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LCA of production of warm mix asphalt: Slovenian experience

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ABSTRACT

Construction of hot mix asphalt (HMA) pavements is associated with high environmental impact due to the consumption of large amounts of materials and energy. In recent years, warm mix asphalt (WMA) emerged as a more environmentally friendly alternative to HMA due to their potential to reduce both mixing and placement temperatures without conceding the performance and workability of asphalt mixture. Different technologies can be employed to reduce the working temperature in the production of WMA, e.g. the addition of organic or chemical additives, or the introduction of cold water into the hot asphalt mixture at a controlled temperature and pressure (i.e. foaming). However, it is often difficult to compare the environmental performance of different WMA technologies, as the environmental performance depends on specific characteristics of the production plant. This paper presents a comparative Life Cycle Assessment (LCA) analysis of the production of WMA with foaming with water and with the addition of chemical additive. LCA was based on real-case production data from a Slovenian asphalt production plant. The LCA results show that focusing only on CO_2 emissions can be misleading, with reduction in CO_2 emissions not necessarily leading to the reduction in the overall environmental impact.

1. Introduction

The road infrastructure connects the urban, rural, and productive centres, allowing commerce and conditions for the economic and social development of the communities (Santos et al., 2017; Fuentes et al., 2019). Asphalt pavement is widely used in highway construction for simple construction, convenient material extraction and good performance (Chang et al., 2020; Liu et al., 2023). However, the construction of pavements demands large amounts of building materials and energy consumption which generates a huge environmental burden that compromises non-renewable and ecosystem resources for future generations (Sartori et al., 2021; Polo-Mendoza et al., 2022). Conventional construction of hot mix asphalt (HMA) with higher production temperatures (>140 ºC) results in increased fuel cost, hazardous fumes and increased gaseous emissions (Sukhija and Saboo, 2021). Over the decades, there have been constant efforts in the HMA industry to conserve non-renewable resources and reduce environmental pollution (Ingrassia et al., 2019). This instigated a search for technologies that can reduce energy and fuel consumption to produce asphalt mixtures without conceding the performance and workability requirements (Sukhija and Saboo, 2021).

From these endeavours, three main approaches to asphalt mixture production with manufacturing temperatures below those of conventional HMA have been established: (i) Cold Mix Asphalt (CMA) produced at temperatures lower than 60 °C, (ii) Half-Warm Mix Asphalt (HWMA) produced at temperatures between 60 °C and 100 °C, and (iii) Warm Mix Asphalt (WMA), produced at temperatures in the 100 °C to 140 °C range (Araujo et al., 2022). Among these new technologies, WMA has received particular attention due to its potential to considerably reduce both mixing and placement temperatures while providing an asphalt material with similar performance to that of conventional HMA (Vidal et al., 2013; Vega A et al., 2019). The production of WMA requires lower production temperatures due to the modification of asphalt binder to ensure a proper aggregate coating during the mixing process compared to HMA (Araujo et al., 2022). The decrease in the mixing and compaction temperatures leads to a lower energy consumption, reduced greenhouse gas emissions and improved working conditions for plant operators and workers (Martin et al., 2019; Guo et al., 2020; Polo-Mendoza et al., 2022).

Additionally, lower production temperatures often lead to the reduction of production cost (Mohd Hasan et al., 2017; Sukhija et al., 2022). Furthermore, WMA technology also allows for a larger amount of reclaimed asphalt (RA) in the recycled asphalt mixtures due to the lower aging of the bitumen in the production phase (Ferrotti et al., 2024). WMA can be divided into three main categories: foaming technology, organic additives and chemical agents (Sukhija and Saboo, 2021). Foaming entails the inclusion of a small amount of cold water, either added directly to the hot asphalt binder or injected into the mixing tank, or use of water-bearing additives, i.e. natural or synthetic zeolites. Organic additives function by reducing the viscosity of the asphalt binder due to the presence of waxes.

The chemical agents lower the surface tension on aggregate – binder contact, enhance the mix's workability and compaction, and improve binder coating of the aggregates. In general, the working principle of chemical agents is entirely different from organic additives: chemical agents primarily improve the coating of aggregates rather than reducing the viscosity (Zhao et al., 2016). Based on the use of thermodynamic equations, researchers often theoretically calculate heat energy and related fuel consumption, emissions of CO2 or other greenhouse gases and airborne pollutants in order to compare environmental performance of different asphalt production technologies or production conditions (Ferrotti et al., 2024).

To analyse the potential environmental impacts of part or all of the asphalt production process, LCA is often performed to assess the environmental performance of different asphalt mixtures and technologies (Vidal et al., 2013; Giani et al., 2015; Rodríguez-Alloza et al., 2015; Sollazzo et al., 2020; Zhang et al., 2022; Farina et al., 2023; Martinez-Soto et al., 2023; Zhu et al., 2023; Ferrotti et al., 2024; Oreto et al., 2024). In general, environmental assessment results indicate that incorporating WMA reduces environmental exposure considering air pollutants, fossil fuel reduction, smog formation and global warming, as well as provides better working conditions for workers at the time of asphalt production and paving operation (Sukhija and Saboo, 2021).

However, the majority of LCA studies are based on laboratory data and focused primarily on evaluating carbon footprint. Therefore, this paper presents the results of a comparative LCA analysis of the production of WMA with foaming with water, WMA with the addition of chemical additive and HMA, which was based on real-case production data from a Slovenian asphalt production plant.

2. LCA framework

2.1. Goal and scope

The aim of the LCA study was to analyse the environmental impacts associated with the production of hot mix asphalt (HMA) and warm mix asphalt (WMA). The main objective of the LCA study was to compare the environmental impact of the production of WMA with the addition of chemical additive and WMA with foaming with water to the environmental impact of the production of HMA. The functional unit was specified as the production of 1 tonne of asphalt mixture. A "cradle-to-gate" approach was adopted for this LCA study, which is a common approach when the analysis is focused on the production stage or analysis is considering the production of new asphalt mixtures (Moretti et al., 2017; De Pascale et al., 2023; Lo Presti et al., 2023; Suwarto et al., 2023). Therefore, the LCA study considered raw material sourcing and extraction, processing of raw materials and consumption of energy and water within the production process. LCA for Experts (formerly GaBi) software was used for modelling (Herrmann and Moltesen, 2015; Lopes Silva et al., 2019).

2.2. Life Cycle Inventory (LCI)

The information on the quantities of raw and auxiliary materials, and energy and water consumption for the production of asphalt mixtures were provided by asphalt manufacturer from Slovenia (Table 1). The production and processing of the majority raw and auxiliary materials and the production and supply of energy and water were evaluated based on the background life cycle inventory data provided in the Sphera Managed LCA Content database. The production of the chemical additive was evaluated based on the background life cycle inventory data provided in ecoinvent 3.8 database. The transport distances for specific materials were the same for all three considered mixtures; therefore, the impact of transport was omitted from the LCA analysis.

Table 1. Inventory data for the production of 1 tonne of asphalt mixture

Inputs	Unit	HMA	WMA (chemical additive)	WMA (foaming)
Aggregates	kg	951.8	951.8	951.8
Bitumen	kg	47.8	47.8	47.8
Natural gas – aggregate drying	m^3	6.474	5.474	5.474
Electricity – heating of delivered bitumen*	kWh	0.96	0.96	4.8
Electricity – maintaining bitumen's temperature	kWh	2.273	2.273	2.273
Electricity – foaming system	kWh	/	/	0.181
Water	l	/	/	1.433
Chemical additive	l	/	0.143	/

* *delivered bitumen has temperature of around 155 ºC and has to be heated to 160 ºC for HMA and WMA with chemical additive, and 180 ºC for WMA with foaming*

2.3. Life Cycle Impact Assessment (LCIA)

The impact assessment phase aims at evaluating the significance and magnitude of potential environmental impacts based on the inventory analysis flow results. In this LCA study, the environmental impacts were evaluated with CML 2001 (version August 2016) life cycle impact assessment (LCIA) method. The CML 2001 is an LCIA method that restricts quantitative modelling to early stages in the cause-effect chain to limit uncertainties, with results being grouped in midpoint categories according to common mechanisms (e.g. climate change) or commonly accepted groupings (e.g. ecotoxicity) (Guinee, 2002). The main principles behind the CML 2001 methodology are based on ISO 14040 and 14044 standards, and the characterisation factors are updated when new knowledge on substance level is available. The results of the CML 2001 impact assessment method can be presented in terms of different impact potentials (Table 2).

Table 2. The impact categories for CML 2001 LCIA method

Impact category	Abbreviation	Unit
Abiotic depletion (elements)	ADP el.	kg Sb eq.
Abiotic depletion (fossil)	ADP fos.	MJ]
Acidification potential	AP	kg SO_2 eq.
Eutrophication potential	EP	kg PO_4^{-3} eq.
Freshwater aquatic ecotoxicity potential	FAETP	kg DCB eq.
Global warming potential	GWP	kg CO_2 eq.
Human toxicity potential	HTP	kg DCB eq.
Marine aquatic ecotoxicity potential	MAETP	kg DCB eq.
Ozone layer depletion potential	ODP	kg R11 eq.
Photochemical ozone potential creation	POCP	kg Ethene eq.
Terrestrial ecotoxicity potential	FAETP	kg DCB eq.

2.4. Interpretation

The interpretation phase of an LCA study generally consists of two types of interpretation steps: (i) procedural steps, which analyses data and results in relation to other sources of information, such as expert judgements and reports on similar products, and (ii) numerical steps, which analyses results without referencing to other sources of information (Heijungs and Kleijn, 2001). The numerical approach of the interpretation phase generally consists of different types of analysis, such as contribution, perturbation, scenario and comparative analysis. The contribution or hotspot analysis is used to decompose LCA results into a number of constituent elements or contributions in order to identify hotspots, i.e. the materials, products or processes that contribute the most to the overall environmental footprint of the analysed system. It is mainly used in majority of LCA studies, with the results usually being expressed in percentages that add up to 100 and visualised as stacked bar diagrams (Heijungs and Kleijn, 2001). The comparative analysis is used to simultaneously look at different product alternatives. It provides a very simple way to systematically look at model results of different scenarios in a way of a tabular list or a bar chart.

However, the analysis has to be done with caution, since the user can be easily induced to make conclusions without any proper evaluation of the uncertainty of the analysis results (Heijungs and Kleijn, 2001). The interpretation phase should reflect that the results are (i) based on a relative approach, (ii) indicate only the potential environmental effects, and (iii) do not predict actual impacts on category endpoints, the exceeding of thresholds or safety margins or risks. In addition, the interpretation phase should consider an assessment and a sensitivity check of the significant inputs, outputs and methodological choices in order to understand the uncertainty and limitations of the results (Heijungs et al., 2005).

3. Results and Discussion

Figure 1 shows the contribution analysis for the production of hot mix asphalt (HMA). Bitumen is the largest contributor to the total environmental impact. It has the highest contribution in the ADP el. (65%), ADP fos. (87%), AP (70%), EP (61%), FAETP (97%), HTP (88%), MAETP (83%), POCP (81%) and TETP (77%) impact categories, and second-highest contribution in the GWP (45%) and ODP (32%) impact categories. The drying of aggregates (i.e. heat from natural gas) has the highest contribution in the GWP impact category (46%). Aggregate has the highest contribution in the ODP impact category (37%). The combined electricity requirements generally have minimal environmental impact, except in terms of the ODP impact category where they represent 31% of total environmental impact.

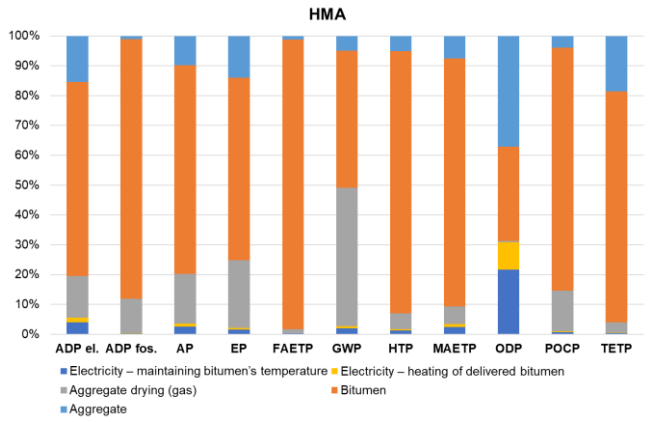

Figure 1. Relative contributions for the production of HMA

Figure 2 shows the contribution analysis for the production of warm mix asphalt (WMA) with the addition of chemical additive. Bitumen is the largest contributor to the total environmental impact. It has the highest contribution in the ADP fos. (88%), AP (70%), EP (47%), FAETP (60%), GWP (49%), MAETP (74%), POCP (81%) and TETP (44%) impact categories, and the second-highest contribution in the ADP el. (21%), HTP (30%) and ODP (23%) impact categories.

The chemical additive has the highest contribution in the ADP el. (68%), HTP (66%), and ODP (28%) impact categories, and the second-highest contribution in the EP (27%), FAETP (39%) and TETP (43%) impact categories. The drying of aggregates (i.e. heat from natural gas) has the second-highest contribution in the GWP impact category (42%), while aggregate has the second-highest contribution in the ODP impact category (27%). The combined electricity requirements generally have minimal environmental impact.

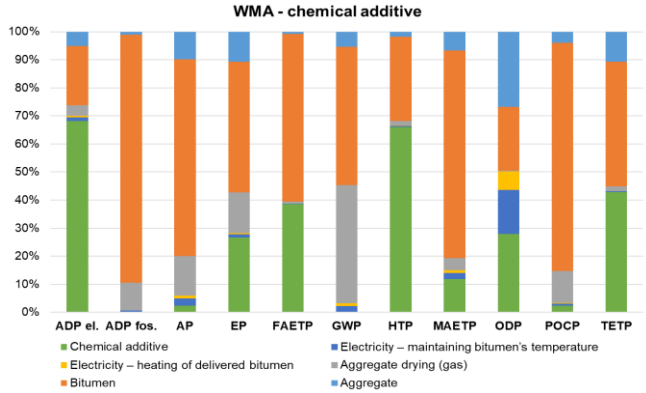

Figure 2. Relative contributions for the production of WMA with chemical additive

Figure 3 shows the contribution analysis for the production of warm mix asphalt (WMA) with foaming with water. Bitumen is the largest contributor to the total environmental impact. It has the highest contribution in the ADP el. (62%), ADP fos. (88%), AP (69%), EP (62%), FAETP (97%), GWP (48%), HTP (87%), MAETP (80%), POCP (82%) and TETP (77%) impact categories. The electricity for heating of bitumen has the highest contribution in the ODP impact category (33%). The drying of aggregates (i.e. heat from natural gas) has the second-highest contribution in the ADP fos. (10%), AP (14%), EP (19%), GWP (41%) and POCP (12%) impact categories, while aggregate has the second-highest contribution in the ADP el. (15%), ODP (27%) and TETP (19%) impact categories. The electricity for the foaming system and water for foaming have negligible environmental impact.

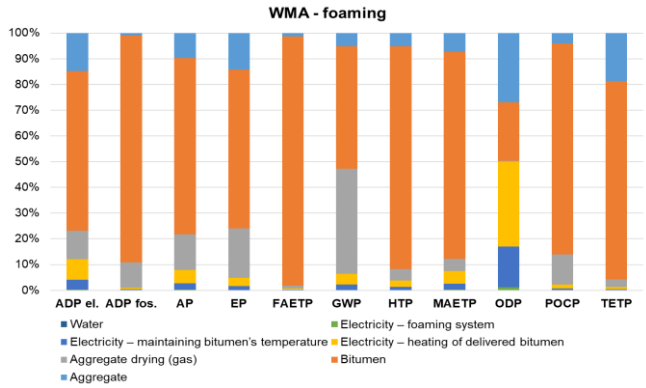

Figure 3. Relative contributions for the production of WMA with foaming with water

Figure 4 presents the comparison of the CO2 equiv. emissions released during the production of HMA and WMA. It shows that the difference in the CO2 equiv. emissions between HMA and WMA with chemical additive is larger than the difference in the CO2 equiv. emissions between HMA and WMA with foaming with water. This is due to the higher consumption of electricity for the heating of bitumen in the production of WMA with foaming with water. In Slovenia, around 30% of electricity is obtained from fossil fuels (IEA, 2024), with the production of electricity in thermal power plants being responsible for the majority of all greenhouse gas emissions related to electricity generation in Slovenia (ARSO, 2024). In addition, the difference in released emissions is dependent on the difference in the consumed energy and the type of the fuel (Sukhija et al., 2022). Natural gas is the cleanest energy source among the fossil-based fuels and there is a relatively small difference in the consumed gas between the production of HMA and WMA (Table 1). Therefore, the reduced energy consumption for the production of WMA leads to a relatively small decrease in the CO2 equiv. emissions compared to the production of HMA.

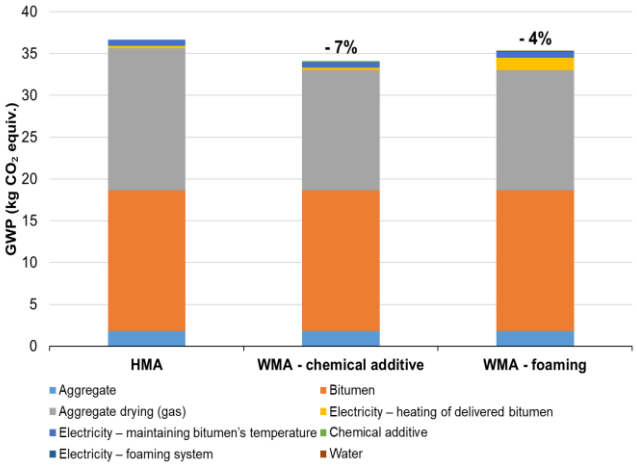

Figure 4. Comparison of the CO_2 equiv. emissions for HMA, WMA with chemical additive and WMA with foaming with water

However, focusing only on the carbon emissions can give a limited or even erroneous picture of the actual environmental performance, as such results do not provide any information about other environmental impacts, e.g. resource depletion, impact on the atmosphere and toxicity to humans and the environment. Figure 5 presents the comparison of the environmental impact for the production of HMA, WMA with the addition of chemical additive and WMA with foaming with water. It shows that WMA with chemical additive has a significantly higher environmental impact in the impact categories that evaluate the depletion of natural resources (ADP el.), eutrophication (EP), freshwater ecotoxicity (FAETP), toxicity for humans (HTP), ozone depletion (ODP) and terrestrial ecotoxicity (TETP).

This is the result of the indirect effect of the production of the chemical additive (e.g. surfactants), with such chemicals having a severe impact on the environment and human health due to being non-degradable, persistent and highly toxic (Badmus et al., 2021). It should be noted that the environmental impact of chemical additives for the production of WMA depends on the chemical composition of the additive and the characteristics of the production process (e.g. energy consumption), and thus varies from additive to additive.

The environmental impact of the WMA with foaming with water is similar to the environmental impact of HMA. The only major difference can be observed in the impact category that evaluates the ozone depletion potential (ODP). In the ODP impact category, the impact of WMA with foaming with water is about 40% larger than the impact of HMA, which is due to the aforementioned higher electricity consumption. As mentioned, the production of electricity based on the use of fossil fuels has a very large negative impact on the environment. Coal-fired thermal power plants emit significant amounts of sulfur dioxide, nitrogen oxides, solid particles and other pollutants (e.g. mercury), which have both directly or indirectly (e.g. acid rain) negative impact on the ozone layer (Shindell and Faluvegi, 2010). All in all, LCA results show that even though there is a benefit in terms of reduced greenhouse gas emissions due to the reduced consumption of energy for aggregate drying, the overall environmental performance of WMA is dependent also on the characteristics of the additives and the indirect impacts (e.g. emissions associated with electricity production).

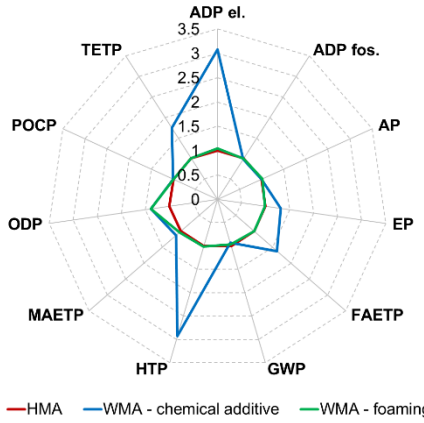

Figure 5. Comparison of the environmental impact for HMA, WMA with chemical additive and WMA with foaming with water

4. Conclusions

This paper presents the results of a comparative LCA analysis, which evaluated the environmental impact associated with the production of hot mixture asphalt (HMA), warm mix asphalt (WMA) with foaming with water, and warm mix asphalt (WMA) with the addition of chemical additive.

The results of the LCA analysis showed that the lower energy consumption in the production of WMA generally leads to lower CO_2 emissions. However, the results of the LCA analysis also showed that even though there is a reduction in carbon footprint, the environmental impact in other impact categories (e.g. ecotoxicity, ozone depletion etc.) can be higher due to the adverse impacts related to the production of additives and energy. Therefore, both direct and indirect environmental impacts have to be considered to thoroughly assess the environmental performance of asphalt production.

This paper considered only the production stage. For a more in-depth environmental assessment, a full life cycle assessment would be needed, which would evaluate also the impacts associated the installation, maintenance and disposal or recycling of both HMA and WMA. In particular, WMA can be produced with a higher proportion of recycled asphalt compared to HMA. This can have a notable effect on the environmental performance, as the use of waste or secondary materials can significantly reduce the environmental impact over different life cycles. However, reliable and accurate industrial-scale data is needed in order to conduct in-depth full life cycle LCA analyses of different types of asphalt mixtures.

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