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A comparative life cycle assessment of hot mixes asphalt containing bituminous binder modified with waste and virgin polymers

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Abstract

This paper presents the results of a life cycle assessment undertaken to compare the potential environmental impacts associated with the use of asphalt surface mixtures produced with polymer modified bitumen with those of a conventional asphalt surface mixture. Seven types of hot mix asphalt mixtures to be used in the surface course are compared, among which one produced with virgin materials and conventional binder, which is used as a reference, and six alternative mixtures containing a bituminous binder modified with different percentages of waste nitrile rubber from shoe sole and Ethylene-Vinyl-Acetate polymer. The ILCD impact assessment method at midpoint level was adopted to assess the environmental performance of the wearing course of a French pavement structure over a 30-year project analysis period considering the following pavement life cycle phases: (1) extraction of raw materials, modification of the bituminous binder and mixtures production; (2) transportation of materials, and; (3) construction and maintenance and rehabilitation.

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Keywords: Life cycle assessment; Waste nitrile rubber (NBR); EthyleneVinyl-Acetate (EVA); Modified bituminous binder

1. Introduction

Recently, increased traffic levels, heavier loads, and extreme weather conditions have urged road authorities to develop new, or advance existing solutions, in order to improve the resistance of the road pavements to the adverse effects of mechanical and environmental loading.

Concomitantly, as greenhouse gas (GHG) and their effect on the climate are increasingly in the spotlight with respect to policy, legislation and general public's concern, the pavement industry and scientific community have been challenged to improve conventional asphalt mixtures materials by developing more sustainable technologies.

Asphalt binder modification by means of polymer addition, either virgin or recycled and used individually or in a blend mode, has proved to have the potential to enhance the bituminous properties, most typically those related to high temperature performance characteristics, thereby postponing the effects of permanent deformation and fatigue damage [1,2]. However, depending on their nature, the manufacturing of these polymers can also increase the environmental impacts of the asphalt binder in the mixture [3].

Therefore, it is of paramount importance to objectively quantify the extent to which the potential environmental benefits associated with the decreasing amount of materials needed over the pavement life cycle as a consequence of the increased service life of pavements is not offset by the environmental impacts originated by their production.

To the best of the authors' knowledge, the only study existing in the literature assessing the environmental impacts resulting from using polymers to modify asphalt binder was performed by [4]. However, neither the waste nitrile rubber (NBR) nor the Ethylene-Vinyl-Acetate (EVA) polymers were among those studied.

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Given the circumstances above stated, the study presented in this paper aims to investigate the extent to which the use of polymer modified bitumen (PMB) in asphalt mixtures applied in the wearing course of flexible road pavements is beneficial from an environmental point of view.

Nomenclature

AADT	average annual daily traffic
AC	asphalt concrete
Ac	freshwater and terrestrial acidification
CC	climate change
CE	carcinogenic effects
EOL	end-of-life
EQ-IR	ecosystem quality- ionising radiation
EVA	ethylene-vinyl-acetate
FEco	freshwater ecotoxicity
FEu	freshwater eutrophication
GHG	greenhouse gas
HDV	heavy duty vehicles
HFO	heavy fuel oil
HH-IR	human health- ionising radiation
LCA	life cycle assessment
LCI	life cycle inventory
LCIA	life cycle impact assessment
LU	land use
M&R	maintenance and rehabilitation
MEU	marine eutrophication
MFR	mineral, fossils and renewables
NBR	waste nitrile rubber
NoCE	No-carcinogenic effects
OLD	ozone layer depletion
PAP	project analysis period
PMB	polymer modified bitumen
POC	photochemical ozone creation
RE	respiratory effects
TEu	terrestrial eutrophication

2. Methodology

A comparative process-based life cycle assessment (LCA) study was performed according to the ISO 14040 series [5,6] and the University of California Pavement Research Center [7] to compare the potential environmental impacts of different asphalt mixtures adopted in the construction, maintenance and rehabilitation (M&R) of a road pavement section during its life cycle.

The stages adopted in this study include goal and scope definition, inventory analysis, impact assessment, and interpretation.

2.1. Goal and scope definition

2.1.1. Goal

The main goal of this study is to compare the potential life cycle environmental impacts arising from the use of asphalt surface mixtures containing different percentages and types of PMB with those of a conventional asphalt surface mixture in the construction and M&R of wearing courses of flexible road pavements (baseline scenario).

Furthermore, in order to assess the robustness of the results to changes in the methodological assumptions, a scenario analysis was performed by considering two alternative scenarios. In the first one, hereafter named AS1, it is assumed that the use of any type of PMB leads to an increase in the durability of the pavement equal to 20%, or in other words 2 years. In the second one, hereafter named AS2, it is assumed that the asphalt plant is run by natural gas rather than by heavy fuel oil (HFO). This is a plausible scenario that stands the best chance of becoming the actual and near-term future practice, thereby replacing the baseline scenario, as new asphalt plants are increasingly switching to natural gas because of its general lower price and cleaner-burning properties.

The comparative findings of this study are intended to be used by highway agencies and pavement practitioners to make more assertive judgments on the pros and contras associated with the use of binder modifiers agents for enhancing the performance of road pavements throughout their life cycle.

2.1.2. System description and boundaries

The system boundaries define the unit processes considered in the LCA study and were drawn to cover the following pavement life cycle phases, modeled through individual but interconnected modules: (1) extraction of materials and mixtures production, consisting of the acquisition and processing of raw materials, and the mixing process of asphalt mixtures in plant; (2) construction and M&R, including all construction and M&R procedures and related construction equipment usage; (3) transportation of materials, accounting for the transportation of materials to and from the construction site and between intermediate facilities; and (4) end-of-life (EOL), which models the destination of the pavement structure after the project analysis period (PAP).

The upstream emissions and resources consumption associated with the production of the energy sources used to power the different processes and construction equipment were also included in the system boundaries. On the other hand, construction equipment, road-related safety and signaling equipment (including road marking), road accessories (fences, road lighting software, etc.), construction and M&R of the remaining layers of the pavement structure and the earthworks required to build the platform over which the pavement foundation will be built were not included in the system boundaries. The environmental impacts resulting from the construction and M&R of the remaining layers were disregarded because their geometry and type of mixture is the same regardless of the type of the mixture considered in the wearing course.

2.1.3. Functional unit

The functional unit is the central core of any LCA and forms the basis for comparisons between different systems with the same utility for the same function. In the pavement domain, this means a unit of pavement that can safely and efficiently carry the same traffic over the same PAP. Then, it is defined by their geometry, service life and level of traffic supported.

The functional unit of the case study presented in this paper is a typical French highway section of 1-km length, composed of two independent roadways, each with 2 lanes with an individual width of 3.5m. The PAP is 30 years, starting in 2015. The initial two-way average annual daily traffic (AADT) was considered to be equal to 6500 vehicles/day, of which 33% are heavy duty vehicles (HDV) equality divided between rigid HDV and articulated HDV.

The geometric characteristics of the wearing course considered are presented in Figure 1. As for pavement maintenance, a pavement M&R strategy derived from French practice was considered in the baseline scenario [9]. It is based on the assumption that asphalt mixtures using conventional binder and PMB will perform likewise. The features of the M&R activities undertaken in the baseline scenario, as well as the application timing are displayed in Figure 1. In the AS1 the increase in the durability of the pavement equal to 20% means that the first and second M&R activities will take place in the years 2026 and 2036. Therefore, there will be no need of applying the 3rd M&R activity, as scheduled in the baseline scenario. In the AS2 a pavement M&R strategy equal to that of the baseline scenario is adopted.

Table 1 presents the formulations of the PMB adopted in the alternative asphalt surface mixtures applied in the wearing courses, as determined by [10]. The design of all mixtures consists of 94.52% aggregates and 5.48% bituminous binder by weigh of asphalt mixture.

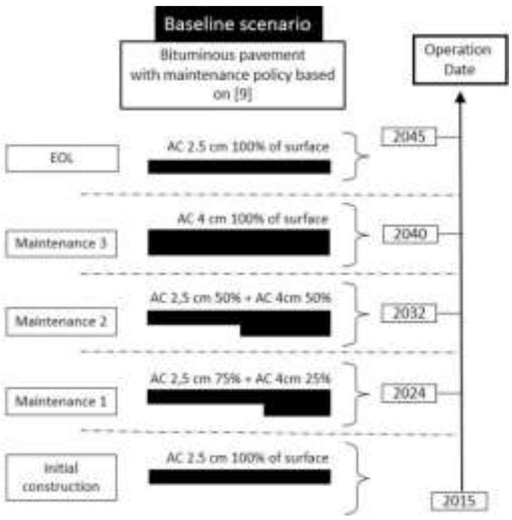

Fig. 1. Geometric characteristics of the flexible pavement structure and M&R strategy adopted in the baseline scenario. Key: AC- asphalt concrete.

Table 1. Formulation of the several PMB considered in the case study.

	PMB ID					
	1	2	3	4	5	6
Total % of polymer (by weight of binder)	2	2	5	5	5	5
% of NBR (by weight of polymer)	50	75	50	75	100	0
% of EVA (by weight of polymer)	50	25	50	25	0	100

2.1.4. Data sources and data quality requirements

The inventory data required to perform a LCA study are classified into two categories: primary and secondary data. Primary data are those specific to the production processes for the product or service studied in the LCA. In turn, secondary data represent generic or average data for the product or service subject to analysis [11].

In this study the data sources were selected in order to be as much time, geographical and technological representative as possible. That means that the most recent and truthful data representing French processes and conditions were used as inputs and outputs when modelling the processes covered by the several sub-components integrating the system boundaries. Specifically, the primary data include mainly: (1) the composition of the mixtures; (2) the annual fuel consumption, production and life period of asphalt mixing plants; (3) transportation distances; and (3) construction vehicles fleet composition.

Regarding the secondary data, they are mainly related to the inventory analysis of (1) raw materials, (2) fuels, and (3) construction, transportation, and on-road vehicles operation, and were obtained from existing publicly available reports and the ecoinvent database version 3.2, but modified whenever possible and suitable to best approximate French conditions by using French energy inputs/mixes.

2.2. Life cycle inventory

The life cycle inventory (LCI) stage consists of the real data collection and modelling of the system. In addition to the data sources, it relies on the several models selected for modelling the processes analyzed by the several considered sub-systems that make up the whole system.

2.2.1. Materials extraction and mixtures production phase

This phase addresses the environmental burdens arising from the acquisition and processing of the materials applied during the initial construction and future M&R of a road pavement segment. This includes all materials manufacturing processes, from extraction of raw materials to their transformation into a pavement input material (material extraction sub-phase), ending with the mixture production at a mixing plant (materials production sub-phase). The latter sub-phase accounts for the environmental burdens associated with the operation of the (1) mixing plant (i.e., dryer, hot screen, mixers, etc.), (2) wheel loader during the movement of aggregates from the stockpiles to the feed bins and (3) electronic group of the asphalt plant setup.

2.2.1.1. Materials extraction sub-phase

The aggregates required to produce the asphalt mixtures were modelled as gravel and the LCI data associated with their production were obtained from the unit process "*gravel, crushed | gravel production, crushed*" of the ecoinvent database. Also taken from the aforementioned database was the LCI data corresponding to the production of asphalt binder ("*pitch | petroleum refinery operation*") and EVA polymer ("*ethylene vinyl acetate copolymer | ethylene vinyl acetate copolymer production*"). The EVA polymer is assumed to be posteriorly transported to the asphalt plant facility where is located a PMB production plant.

As for the NBR processing (sole shoe milling), a representative production rate of a Comas FD1-A milling shoe sole machine equal to 90 kg milled shoe sole/hour was considered when determining the electricity consumption requirements (200 kWh/ton milled shoe sole) [12].

Furthermore, from the perspective of the LCA methodology, the consideration of NBR as pavement material was made on the basis of the "cut-off" approach [13]. The production of the several types of PMB (Table 1) is assumed to be performed according to the average conditions allowed by an IKA DISPAX-REACTOR® DR 2000/50 PMB production plant [14]. They corresponds to a production rate of approximately 26 ton PMB/hour, to which it is associated an electricity consumption of 7.1 kWh/ton of PMB and an energy consumption for thermal oil heating of approximately 98 MJ/ton of PMB.

The LCI data related to the production and distribution of those energy resources representing the French conditions were posteriorly taken from the ecoinvent database.

2.2.1.2. Mixtures production sub-phase

This sub-phase addresses the LCI of the asphalt mixtures production process. In this case study it was assumed that all asphalt mixtures were produced through a conventional heavy fuel oil-fired batch mixing plant. The energy required for producing 1 ton of asphalt mixture and storing the binder in the asphalt plant were respectively 255 and 40 MJ. The fuel consumed by the wheel loader was 0.194 liters and the electricity consumed by the electric group of the asphalt plant was 5 MJ per ton of asphalt mixture produced. The values presented above correspond to the average French practices. Finally, the LCI data corresponding to the process "*heat production, heavy fuel oil, at industrial furnace 1MW | heat, district or industrial, other than natural gas | cut-off, U*" existing in the ecoinvent database was taken as reference when modelling the operation of the burner existing in the asphalt plant during the production of the mixtures.

2.2.2. Construction and M&R phase

In the construction and M&R phase, the environmental burdens are due to the combustion-related emissions from the construction machinery operation. The consumption-related emissions associated with the operation of each construction equipment were determined by combining the LCI data corresponding to the ecoinvent database process "*machine operation, diesel, >= 74.57 kW, high load factor | machine operation, diesel, >= 74.57 kW, high load factor*" with the typical productivity of each operation involved in pavement construction and maintenance activities. Furthermore, it was considered that the paving operations were equal for all the mixtures analyzed.

2.2.3. Transportation of materials phase

The environmental impacts resulting from the transportation of materials are due to the emissions released during the combustion process of the transportation vehicles when performing two-way trips from the site where the extraction of the raw materials takes place to the asphalt plant and from the asphalt plant to the work site. All materials and mixtures were assumed to be hauled by HDV, and a modified version of the ecoinvent database process "*transport, freight, lorry >32 metric ton, EURO4 | transport, freight, lorry >32 metric ton, EURO4 | cut-off, U*" was used to determine the environmental burdens associated with the transportation of materials movements. The original process was modified in order to disregard the inventory corresponding to the construction of the road infrastructure that is considered by the original process. The transportation distances considered for each material and mixtures used in this case study are representative of the French conditions and are shown in Table 2.

Table 2. Transportation distances considered in the case study.

Type of material	One-way trip distance (km)
Aggregates	20
Binder	100
Asphalt mixtures	20
EVA	100
NBR	100

2.2.4. EOL phase

When a road pavement reaches the end of the PAP, it can be given two main destinations: (1) remain in place; or (2) be removed. In this case study, it is assumed that the pavement remains in place and undergoes the M&R activity illustrated in Figure 1. The environmental burdens assigned to this phase are due to the materials extraction and mixtures production and the combustion-related emissions from the use of the construction equipment and transportation HDV.

2.3. Life cycle impact assessment

The life cycle impact assessment (LCIA) stage of the standardized LCA methodology comprises several steps, namely, classification, characterization, normalization, group and weighting [5]. Among these steps, only classification and characterization were undertaken in this study. The calculation of the impact category indicator scores was performed at midpoint level by applying the ILCD 1.0.8 2016 method [15]. Finally, the OpenLCA software version 1.5.0 was used for modelling the processes analyzed in this case study [16].

3. Results

3.1. Baseline scenario

Table 3 summarizes the LCIA results for the baseline and alternatives scenarios in which the conventional bituminous binder (no modified) is used in the production of the asphalt surface mixtures. Figure 2 shows the relative variation of the impacts scores for each asphalt surface mixture produced with PMB in relation to those associated with the conventional asphalt surface mixture. The relative values should be understood as follows: positive relative numbers mean that the use of PMB improves the LCIA results in relation to those associated with the conventional asphalt surface mixture. In turn, negative numbers represent a worsening of the environmental profile.

Table 3. LCIA results referring to the case in which the bituminous binder used in the production of the asphalt surface mixtures is not modified.

Impact category	Reference unit	Baseline scenario	Alternative scenario	
			AS1	AS2
CC	kg CO2-Eq	453306	371038	406746
Ac	mol H+-Eq	4455	3647	3186
FEco	CTUh.m3.yr	2465819	2018343	2375463
FEu	kg P-Eq	63	52	66
EQ-IR	mol N-Eq	8.3E-1	6.8E-1	7.7E-1
MEu	kg N-Eq	520	425	440
TEu	mol N-Eq	5768	4721	4884
CE	CTUh	2.1E-2	1.7E-2	2.1E-2
HH-IR	kg U235-Eq	136657	111858	128349
NoCE	CTUh	9.2E-2	7.5E-2	8.7E-2
OLD	kg CFC-11-Eq	3.2E-1	2.6E-1	3.1E-1
POC	kg ethylene-Eq	2138	1750	1842
RE	kg PM2.5-Eq	378	309	262
LU	kg Soil Organic Carbon	5277339	4319656	4907831
MFR	kg Sb-Eq	29	23	29

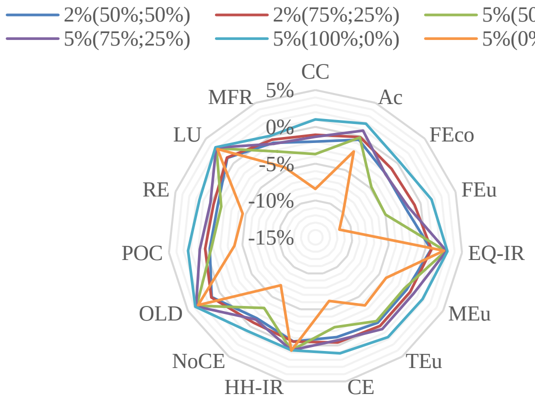

Fig. 2. Relative variation of the LCIA results in the baseline scenario for each alternative asphalt surface mixture. Key: Polymer%(NBR%;EVA%).

The analysis of the results presented in this figure shows that overall the use of EVA polymer as a modifier agent leads to a deterioration of the life cycle environmental profile of the pavement structure in relation to that corresponding to the use of conventional (no modified) binder. The only exception to this general trend is observed for the impact categories ionizing radiation, ozone layer depletion and land use. Given those results, it is not surprising that the greatest negative relative variation of the impacts scores are observed when the binder is modified by means of the use of 5% of EVA polymer by weight of binder. In these circumstances, the greatest relative variation in absolute value (approximately 12%) is registered in the impact category freshwater eutrophication.

In turn, the use of NBR polymer as a modifier agent leads to an improvement of the life cycle environmental profile of the pavement structure in relation to that corresponding to the use of conventional (no modified) binder. That improvement is observed for all impact categories and can be as high as approximately 4% (ozone layer depletion) whereas the lowest and marginal improvement is observed in the impact category land use (approximately 0.1%). Notwithstanding the environmental benefits obtained with the use of the NBR polymer, when it is combined with the EVA polymer in a formulation in which the total amount of polymer is equal to 2%, it is not enough to offset the negative effects resulting from the use of the EVA polymer. However, when the total amount of polymer totals 5% and the percentages of NBR and EVA polymers are equal to 75% and 25% of that value, in 9 out of 15 impact categories the positive environmental effects resulting from the use of NBR polymer cancels out the negative environmental effects associated with the use of EVA polymer. The greatest relative improvement is once again observed in the impact category ozone layer depletion (approximately 4%), whereas the most tenuous is registered in the impact category respiratory effects.

3.2. Alternative scenarios

Figures 3 and 4 show respectively for AS1 and AS2 the relative variation of the impacts scores for each alternative asphalt surface mixture in relation to those corresponding to the use of the conventional asphalt surface mixture in the baseline scenario.

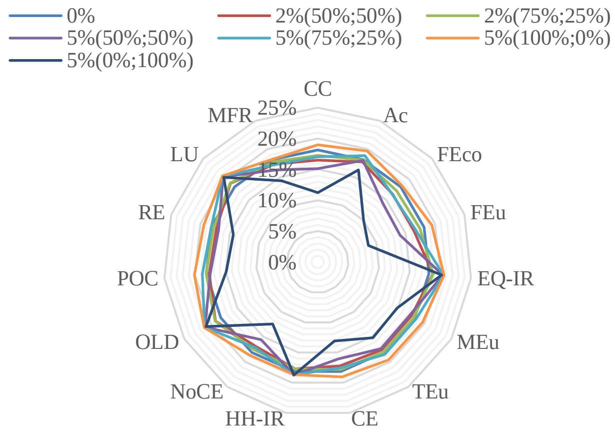

Fig. 3. Relative variation of the LCIA results obtained in the AS1 in relation to those corresponding to the use of conventional asphalt surface mixture (no PMB) in the baseline scenario. Key: Polymer%(NBR%;EVA%).

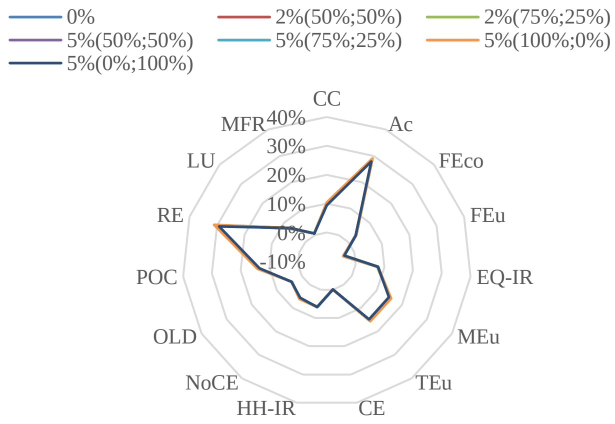

Fig. 4. Relative variation of the LCIA results obtained in the AS2 in relation to those corresponding to the use of conventional asphalt surface mixture (no PMB) in the baseline scenario. Key: Polymer%(NBR%;EVA%).

The analysis of Figure 3 reveals that if the use of PMB in asphalt mixtures has the capacity to improve pavement performance according to the conditions considered in this case study, then considerable environmental benefits can be obtained regardless of the type of PMB used in the asphalt mixture applied in the wearing course of the pavement structure and subsequent M&R activities. The most prominent reduction in the impacts scores are obtained when the total percentage of polymer in the PMB amounts to 5%, and particularly when that percentage is fully made up of NBR polymer. The greatest life cycle impacts saving is equal to approximately 21% (impact category ozone layer depletion in the asphalt mixture adopting PMB 5%(100NBR%;0%EVA)) while the lowest life cycle impacts saving is equal to approximately 9% (impact category freshwater eutrophication in the asphalt mixture adopting PMB 5%(0NBR%;100%EVA)).

When analyzing the extent to which the alternative asphalt plant fuel affects the variation of the scores of a given impact category across the alternatives asphalt surface mixtures, Figure 4 shows that overall shifting from HFO to natural gas offers considerable potential and uniform environmental benefits across the six alternative asphalt surface mixtures. The most expressive improvements in the environmental profiles are observed in the impact category respiratory effects (approximately 30%) followed by the impact category acidification (approximately 28%). The only exception to the global improvement in the environmental profiles resulting from changing the type of fuel consumed by the asphalt plant is observed for the impact category freshwater eutrophication, which is expected to see its scores increased by roughly 4%.

4. Summary and conclusions

In this paper, the results of a process-based LCA of the construction and M&R of the wearing course of a French road pavement section using PMB asphalt surface mixtures, were presented and compared with those in which a conventional asphalt surface mixture (no modified binder) is alternatively applied. Furthermore, two alternative modelling scenarios were considered. In the baseline and second alternative scenarios the conventional asphalt surface mixture (using no modified binder) and the six alternative asphalt surface mixtures (using PMB) were assumed to perform likewise throughout the pavement life cycle. In turn, in the first alternative scenario, the six alternative asphalt surface mixtures were assumed to extend the service life of the wearing course, comparatively to that provided by conventional asphalt surface mixture.

The life cycle of the road pavement sections was divided into four main phases: (1) materials extraction and mixtures production; (2) construction and M&R; (3) transportation of materials; and (4) EOL. The LCI of inputs and outputs associated with the processes considered by the several pavement life cycle phases was determined by combining primary data, representing the current French practices and conditions, with secondary data taken primarily from the ecoinvent database version 3.2. The ILCD 1.0.8 2016 impact assessment method was adopted to characterize the environmental performance of the road pavement section.

The LCIA results of the case study showed that in the baseline scenario the use of EVA polymer as a modifier agent leads to a deterioration of the life cycle environmental profile of the pavement structure in relation to that corresponding to the use of conventional (no modified) binder. This result contrast with that in which the NBR is the binder modifier agents, as it was found to improve the life cycle environmental performance of the road pavement section.

However, if the use of PMB asphalt mixtures succeed in improving pavement performance as proven in literature, thereby reducing the frequency of the application of M&R activities, then considerable environmental benefits can be obtained regardless of the type of PMB used in the asphalt mixture implemented in the wearing course of the pavement structure and subsequent M&R activities.

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