Environmental benefits of microwave-assisted self-healing technology for pavements – A Life Cycle Assessment comparative study

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ABSTRACT: The maintenance and rehabilitation of roads is becoming a key challenge in the pavement industry to decrease the consumption of natural resources. Microwave-assisted self-healing technology extends the life-service of asphalt pavements for roads reducing the need for fossil fuels over its lifespan and saving the use of natural resources. This technique takes advantage of the thermoplastic and dielectric properties of asphalt mixtures that allows cracks to be closed, hence, heal and restore the asphalt mixtures mechanical behaviour without implementing more invasive traditional maintenance operations like milling and replacing the pavement. A Life-Cycle Assessment was carried out to determine the potential environmental benefits of using this technology quantifying its potential environmental impacts. Different scenarios in which the heating energy and the addition of slag varies has been evaluated and compared with a conventional road. Results shows that this technology could decrease a significant number of environmental impacts over the lifecycle.

KEY WORDS: Life cycle assessment; Pavement rehabilitation; Microwave-assisted healing pavements; Steel slag.

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RESUMEN: *Beneficios ambientales de la tecnología de autorreparación de mezclas asfálticas mediante calentamiento por microondas: un estudio comparativo mediante un Análisis de Ciclo de Vida.* La rehabilitación de carreteras supone un desafío clave para promover el progreso socioeconómico, mejorar la seguridad vial y preservar el medio ambiente. La tecnología de autorreparación de mezclas asfálticas mediante calentamiento por microondas extiende la vida útil de los pavimentos, reduciendo el consumo de combustibles fósiles y ahorrando el uso de recursos naturales durante su vida útil al aprovechar las propiedades termoplásticas y dieléctricas del asfalto para cerrar grietas en pavimentos dañados sin destruir la estructura original. En este estudio se llevado a cabo un Análisis de Ciclo de Vida para determinar los beneficios ambientales del uso de esta tecnología cuantificando sus impactos potenciales y se han comparado diferentes escenarios en los que varía la energía microondas y la adición de escorias. Los resultados muestran que esta tecnología podría disminuir una cantidad considerable de emisiones durante el ciclo de vida en comparación con una carretera convencional.

PALABRAS CLAVE: Análisis de ciclo de vida; Rehabilitación de pavimentos; Autorreparación de mezclas asfálticas mediante calentamiento por microondas; Escorias siderúrgicas.

1. INTRODUCTION

The transport sector is responsible of large amount of the global greenhouse gas (GHG) emissions, and, within this sector, road transport is by far the biggest emitter accounting for nearly three-quarters (74%) of all GHG (1). Adequate asphalt pavement maintenance represents an important opportunity for mitigating the GHG emissions derived from the road transport sector. In fact, it was observed that asphalt pavement conditions strongly affect the fuel consumption of vehicles, thus increasing the GHG emissions (2). Furthermore, rehabilitation of deteriorated pavements requires the consumption of a great number of non-renewable resources and energy. Taking active preventive maintenance actions can effectively impede early disease and prolong the lifespan of asphalt pavements (3). By delaying the need for rehabilitation, energy consumption could be saved as well as emissions, costs, and use of non-renewable resources (4, 5).

Microwave (MW) assisted healing is an innovative technique to increase the durability of the pavement by healing cracks and restoring pavement performance without destroying the original structure (6). The technique takes advantage of the thermoplastic and dielectric properties of asphalt mixtures for closing cracks in damaged pavements. Asphalt mixture is a self-healing material and due to its thermoplastic nature, bitumen reduces its viscosity with the increase in temperature. Above a specific temperature, the bitumen behaves as a Newtonian fluid, filling the cracks inside the pavement in a sort of capillarity flow (7).

To allow the sealing phenomenon and to accelerate the crack-healing process, MW energy can be employed (8). As a dielectric material, asphalt mixture can be polarized by an applied electric field. Under a high-frequency electromagnetic field (i.e., MW), the dipoles do not have sufficient time to respond to the oscillating field (9, 10). The dielectric properties of the asphalt mixture govern the MW heating generation. Dielectric loss factor represents the ability of the material to convert electromagnetic radiation energy into heat (11) and MW heating efficiency can be also enhanced by tuning the frequency of the MW generator. In most of the studies performed MW heating of the asphalt was implemented with a conventional MW oven (2.45 GHz). However, it has been revealed that the use of 5.8 GHz can led to an increase in the heating rate (calculated as the percentage of final Indirect Tensile Strength (ITS) versus the initial ITS) of asphalt mixtures (11, 12). The heating rate is useful to calculate the necessary heating times for reaching a specific temperature by the MW oven model used in the investigation or another oven with the same output power.

To reduce heating time and thus increase the energy efficiency of the MW heating process, some MW absorbers are often incorporated into the asphalt pavement slags from the steelmaking sector represent a promising solution for this purpose (13, 14). Electric arc furnace slag (EAFS), also known as simply slags, comes from the steelmaking industry and is by-product, generated after the melting and the primary acid refining of liquid steel (15). Utilization of slags as an artificial aggregate provides several benefits in terms of Polishing Stone Value (PSV) (16), Los Angeles Abrasion coefficient (17), angularity, and roughness (18). Thanks to its excellent dielectric response, EAFS is also used for enhancing the MW heating efficiency of asphalt mixtures (19, 20). It was observed that by adding EAFS at 10% by volume of aggregates in the fine fractions (0.5/2 mm), the heating rate of asphalt mixtures passed from 4065 °C/kWh to approximately 7500 °C/kWh, for each kg of mixture.

The effectiveness of the MW-assisted healing technique has been widely assessed on the laboratory scale (21-24). In laboratory assessments, asphalt mixture specimens are previously broken, then exposed to MW heating treatment, and finally broken again. The effectiveness of the MW heating treatment is typically evaluated through the recovery rate, which is calculated as the percentage of the original performance of the sample that is regained after the heating treatment. In addition, the feasibility of this technology was recently proved at full-scale (25). Despite this, it has been studied that if only heat is applied it will not be possible to restore the asphalt pavement original behavior being recovery ratios between 65 -90%.

To overcome this limitation, it has been recently proposed a novel thermomechanical treatment, consisting of combining MW heating treatment and re-compaction energy for achieving complete healing of damaged asphalt mixtures (26). In the field, the thermomechanical treatment would be implemented by heating the deteriorated pavement with a MW generator and then re-compacting the pavement (27). The effectiveness of this technology was also assessed for Half-Warm Asphalt Mixes (HWMA) containing EAFS and Reclaimed Asphalt Pavement (RAP) (28).

To scale up MW-assisted healing technology, Life Cycle Assessment (LCA) analyses are urgently required (29, 30). LCA is a tool for estimating and quantifying potential environmental impacts of products, processes, and services throughout their entire life cycle, from raw material extraction through transport, manufacturing, use, and the end of life. LCA studies for asphalt mixtures and roads has been carried out recently as many sustainable pavement technologies are being developed in the recent years due to the need to determine environmental impacts and their contribution to climate change.

A review of the state of the art of LCA for binders and asphalt mixtures has been previously made (31-36), however, very few had evaluated different pavement rehabilitation strategies or the benefits of using MW-assisted healing technology. In any case, the are promising results according to the research made.

A hybrid input–output-assisted Life-Cycle that compared a traditional road with one in which the self-heal-

ing technology was implemented concluded that self-healing roads can be an alternative as emissions could be decreased up to 16% as well as lower costs could be achieved over the road life (37). Also, a pavement LCA model that was developed to evaluate energy use and GHG emissions from pavement rehabilitation strategies concluding that savings accumulated during the use phase due to reduced rolling resistance for roads with high traffic could be considerably higher than the impacts from material manufacturing and construction (38). Besides, a recent study that considered bitumen and its self-healing capacity as a parameter and that developed an Open Life Cycle Assessment framework showed that a significant reduction in GHG emission and energy consumption could be achieved (39).

As the introduction of new pavement materials and technologies can improve the maintenance and rehabilitation process, further research on this topic is necessary. The novelty of this research is that no studies have assessed the feasibility of the thermomechanical treatment (MW heating and re-compaction) on the overall emissions and energy consumption of maintenance activities. This research aims to fill these gaps performing a LCA for evaluating the feasibility of MW-assisted healing technology evaluating different scenarios in which the heating energy and the addition of EAFS varies.

2. METHODOLOGY

2.1. LCA framework

LCA is a tool for estimating and quantifying potential environmental impacts of products, processes, and services throughout their entire life cycle, from raw material extraction through transport, manufacturing, use, and the end of life. Life cycle is a term created by environmental evaluators to quantify the environmental impact of a material or product from when it is extracted from nature until it returns to the environment as waste. According to ISO 14040 (40), the LCA framework has four steps that are iterative, as presented in Figure 1.

LCA consists of four stages differentiated. To understand the sustainability of a new asphalt pavement technology requires a thorough evaluation of environmental impacts within all stages of a pavement's life with the LCA framework. These main stages that allows to obtain results based on scientific rigor, traceability and transparency in its implementation are described in the following sections.

2.2. Definition of goal and scope

In first stage a series of questions must be responded as this will determine the nature of the LCA and
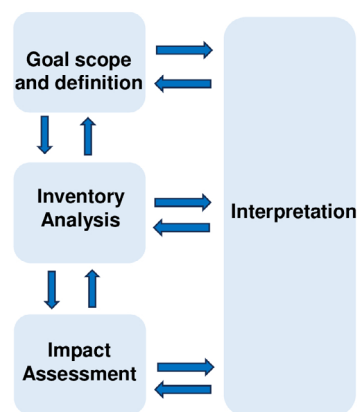

Figure 1. LCA framework according to ISO 14040 and 14044.

that constitute the objective, such as the reasons that lead to the study or the intended application. Objectives and scope must be defined in a consistent way. Also, the functional unit (FU) which is defined by ISO 14040 as 'quantified performance of a product system for use as a reference unit' must be included.

In this study the objective is to determine the potential environmental benefits of implementing the MW-assisted self-healing technology for asphalt pavements when compared to a conventional road with traditional maintenance strategies. Two different scenarios in which the energy applied to restore the pavement and the addition of slag varies has been studied.

The FU in this study is 'm² ' of road and for the sensitivity analysis in which the road lifespan parameter is included the FU is 'm² year'. Different time frames will be considered and compared since this is key of the purpose of the application of the MW-assisted self-healing technique: the extension of life service of asphalt pavements.

Different scenarios have been analyzed and they were selected and based on a previous laboratory research (26). In that preceding study there were different scenarios with different repair rates. To assess this LCA only the scenarios in which the asphalt reaches a total repair of the pavement were selected and are the following:

In Scenario 1 (SC1), the asphalt mixture does not contain slags and the thermo-mechanical treatment was able to completely repair the pavement (being healing rates sometimes higher than 100%). The energy needed to heat this mixture without slag was 0.0098 kWh for each kg of bituminous mixture.

In Scenario 2 (SC2), slags are added (10% by volume of aggregates). MW heating is applied as well as a re-compaction treatment just like in SC1. In this case, to reach a completely repair the mixture energy required for heating was 0.0054 kWh for each kg of bituminous mixture. In this scenario, the use of slag made it possible to reduce the energy required for heating. In Table 1 a summary of the different scenarios studied for the MW self-healing treatment are presented:

TABLE 1. MW-assisted self-healing different scenarios.

Scenario	EAFS addition	MW treatment	Re-compaction treatment	Energy required for heating a kg of mix	Repair rate
Scenario 1 (SC1)	no	yes	yes	0.0098 kWh	100%
Scenario 2 (SC2)	yes	yes	yes	0.0054 kWh	100%

According to ISO 14040, in this study, the system boundaries include all the significant life cycle phases: construction, rehabilitation road opeations and a final road dismantling. This covers the production and transportation of materials, their placement in the road structure, the road maintenance operations, and the demolition of the infrastructure. The analysis period considered included the entire life cycle of the road ("cradle-to-grave" LCA), from the extraction of raw materials.

Figure 2 shows the different operations/strategies considered during the life service of of the conventional road and the MW-assisted self-healing roads (SC1 and SC2 has the same system boundaries) in which the MW treatments are applied during the life service to restore the asphalt pavement.

2.3. Life Cycle Inventory

In the Life Cycle Inventory (LCI) analysis, inputs and outputs are collected and quantified, and the results of a product system during its life cycle. The data refer to the previously defined functional unit. Within the previous specified system boundaries, in this stage wide data is collected for each life cycle stage.

In this LCA stage, the data and calculation procedures are collected. This process is an iterative task, which implies that as progress is made in the inventory, a change in the data collection procedure may be chosen, or the objectives and scope of the study may even be reconsidered. There are commercial and public databases. In this study, ecoinvent database was employed. Also, data needed for this LCA study were obtained primarily from materials suppliers and contractors. It must be noted that part of the data used is subjected to confidentiality agreements by the companies, hence, this data not accessible for the public.

2.3.1. LCI for the conventional road

The construction phase of a road involves the following sub-processes:
- manufacture of bituminous mixtures (surface, intermediate and base course).
- transportation (of materials from the mixing plant to the construction site).
- placement and compaction of layers.
- irrigation of prime and task coatings.

The consumption of the whole process was calculated. For the conventional layers, truck transport from the asphalt plant to the on-site working site considered, taking an average of 40 km. In the case of gravel, the distance considered is 30 km. The placement of the asphalt mixtures has been carried out with machinery whose total consumption is diesel. In the case of gravel, a motor grader has been considered. In the construction phase, both prime and tack coat are applied. The quantities of each of the irrigation materials, the energy consumption for its manufacture and commissioning and the transport considered from the asphalt plant to the work site some 80 km have been considered.

In the slurry phase, firstly, the material is manufactured at room temperature and the transportation from the mixing plant to the slurry´s on-site work, an average distance of 40 km has been considered. The distance for transporting the emulsion has been 80 km.

Regarding milling and replacement, it was considered that 5 cm of the wearing course was removed and later replaced with the same type of mixture. For this maintenance technique the operations considered were the following: milling, swept, transport of the waste generated, manufacture of replacement mix, transport of the replacement mixture, extension and compaction, tack coat (manufacture, transport, and placement). A milling machine and a sweeper
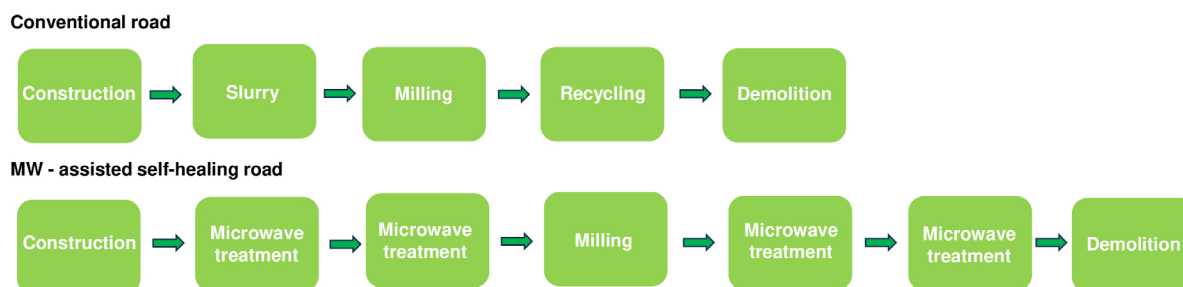

FIGURE 2. System boundaries for each type of road during life service.

were considered for removing the surface layer. The asphalt mixture used to replace the wearing course was the same as the initially manufactured for construction phase. Its placement and compaction were considered. In relation to the transport of the replacement mixture and the transport by truck of the waste generated 40 km has been considered Regarding the tack coat, the same composition is considered as that applied in the construction phase.

The recycling and replacement phase involves the following subprocesses: milling, swept, transport of the generated waste, manufacture of recycled replacement mix, transportation of the replacement mixture to the site, laying and compaction and the tack coat (manufacturing, transportation, and placement) and in the demolition operation all layers are removed using an excavator-drill and the waste materials are transported to a landfill (an average distance of 80 km is considered).

2.3.2. LCI for the self-healing roads

For the construction of the self-healing road- SC1, the same layers were considered as the tradional road and for the SC2- road, the surface layer incorporates 10% of slags by volume of aggregates while the rest of the layers (binder layer, base layer, sub-base) it is considered that they will be the same as the others. The values for the inputs for the milling and replacement and the demolition phase were the same as for the conventional road.

Regarding the MW treatment, it has been considered that the self-healing roads, both SC1 and SC2 will receive a MW healing and re-compaction treatment four times during its lifespan. This treatment will be implemented when it could be observed that deterioration (cracks) appears on the asphalt surface. When this happens, over the wearing course the MW-heat will be applied with the corresponding machine and will go over the surface of the road, consequently heating the binder and the slags if previously included. Once the heat is applied, the bitumen will be able to fill the cracks healing the asphalt. Once the MW is applied a re-compaction will be made.

Self-healing roads have an extended life service and due to the MW and re-compaction treatment other maintenance operations like the traditional milling and replacement operation can be delayed. In this LCA, the demolition stage of self-healing roads was also considered.

2.4. Life Cycle Impact Assessment

In this third stage of the LCA the amount of impact associated with the data collected in the inventory phase of the life cycle is determined. The inventory data will be related to the impact categories selected in the study and their corresponding indicators.

To carry out the calculations in this research, the professional tool SimaPro® was used, which is widely used by the international scientific community. The ecoinvent database and the updated ILCD 2011 midpoint characterization method (EF 2.0) have been included, among others.). The sixteen selected environmental impact categories and their units can be seen in Table 2.

TABLE 2. Environmental impact categories.

Impact category	Unit
Climate change (CC)	kg CO_2 eq
Ozone depletion (OD)	kg CFC11 eq
Ionizing radiation (human health) (IR)	kBq U-235 eq
Photochemical ozone formation (PO)	kg NMVOC eq
Respiratory inorganics (RI)	disease inc.
Human toxicity (non-cancer effects) (Hhnc)	CTUh
Cancer human health effects (Hhc)	CTUh
Acidification (AC)	mol H^+ eq
Eutrophication (freshwater (Euf)	kg P eq
Eutrophication marine (Eum)	kg N eq
Eutrophication terrestrial (Eut)	mol N eq
Ecotoxicity (freshwater) (EC)	CTUe
Land use (LU)	Pt
Water scarcity (WS)	m³ depriv.
Resource use, energy carriers (Ruec)	MJ
Resource use, mineral, and metals (Rumm)	kg Sb eq

2.4.1. LCA results of the conventional road

The results of the conventional road by stages and/or operations and by materials and/or processes are presented in Figure 3 and Figure 4, respectively.

In Figure 3 it can be observed the construction stage of the road the main responsible of all the category impacts: 41%-56%. Also, the recycling is responsible of the 18-31% total environmental impacts. It can also be noted that the slurry maintenance operation is the maintenance operation that hardly contributes to the impacts.

Figure 4 shows that the main impacts are due to the production of bitumen, the consumption of diesel and the transportation. Electricity use hardly contributes to the impacts. However, it can be also observed that the contribution of the production of bitumen is different depending on the environmental category impact. For ozone depletion (OD) is 96% of total impacts while for respiratory inorganics (RI) is only 5%. Besides, for RI diesel is 81% while for OD is 2%. And gravel contributes 52% for land use (LU) but only 4% for climate change (CC).
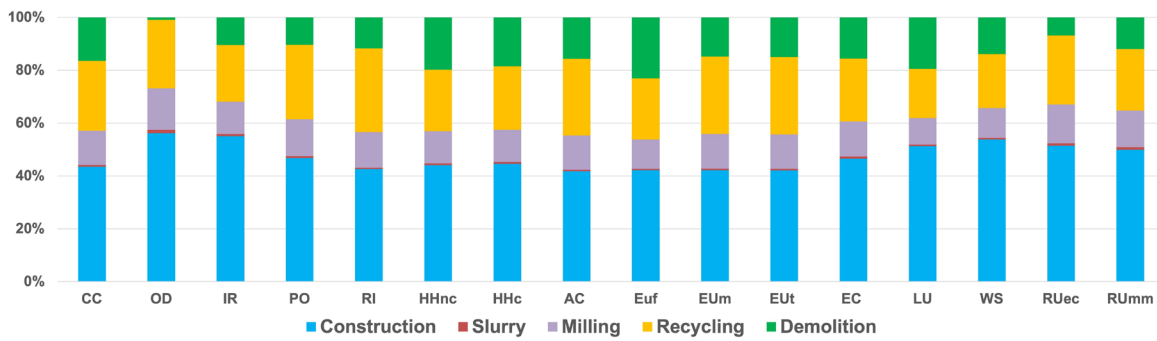
FIGURE 3. LCA results of the conventional road by stages and/or operations per m².
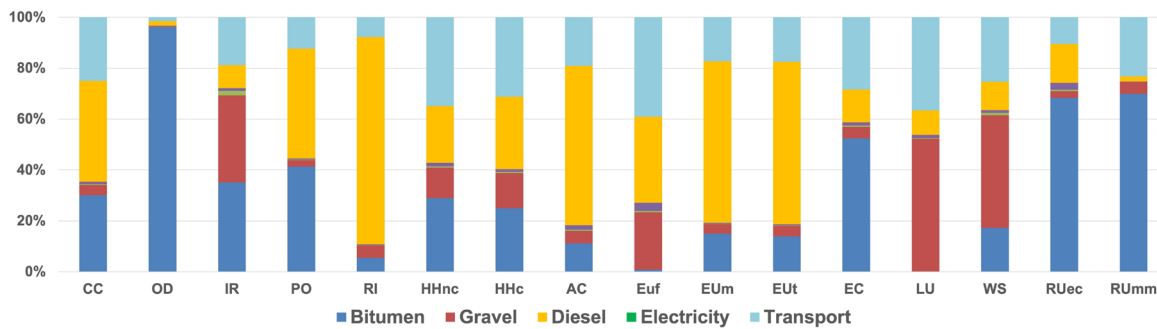

FIGURE 4. LCA results of the conventional road by materials and/or processes per m².

2.4.2. LCA results of the MW-assisted self-healing roads

In Figure 5 and 6 the results by stages and/or operations by m² with the two different scenarios of the MW-assisted self-healing roads are presented.

It can be observed that in both cases construction still has an important role regarding the impacts in all the categories. Besides, the MW and re-compaction treatment stage is only responsible for the 2-3% of all the impacts and for some categories the impacts the value is negligible. This shows that it is possible to recover the original asphalt properties with very low environmental impacts. Also, likewise the conventional road, construction stage is the responsible of the greatest number of impacts, varying from 46-77% for SC1 and from 52-76% for SC2.

It can be observed from Figure 7 and Figure 8 that the bitumen contributes to the impacts depends on the environmental category: bitumen is responsible of 96% of the OD while for respiratory inorganics (RI) is only 4-6%. Same as diesel, which has hardly impact for resource use, mineral, and metals (Rumm) impact, only 4-5% but 82-84% for RI. Hence, it can be seen the importance of LCA which yields different impact results depending on the category. Besides, it can be noted that addition of slag does not contribute to the environmental impacts, only 1% for cancer human health effects (Hhc).

2.4.3. Comparison results

The comparison results of the impacts of the total environmental impacts for the conventional road
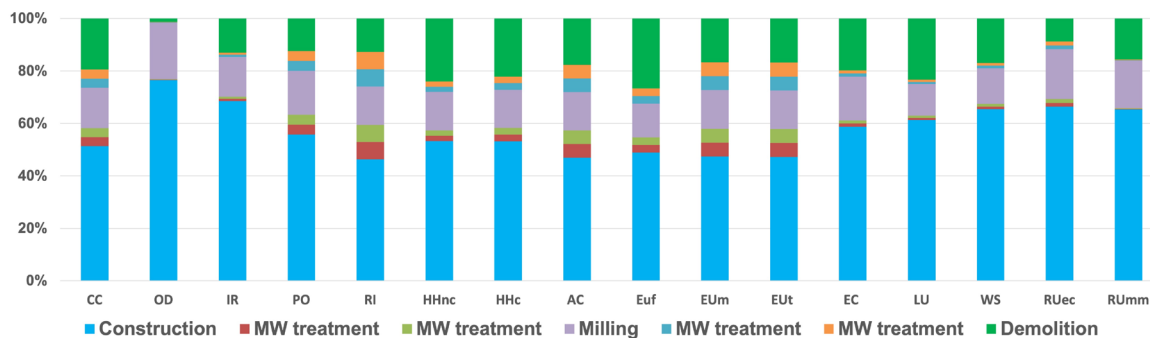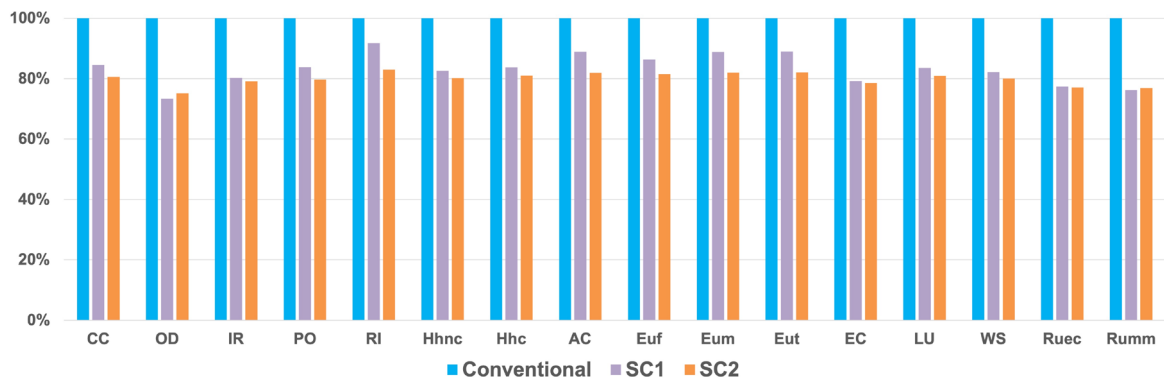

FIGURE 5. LCA results of SC1 self-healing road by stages and/or operations per m².

FIGURE 6. LCA results of SC2 self-healing road by stages and/or operations per m².

FIGURE 7. LCA results of SC1 self-healing road by materials and/or processes per m².

FIGURE 8. LCA results of SC2 self-healing road by materials and/or processes per m².

FIGURE 9. Percentual comparison environmental impact categories results per m².
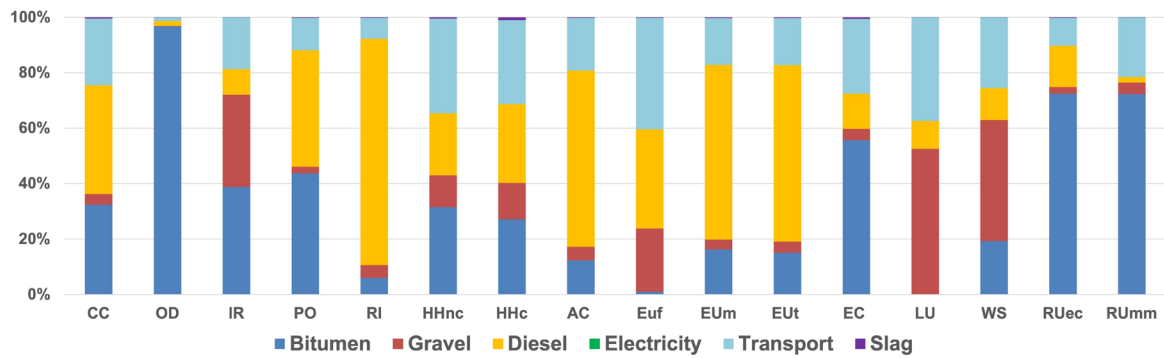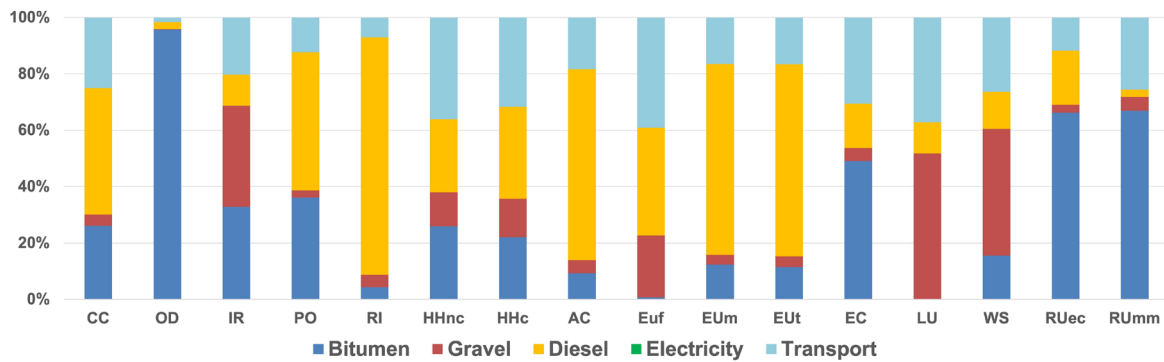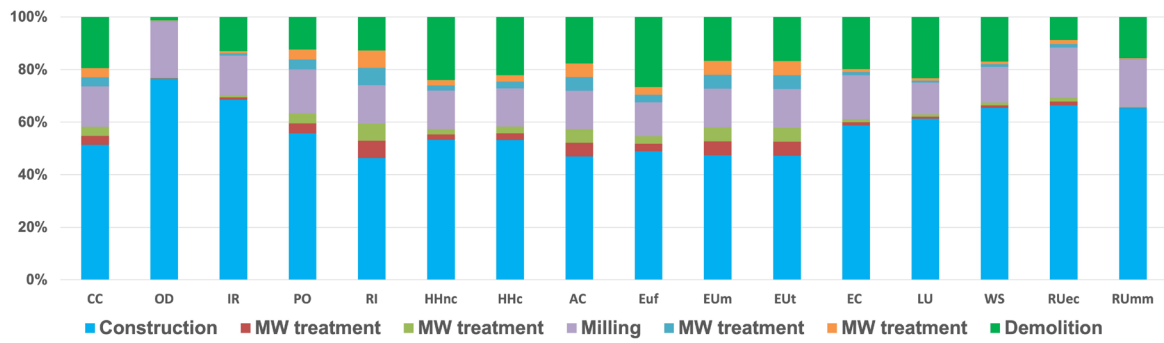
and for the two different scenarios of the MW-assisted self-healing road are presented and compared in Figure 9.

The results shows that the best scenario for all the category impacts is SC2 (in which MW heating is applied as well as a re-compaction treatment for a pavement with slag addition) when compared to the conventional road. In SC1 the lack of slag leads to an increase in the energy needed for heating which is translated in higher environmental impacts. The addition of slag allowed to reduce the heating energy required which, in additions to the re-compaction made after, a healing rate of 100% can be achieved. The decrease in all environmental categories impacts varies from 17-25%. when SC2 is compared with the conventional road. It can be observed that a decrease of 20% is achieved for the CC category. It must be noted that the lifespan parameter has not been considered.

2.4.4. Sensitivity analysis

Sensitivity analysis is a tool through which the changes that occur in a variable are studied when certain variations are introduced into the model. In this study the variable is the lifespan of each road as the potential of the MW-assisted self-healing technology is to repair cracked and deteriorated asphalt pavements so the road durability could be increased, maintenance operations reduced, hence, environmental impacts could be decreased during the road life span.

Sensitivity analysis is also known as a hypothetical analysis, since it is essential to determine how the different values that parameter can adopt affect a dependent variable. In the sensitivity analysis performed in this LCA all impact category indicators have been divided by year, so the lifespan of each road can be now considered, being the FU 'm² year'.

Pavements systems has a long-life span: the expected lifespan of a typical road with double or triple asphalt layers is 20–40 years (41). Hence, in this research the life service of the conventional road studied considered is 30 years. On the other hand, it is expected that if MW-assisted self-healing technology is implemented road maintenance operations could be delayed and even some of them not necessary.

In this research different life spans have been considered for the self-healing road (to simplify, the results of the best scenario (SC2) are the ones compared with the conventional road). Lifespans are: 30 years (the same as the conventional one so both can be compared (SC2 30)) and 32, 35 and 42 years (SC2 32, SC2 35 SC42, respectively) to determine the benefits of MW-assisted self-healing emerging technology as the lifespan increases. The comparison results are presented in Table 3.

TABLE 3. Environmental impacts results per m² year.

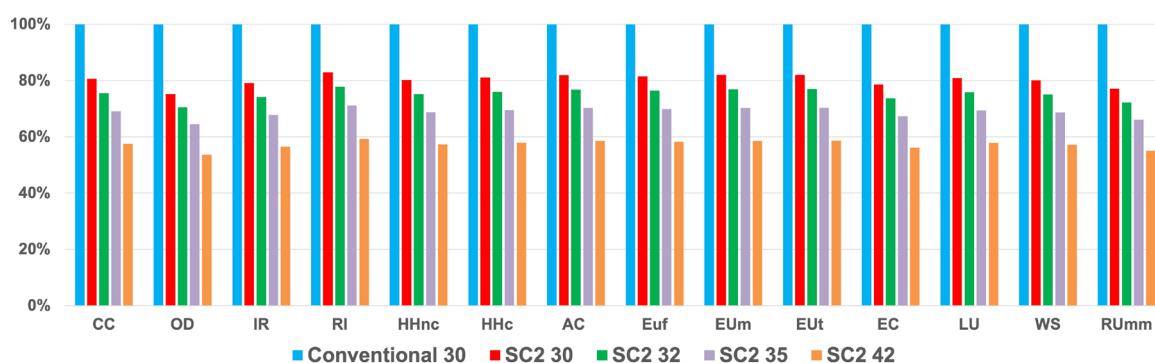| Category impact | Conventional lifespan | MW-assisted self-healing road (SC2) lifespan | | |
	30 years	30 years	32 years	35 years	42 years
CC	3.989400507	3.215537824	3.01456671	2.756175278	2.296812732
OD	1.31688E-05	9.90026E-06	9.2815E-06	8.48594E-06	7.07162E-06
IR	0.497189466	0.393283155	0.368702958	0.337099847	0.280916539
PO	0.050016211	0.039891137	0.037397941	0.034192403	0.028493669
RI	5.2697E-07	4.37189E-07	4.09865E-07	3.74734E-07	3.12278E-07
Hhnc	2.31934E-07	1.85988E-07	1.74364E-07	1.59418E-07	1.32849E-07
Hhc	4.21924E-08	3.4194E-08	3.20569E-08	2.93092E-08	2.44243E-08
AC	0.026644056	0.02183952	0.02047455	0.018719588	0.015599657
Euf	0.000224758	0.000183229	0.000171777	0.000157053	0.000130878
Eum	0.011324645	0.009286474	0.008706069	0.007959835	0.006633196
Eut	0.122940376	0.100909324	0.094602491	0.086493706	0.072078089
EC	2.2723725	1.785754879	1.674145199	1.530647039	1.2755392
LU	7.780079291	6.295015283	5.901576828	5.395727385	4.496439488
WS	204.8744969	164.0181118	153.7669798	140.586953	117.1557941
Ruec	144.6522779	111.4508233	104.4851469	95.52927713	79.60773094
Rumm	1.16311E-05	8.94524E-06	8.38617E-06	7.66735E-06	6.38946E-06

Figure 10. Percentual comparison of the conventional and SC2 road with different life spans.

Table 3 shows than even when the lifespan is the same the MW-assisted self-healing technology decreases all the environmental category impacts. In Figure 10 a percentual comparison is presented so the benefits can be better observed. The more the lifespan of self-healing road increases, the more the environmental benefits will increase as well.

In Table 4 a percentage comparison of the environmental benefits of implementing the MW-assisted self-healing technology are presented when lifespan increases due to the implementation of this technology.

Table 4 shows that there is a substantial reduction of the environmental impacts in all categories with respect to a road with conventional maintenance strategies even when the life span is hypothetically the same.

By adding slags to the asphalt pavement (SC2), further reduction of the environmental impact for each category is attained. This is due to the fact the addition of EAFS allows for a more efficient heating process, reducing energy consumption and showing the benefits of applying both MW and re-compaction of the environmental impact. It can be noted that CC category impact is reduced by 42% with respect to the conventional strategy.

2.5. Interpretation of the results

In this phase, all the results derived from the two previous stages are extracted, in line with the objectives and scope of the study, and that can provide conclusions and recommendations for decision-making regarding product strategy. In this stage, the adequacy of the selected impact categories is verified based on the results obtained, allowing the most significant impacts to be identified, conclusions to be drawn, and possibilities of action to be outlined for the global improvement of the environmental behavior of the product, process or service studied.

This study has shown that the use of thermomechanical treatment (MW and re-compaction) permits, not only to completely repair the original mechanical

Table 4. Percentage of environmental benefits by impact category.

	SC4 30	SC4 32	SC4 35	SC4 42
CC	19.40%	24.44%	30.91%	42.43%
OD	24.82%	29.52%	35.56%	46.30%
IR	20.90%	25.84%	32.20%	43.50%
PO	20.24%	25.23%	31.64%	43.03%
RI	17.04%	22.22%	28.89%	40.74%
HHnc	19.81%	24.82%	31.27%	42.72%
HHc	18.96%	24.02%	30.53%	42.11%
AC	18.03%	23.16%	29.74%	41.45%
Euf	18.48%	23.57%	30.12%	41.77%
EUm	18.00%	23.12%	29.71%	41.43%
EUt	17.92%	23.05%	29.65%	41.37%
EC	21.41%	26.33%	32.64%	43.87%
LU	19.09%	24.15%	30.65%	42.21%
WS	19.94%	24.95%	31.38%	42.82%
RUmm	22.95%	27.77%	33.96%	44.97%

properties of asphalt pavements, but to reduce environmental impacts during the life service of the road. The use of slags in the asphalt pavements represents not only an opportunity for recycling and valoraizing of an industrial waste but providing environmental benefits to the MW-assisted self-healing roads.

CONCLUSIONS

Determining accurately the benefits of the actual emerging technologies will lead towards successful paths of sustainable decision-making and to achieve climate change goals. Microwave (MW)-assisted self-healing technology can repair the pavement by

heating with MW energy the cracked asphalt surface as bitumen can melt and flow through the cracks sealing them. To determine how sustainable this technology could be it is necessary to carry out a Life Cycle Assessment (LCA) so environmental impacts could be compared with a traditional road with conventional maintenance operations, hence, environmental benefits determined.

In this study, to determine how sustainable this technology could be, a ''cradle-to-grave'' (LCA) has been carried out to determine the potential environmental benefits by comparing a conventional road with traditional maintenance operations with different self-healings road scenarios in which the use of Electric Arc Furnace slag (EAFS) and different MW heating energy were considered.

From this research, the following findings were obtained:

- There is a notable decrease in all impact categories for the MW self-healing roads (for both different scenarios studied) compared to a conventional road with traditional maintenance strategies.
- For conventional and self-healing roads, materials and/or processes impacts contribute in a different way depending on the category, demonstrating that in LCA for pavements it is necessary to include each environmental category to truly understand the impacts.
- LCA results for self-healing roads demonstrated that it is possible to recover the original asphalt performance with very low environmental impacts: MW treatment is only responsible for the 2-3% of all the impacts and for some categories the impacts the value is negligible, hence, this technique can be applied as many times as necessary due to its low environmental impacts.
- The best results were obtained by using MW heating treatment followed by a re-compaction treatment on asphalt pavements with EAFS, which in this study corresponds to Scenario 2 (SC2).
- When energy consumption for maintenance operations is reduced, environmental impacts decrease.
- The results for the climate change category for SC2, measured in kg of CO_2 equivalent, showed that self-healing roads can reduce these emissions by up to 42%.
- For all case studies, the greatest contribution for all the impact categories considered is the initial road construction stage.
- The combination of bitumen production, all transport and energy consumption to manufacture the mixtures, contributes to the total environmental impact in all categories for both conventional and self-healing roads.
- The addition of slag to the asphalt mixtures not only do not seem to contribute to increase the overall impacts but is able to improve the self-healing performance of the road.

- When lifespan of the self-healing roads varies total environmental impacts also vary significantly showing that a prolonged pavement lifespan will reduce a great amount environmental impact in all categories.
- Even if the lifespan is not increased when comparing both types of roads, the self-healing roads still have lower environmental impacts in all categories.
- Traditional maintenance operations could be eliminated or delayed if MW-assisted self-healing is implemented.
- It seems that asphalt pavement design standards not only have to focus on enhancing its performance and increasing its durability but in allowing it to repair itself to its original state and reducing maintenance operations environmental impacts.

In terms of future development, supporting the implementation of this innovative pavement technology and conducting LCA studies are necessary as it will help engineers, project managers as well as stakeholders and policy makers to take decisions and actions to develop a more sustainable pavement sector. Also, in future research, full-scale studies and further LCA with different assumptions are necessary as well as it should be also evaluated the effect of using different materials to enhance the MW heating efficiency.

Authorship contribution statement

Ana María Rodríguez-Alloza: Conceptualization, Data cleasing, Formal analysis, Fund raising, Research, Methodology, Project administration, Resources, Supervision, Validation, Visualization, Write-up - original draft, Write-up - review & editing.

Daniel Garraín: Data cleasing, Formal analysis, Research, Methodology, Software, Visualization.

Federico Gulisano: Research, Visualization.

Declaration of competing interest

The authors of this article declare that they have no financial, professional or personal conflicts of in-terest that could have inappropriately influenced this work.

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