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Comparative Environmental Analysis for Using Waste Polyethylene and Steel Slag in Semi-Dense Asphalt Pavements

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ABSTRACT

This study presents a life cycle assessment (LCA) evaluating the use of virgin materials, waste polyethylene (PE) and electric arc furnace steel slag (EAFSS) in semi-dense asphalt (SDA) surface courses, which is primarily used for low-noise pavements. Three types of SDA mixtures with virgin materials, waste PE and EAFSS were prepared and water sensitivity tests were conducted to determine the mechanical performance. The LCA defined three scenarios using system expansion, namely (1) the reference scenario using virgin materials in SDA and disposal of waste PE and EAFSS by municipal solid waste incineration (MSWI) and landfill, respectively; (2) the test scenario using waste PE and straight run binder in SDA, with landfilling of EAFSS; (3) the

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test scenario using EAFSS in SDA, with the disposal of waste PE by MSWI. The data from the experiments, Swiss industries, official reports and standard databases were used for the inventory analysis. The results show that compared to the reference, the scenarios using waste PE and EAFSS in SDA would reduce 15 and 36% of greenhouse gases emissions, respectively. The reason for the improved environmental performance when waste PE is used in asphalt can be attributed to the use of straight run binder to replace polymer-modified binder (PmB) and the avoided MSWI. For the EAFSS scenario, the improved environmental performance is due to the avoided landfilling. The results also indicate that the recycling of waste PE and EAFSS in SDA would not have benefits in non-renewable cumulative energy demand.

Keywords

life cycle assessment (LCA), waste polyethylene (PE), electric arc furnace steel slag (EAFSS), semi-dense asphalt pavements, environmental impacts

1. Introduction

The urban mining for the surface course of asphalt pavements has been a popular topic in the laboratory research and industrial investigations.[1] This is motivated on the one hand due to the sustainability considerations, which aims at improving the disposal of waste materials and reducing the consumption of natural resources by pavements, and on the other hand by cost reduction.[2] Waste polyethylene (PE) and electric arc furnace steel slag (EAFSS) are general waste materials produced in great quantities annually, leading to large pressure on their disposal and treatment, along with the need to improve their recycling.[1] For asphalt mixtures made of natural aggregates, asphalt binder, and polymer modifier, there is potential of urban mining by using waste

PE and EAFSS to replace the virgin materials of the mixtures. For example, previous studies[3-5] have investigated the use of waste PE and EAFSS as binder modifiers and aggregates in hot mix asphalt (HMA), respectively, presenting comparable mechanical and durability performance to that of the unaltered asphalt mixtures. This demonstrates the technical feasibility for developing HMA with waste PE and EAFSS modifications.

In addition to the durability, it is also necessary to consider the environmental impacts in the decision making of asphalt pavement construction. Apparently, the incorporations of waste PE and EAFSS in pavements promote the urban mining and might be eco-friendly. However, the environmental impacts of using waste materials in asphalt mixtures depend on the whole value chain of a system and need to be benchmarked against the alternative use or treatment of waste materials. For instance, waste PE might be disposed of by municipal solid waste incineration (MSWI) for energy recovery, and EAFSS might be landfilled if they are not recycled in pavement surfaces. Thus, it is to be assessed if the use of alternative materials in asphalt surface course results in net environmental benefits or impacts (or burden shifts and trade-offs between various impact categories, such as global warming, energy demand and human health). For this reason, life cycle assessment (LCA) was applied with popularities to evaluate the environmental performance of asphalt pavements.[6-8] LCA quantifies environmental impacts in various indicators, focusing on products from their raw material productions to the end-of-life (EOL).[9, 10] This "cradle-to-grave" analysis makes it possible to identify burden shifts due to a modified value chain.[11] For the recycling of waste materials, system expansion is also conducted considering the alternative waste treatments.[8]

To evaluate the environmental feasibility of asphalt pavement modified by waste plastics and EAFSS, several recent LCA studies were considered.[12-17] Table 1 presents a summary of these research in terms of pavement layers, type of mixtures, waste materials, system boundary, and avoided impacts. It should be noted that "system boundary" refers to the processes investigated by the LCA, "avoided impacts" indicates the impacts of the processes that are avoided by using waste PE and EAFSS in pavements. It can be seen that most studies focus on the surface course of pavements using HMA, while Ferreira et al. (2016)[12] also includes the base course and Georgiou and Loizos (2021)[14] considers warm mix asphalt (WMA). Moreover, the research in Table 1 mainly investigates waste plastics or EAFSS individually, except Georgiou and Loizos (2021)[14] and Yao et al. (2022)[16], which also incorporate reclaimed asphalt pavement (RAP) into asphalt mixtures with waste plastics or EAFSS modifications. In addition, Table 1 shows that LCA research mainly includes "cradle-to-gate" analyses, while "cradle-to-grave" analyses can be found in Esther et al. (2020)[13] and Yao et al. (2022)[16]. A possible reason for selecting "cradle-to-gate" analyses could be the inventory data, which are more available for virgin materials production, waste material processing, material transportation, and asphalt mixing, compared to other processes of pavements. The use phase of pavements is seldom investigated by the LCA in Table 1, where only Esther et al. (2020)[13] quantifies the leaching impact of EAFSS-modified asphalt during the use of pavements. For the avoided impacts, all the LCA research considers the reduced production of virgin materials, such as natural aggregates and binder modifier, by using waste plastics or EAFSS in pavements. Furthermore, some studies take alternative treatments of waste materials (e.g. landfilling) into account, since they can also be avoided by producing waste plastic/EAFSS-modified asphalt.[12, 16] The results of the research in Table 1 show that the recycling of waste plastics and EAFSS in pavement surface is able to bring about net environmental benefits in comparison to traditional pavements. However, these benefits are closely related to the properties of waste materials, transportation distance, and mix design, implying uncertainties in the results.[12-14]

TABLE 1 Review of the state-of-the-art LCA research regarding asphalt pavements with waste plastics and EAFSS, and the relevance to the current study

Research	Pavement layer	Asphalt mixture	Waste material	System boundary of LCA	Avoided impacts in LCA
Ferreira et al. (2016)[12]	1).surface course 2).base course	HMA	EAFSS	1).virgin material production 2).waste material processing 3).material transportation 4).asphalt mixing 5).construction 6).EAFSS landfilling	1).production of virgin aggregates 2).EAFSS landfilling
Esther et al. (2020)[13]	surface course	dense-graded HMA	EAFSS	1).virgin material production 2).waste material processing 3).material transportation 4).asphalt mixing 5).construction 6).use 7).EOL	1).production of virgin aggregates
Georgiou and Loizos (2021)[14]	surface course	1).semi-open graded HMA 2).semi-open graded WMA	1).EAFSS 2).RAP	1).raw material production 2).material transportation 3).plant operation 4).construction	production of virgin aggregates
Santos et al. (2021)[15]	surface course	HMA	waste PE	1).virgin material production 2).waste sorting 3).waste material processing 4).material transportation 5).asphalt mixing	1).production of virgin aggregates 2).production of virgin polymer for asphalt binder
Yao et al. (2022)[16]	surface course	HMA	1).waste PET 2).RAP	1).virgin material production 2).waste material processing 3).material transportation 4).asphalt mixing 5).construction 6).EOL 7).waste PET landfilling	1).production of virgin aggregates and binder 2).production of virgin polymer for asphalt binder 3).landfilling of waste PET
Salehi et al. (2022)[17]	surface course	HMA	waste PE	1).virgin material production 2).waste sorting 3).waste material processing 4).material transportation 5).asphalt mixing	production of virgin aggregates and binder
This research	surface course	hot mix SDA	1).waste PE 2).EAFSS	1).virgin material production 2).waste material processing 3).material transportation 4).asphalt mixing 5).construction 6).EOL 7).MSWI for waste PE 8).EAFSS landfilling	1).production of virgin aggregates 2).production of virgin polymer for asphalt binder 3).MSWI for waste PE 4).EAFSS landfilling

As indicated in Table 1, some research gaps can be found in the previous LCA studies of waste plastic/EAFSS-modified asphalt pavements. Firstly, there are insufficient "cradle-to-grave" analyses quantifying processes from material productions to the EOL of pavements. Secondly, although the alternative treatments of waste materials are important concerns to evaluate the net environmental impacts, they are not always quantified in previous research. This is notably inadequate in the municipal solid waste incineration (MSWI) of waste plastics for energy recovery, which is a popular treatment method of waste plastics but is not discussed by the LCA in Table 1. In addition, there is also insufficient focus on the urban mining for low-noise pavements, while most studies are dedicated to dense-graded pavements with waste materials. Therefore, this article aims at closing the research gaps that are apparent with the comparison between this research and previous studies presented in Table 1. In this paper, LCA is performed to investigate the environmental impacts for using waste PE and EAFSS in the surface course of semi-dense asphalt (SDA) pavements in Switzerland. SDA is a gap-graded asphalt (with porosity between 12% – 16%), which is applied as a type of low-noise pavements to mitigate tire/road noise.[18, 19] The LCA considers the "cradle-to-grave" processes of SDA together with system expansion to include the current treatments of waste PE and EAFSS in Switzerland. The impact assessment considers representative indicators which are related to a series of environmental impacts. As a part of inventory data, SDA mixtures were prepared in the lab, followed by mechanical testing to compare the durability of asphalt mixtures with different waste materials.

2. Materials and Experiments

As listed in Table 2, this study investigated three SDA mixtures with maximum aggregate size of 4 mm. The reference SDA uses only virgin materials, including natural sandstone aggregates and polymer-modified binder (PmB, with the styrene-butadiene-styrene (SBS)). For the second SDA mixture, waste PE (shreds with an average length of 10 mm) from the collection were firstly treated by the recycling plant in Switzerland, with the majority of the high density polyethylene recycled into the production of pipes (e.g. for cables). The by-products were waste PE that cannot be recycled into pipes due to the presence of impurities (medium density PE, other plastics). In the authors' previous study of this material,[20] these impurities were demonstrated to not be obstacles in using them in asphalt. Hence, apart from the use as alternative fuels for energy, these waste PE can also be used as polymer modifier for asphalt. It should be noted that waste PE were included by the dry process into the second SDA mixture, using straight run binder instead of PmB. The third SDA mixture replaced natural aggregates by EAFSS (with a size between 0.125/4 mm as fine and coarse aggregates), with a content of 14.4% by weight of mixture. Due to the porous structure of EAFSS, the third mixture required around 0.8% more asphalt binder to keep the same effective binder content as the other two mixtures.[21] All the mixtures had maximum aggregate size of 4 mm and porosity of 16±2%.

TABLE 2 Information of SDA Mixtures with Reference Materials, Waste PE and EAFSS (M%: by weight of asphalt mixture, PE: polyethylene, EAFSS: electric arc furnace steel slag, PmB: Polymer-Modified Binder)

Asphalt mixtures	Natural aggregates content [M%]	Binder content [M%]	Waste PE content [M%]	EAFSS [M%]	Bulk density [t/m^3]
Reference	93.9	6.1 (PmB)	0	0	2.1
Waste PE	93.6	6.1 (base)	0.3	0	2.1
EAFSS	78.7	6.9 (PmB)	0	14.4	2.1

Since the durability performance of SDA mixtures would have an effect on the service life of surface course, this paper compared the durability properties of the three SDA mixtures using the water sensitivity test. The test evaluates the water sensitivity of asphalt mixtures in terms of indirect tensile stress ratio (%ITSR), which is specified by the Swiss standard for SDA pavements, with the minimum ITSR of 70%.[22] The experiments followed the European standard EN 12697-12.[23] In detail, for each of the three SDA, six cylindrical specimens were prepared with diameter and height of 100 and 60 mm, respectively. Three of the six specimens were submerged in a water tank with constant temperature at 40°C for 68 to 72 hours. The rest of three specimens were laid in a chamber with dry climate at 22°C. Then the indirect tensile strengths (ITS) were tested for the six specimens, taking the average ITS values for the three dry and three wet specimens, separately. Finally, the % TSR ratio of the average ITS values between wet and dry specimens was determined.

3. Goal and Scope Definition

The goal of this analysis is to compare the environmental impacts of using virgin materials, waste PE and EAFSS in the surface course of SDA pavements. The functional unit (FU) was defined as 1 km of SDA surface course (with 7.5 m of width and 30 mm of thickness), which was suitable for the traffic load of 300 – 1000 ESAL per day under the average climate conditions (Type B) in Switzerland. The thickness of pavement surface, the traffic load and climate condition were determined according to the Swiss standard SN 640-430c,[24] which recommends 30 mm as the thickness of pavement surface under the daily traffic load of 300 – 1000 ESAL in Swiss average climate conditions. The time period for the analysis is 10 years, which is the typical service life of SDA surface course in Switzerland.[25]

Considering the use of different recycled materials, this paper defined three scenarios with system expansion, which implies that the LCA system not only includes the processes of pavements (e.g. materials production and processing, asphalt mixing, construction, demolition, materials transportation), but is also expanded to consider the alternative treatments of waste materials (e.g. landfilling and MSWI). As shown in figure 1a, the reference scenario only uses virgin materials in the SDA surface course. The transportations of materials were attributed to these processes correspondingly. Since this study assumed that all the reclaimed asphalt pavements (RAP) can be recycled in the binder course, base course or foundation of other pavements, RAP was regarded as burden-free and excluded in the analysis. The EAFSS and waste PE were not recycled in the reference scenario, thus the system was expanded to include their original treatments. The EAFSS were assumed to be landfilled. Waste PE were assumed to be used as alternative fuels for the clinker production or disposed by municipal solid waste incineration (MSWI). Considering the availabilities of the data source, this paper focused on the possible treatment of waste PE by MSWI. Figure 1b shows the scenario for recycling waste PE into SDA, which led to the replacement of PmB by the straight run binder. Since the treatment and recycling of PE into pipes were conducted in all the three scenarios, these identical processes can be omitted in this comparative analysis. In addition, there were losses of electricity and heat when waste PE were not disposed by MSWI, thus the losses were compensated by conventional electricity and heat plants. Figure 1c presents the scenario using EAFSS in SDA. Based on the communications with Swiss steel industries, 5% of the EAFSS from steel production cannot be recycled due to impurities, while they were disposed by landfilling. Most EAFSS (95%) were used as the replacement of natural aggregates in SDA. In summary, all the three scenarios resulted in 1 km of SDA surface course, along with the treatments of waste PE (1.4 t) and EAFSS (71.6 t) by different methods.

FIGURE 1 System boundary of the scenarios with (A) reference materials, (B) waste PE and (C) EAFSS in SDA Surface Courses (PE: polyethylene, EAFSS: electric arc furnace steel slag, PmB: polymer-modified binder, MSWI: municipal solid waste incineration, RAP: reclaimed asphalt pavement)

4. Inventory Analysis

This section discusses the inventory data of the processes in figure 1. Since the ecoinvent database[26] (an international environmental database for the life cycle inventory) was used to obtain the secondary data in this paper, it should be noted that only the version 3.8 (using the cut-off system model) of this database was considered.

4.1 VIRGIN RAW MATERIALS

The inventory of natural aggregates production was based on "Gravel, crushed CH| production | Cut-off, U" from the ecoinvent. For the production of base asphalt binder and PmB, the inventory data were obtained from recent Eurobitume reports,[27, 28] considering the extraction of crude oil, the oil transportation to Europe, the production of base asphalt binder in the refinery, the production and grinding of polymer (styrene butadiene styrene), the mixing of polymer with straight run binder, and the storage of binder.

4.2 WASTE MATERIALS FOR RECYCLING

The treatment of EAFSS for recycling into SDA was based on the experience of a Swiss steel factory, including the consumptions of water for grinding and cooling (0.25 m^3 per tonne of EAFSS), diesel (1 liter per tonne of EAFSS) and electricity (0.5 kWh per tonne of EAFSS). The density of diesel was assumed as 0.85 kg/l, and 1 MJ was equal to 0.0234 kg of diesel.[29] As indicated by the ecoinvent database, the machine for slag treatment was assumed to have a weight of 150 t and a service life of 25 years. The annual capacity of slag treatment was 100 000 t. Then it is possible to attribute the consumption of machine to one tonne of EAFSS. The inventories of water, diesel, electricity and machine were based on "Water, cooling, unspecified natural origin, CH", "Diesel, burned in building machine GLO| market for | Cut-off, U", "Electricity, medium voltage CH| market for | Cut-off, U" and "Industrial machine, heavy, unspecified RER| market for industrial machine, heavy, unspecified | Cut-off, U" from the ecoinvent, respectively. As indicated in Section 3, the waste PE for SDA were by-products that cannot be used for pipes. The treatment and recycling of waste PE into pipes were identical for the three scenarios, thus they were excluded in the system of this comparative study.

4.3 ASPHALT MIXING

The asphalt mixing referred to the transportations of raw materials from suppliers to mixing plant, along with the energy consumption in the plant. The transportations of raw materials were performed by the lorry with loading capacity of 25 t and total weight of 40 t. The aggregates, waste PE and EAFSS were assumed to be transported with distance of 50 km. The asphalt binder was imported from the surrounding countries of Switzerland, with an average transport distance of 100 km. The inventory of lorry transport was based on "Transport, freight, lorry >32 metric ton, euro6 RER| market for transport, freight, lorry >32 metric ton, EURO6 | Cut-off, U" from the ecoinvent. For producing 1 t of SDA mixture, a Swiss mixing plant consumes 216.3 MJ of natural gas and 8.64 kWh of electricity.[8] The dataset of "Heat, district or industrial, natural gas CH| market for heat, district or industrial, natural gas | Cut-off, U" was used as the inventory of natural gas.

4.4 CONSTRUCTION AND DEMOLITION

The construction of SDA was related to the transportation of asphalt mixtures from the mixing plant to the site, as well as the diesel consumption by the machines during on-site working.

The transportation distance was assumed to be 50 km using lorry. The diesel consumptions by the paver, material transfer machine, roller and generator were 4.8, 4.5, 12.9 and 11.9 MJ per tonne of asphalt mixture, respectively. The end-of-life includes the demolition of the used surface course and the transportation of RAP from the site to the mixing plant. The diesel consumption by the milling machine and generator were 11.5 and 4.8 MJ per tonne of asphalt mixture, respectively. The lorry and distance for transporting RAP were same as the transportation of asphalt mixtures. The dataset "Diesel, burned in building machine GLO| market for | Cut-off, U" from the ecoinvent was used as the inventory of diesel used in generators. For the construction and demolition, all the consumption data of diesel were based on the experience from the Swiss road industry.

4.5 ALTERNATIVE TREATMENTS OF WASTE MATERIALS

The inventories of landfill (for EAFSS) and MSWI (for waste PE) were obtained from the dataset "Electric arc furnace slag CH| treatment of electric arc furnace slag, residual material landfill | Cut-off, U" and "Waste polyethylene CH| treatment of, municipal incineration | Cut-off, U" from the ecoinvent, respectively. As indicated in Section 3, the scenario of using waste PE in SDA had losses of electricity and heat generated by MSWI. They were compensated by traditional plants based on the datasets "Electricity, medium voltage CH| market for | Cut-off, U" and "Heat, district or industrial, natural gas CH| market for heat, district or industrial, natural gas | Cut-off, U" for electricity and heat, respectively. The amounts were based on the dataset "Waste polyethylene CH| treatment of, municipal incineration | Cut-off, U", assuming that 1 kg of waste PE in MSWI was able to generate 1.4 kWh of electricity and 10.02 MJ of heat.

5. Life Cycle Impact Assessment

For the impact assessment, this paper considered two impact indicators which related to several environmental impacts:[30]

(1) Greenhouse gases emissions using global warming potentials for 100 years, in CO_2-eq.[31]

(2) Non-renewable cumulative energy demand, in MJ.[32]

Based on the inventory data in Section 4, the impact assessment was performed using the software of Simapro v9.3.

6. Results and Discussion

6.1 EXPERIMENTAL RESULTS

The water sensitivity results are shown in Table 3, indicating that all the SDA specimens satisfied the ITSR requirement of Swiss standard SNR 640-436 (≥ 70%).[22] The SDA incorporating waste PE and EAFSS presented nearly the same ITSR, while the reference SDA showed higher values by 4% than the other two. Due to acoustical ageing, the noise mitigation level of an SDA deteriorates during the use of pavements.[33] In Switzerland, when the noise mitigation of a SDA compared to the traditional pavements is less than required (e.g. < 1 dB), the used SDA should be replaced.[34] Therefore, the service life of SDA depends not only on the mechanical performance, but also on the noise mitigation. In this research, although there is a small decrease in the mechanical property (ITSR) of SDA by using waste PE or EAFSS, both the reference and test SDA fulfilled the standard requirement (SNR 640-436[22]) from a mechanical perspective (ITSR ≥ 70%). Moreover, considering the fact that the acoustical service life of SDA is generally shorter than the mechanical durability,[25] the service life of SDA is dependent on the effects of using waste PE or EAFSS on the acoustical performance of SDA. According to previous research,[19] the incorporation of waste PE and EAFSS would not change the acoustical properties (e.g. the porosity, sound absorption, and surface texture of asphalt mixtures) of SDA with the contents that were used. Therefore, it is possible to assume the same service life for the reference and test SDA in this paper.

TABLE 3 Results of indirect tensile stress ratio (ITSR) from water sensitivity test (EN 12697-12)

	Reference	Waste PE	EAFSS
ITSR [%]	85.3	81.2	81.0

6.2 GREENHOUSE GASES EMISSIONS AND NON-RENEWABLE CUMULATIVE ENERGY DEMAND

Figure 2a shows the greenhouse gases (GHG) emissions of the three scenarios. Compared to the reference scenario, the waste PE and EAFSS scenarios presented lower GHG by 15% and 36%, respectively. For the waste PE scenario, the main reduction of GHG came from the use of straight run binder and the avoided disposal of waste PE in MSWI. These benefits can offset the losses of electricity and heat generated by MSWI. For the EAFSS scenario, the benefits of GHG reduction can be attributed to the lower amounts sent to landfill. Considering different processes in the system, the landfill of EAFSS was the largest contributor to GHG. As indicated by the ecoinvent database, this can be explained by the practice of solidifying landfill waste using cement, which generated considerable amounts of GHG. In contrast, the treatment of EAFSS for recycling into SDA had minor GHG emissions. Apart from the landfill, other major contributors of GHG were binder production and asphalt mixing.

The results of non-renewable cumulative energy demand (CED) are presented in figure 2b. It can be seen that the total CED were comparable for all the scenarios, without benefits from the recycling of waste PE and EAFSS. The asphalt binder production was the largest consumer of energy, accounting for 75 – 80% of the total CED. Since the binder content of SDA with EAFSS was 0.8% more than the others, the EAFSS scenario showed higher CED in the binder production. It can also be found that the difference of CED was limited between the production of PmB and straight run binder. Thus, the amount of binder was more important than the type of binder for CED.

FIGURE 2 Greenhouse gases emissions (A) and non-renewable cumulative energy demand (B) of the three scenarios (PE: polyethylene, EAFSS: electric arc furnace steel slag, MSWI: municipal solid waste incineration).

6.3 UNCERTAINTIES

This study presented a cradle-to-grave LCA for recycling waste materials in SDA. Some limitations should be noted for the results:

(1) The water sensitivity was based on the SDA mixtures prepared in the lab, which might not be the same as the performance in the field. Moreover, only a part of mechanical properties were considered in this analysis. It is recommended to include additional material testing, such as fatigue and rutting tests, to improve the accuracy for estimating the service life of SDA.

(2) The emissions during the asphalt mixing were not included in the inventory analysis. This can underestimate the environmental impacts of asphalt mixing compared to other processes. For this paper, although the service life and the total amounts of mixtures were same for the three scenarios, the EAFSS scenario had higher binder content, indicating more emissions than the other scenarios during mixing.

(3) Since Switzerland has no refineries for binder production, all the binders were assumed to be imported from the surrounding countries. This may not be representative for other countries with a domestic supply chain of asphalt binder, or on the contrary, where importation is more costly.

(4) The results presented here were based on the waste management policy in Switzerland for these particular waste streams. The assumption of waste PE treatment by MSWI is debatable, as the sorting losses from recycling plants are increasingly co-processed for clinker production, substituting fossils (typically coal). This may reduce (or even offset) the comparative benefits of using waste PE in SDA.

7. Conclusion

This paper performed a comparative LCA evaluating the use of waste PE and EAFSS in the surface course of SDA pavements. The conclusions are drawn as follows:

(1) The SDA specimens with virgin materials, waste PE and EAFSS presented comparable water sensitivity from laboratory testing. All the specimens satisfied the durability requirements of Swiss standards for SDA.

(2) The waste PE scenario showed 15% less GHG than the reference (assuming MSWI as alternative treatment). The main reasons were the replacement of PmB by straight run binder and the avoided MSWI. These benefits exceeded the losses due to electricity and heat generated by MSWI. The EAFSS scenario emitted 36% less GHG than the reference scenario. This was due to avoided landfilling of EAFSS.

(3) In terms of CED, the incorporations of waste PE and EAFSS in the SDA surface course showed limited difference in comparison to the reference scenario. Binder production was the major energy consumer. The amount of binder had more influence on CED than the type of binder.

In future studies, it is recommended to include more mechanical testing on waste-modified asphalt mixtures, in order to improve the reliability of the durability performance data. Moreover, it is also suggested to consider the difference in surface roughness between the reference and test pavements, since this may alter the fuel consumption of vehicles during the use phase.

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