

CRADLE-TO-GATE LIFE CYCLE ASSESSMENT OF RECYCLING AND IMPACT OF REDUCED PRODUCTION TEMPERATURE FOR THE ASPHALT SECTOR IN BELGIUM

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ABSTRACT

Bituminous mixture is the premier material for road construction in Belgium. Innovative technologies with regard to improve energy and material efficiency of pavement construction are necessary. Warm mix asphalt (WMA) may provide significant energy savings to the asphalt industry. Also, the use of reclaimed asphalt pavement (RAP) into new bituminous mixtures may diminish the extraction and processing of minerals and binders. Using life cycle assessment, the environmental impact of the production of WMA is compared with hot mix asphalt (HMA) containing reclaimed asphalt pavement and with conventional hot mix asphalt as a reference. Contribution analyses were performed in order to determine which processes are significant for the results and sensitivity analyses were conducted in order to take into account the influence of the most important assumptions in the process on the results.

It was found from the results in the current study that a greater reduction of the environmental impact is obtained by using RAP in asphalt mixtures compared to reducing the mixture temperature. It was seen from the contribution analyses that mainly the production of bitumen, the transport of raw materials from the quarry or production site to the asphalt plant and the energy in order to generate heat, contribute to the total environmental impact. The results of the sensitivity analyses show that the total environmental impact of the asphalt mixtures varies mostly on the choice of the data source and the transport method.

INTRODUCTION

In recent years, more environmental awareness and increasing energy costs have encouraged industries to consider research on environmental friendly technologies. For the bituminous pavement sector, this culminates the development of technologies designed in order to reduce energy consumption and increase recycling, this latter in order to decrease the virgin material extraction.

A number of software tools have been developed with regard to analyze the environmental impact of road pavements. Some of these tools are based on the life cycle assessment method and allows including processes from different phases in the life cycle of a road pavement, e.g. asphalt production, road construction, maintenance and end of life. At the other hand, simplified tools are used to assess in a more general way the environmental impact of road pavements and are often limited to a single impact (i.e. global warming potential). However, it is recognized internationally (1) that the assessment of CO₂-equivalents or in general any single metric (e.g. carbon footprint, water footprint) is too limited to assess a correct and significant environmental impact. An evaluation by only CO₂-equivalents does not reveal the full picture of the effect on the environment. The life cycle assessment (LCA) approach includes multiple environmental issues. These life cycle impacts are being used increasingly as a selection criterion for products and materials since a more accurate impact is provided.

In this study the LCA methodology was chosen as the most adapted method for the current comparative cradle-to-gate assessment. The study takes into account the asphalt production and all upstream processes including resource extraction, material production, transport etc. Otherwise stated, the analysis includes all processes involved in asphalt production until the asphalt mixture reaches the gate of the asphalt plant i.e., excluding the transport to the consumer or work site.

The *SimaPro* software version 8.0 was used to elaborate the analysis. This software was developed by the Dutch company Pré. Depending on the license type and duration, the charge is between €1,800 (\$2,466) and €21,000 (\$28,770).

This paper will set forth the method and results from the LCA case study. In a first section, the applied methodology is illustrated including the different stages of an LCA as defined in the LCA standard (ISO 14040 (2)): goal, scope, life cycle inventory and life cycle impact assessment. In the second section, the results of these LCA calculations are presented, including a comparison of three different cases, a contribution analysis and sensitivity analysis. In the last section, the conclusions and recommendations are described.

LITERATURE

The objective of this life cycle assessment is to compare the environmental impact of two different technologies, implemented in order to reduce the environmental impact of asphalt production. The comparative study is done for the foamed-bitumen process for WMA production and HMA with and without recycling.

Warm Mix Asphalt

Decreasing the production temperature of asphalt mixtures is seen as the most important way to reduce the energy consumption of asphalt production. In Belgium it is assumed that HMA is manufactured between 140°C till 190°C while the production of WMA is situated between 70°C and 140°C (3). It is assumed that the production of WMA will have an average reduction in energy consumption of 20% compared to the conventional HMA production (3). The fundamental idea while developing warm mix asphalt (WMA) is to reach equal or better performance characteristics compared with the conventional hot mix asphalt (HMA). This is mainly reached by reducing bitumen viscosity, which in turn improves mix workability, produces fewer emissions, and generally yields better working conditions (4).

Initially, German research focused on adding additives to the asphalt mixture in order to facilitate the production and processing of WMA; while in Norway the WMA-foam process was developed (3). The various technologies which have been developed in order to produce WMA can be classified in the following three groups: organic additives, chemical additives, and water-based or water-containing foaming processes. Several studies have investigated the environmental impact of WMA, of which some compared WMA to the impact of a conventional HMA mixture. Study (5,6) found that the reduction in the impact of WMA resulting from decreasing the manufacturing temperature was countered by the impacts of the materials used, specifically the impacts of additives e.g., synthetic zeolites.

Study (7) investigates the WMA production with foamed bitumen technology and describes the Double Barrel Green technology which uses multiple nozzles to inject directly cold water into the hot binder flow. The production technique requires 0.45 liters of water per ton asphalt mixture and provides 20 to 30°C production temperature reduction. No additive is required in order to apply this technique. Nevertheless, an advantage of WMA compared to HMA is the potentially higher use of RAP. A decrease of production temperature leads to less ageing of the binder, thus counteracting the stiffer RAP binder (4). Analogous, an improved moisture sensitivity and rutting resistance were obtained by including up to 50% RAP in the WMA mixture compare with the virgin WMA (7). In the same way, study (8) ranked mixtures from worse to better rutting and moisture resistance as follows: WMA mixtures with low RAP content, WMA mixtures with high RAP content, and HMA mixtures with high RAP content.

In Belgium, the applicability of WMA is a current research item. A few pilot projects are finished in order to investigate the applicability and performance of WMA techniques. Some of the projects have led to promising results but until now, the projects in which these techniques are used are rather small-scale. Moreover, in 2014, no mixtures based on specific technologies in order to facilitate WMA are defined in the Flemish standard SB250 v.2.2., the 'Standaard Bestek SB250' that defines the rules for public tenders in Flanders.

Reclaimed Asphalt Pavement

Recycling asphalt pavements is the current valuable approach for technical, economic and environmental reasons. The use of RAP in new asphalt mixtures is mainly encouraged by the increasing cost of bitumen and the scarcity of quality aggregates. The international regulations in order to decrease polluting emissions and preserve the environment forces industries to move towards extensive recycling.

From an environmental point of view, the use of RAP in new bituminous mixtures avoids the need to mine virgin raw materials, the need to process bitumen, and the need to dispose of the released asphalt to landfill (5). At the other hand, some screening is needed in order to detect and eliminate tar containing RAP. Preliminary to the reuse, the RAP is processed by sieving and crushing in order to provide proper material for new high quality asphalt mixtures. The environmental impact of using RAP is affected by a few factors, such as moisture content (9,10), hot mix asphalt discharge temperature (10), RAP content (10) and transport process (11). Furthermore, study (9) found that recycling of asphalt to bound courses (in particular surface-to-surface) is favored compared with recycling asphalt to unbound applications (sub-base or fill) or waste management alternatives (landfill or incineration).

All asphalt production plants in Flanders are batch types and about 80% of them are provided with a parallel drum to preheat the RAP before addition to the mixer (12). The SB250 defined a minimum preheating temperature for RAP of 110°C. In practice, the temperature of the RAP is limited to 140°C in order to minimize binder oxidation and explosion risk. It was noticed (13) that the energy consumption of the asphalt plant for drying and heating aggregates increases with 14 to 17% when this second, parallel drum is used. Despite the lower temperature for RAP ($\pm 130^\circ\text{C}$) compared to virgin aggregates for HMA ($\pm 160^\circ\text{C}$), an elevated energy demand is observed caused by the additional drum.

In the current versions of the SB250 (v.2.2 and v.3.0), it is still prohibited to use RAP in new asphalt mixtures for top layers. For binder layers, this SB250 defines asphalt mixtures based on either mixture composition or on the performance requirements. The first method allows a maximum of 20% (cold addition) and 50% (warm addition by parallel drum) of the bitumen content from RAP. The second method does not define a maximum quantity of bitumen content from RAP in the asphalt mixture. Based on figures from the certified asphalt plants in Flanders (*unpublished data – interview expert at COPRO*), the minimum quantity of RAP is assessed to be 40%, the maximum 75% and the average $\pm 55\%$ RAP in new asphalt mixtures. The use of tar containing RAP is prohibited in Belgian asphalt mixtures.

GOAL, SCOPE AND METHODOLOGY

This paper presents the comparative life cycle assessment (LCA) for the production of three different asphalt mixtures. Therefore, only the asphalt production is included because other parameters are (assumed to be) the same. The pavement construction, including site preparation, tack coating, paving and compaction is independent of the asphalt mixture. Furthermore, the asphalt mixture used in the binder layer does not affect the use phase (e.g., rolling resistance and associated fuel consumption). The service life of the pavement layers constructed with the three different asphalt mixtures is assumed to be equal and therefore no difference in maintenance should occur. Finally the recyclability and waste treatment is assumed to be similar for these bituminous mixtures.

Goal

The aim of the current study is to compare the environmental impact of the production of three different asphalt mixtures: a conventional reference hot mix asphalt (referred to as REF); a warm mix asphalt produced with foamed bitumen technology (referred to as WMA); and a hot mix asphalt including reclaimed asphalt pavement (referred to as RAP). The goal of the paper is to study the difference of these three asphalt mixtures which to achieve by using LCA and sensitivity analyses. The three asphalt mixtures investigated are dense grade mixtures for binder layers with the same composition. The foaming process for the WMA relies on the capability of hot bitumen to foam when cold water is directly added to the hot binder flow with special nozzles. The third asphalt mixture contains 50% RAP. Both virgin aggregate and virgin binder are replaced for 50% with RAP.

The current study is in this stage only a theoretical study; it is aimed to use this strategy in upcoming cases in practice. The aim of the current study is to compare the two different techniques (warm mix asphalt and recycling) in general with a conventional asphalt mixture. Data was used which is representative for the specific techniques and for the Flemish situation. Besides comparing the three asphalt mixtures, the aim of this study was also to determine the processes which are playing a significant role in the results and to evaluate the influence of the most important assumptions on the results. Therefore some contribution and sensitivity analyses were performed.

Scope

In this section, the system boundaries and assumptions for the baseline scenario for the three mixtures (reference, WMA and RAP) are described. The functional unit used is the production of 1 ton asphalt mixture. In order to guarantee equal functionality, the mechanical performance of the three asphalt mixtures is assumed to be the same. This assumption is based on findings in literature of equal performance between HMA with and without RAP (14–20) and between HMA and WMA (21,22). In this way, a surface with equal dimensions and equal technical requirements can be paved with the three mixtures investigated. The analysis includes all direct and indirect processes related to the production of asphalt and thus a “cradle-to-gate” life cycle was considered (Figure 1).

Following processes are beyond the scope of the study:

- Additives (in order to improve the performance of the asphalt mixture);
- Overhead (energy and material consumption for the construction of the asphalt plant and for the operation of the asphalt plant, offices etc.).

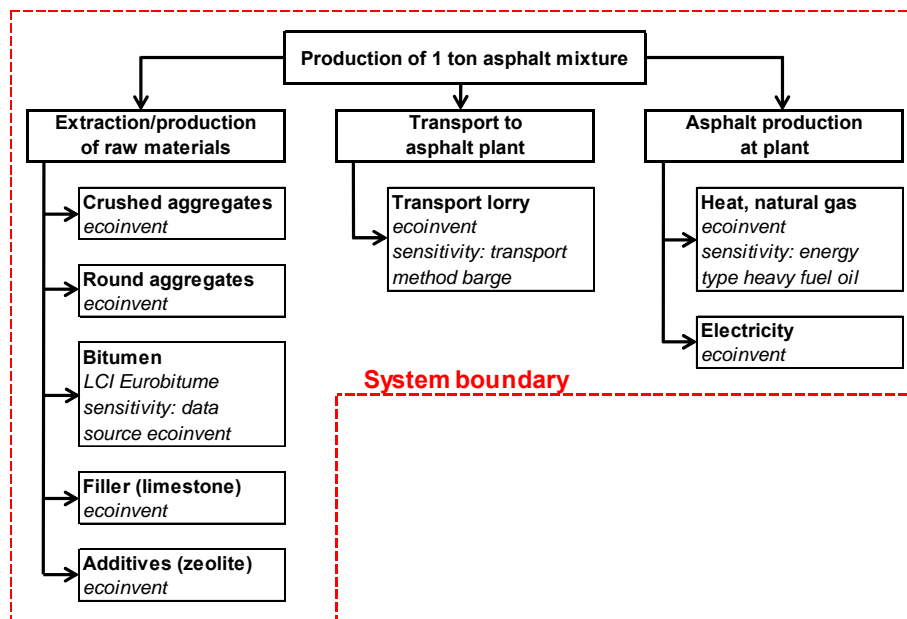


Figure 1: System boundary, data sources and sensitivity analyses.

The life cycle assessment in this case study takes only ecological aspects into account, not the social and economic factors which must be considered as well for decision-making in civil engineering. There are only few differences between the three mixtures investigated. The production temperature for the HMA control mixture is 160°C while the production temperature for the WMA mixture is 130 C; the RAP is preheated in a parallel drum up to 130 C. In order to foam the bitumen for the WMA, a quantity of 4.5% (mass of the binder fraction) of cold water is added to the hot bitumen.

Some assumptions have been made for the calculations in order to deal with the lack of case specific information. The default assumptions for the baseline scenario are explained and the influence on the results of some of them is investigated with sensitivity analyses below.

- All raw materials are supplied to the asphalt plant with a truck;
- The temperature of the aggregates before heating is 10°C;
- The moisture content before heating is 2% for coarse aggregates and 5% for sand;

- The fuel type for drying and heating aggregates in the asphalt plant is natural gas;
- The flue gas temperature of the white drum (virgin aggregates) is 140°C and the flue gas temperature for the parallel drum (RAP) and during the production of WMA is 110°C;
- The theoretically calculated energy consumption for the HMA case to dry and heat aggregates is multiplied by 1.16 for the RAP case in order to take into account the extra fuel consumption in practice by the second drum.

Life Cycle Inventory

The inventory was drawn up by combining data from the *Ecoinvent* database, international literature and average, but specific data for the Belgium area. Representative transport distances for the raw material supply to the Flemish asphalt plant have been calculated. It was found that the average distance between a random asphalt plant and a random quarry is 114 km. The average distance specific for the crushed aggregates is 122 km and the average distance specific for round aggregates is 98 km. In the same way, the average distance from the port of Antwerp to a Flemish asphalt plant was calculated to be 57 km, what is used for the supply of bitumen.

Data from the *Ecoinvent* database version 2.2 was used for all raw materials and processes, except for bitumen and RAP (see Figure 1). Data for bitumen was taken from a life cycle inventory (LCI) published by Eurobitume (23) because this LCI is more recent compared to the data for bitumen in *Ecoinvent* (respectively published in 2012 and 2007) and the LCI from Eurobitume is specific for the Amsterdam-Rotterdam-Antwerp territory. The energy consumption for the heated storage of the bitumen was found in study (9). Burdens from RAP have not been included because this material is declared as waste and therefore has no direct burdens associated to it (5). Finally, the electrical energy consumption for engines at the asphalt plant (sieving, dosing, conveyor belt, etc.) was taken from study (12).

Life Cycle Impact Assessment

ReCiPe was chosen as life cycle impact assessment method (LCIA-method) because it implements both midpoint (impact categories) and endpoint (damage categories) categories. Furthermore, *ReCiPe* Endpoint contains a set of weighting factors with regard to calculating a single score impact from the three damage categories. The default perspective is the hierarchist, which is based on the most common policy principles with regards to time-frame and other issues. Furthermore, the *ReCiPe* version with European normalization and average weighting set was chosen. More information about the chosen LCIA-method can be found in the literature (24–26).

RESULTS AND DISCUSSION

The life cycle assessment results are discussed in this section. The comparison of the three mixtures and the contribution analysis only includes results from the baseline scenario as described above. This baseline scenario is adapted for the sensitivity analyses. It is important to note that the accuracy and precision of the LCA-calculations based on the used data might be about 10% and therefore conclusions have to be refined accordingly.

Comparison of the Three Asphalt Mixtures

Figure 2 illustrates the single score impact per damage category for the three different mixtures: REF, WMA and RAP. The reference asphalt mixture holds the largest impact factor. The single score impact

of the WMA mixture and the mixture with RAP are decreased with respectively 2% and 41% compared with REF. The damage category resources represents more than 70% of the total single score impact for the three mixtures.

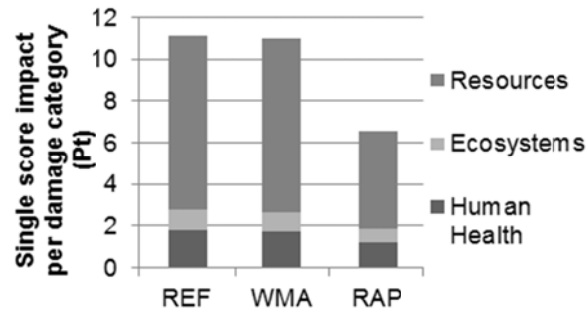


Figure 2: Comparison of single scores - REF, WMA, and RAP.

For the three mixtures, the comparisons for each impact category are presented in Table 1. It can be seen from the table that the ranking of the different mixtures is equal in each impact category assessed with the selected LCIA-method. Therefore, no weighting to a single score was actually needed to indicate a favorable mixture. The results obtained based on natural sciences (characterization) do clearly favor the RAP mixture. The single score is only used to simplify the presentation of the results. The impact categories are ranked from highest to least impacting for the reference mixture. It can be seen from Table 1 that this ranking is the same for the WMA and the RAP mixture. The four main impacting categories for all mixtures are fossil depletion, climate change human health, climate change ecosystems and particulate matter formation.

Table 1: Characterization Results per Impact and Damage Category - REF, WMA, RAP

Impact category	Unit	REF	WMA	%	RAP	%
Total	mPt	11137.564	10953.813	-2%	6554.656	-41%
Fossil depletion	mPt	8371.037	8277.348	-1%	4680.881	-44%
Climate change Human Health	mPt	1319.470	1267.152	-4%	941.191	-29%
Climate change Ecosystems	mPt	862.902	828.688	-4%	615.515	-29%
Particulate matter formation	mPt	407.172	404.989	-1%	218.030	-46%
Natural land transformation	mPt	77.624	76.744	-1%	43.441	-44%
Human toxicity	mPt	60.768	60.403	-1%	34.929	-43%
Urban land occupation	mPt	25.449	25.418	0%	12.988	-49%
Agricultural land occupation	mPt	4.477	4.461	0%	2.547	-43%
Ionising radiation	mPt	3.214	3.207	0%	2.082	-35%
Terrestrial acidification	mPt	2.672	2.654	-1%	1.448	-46%
Metal depletion	mPt	1.013	1.009	0%	0.532	-48%
Terrestrial ecotoxicity	mPt	0.849	0.839	-1%	0.490	-42%
Freshwater eutrophication	mPt	0.375	0.372	-1%	0.224	-40%
Ozone depletion	mPt	0.276	0.262	-5%	0.212	-23%
Photochemical oxidant formation	mPt	0.213	0.212	-1%	0.114	-46%
Freshwater ecotoxicity	mPt	0.054	0.054	-1%	0.031	-43%
Marine ecotoxicity	mPt	1.80E-04	1.78E-04	-1%	1.05E-04	-41%
Damage category	Unit	REF	WMA	%	RAP	%
Total	mPt	11137.564	10953.813	-2%	6554.656	-41%
Human Health	mPt	1791.113	1736.226	-3%	1196.559	-33%
Ecosystems	mPt	974.401	939.230	-4%	676.684	-31%
Resources	mPt	8372.050	8278.357	-1%	4681.412	-44%

The reduction of the single score impact from the WMA mixture compared with the reference mixture is steadily spread in the different impact categories and counts 0 to 5% per impact category. The major difference is the ozone depletion impact category, which is in this study dominated by the transport of natural gas in an on-shore pipeline. The reduction of the production temperature causes a reduction of natural gas demand for heating the aggregates; therefore less natural gas has to be transported. The difference between the RAP mixture and the reference pavement is spread in the different impact categories as well and ranges from 23 to 49% reduction for the RAP mixture. The main differences are found in the urban land occupation (49%) and metal depletion (48%). The category urban land occupation is for this study dominated by the mining and processing of the gravel. A reduction of the impact with $\pm 50\%$ is noticed for this process because 50% less virgin gravel has to be mined in order to produce the asphalt mixture. The category metal depletion is in this study dominated by the mining of iron ore which is associated to the transport process and the production of crushed gravel. The demand for crushed gravel and transport to supply raw materials to the asphalt plant is halved and thus the impact related to iron ore is almost halved as well.

Contribution Analyses

From the process network in *SimaPro*, the relative contributions of the processes to the single score impact can be calculated. The contribution of the most impacting processes is depicted in Figure 3. Among all processes, it is observed that bitumen is the major contributor to the total single score impact for all mixtures of the baseline scenario, with 56% to 67%. Furthermore all transport of raw materials represents 13% to 16% of the total single score. The natural gas used to generate heat is responsible for 11 to 25% of the total single score impact. The difference between the HMA (12.6%) and WMA (11.1%) is small. The high impact in the RAP mixture is due to the increase of the energy consumption with 16% compared with HMA.

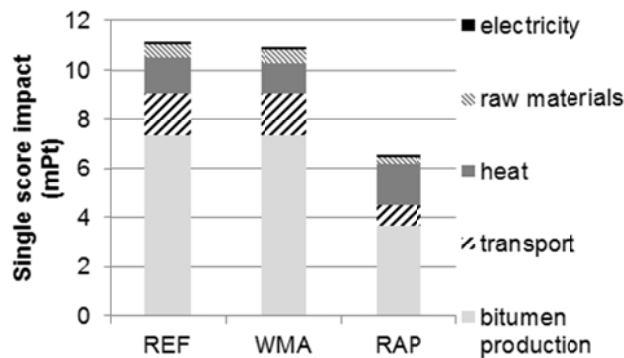


Figure 3: Contribution of processes to the single score impact.

The interpretation of these percentages is important. A smaller percentage of contribution does not always indicate a smaller absolute impact of a certain process or material. Nevertheless the percentage of the contribution gives for a single cradle-to-gate life cycle an idea of the main contributors. Besides the contribution of different processes, the contribution of elementary flows to the total environmental impact can be analyzed. The five most impacting elementary flows are the same for the three life cycles investigated: crude oil, fossil carbon dioxide, natural gas, carbon dioxide, and nitrogen oxides. The impact from 'oil, crude, in ground' comes for $\pm 90\%$ from the bitumen and for $\pm 9\%$ from transport in all life cycles. The impact from 'carbon dioxide, fossil' is diffuse and comes from different processes e.g., transport by truck and heat from natural gas. About 72% (REF and WMA) or 85% (RAP) of the total

impact due to 'gas, natural, in ground' comes from the heat used to dry and heat aggregates and to store bitumen. The impact from 'carbon dioxide' derives for 100% from the production of bitumen for the three mixtures investigated. Finally, the impact from 'Nitrogen oxides' originates for 56 to 60% from transport and for $\pm 25\%$ from the production of bitumen.

Sensitivity Analyses

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 truck, transport type, fuel type, etc. Only one parameter of the baseline scenario is changed in each sensitivity analysis. In a first analysis, the environmental impact for the production of bitumen from *Ecoinvent* and from Eurobitume (23) is compared. Figure 4 shows that the single score impact increases (9 to 11%) if *Ecoinvent* data is used for the production of bitumen. However, the ranking of the single score impact from the different cases does not change when the data source for bitumen is changed.

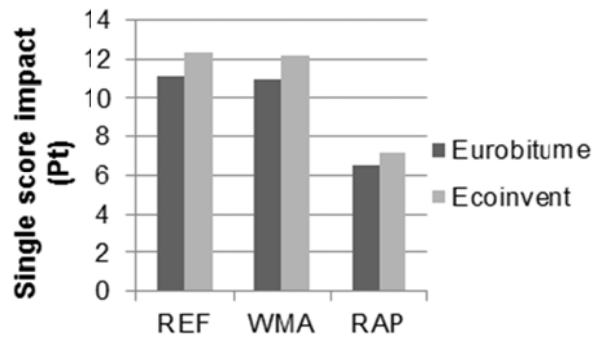


Figure 4: Sensitivity data source bitumen.

In the baseline scenario, all raw materials are supplied to the asphalt plant by truck. Nevertheless, the supply of raw materials (aggregates, bitumen and filler) is likewise possible by inland ship transport (Figure 5).

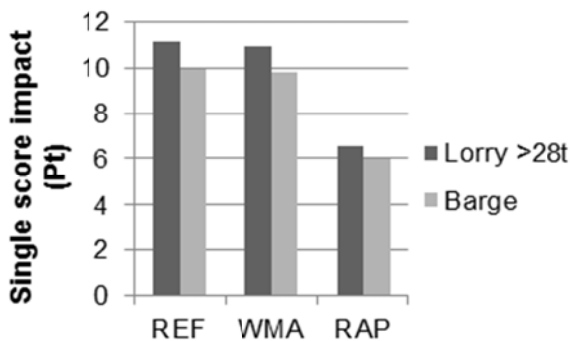


Figure 5: Sensitivity transport method

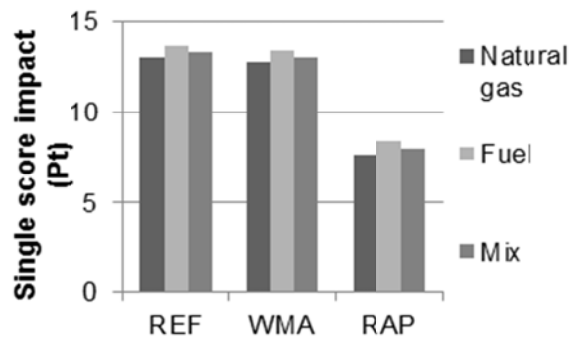


Figure 6: Sensitivity fuel type

The transport distance is kept constant in order to investigate only the influence of the transport method (truck or barge) on the results. The single score impact decreases (11% to 9%) when the raw materials are supplied by barge instead of a truck >28 ton. The ranking of the three cases does not

change with an alternative transport method. In the baseline scenario, natural gas is used for drying and heating the aggregates and the heated storage of bitumen. In general, 60% of the asphalt plants in Belgium uses natural gas as energy source for drying and heating. Nevertheless, 40% uses different energy types. In the sensitivity analysis the use of natural gas, heavy fuel oil and a mix (60% natural gas and 40% heavy fuel oil) is compared. It can be seen from Figure 6 that the difference between the different scenarios is rather small (2 to 10%) and the ranking of the three cases is unchanged.

Another parameter investigated in this sensitivity analysis is the amount of RAP. It can be seen from Figure 7 that even with a small amount of 10% RAP, this mixture is less impacting compared to the WMA and the reference. The single score impact of the mixture with 10% RAP is decreased with 3% compared with the reference and with 1% compared with the WMA. The total single score impact increases with 38% if 40% less RAP is added to the mixture.

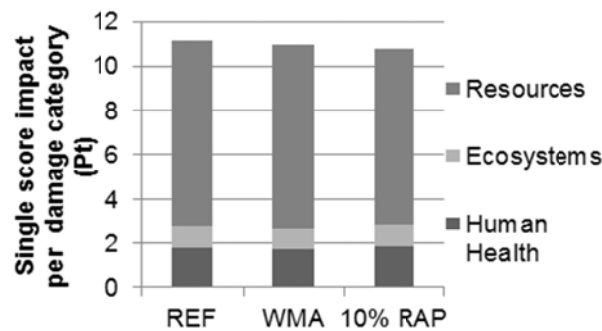


Figure 7: Sensitivity % RAP.

Another choice made for the analysis of the baseline scenario was the life cycle impact assessment method (LCIA-method). The single score impact results obtained with other LCIA-methods are illustrated in Figure 8. It can be seen that the ranking of the three cases does not change significantly by LCIA-method. Although the results from the different LCIA-methods are depicted on the same figure, it is not possible to compare the results from different LCIA-methods with each other. All results are expressed in points (Pt), but are calculated in a different way.

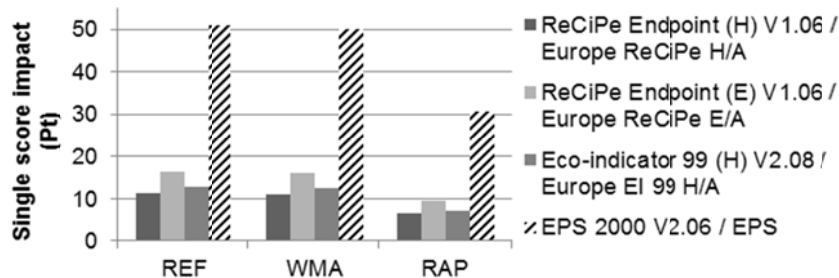


Figure 8: Sensitivity LCIA-method.

Besides the LCIA-methods analyzed in Figure 8, three more methods are analyzed. The single score results (in points) generated with LCIA-methods IMPACT 2002+ V2.10 and EDIP 2003 V1.03 are too small to depict on the same figure. At the other hand, the single score impact (in points) generated with LCIA-method Ecological Scarcity 2006 V1.06 is too high to depict on the same figure. Table 2 presents the single score impact of the three baseline mixtures, calculated with different life cycle impact

assessment methods and relative to the single score impact of the reference case. The three undermost LCIA-methods were excluded from Figure 8. It can be seen from Table 2 that the ranking of the three cases is independent of the LCIA-method selected and the trend observed is similar for the different LCIA-methods: 1 to 2% reduction for the WMA and 39 to 44% decrease for the mixture with RAP.

Table 2: Single Score Impact Relative to the Reference

Life Cycle Impact Assessment Method	REF	WMA	RAP
<i>ReCiPe</i> Endpoint (H) V1.06 / Europe <i>ReCiPe</i> H/A	1.00	0.98	0.59
<i>ReCiPe</i> Endpoint (E) V1.06 / Europe <i>ReCiPe</i> E/A	1.00	0.99	0.57
Eco-indicator 99 (H) V2.08 / Europe EI 99 H/A	1.00	0.99	0.56
EPS 2000 V2.06 / EPS	1.00	0.98	0.60
IMPACT 2002+ V2.10 / IMPACT 2002+	1.00	0.99	0.58
Ecological Scarcity 2006 V1.06 / Ecological scarcity 2006	1.00	0.99	0.57
EDIP 2003 V1.03 / Default	1.00	0.98	0.61

Figure 8 and Table 2 demonstrate that results from different (case) studies in the literature may not be compared based on the absolute values (in points) if another LCIA-method was used for the calculations. The ranking of different subcases within a study may be compared with the ranking of subcases within another study, but the LCIA-method will, nevertheless, have an influence on the results and even on the ranking of different sub-cases in other studies. It can be seen from the sensitivity analyses that the conclusion on the ranking of the three mixtures is robust because the ranking is not changed with the alternative scenarios investigated in the sensitivity analyses. Nevertheless, these alternative scenarios resulting from altering assumptions may have a significant influence on the single score impact of each individual mixture, e.g. an increase of the single score with $\pm 10\%$ if the data source for bitumen or the transport method changes; and an increase of 38% if 40% less RAP is added to the HMA.

Equal performance of REF, WMA and RAP is assumed in the baseline scenario, based on research findings. Nevertheless, it is important to note that a conscientious execution of the works (asphalt production and road construction) is needed in order to reach the same quality with WMA and RAP mixtures compared to traditionally used HMA mixtures. Furthermore, extreme weather conditions, traffic load, performances of other layers in the road construction, etc. may influence the service life of a layer in the road construction. Therefore, the last sensitivity analysis is related to the performance of the asphalt mixtures. If a service life of 25 years of the binder layer is assumed in the baseline scenario, this is reduced to 20 years for WMA and RAP in the sensitivity analysis. This means that over an analysis period of 25 years 1 ton REF, 1.25 ton WMA and 1.25 ton RAP is needed in order to meet the same performance. It is seen from Figure 9 that the environmental impact of WMA exceeds (23%) the environmental impact of REF, while the environmental impact of RAP is still lower (26%) compared with REF. The service life of a binder layer with RAP should decrease to 14 years in order to exceed the environmental impact of REF in this case study.

CONCLUSIONS AND RECOMMENDATIONS

The objective of this paper was to compare by LCA methodology the environmental impact of two different technologies, implemented in the asphalt production process: WMA and recycling. Both technologies are expected to reduce the environmental impact of asphalt production and are compared with a reference conventional asphalt mixture. A second objective was to determine the processes which are significant for the LCA results and to evaluate the influence of the most important

assumptions on the results. Cradle-to-gate analysis of the baseline scenario has highlighted that the mixture with RAP is significantly less impacting compared to both other mixtures.

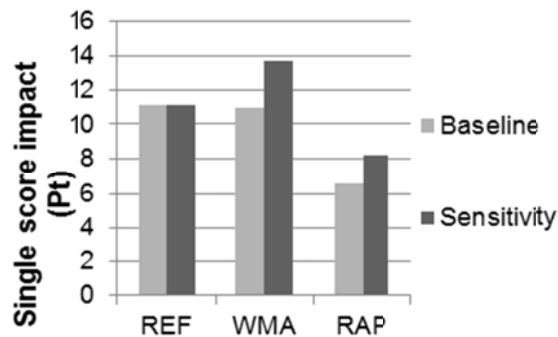


Figure 9: Sensitivity service life.

The environmental impact of the WMA mixture is close to the impact of the conventional HMA. The comparative study demonstrates clearly that the reduction of the mixture temperature by 30°C leads to a very small reduction of the total single score impact. This might be caused by the major contribution of the moisture content in the aggregate to the fuel consumption for drying and heating. This indicates that reducing the moisture content might have a more distinct effect on the environmental impact in the asphalt production. Solutions might be to protect aggregates from moisture by storing it under a shelf or dried continuously by the chimney heat flow. It is important to note that the aggregates used for asphalt production in Belgium are washed and thus supplied to the asphalt plant in a wet condition.

If the relative difference between two single score impacts is less than 20%, it is often considered in LCA to be impossible to draw robust conclusions based on this relative difference. Therefore, other and broader studies are required in order to compare the total environmental impact of HMA compared to WMA. In terms of future enhancement, other WMA techniques may be investigated as well, for example with various additives. It is important to note that several advantages of WMA are not included in the current cradle-to-gate study. Diffuse emissions during production and road construction with WMA might be significantly reduced compared to HMA which is in favor of the health of the workers. Furthermore it is suggested by other studies that WMA might allow higher percentages of RAP in the mixture, which might reduce the environmental impact of WMA compared with HMA as well. These kinds of issues need further investigation and a cradle-to-grave analysis is appropriate in order to formulate more conclusions.

From the contribution analysis of the baseline scenario, it was demonstrated that mainly the production of bitumen and the transport of raw materials to the asphalt plant contribute to the total environmental impact of the reference and the WMA mixture. For the HMA mixture with RAP, the production of bitumen and the energy in order to dry and heat aggregates are the main contributors to the total single score impact.

The results from the sensitivity analyses show that the total environmental impact can vary significantly based on the choice of data source and transport method. Nevertheless, the ranking of the three mixtures is robust in this study and does not change with different assumptions. On the other hand, this finding is an important note to consider when developing Product Category Rules to ensure a robust Environmental Product Declaration program.

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