of the most complete and consistent databases; it is especially representative for the Western European context and is updated regularly.
Data for bitumen were taken from a life cycle inventory (LCI) published by Eurobitume (Eurobitume 2012) which is in compliance with ISO 14040 and ISO 14044. The LCI is specific for the Amsterdam-Rotterdam-Antwerp area and is more recently dated compared to the data for bitumen in Ecoinvent (respectively published in 2012 and 2007). The allocation between bitumen and other

co-products made from crude oil is based on mass balances at the crude oil extraction and the transport stages; while at the refining level, the allocation is based on relative economic values. Within the LCI, no quantitative uncertainty assessment was provided since the standard deviation for each input and output of the process is not available. The LCI is less accurate for analysing toxicity and eco-toxicity indicators.

Environmental data for the additive Fischer-Tropsch (FT) wax are not included in the Ecoinvent database. Information on the production process and the global warming potential of FT wax was found in the cradle-to-gate study (Allen et al. 2010). The primary resource for the wax additive is natural gas. The carbon monoxide, gained from the natural gas is reacted over catalysts together with hydrogen to form syngas, which are the desired hydrocarbon molecules. The reaction product, a mix of n-alkenes over a large c-number distribution is then distilled into fractions of different molecular weight. The wax additive is the heaviest fraction, with a chain length from C40 to more than C115. Mass allocation was applied to divide the global warming potential and the consumption of natural gas among the different products. It is important to notice that the data for the wax additive are only dealing with global warming and fossil depletion because of a lack of more complete data in literature.
No feedstock energy, which is the energy potentially released by ignition, was considered for the studied materials.

2.3 Life cycle impact assessment

The first step in the impact assessment is selecting appropriate impact categories (see Figure 1). Once the impact categories are defined and the LCI results are assigned to these impact categories (classification), it is necessary to define characterisation factors. This is the last obligated step in an LCA study according to the standards. Characterisation factors reflect the relative contribution of an LCI result to the impact category. For example, on a time scale of 100 years the contribution of 1 kg CH_4 to global warming is 25 times as high as the emission of 1 kg CO_2. This means that if the characterisation factor of CO_2 is 1, the characterisation factor of CH_4 is 25. Multiplying the inventory result by the characterisation factor gives the impact category indicator. Characterization uses science-based conversion factors, many of them were found through European research (Scientific Applications International Corporation (SAIC) 2006). The characterized results are thus based on science findings.
An optional step to generate midpoint results is the use of normalisation. This is a procedure needed to show to what extent an impact category has a significant contribution to the overall environmental problem in a defined region (e.g. Europe). Sensitivity analysis is performed by dividing the impact category indicators by a “normal” value. The most common procedure to define the “normal” value is the determination of the impact category indicators for a region during a year and, if desired, divided by the number of inhabitants in that area. Normalization is used to express the data in a way that can be compared among impact categories.
Another optional step to facilitate interpretation of the results is to group and rank the impact category indicators. Impact category indicators that have some common features may be presented as a group. Ranking refers to a procedure, where impact categories are sorted by a panel in a descending order of significance. Weighting is the most controversial and most difficult step in life cycle impact assessment.

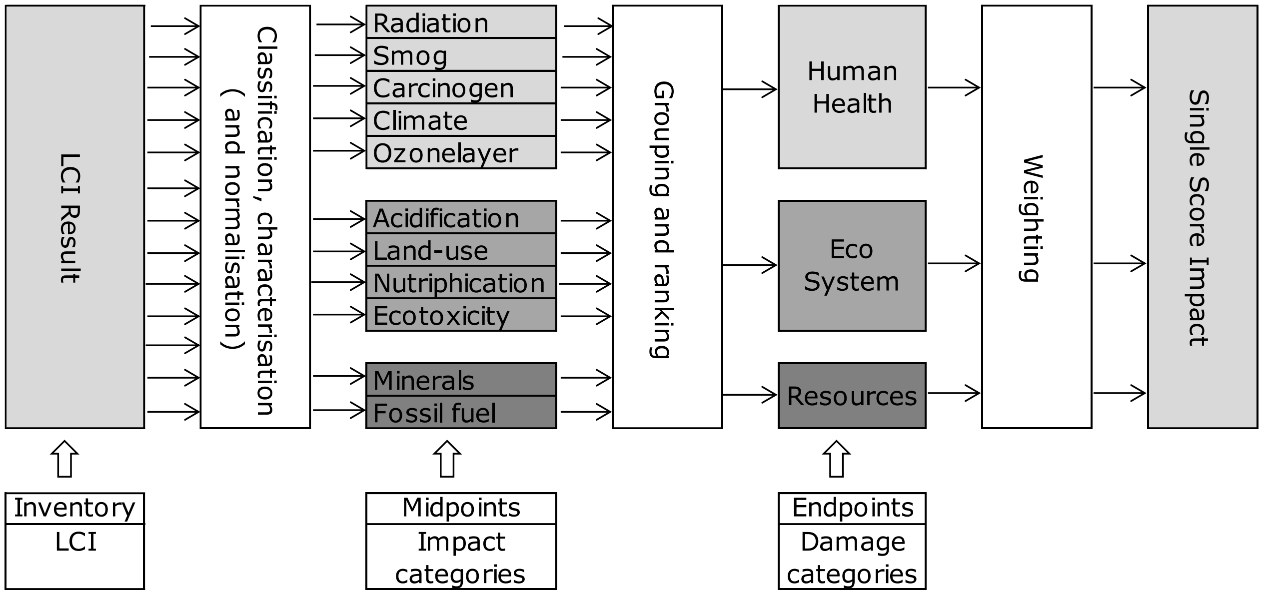


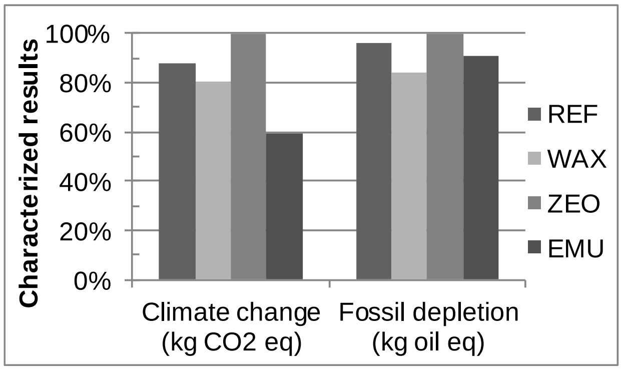
Figure 1: Methodology - Inventory, Midpoints (non-exhoustive), Endpoints & Single score impact

In connection with the selection of an appropriate life cycle impact assessment (LCIA) method for the current case study, it was obvious from the goal and scope that multiple environmental impacts have to be included in the analysis. Furthermore, ISO 14044 does not allow weighting of the impact categories for calculation of a single score impact for public comparisons between products, however, weighting is explicitly allowed for other applications (Goedkoop, Oele, et al. 2013).
ReCiPe is chosen as life cycle impact assessment method (LCIA-method) because it implements both midpoint (impact categories) and endpoint (damage categories) impact categories. Furthermore, ReCiPe Endpoint contains a set of weighting factors with regard to calculating a single score impact from the three damage categories, used for the internal interpretation of the results. The default perspective is the hierarchist, which is based on the most common policy principles with regards to time-frame and other issues. Besides the hierarchist perspective, ReCiPe has an individualist and an egalitarian variant that respectively assume a short time frame and a long term perspective. The hierarchist ReCiPe version with European normalization and average weighting set was chosen. More information about the chosen LCIA-method can be found in the literature (PRé 2013; Goedkoop, Heijungs, et al. 2013; Sleeswijk et al. 2008).

3 RESULTS OF THE CASE STUDY

It is important to keep in mind that the commonly accepted precisions of LCA-calculations may vary between 10 and 20% for single score results and about 10% for characterized results.

Figure 2 and Figure 3 respectively illustrate the characterized and normalized results of the comparison of the cradle-to-grave life cycle of the four road pavement test sections. It must be taken into account that, due to a lack of appropriate data, the environmental data for the production of the FT wax additive is only based on the emission of CO_2eq and a consumption of natural gas resource. Therefore, only the associated impact categories of the ReCiPe LCIA-method were used in these two figures, namely climate change and fossil depletion. In all following figures and results, discussed in this paper, all 18 impact categories included in the ReCiPe method are taken into account.



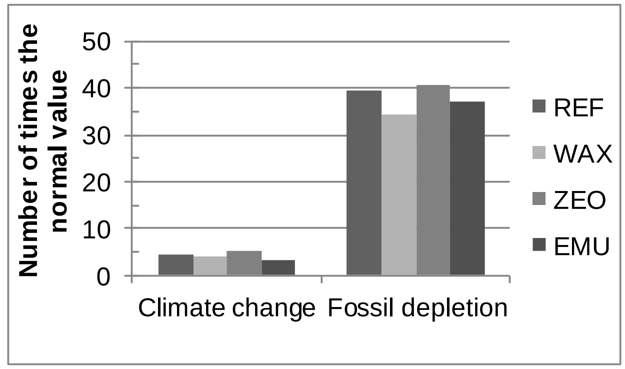


Figure 2: Results of comparison after characterization   Figure 3: Results of Comparison after normalization

The results presented in Figure 2 show a significant reduction (> 40%) of the impact on climate change for the pavement with emulsion compared to the reference pavement. The reduction is due to the absolute reduction of the impact from the production of emulsion compared to the production of bitumen and the reduction of the impact from heat demand.

The reduction of the impact for the emulsion case compared to the reference case is less pronounced in the category of fossil depletion (± 9%)[i]. The main contributors to this impact category are the production of the binder (bitumen or emulsion) and the transport. Because the impact of the production of two different binders on fossil depletion is similar in absolute value, and because the heat has an inferior impact on fossil depletion, the difference between reference and emulsion is less distinct for the impact on fossil depletion compared to the major difference in the climate change impact category.

The increased impact of the zeolite case compared to the reference case is due to the production of the zeolite additive. The absolute impact on climate change from the zeolite production is equivalent to the impact of the energy for heat in the same case. Similar, in the category fossil depletion, the increased impact in the zeolite case comes from the additive. The reduced impact of the wax case, compared to the reference, is mainly due to the longer service life and therefore the reduced amount of maintenance interventions.

In Figure 3, the normalised results are given for the two impact categories and the four life cycles. The impact category indicators (presented in Figure 2) are divided by a normal value. In ReCiPe, with European normalisation factors, the normal value is the total environmental impact of whole Europe during one year, divided by the number of European inhabitants. Put in another way, the normal value is the impact in the certain impact category of an average European citizen during one year.

It can be seen that the normalized impact on fossil depletion is very high (34 to 41 times the impact of an average European citizen per year) compared to the normalized climate change impact (namely 3 to 6 times the normal value). Hence, the fossil depletion impact of the pavement in this case contributes significantly to the total fossil depletion related environmental problem. The contribution of the road sections to the European environmental problem on climate change is less pronounced. This does not mean that the impact from the road sections on climate change is negligible, but it imputes that the yearly impact on climate change of a European person is large when compared to the yearly impact on fossil depletion of a European person.

The single score impact (including all 18 impact categories) of the pavement with wax, differs less than 1% compared to the single score impact of the pavement with emulsion (see Figure 4)[i]. It is important to take into account that the life cycle of the pavement with wax includes only 2.5 maintenance interventions compared to 3 maintenance interventions for all other life cycles. The extended life time for the pavement with wax is an assumption based on performance characteristics tested in the laboratory (i.e., rut resistance).

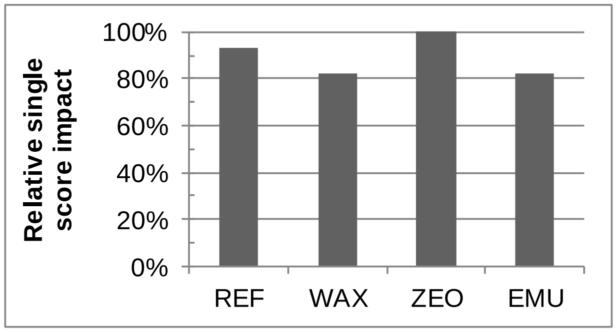


Figure 4: Single score impact, relative to the highest single score impact (zeolite case)

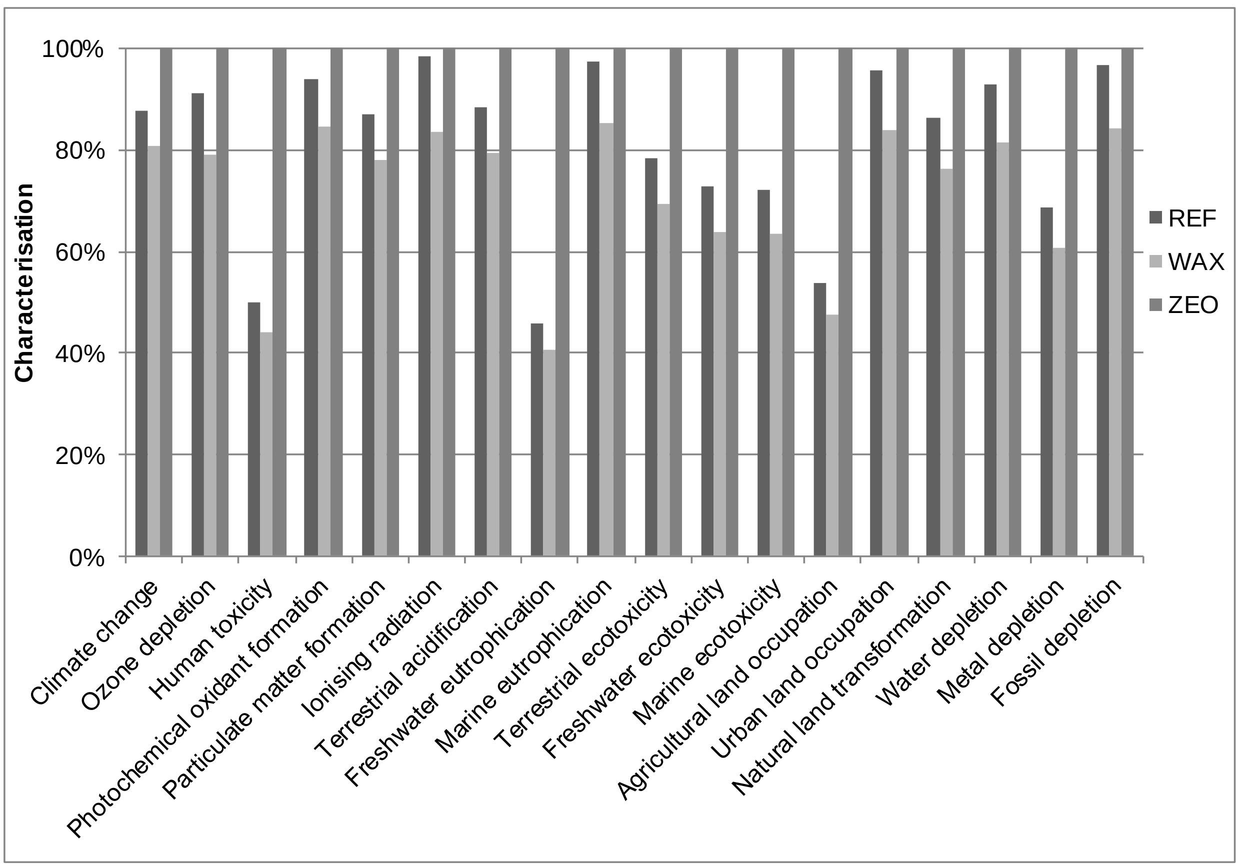


Figure 5: Characterisation results of life cycles reference, wax and zeolite

Neglecting the emulsion pavement, the ranking of the characterized results of the three other pavements (baseline scenario) is the same in all 18 impact categories (see Figure 5). This means that no weighting to a single score is actually needed to find the most favourable case. The results obtained based on sciences (characterisation) point to the wax pavement as the best choice (when excluding the emulsion pavement). The environmental impact during the life cycle of the zeolite

pavement is the highest. Including the emulsion pavement, the ranking of the four cases is not the same in the different impact categories (wax and emulsion mutually exchange), and therefore weighting is necessary to prefer a certain case.
All results are based on the data that were available (which might be incomplete i.e., data for wax). The determination of the reliability of those published data is beyond the scope of the project. Changing the data source might have influenced the results (see 3.2.).

An analysis showed that the environmental impact (single score) from 1 kg wax is higher when compared to 1 kg bitumen. Analogous, it is found that the single score impact of the filler is small compared to the impact of the same mass of zeolite.
The analysis of the environmental impact of the asphalt mixture production (cradle-to-gate) includes the acquisition and production of raw materials; transport of raw materials to asphalt plant; energy to heat and dry aggregates and store bitumen; and electrical energy for engines. The impact of 1 ton reference mixture is almost equal to the impact of 1 ton mixture with wax additive (note the limited data for wax). The impact of the mixture with zeolite is on the other hand 10% larger compared to the reference and the impact of the mixture with emulsion is 15% smaller compared to the reference[i].

3.1 Contribution analyses

The processes that have a significant part in the results can be determined by a contribution analysis. This is an impact analysis breakdown. It is often found in contribution analysis that 95 to 99% of the results are determined by just a few processes (Goedkoop, Oele, et al. 2013). With this information, it is possible to focus the attention on these processes and analyse if these processes are sufficiently representative, complete, and if there are important assumptions within these processes. Furthermore, researchers might focus on these processes in order to optimize the environmental impact of the product system and apply measures.

Figure 6 illustrates that, among important processes, the binder (bitumen or emulsion) is the major contributor to the total single score impact (all 18 impact categories in ReCiPe are included) for all cases of the baseline scenario, with 55% to 62% depending on the case. Furthermore all transport of materials and equipment (excluding transport of waste, that is assigned to the waste treatment) represents 18% to 21% of the total single score[i]. The natural gas used to generate heat is responsible for 7% to 9% of the total single score impact, respectively for the WMA cases and for the HMA case[i]. The impact of heat from natural gas represents less than 0.1% in the life cycle of the cold pavement with emulsion[i].
The contribution to the single score impact of the fuel consumption by equipment for road construction (paver, roller) ranges from 18 to 21%[i]. The contribution of the production of the additive to the total single score impact is small for the wax (2.8%) but larger for the zeolite (7.8%), which explains the variation in the contribution of the impact from raw materials (ranging from 4 to 12%)[i]. Finally the ‘other’ processes including the waste treatment from maintenance and end-of-life; the electricity consumption and the installation emissions represent ±6% of the total single score impact[i].
The interpretation of these percentages is important. A smaller percentage of contribution does not indicate a smaller absolute impact of a certain process or material. Nevertheless the percentage of the contribution gives an indicative idea of the main contributors.

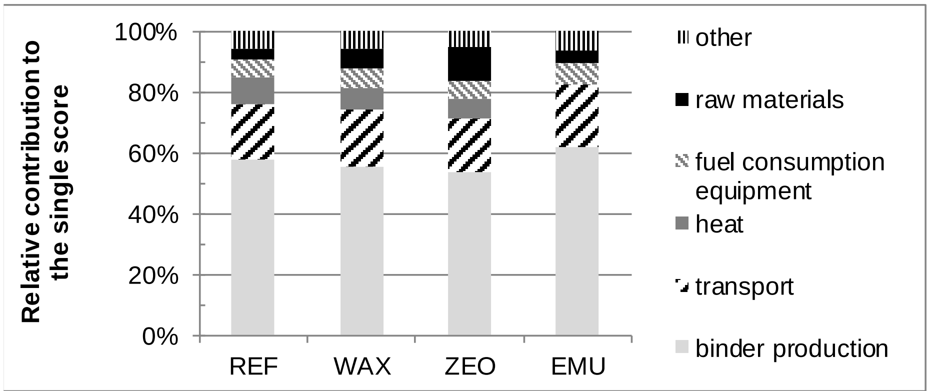


Figure 6: Contribution of different processes to the single score impact

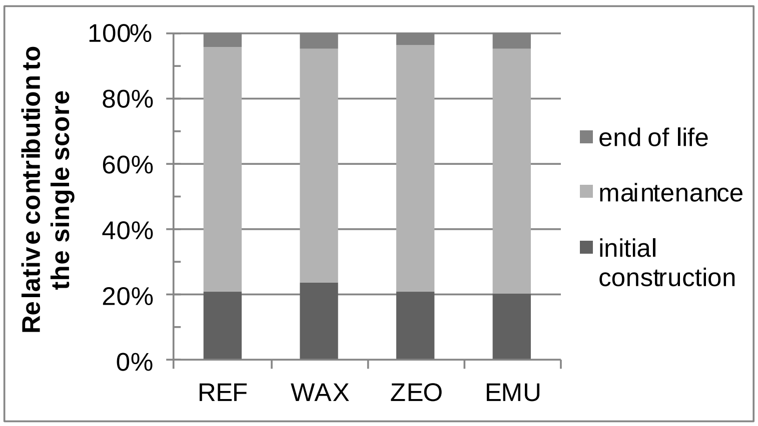


Figure 7: Contribution of different life cycle processes to the single score impact

The division of the total single score impact between the three main life cycle stages is illustrated in Figure 7. The impact of the initial construction contributes 20 to 24% to the total single score impact. The maintenance stage represents 71% in the wax life cycle and 75% in the three other life cycles. The decrease of the relative impact during the maintenance stage (due to the longer service life for the wax pavement) leads to a relative increase of the impact in the construction and end-of-life stage. At last, the end-of-life stage is responsible for 4 to 5% of the total single score impact[i].

3.2 Sensitivity analyses

In this chapter, the influences of some assumptions on the LCA-results were analysed. Sensitivity analyses are carried out in order to investigate the influence of some alternatives for a certain assumption e.g., data from different data sources, haulage of a lorry, transport type, fuel type, etc. Among others, the most important contributors to the single score impact are investigated by sensitivity analyses: bitumen (data source), transport (method) and heat (fuel type). The variant of these parameters, used in the baseline scenario is indicated by 'default'.

It can be seen from Figure 9 and Figure 10 that the effect, respectively of the transport method (±5%) and the fuel type (±3%), is rather small[i]. At the other hand, the total environmental impact of the life of the pavement can vary more significantly based on the choice of data source of bitumen (±10%) (Figure 8)[i].

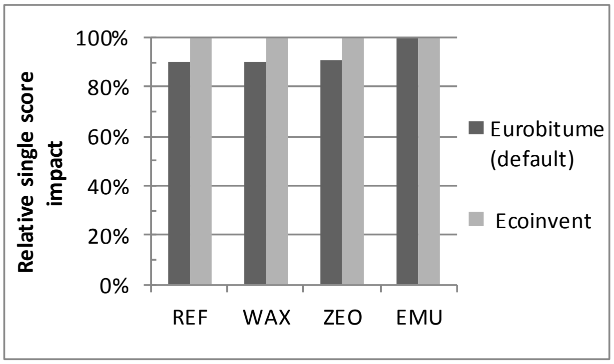


Figure 8: Sensitivity analysis data source bitumen

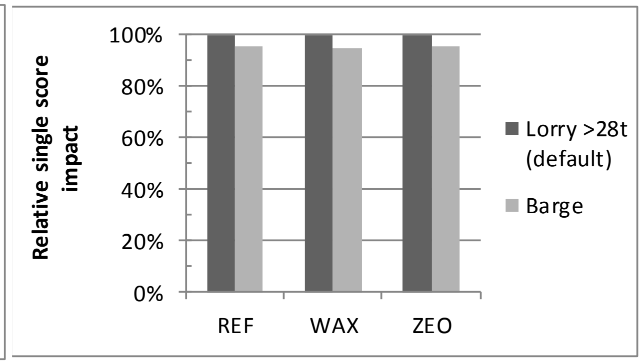


Figure 9: Sensitivity analysis transport method for supplying raw materials to the asphalt plant

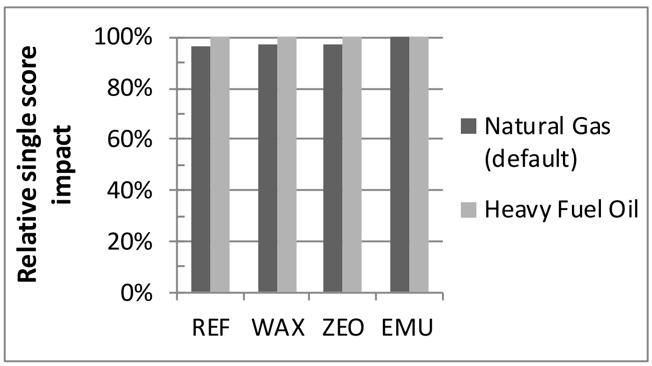


Figure 10: Sensitivity analysis fuel type for drying and heating raw materials

Furthermore, the ranking of the single score impact of the four cases investigated may change when changing the service life or the LCIA-method.

The emulsion case is only added as a theoretical calculation, and the pavement life as for the reference case is assumed. In practice, it is not sure if this pavement can be constructed and certainly not sure what pavement life may be achieved. Therefore, the sensitivity of this assumption is analysed. The service life of the road pavement and hence the number of maintenance interventions during the analysis period is varied in Figure 11. The baseline scenario of 19 years of service life (2.5 maintenance interventions) for the wax pavement and 14 years of service life (3 maintenance interventions) for the other pavements is changed to an equal service life for all four pavements (14 years, or 3 maintenance interventions) and is changed to 10 years (4 maintenance interventions) for the cold pavement and an equal service life of 14 years for the other top layers. Changing the expected pavement life from 19 to 14 years or from 14 to 10 years, is enough to change the rankings of the various construction modes. This indicates that service life, and techniques for enhancing service life, are very important when developing sustainable pavements.

Detailed results showed that the ranking of the cases was not the same in all impact categories for both sensitivity analyses. Hence, no absolute ranking can be presented without weighting.

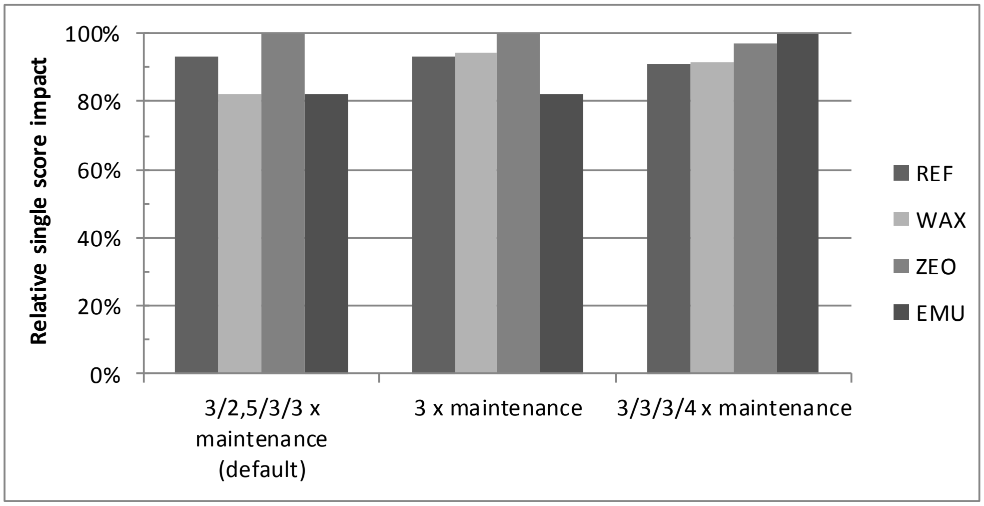


Figure 11: Sensitivity analysis service life top layer pavement

Table 2: Sensitivity analysis LCIA-method (single score impact relative to the reference)

LCIA-method	REF	WAX	ZEO	EMU
ReCiPe Endpoint (E) V1.06 / Europe ReCiPe E/A	1,00	0,88	1,15	0,90
ReCiPe Endpoint (H) V1.06 / Europe ReCiPe H/A	1,00	0,88	1,07	0,88
ReCiPe Endpoint (I) V1.06 / Europe ReCiPe I/A	1,00	0,88	1,06	0,89
Eco-indicator 99 (E) V2.08 / Europe EI 99 E/A	1,00	0,88	1,10	0,92
Eco-indicator 99 (H) V2.08 / Europe EI 99 H/A	1,00	0,88	1,08	0,93
Eco-indicator 99 (I) V2.08 / Europe EI 99 I/A	1,00	0,90	1,77	0,85
ReCiPe Endpoint (H) V1.06 / World ReCiPe H/A	1,00	0,88	1,07	0,89
EPS 2000 V2.06 / EPS	1,00	0,89	1,16	0,89
Ecological Scarcity 2006 V1.06 / Ecological scarcity 200	1,00	0,88	1,03	0,90
EDIP 2003 V1.03 / Default	1,00	0,88	1,09	0,98
IMPACT 2002+ V2.10 / IMPACT 2002+	1,00	0,89	1,08	0,90

Table 2 presents the single score impact (relative to the reference case) of the four baseline cases (note the longer service life for the wax pavement), calculated with different LCIA-methods. The results in table 2 indicate that the ranking of the single score impact of the different pavements is influenced by the LCIA-method. The wax and emulsion pavement swapped places. The ranking of the four cases with Europe ReCiPe H/A (default) and Europe EI 99 I/A is different compared to the ranking obtained with all the other methods.

The trend is similar for the different LCIA-methods: 10 to 12% reduction for the wax case, 3 to 16% increase for the zeolite case and a decrease of 2 to 12% for the emulsion pavement compared to the reference (in the baseline scenario)[i]. One exception is found for the LCIA-method Europe EI 99 I/A, where an increase of 77% of the single score is noticed for the zeolite pavement compared to the reference. This is due to a large impact in the minerals impact category (4.5 times the impact of the reference in the same category), which stems from the zeolite powder production.

4 CONCLUSIONS AND RECOMMENDATIONS

The objective of this paper was to compare sustainability aspects of four wearing courses of pavement sections made of hot mix asphalt, warm mix asphalt and cold asphalt; to determine the processes that play a significant role in the results and to evaluate the influence of the most important assumptions on the results. The focus was not laid on the results only but also on the methodology, difficulties and challenges of conducting an LCA study on bituminous pavements.

Analysis of the baseline scenario highlighted that the impact of the life cycle of the pavement is dependent on the type of additive and the expected service life. From the results of this analysis, no preference could be given to either HMA or WMA. Based on science, and excluding the emulsion mixture, the three cases in the baseline scenario are ranked from most to less impacting as follows: zeolite, reference, wax. It is important to keep in mind that at this moment we still assume a longer service life for the pavement with the wax additive. A study by (Vidal et al. 2013) concluded the same: 'The reduction in the impacts of WMA resulting from the lowering of the manufacturing temperature was offset by the greater impacts of the materials used, especially the impacts of the synthetic zeolites'.
Other and broader studies are required in order to compare the total environmental impact of HMA and WMA with different additives and production techniques. Uncertainties, however, remain on these additives (i.e. wax) for which full life cycle inventories were not found. Furthermore, uncertainties in the actual service life of the pavement materials remain. More information about the intrinsic inaccuracy of LCIA-methods is needed to draw firm conclusions.
From the contribution analysis of the baseline scenario, it was seen that mainly the combination of production of bitumen, all transport and energy for generating heat, contributes to the total environmental impact. Furthermore the impact of the additive might be significant, even though a very small quantity of the material is used in the asphalt mixture.
The results from the sensitivity analyses show that the total environmental impact of the life of the pavement can vary significantly based on the choice of data under analysis, service life and LCIA-method.

An important advantage of WMA compared to HMA is the lower diffusion emissions during road construction, which is clearly visible to the naked eye. This is associated with higher safety for the road workers who work day after day in the fumes of the hot or warm material. Nevertheless, the advantages of WMA for the human health of the road workers do not show up in the results of the calculations. This is due to the fact that the environmental impact from e.g., the production of bitumen, and the energy for drying and heating the aggregates is very large and therefore the relative reduction of the emissions from the diffusion emissions due to the warm mix technology is invisible. Furthermore, some aspects are not included (e.g., increased safety), because at this moment, it is not possible to model it in LCA. Hence it is important to always critically evaluate the results from LCA and even look further than these numerical values.

In terms of future development, more information on the life time of different asphalt pavements would be extremely useful. As is the case with many life cycle based studies of construction products, the rate of replacement of materials is very significant in environmental terms. In Belgium, WMA is not frequently used. The evaluation of the service life takes some time and more (test) sections are needed to allow for robust conclusions on this parameter.
Furthermore some environmental data on some specific products like the wax additive in this case is still missing. Companies should be encouraged to register and monitor the production process of their products for generating environmental data, available for research.

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[i] This small value or difference falls outside the validity range of the ReCiPe method as described in §4 and so we need to be careful with the interpretation and firm conclusions are not allowed based on this result.