Environmental Engineering and Management Journal

October 2025, Vol. 24, No. 10, 2139-2150
http://www.eemj.icpm.tuiasi.ro/; http://www.eemj.eu
http://doi.org/10.30638/eemj.2025.165

"Gheorghe Asachi" Technical University of Iasi, Romania

SYNERGISTIC EFFECTS OF REJUVENATORS AND WARM MIX ASPHALT: A LIFE CYCLE ASSESSMENT FOR SUSTAINABLE ROAD CONSTRUCTION

Carlo Carpani*, **Loretta Venturini**

Iterchimica S.p.A., via Guglielmo Marconi 21, 24040 Suisio (Bergamo), Italy

Abstract

Atmospheric emissions have recently reached extremely high levels, approaching a point of no return. For this reason, global policy is moving towards reversing this trend. In road construction, two technologies are gaining importance: rejuvenators for reusing recycled asphalt pavements (RAP) and thermos regulators to lower asphalt concrete (AC) production temperatures. However, the need for the asphalt plant to simplify logistics led to the development of a single product that could fulfil both objectives.
This paper therefore aims to evaluate the environmental impact of a new bio-based single product for this dual functionality. In order to estimate the environmental impact, a Life Cycle Assessment (LCA) analysis was carried out. LCA estimations were carried out for CO_{2eq} and energy consumption to produce 1 ton of asphalt concrete. Three types of asphalt concrete were evaluated: AC with neat bitumen, AC with modified bitumen (PMB-wet modification method), and AC with neat bitumen and polymeric compound (PMA-dry modification method). Results showed that using more RAP could lead, on the one hand, to significant environmental (up to 44% reduction in CO_{2eq}) and energy savings (up to 78% reduction in energy consumption). On the other hand, the decrease of production temperatures allows a reduction of CO_{2eq} and energy up to 7% and 6% respectively, regardless of the percentage of recycled material used. The synergy between the two technologies leads to a maximum reduction of about 50% in CO_{2eq} and 80% in energy consumption. These results align with the European Green Deal's goal of reducing emissions by 50% by 2035.

Key words: life cycle assessment, sustainability, reclaimed asphalt, rejuvenator, warm mix asphalt

Received: May, 2025; Revised final: August, 2025; Accepted: September, 2025; Published in final edited form: October, 2025

1. Introduction

In recent decades, road traffic has grown exponentially due to increasing urbanisation and economic development (Grael et al., 2021). This has led to an expansion of the road infrastructure and a consequent growth in maintenance work, resulting in an increased environmental impact (Elliot et al., 2023; Ma et al., 2021; Wang et al., 2021). Faced with this situation, the international community has taken measures to significantly reduce the environmental impact of the transport sector (Chen et al., 2021). The most challenging of these targets is to reduce greenhouse gas emissions to zero by 2050 (Yaro et al., 2023). Within this context, the academic and industrial communities have become increasingly interested in innovative technologies that can reduce the release of greenhouse gases (GHG) into the atmosphere (Abdalla et al., 2022).

One of the ways to reduce the environmental impact of a road, and therefore energy consumption, is to lower the processing and mixing temperatures of the AC mixture (Araujo et al., 2023). In fact, conventional hot mix asphalt (HMA) is produced at temperatures between 150°C and 190°C (Cheraghian et al., 2020), but there are technologies that can reduce the processing temperature of an AC from 20°C to 40°C (Caputo et al., 2020; Ferrotti et al., 2024; Vishal

* Author to whom all correspondence should be addressed: e-mail: carlo.carpani@iterchimica.it

et al., 2020). There are three main methods of reducing production temperatures, including organic additives (waxes), chemical additives and foaming process, each of which acts differently to improve the workability of the bituminous mixture (Bueche et al., 2024; Prakash and Suman, 2022; Zhang et al., 2021).

The use of WMAs provides several benefits including reduced atmospheric emissions and energy consumption (Sukhija and Saboo, 2021), improved working conditions for workers (Vaitkus et al., 2016), increased transport distances (Praticò et al., 2020), the possibility of laying the material even in colder seasons by extending operating periods (Bueche et al., 2024) and less ageing of the bituminous binder constituting the mixture (Keymanesh et al., 2023). Quantifying the environmental benefits of these technologies is by no means straightforward, and indeed the results vary widely in the literature. For this reason, the European Asphalt Pavement Association (EAPA) carried out a life cycle assessment study comparing WMA with HMA, which showed a 24% decrease in air pollutants, an 18% lower fossil fuel consumption, a 10% less formation of smog and a 3% reduction in global warming potential using WMA technologies (EAPA, 2022).

Another way to make a road pavement sustainable is to use recycled material (Mariyappan et al., 2023). One of the most reused construction products worldwide is the reclaimed asphalt pavement (RAP) (Tarsi et al., 2020). The reuse of this material provides numerous advantages from an economic, but above all environmental point of view (Saltan and Khaliqi, 2024; Xiao et al., 2019). In fact, the use of RAP makes it possible to reduce road construction waste by incorporating it into new pavements, saving bitumen and virgin aggregates (Baghaee Moghaddam and Baaj, 2016; La Macchia et al., 2024). It also reduces energy consumption and environmental impact associated with the extraction and transport of virgin materials (Aurangzeb et al., 2014; Harvey et al., 2020). Finally, another environmental benefit is the reduction in landfill space required for the disposal of RAP (West, 2010). One of the disadvantages of this material is that the bitumen covering the aggregate is highly oxidised after its service life, which leads to stiffening and consequent brittleness of the asphalt mixture (Prosperi and Bocci, 2021). For this reason, road agencies usually limit the maximum amount of RAP that can be recycled in new hot mixes (Zaumanis et al., 2016). However, nowadays there are products on the market that can partially or fully restore the chemical properties of oxidised bitumen, allowing asphalt mixtures to be produced with high RAP content (Caputo et al., 2021). The maximum amount of RAP that can be reused in HMA production depends not only on the ability to correct the physico-chemical properties of the aged bitumen, but also on the production technology. When considering hot-in-place recycling, the percentage of reusable RAP in batch plants ranges from 10% to 30%, whereas most conventional drum plants can accommodate 50% RAP (Mazzoni et al., 2018). However, in recent years, new plants (with double drum) have been developed capable of increasing RAP percentages without the need to excessively superheat the virgin aggregates or expose RAP to direct flame (Zaumanis and Mallick, 2014). A notable example of the effective use of high RAP content in combination with a rejuvenating agent is found on the A4 Turin–Milan motorway (Italy), where the binder and base layers of the slow lane were constructed using an asphalt mixture containing 67% RAP, a bio-based rejuvenator, and a graphene-enhanced polymeric compound. The study began with a 2 km trial section, followed by comprehensive laboratory testing and in-situ performance monitoring over a two-year period. The results demonstrated an increase in service life of up to 75% compared to the conventional mixture typically employed by the motorway operator, which consists of PMB and 30% RAP (Sogno et al., 2024).

A further solution to reduce the environmental and energy impact of an asphalt concrete is the simultaneous use of WMA and RAP (adequately treated with rejuvenators) (Guo et al., 2020). The two technologies are highly compatible, as the use of the former, especially in large quantities, leads to a decrease in the viscosity of the mixes, which can be compensated by the use of WMA which instead leads to a reduction in workability (Guo et al., 2020; Ingrassia et al., 2021). The long-term effectiveness of these technologies was studied by Spadoni et al. (2022) in a motorway trial section. Specifically, SBS-modified WMA+RAP (with chemical additive) mixtures were compared with SBS-modified HMA+RAP mixtures (25% RAP for the binder course and 30% RAP for the base course). The section was then monitored for 6 years evaluating the evolution of the stiffness and fatigue behaviour of the mixes. The results showed that WMA+RAP section has better long-term performance with respect to the reference section (Spadoni et al., 2022). This result is probably due to the presence of anti-stripping agents within the chemical additives, which allow a decrease in the ageing of the mixtures during the service life (Monu et al., 2019).

A few studies assessing the feasibility of incorporating high RAP content into WMA suggesting that this technology could be applied with very high RAP amounts close to 100% (D'Angelo et al., 2008; Lu and Saleh, 2016; Mallick et al., 2008; Tao and Mallick, 2009; Wang et al., 2022).

Life Cycle Assessment (LCA) is an increasingly important method of quantitatively assessing the environmental impact of a product or technology over its life cycle (Lvel et al., 2020; Vega et al., 2022). In fact, the impacts of a product are not limited to the manufacturing stage but occur throughout its entire life cycle, encompassing the extraction and transportation of raw materials, usage and maintenance, potential reuse, and disposal at the end of its life (Bonoli et al., 2020). For this reason, there are several approaches to assessing the impact of a technology, including "from cradle to grave", "from cradle to gate", "from cradle to laid" and "from cradle to cradle" (Moretti et al., 2017; SETAC, 1993; Vega et al., 2022).

From the LCA point of view, there are numerous studies on WMAs (Hassan, 2010; Ma et al., 2019; Mazumder et al., 2016; Wu and Qian, 2014), as well as on RAP and rejuvenators (Elkashef et al., 2020; Forton et al., 2021; Moins et al., 2021; Tushar et al., 2025; Vandewalle et al., 2020), but also on WMA+RAP technologies (Aurangzeb et al., 2014; Bizarro et al., 2021; Ferrotti et al., 2024; Martinez-Soto et al., 2023; Santos et al., 2018; Vidal et al., 2013). However, the literature lacks a more in-depth study of the environmental impact of RAP percentages in HMAs and RAP percentages in WMAs, as well as detailed investigations on products that function simultaneously as rejuvenators and thermos-regulators. In fact, while WMAs and RAP have been studied separately, their combined effects, especially with a single multifunctional additive, remain underexplored. The objectives of this study were to: (1) compare the environmental impact of WMA and HMA; (2) evaluate the effect of RAP content on the environmental performance of HMA; and (3) investigate the potential synergistic environmental effects of combining WMA and RAP using an innovative bio-based dual-function additive.

In particular, the RAP content was varied from 0% to 100%, with a growth rate of 10%. Analyses were carried out considering three different types of asphalt concrete traditionally used in road construction, namely an AC with neat bitumen, a SBS-polymer modified AC, and an AC modified with polymeric compounds.

2. Methods

The LCA analysis was conducted in five different steps, as suggested by European stardards (UNI EN ISO 14040, 2021; UNI EN ISO 14044, 2021):

- goal and scope definition;
- functional unit and system boundaries;
- inventory analysis;
- impact assessment;
- interpretation of results.

The following sections will go into detail about the considerations made for each of the steps.

2.1. Goal and scope definition

The main objective of this study was to assess the environmental impacts of WMA containing RAP and rejuvenators. To do this, three further subgoals were defined:

- compare the environmental impacts of WMAs with conventional HMAs, varying the type of AC;
- evaluate the environmental impacts of HMAs as a function of RAP content (and rejuvenator), as the AC type varies;
- assessing the environmental impact of WMA as a function of RAP content (using a product that can fulfil the two different functions simultaneously), as the type of CB varies. The AC studied in this research were of 3 different types:
- an asphalt concrete with neat bitumen (NB);
- an asphalt concrete modified (wet modification method) with SBS polymers (PMB);
- an asphalt mix modified (dry modification method) with polymeric compounds (PC).

2.2. Functional unit and system boundaries

To achieve these objectives, several "cradle-to-laid" LCA were therefore performed. This approach was chosen to evaluate the impact of different additives and technologies during the production processes of bituminous mixtures. However, it does not consider the actual performance of the material (i.e., service life) or the use phase of the road pavement. In other words, the LCA analysis included the following steps: raw material supply (A1), transport to plant (A2), manufacturing (A3), transport to site (A4), and construction process (A5). Specifically, in the case of CP, it includes the following processes which follow chronologically within the life cycle assessment (Diab & Al-Qadi, 2024):

a) transportation of waste plastics from the landfill to the recycling facility for processing;
b) sorting of plastics according to colour, type and thickness at the recycling facility;
c) shredding and removal of impurities at the recycling facility;
d) processing plastics into granulates for ease of use;
e) transportation of processed plastic to the asphalt plant;
f) supply and transport of virgin materials including aggregate, RAP and bitumen to the asphalt plant;
g) AC production;
h) transport of the AC to the construction site;
i) on-site construction operations.

Differently, the PMB asphalt production operations are summarised as follows:

a) raw polymer production;
b) transport of hot bitumen and polymer to the refinery;
c) polymer modify bitumen production;
d) supply and transport of virgin materials including aggregate, RAP and polymer modified bitumen to the asphalt plant;
e) AC production;
f) transport of the AC to the construction site;
g) on-site construction operations.

The processes and system boundaries of the AC production for both the PC and PMB asphalt concrete are shown in Figs. 1-2. In the scope of this LCA, the functional unit was defined as 1 ton of manufactured AC mixture. The AC mixture studied in this paper is typical for a binder course and consists of 95.4% raw aggregate and 4.6% bitumen.

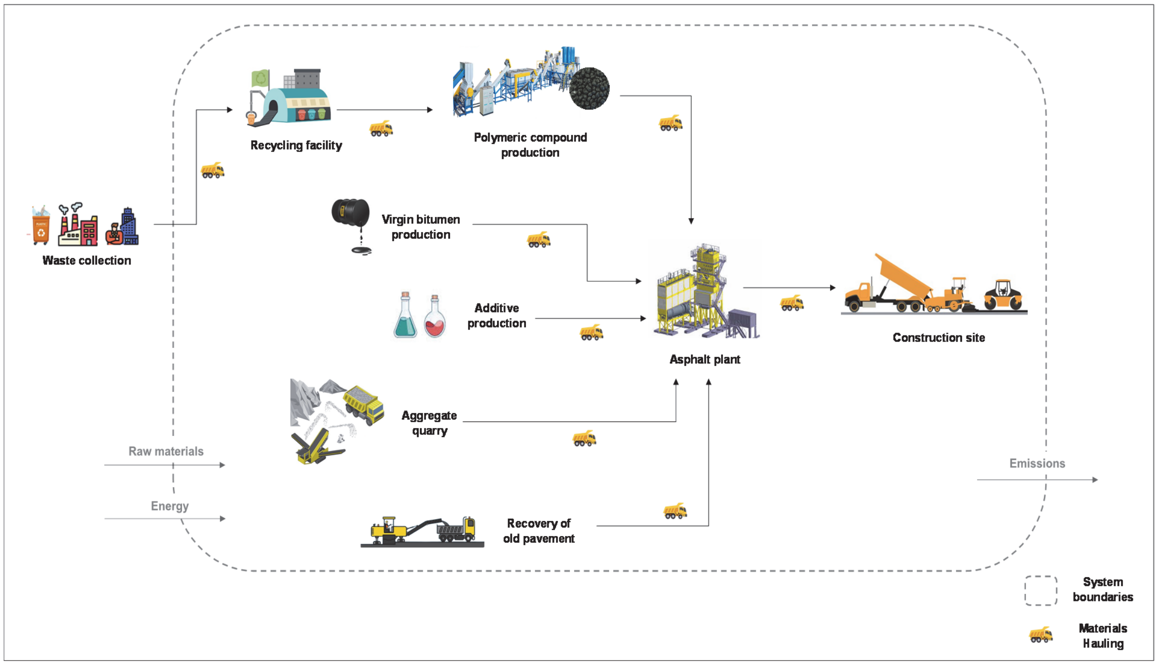


Fig. 1. Materials stage boundaries and processes for PC mixture production

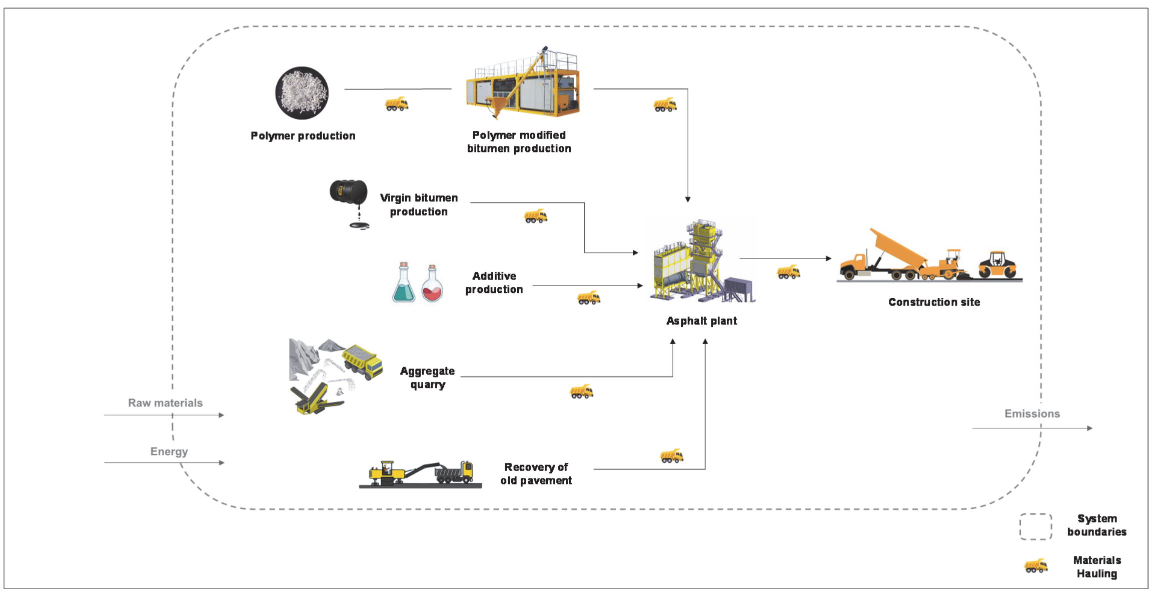


Fig. 2. Materials stage boundaries and processes for PMB mixture production

When RAP was introduced into the mixture, the quantities of raw aggregate and bitumen (assuming complete regeneration of the bitumen covering the RAP aggregate through the use of a bio-based rejuvenator dosed at 0.2% of the RAP content) were consequently reduced. This assumption is based on the fact that these rejuvenators are capable of fully restoring the properties of the bitumen surrounding the RAP, as confirmed by a study carried out in collaboration with the University of Calabria in Italy (Caputo et al., 2023). The amount of polymer (derived 100% from recycled hard plastics) included in the PC mixture was 5% by weight of the total bitumen. For the PMB mixture, a 45/80-70 modified bitumen was considered. A chemical additive at 0.3% by bitumen weight was used to investigate the impact of mixtures produced at reduced temperatures. Finally, when mixtures produced and laid at reduced temperatures (20 °C less) and containing RAP were studied, a chemical additive (0.1% by bitumen weight) that could guarantee the reduction of temperatures and at the same time the regeneration of the RAP bitumen was taken into account. The AC production temperatures considered in the analysis were 160 °C for the NB mixture and 170 °C for PMB and PC mixtures. In the case of WMA, these temperatures were reduced to 140 °C and 150 °C respectively. The location of the asphalt plant and the construction site were assumed in the north of Italy.

2.3. Inventory analysis

In this section, data collection and calculation procedure are described. The analyses were carried out using a software tool developed in-house by Iterchimica S.p.A., which was validated through comparison with other commercially available LCA calculation tools in collaboration with Italian universities.

The inventory data used were obtained from surveys of asphalt plant operators and contractors in northern Italy and from the literature. Tables 1 to 4 summaries the data used, list their respective sources, and indicate whether the data are primary or secondary. For example, with regard to transport distances, average values were provided by the manufacturer.

The Environmental Product Declarations (EPD) of the products were used to define the environmental impact of the chemical additives (WMA additive, rejuvenator, and WMA+RAP additive).

2.4. Impact assessment

The fourth part of the LCA is the life cycle impact assessment. For this study, two different parameters were used to compare the environmental impact of different technologies, i.e. CO_{2eq} production and energy consumption.

3. Results

3.1. WMA vs HMA

Figures 3 and 4 show the impact values (CO_{2eq} and energy consumption) of 1 ton of three different types of AC mixtures: NB, PMB, and PC.

Table 1. Machine consumptions

Machine	*Unit*	*Value*	*Source (primary data)*
240 t/h AC production plant	kWh/t_{AC}	9	Asphalt plant operators and contractors' data
	m^3/t_{AC}	8	
30 t dumping truck	l/km	0.6	
Front-end loader for AC production plant	l/h	23	
Asphalt paver	l/h	21	
Asphalt milling	l/h	99.8	
Spraying tank for bitumen emulsion	l/h	8.5	
Road sweeper	l/h	15	

Table 2. Material transport distances

Operations	*Unit*	*Value*	*Source (primary data)*
From quarry to AC plant	km	20	Asphalt plant operators and contractors' data
From refinery of bitumen/modified bitumen/bitumen emulsion to AC plant	km	200	
From PC recycling facility to AC plant	km	175	
From AC plant to construction site	km	50	

Table 3. Machine productivity

Machine	*Unit*	*Value*	*Source (primary data)*
AC production plant	t/h	240	Asphalt plant operators and contractors' data
Front-end loader for AC production plant	t/h	220	
Road roller	m^3/h	40	
Asphalt paver	t/h	140	
Road sweeper	km^2/h	0.038	
Spraying tank for bitumen emulsion	km^2/h	0.025	
Asphalt milling	t/h	200	

Table 4. Bitumen and modifiers production

Materials	*Unit*	*Value*	*Source*
Bitumen environmental impact	kg_{CO2eq}/t	207.5	Eurobitume (2019), Asphalt Institute (2019) ***(secondary data)***
Bitumen energy consumption	MJ/t	45,772	
SBS-polymer modified bitumen environmental impact	kg_{CO2eq}/t	350	Asphalt Institute (2019); Eurobitume (2011), Reeves et al. (2020) ***(secondary data)***
Polymer modified bitumen energy consumption	MJ/t	55,200	
SBS polymer environmental impact	kg_{CO2eq}/t	4,000	Asphalt Institute (2019) ***(secondary data)***
SBS polymer energy consumption	MJ/t	-	
PC environmental impact	kg_{CO2eq}/t	611	EPD International (2023) ***(primary data)***
PC energy consumption	MJ/t	9,350	

Overall, the reduction of production and paving temperatures allows a reduction of both the carbon footprint and energy consumption, regardless of the type of mixture considered (between 5% and 7% in terms of CO_{2eq} and between 5% and 6% in terms of energy consumption). The results in terms of CO_{2eq} (Fig. 3) are fully in line with a document from the National Asphalt Pavement Association (NAPA), which reports savings of 3.6-6% considering stages A1-A3 (Shacat et al., 2024). Comparing the three different mixtures produced at conventional temperatures (HMA), NB is clearly the mixture with the lowest environmental (45,500 kg of CO_{2eq}, Fig. 3) and energy (2.45 GJ, Fig. 4) impact per ton of AC produced. PC mixture was slightly more impactful than NB due to the use of the polymer compound, +6% environmentally (48,500 kg of CO_{2eq}) and +2% in terms of energy (2.5 GJ).

Finally, the PMB mixture had +17% and +41% for environmental (58,000 kg of CO_{2eq}) and energy (4.16 GJ) impact, respectively. This last result is linked to the modified bitumen production processes, which require the bituminous binder to be maintained at high temperatures to homogenously disperse the polymer within it (Akimov et al., 2024).

3.2. Environmental and energy impact of HMA as a function of the RAP content

The comparison of HMA and HMA+RAP+Rejuv. (Figs. 5-6) allowed the influence of the RAP content on the emissions and energy consumption resulting from the production of one ton of AC to be determined. First of all, it should be emphasized that the results for the PMB material consider a maximum RAP content of 50%. This is because in these materials the polymer is added by means of bitumen (wet process).

As the amount of RAP increases, the amount of modified bitumen added decreases and so does the content of polymer in the mix (Bocci et al., 2024; Bruno et al., 2024; Suchismita and Singh, 2023), making these materials inadequate for the contexts in which they are normally used, i.e. high traffic density roads. In addition, a maximum content of 70% RAP was considered for all mixtures, as higher contents are possible, but the technologies available today do not allow adequate performance ACs to be obtained with such high levels of recycled material content, except for roads with low traffic levels.

Comparing the three different mixtures, PMB results in higher CO_{2eq} (Fig. 5) and energy consumption (Fig. 6), followed by PC and finally NB, regardless of RAP content. As can be seen from Fig. 5, the environmental impact decreases as the RAP content increases and the raw materials (aggregates and RAP) decrease, regardless of the type of AC considered. Specifically, the carbon footprint of the NB mixture is reduced by 12% with 30% RAP, 20% with 50% RAP, 30% with 70% RAP and 44% with theoretical 100% RAP, compared to the mix without recycled aggregates.

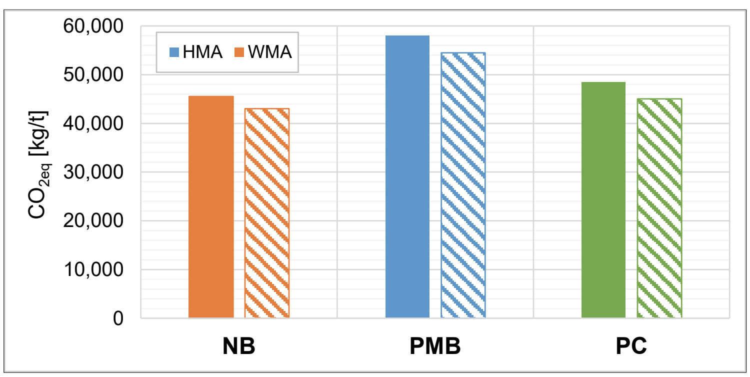


Fig. 3. Equivalent CO_2 consumption for 1 t of NB, PMB and PC mixtures (HMA vs WMA)

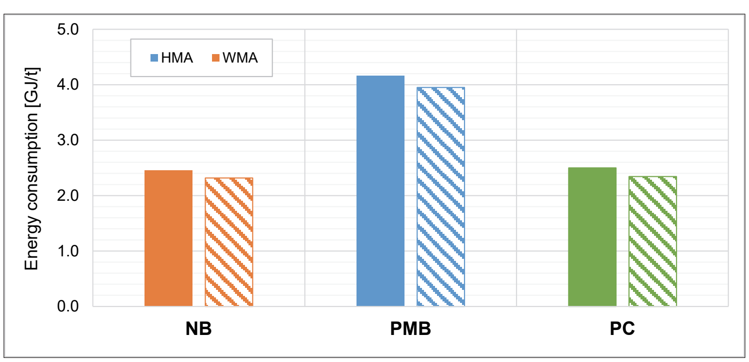


Fig. 4. Energy consumption for 1 t of NB, PMB and PC mixtures (HMA vs WMA)

For the PMB mix, the environmental savings were 14.6% and 24% for 30% and 50% RAP content respectively. Finally, for the PC material, the CO_{2eq} reductions were 12% for 30% RAP, 20% for 50% RAP, 28% for 70% RAP and 41% for a theoretical use of 100% recycled aggregate from old pavements. In general, it results that for every 1% of RAP recycled, there are approximately 0.37-0.44% less CO_{2eq} emissions, according to the type of mixture considered. As far as energy consumption is concerned (Fig. 6), the same trend of decreasing energy consumed as RAP increases (mainly due to energy savings for the production and transport of aggregates and bitumen) can be observed. Considering the NB mixture, energy savings were 23% at 30% RAP, 38% at 50% RAP, 54% at 70% RAP, and 78% at 100% RAP. When the PMB is considered, the savings were 24% and 40% for 30% and 50% RAP, respectively, while with PC were 22%, 37%, 53% and 76% for 30%, 50%, 70% and 100% RAP, respectively. In general, it results that for every 1% of RAP recycled, there are approximately 0.71-0.78% less energy consumption.

3.3. Environmental and energy impact of WMA as a function of the RAP content

This section analyses the results of CO_{2eq} and energy consumption during the life cycle of AC made with a special additive that is able to lower production temperatures and at the same time allow the regeneration of the RAP. The results are presented for both NB (Fig. 7), PMB (Fig. 8) and PC (Fig. 9) material. The multifunctional additive further reduces emissions and energy consumption, depending on the different percentages of recycled material and the type of modification used. As showed in Fig. 7a, taking the HMA without RAP as a reference, the estimated benefits for emissions in the case of NB are 17% with 30% RAP, 25% with 50%, 34% with 70%, and finally 48% with a theoretical use of 100% RAP. In the case of PMB and PC (Fig. 8a and 9a respectively), emissions are reduced by 21% and 19% with 30% RAP, and 30% and 26% with 50% RAP, respectively.

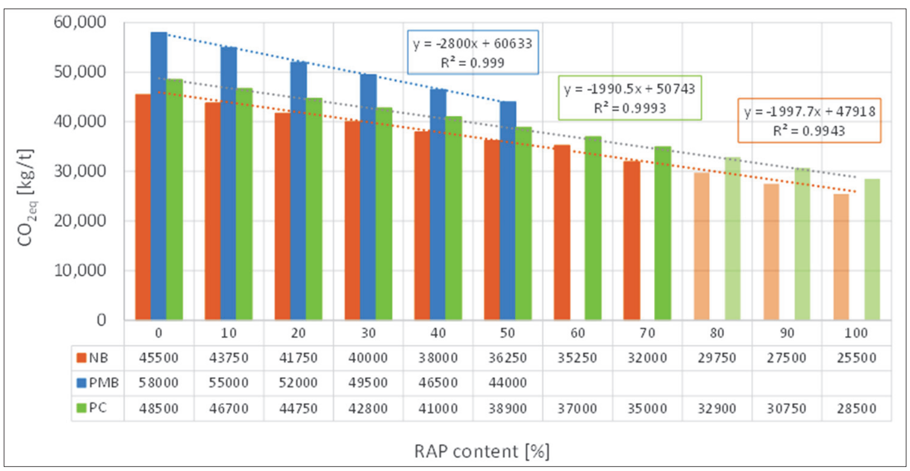


Fig. 5. Equivalent CO_2 consumption for 1 t of HMA (NB, PMB and PC) as a function of the RAP content

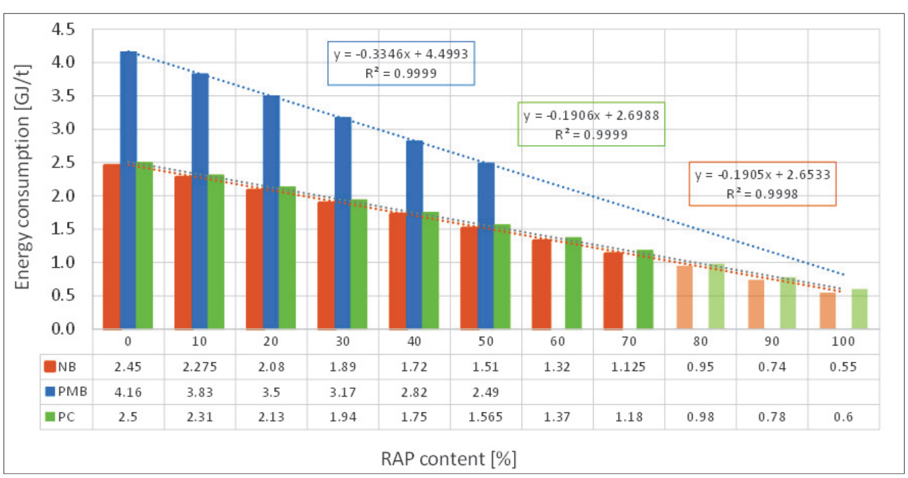


Fig. 6. Energy consumption for 1 t of HMA (NB, PMB and PC) as a function of the RAP content

With 70% recycled aggregate content, PC results in a 35% reduction in CO_{2eq}, which becomes 48% with a theoretical use of 100% RAP. In general, it emerges that for every 1% RAP added in the mixture, there is approximately 0.48-1.12% less CO_{2eq} emissions. Lastly, as far as energy consumption is concerned, it ranges from 27% to 80% with NB (Fig. 7b), 13% to 44% with PMB (Fig. 8b) and 28% to 80% with PC (Fig. 9b). For every 1% RAP, there is approximately 0.8-1.3% less energy consumption.

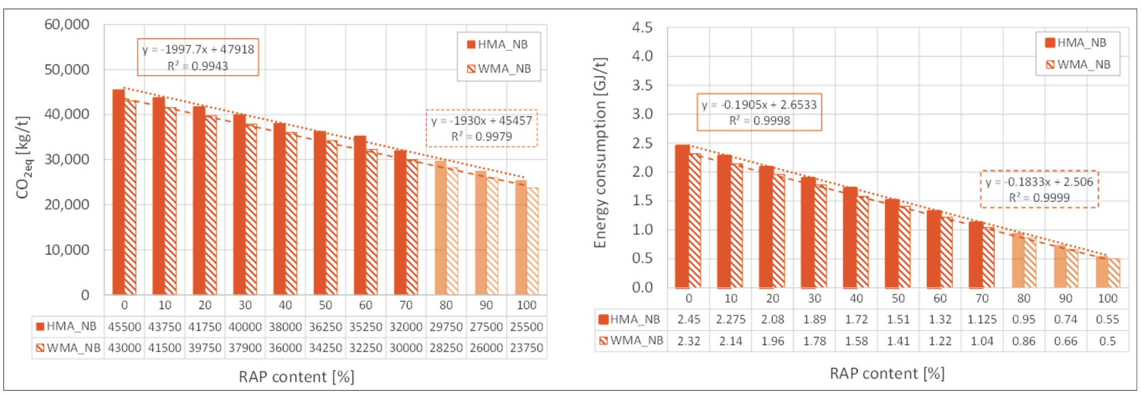
4. Discussion and limitations

The results described in the previous chapter are highly significant when compared with industry benchmarks and align with the European Union's Green Deal targets, which include a 55% reduction in CO_{2eq} emissions by 2030, climate neutrality by 2050, improved energy efficiency of over 11.7% by 2030, and, above all, the promotion of recycling and the reduced use of raw materials.

It is important to note, however, that the results are strongly influenced by the assumptions made during the modeling phase; particularly regarding parameters such as transport distances, plant and fuel types, and the characteristics of the RAP (bitumen content, presence of polymer modification, and the degree of bitumen oxidation). These factors can introduce substantial variability in the outcomes, which was not explored in detail within the scope of this study.

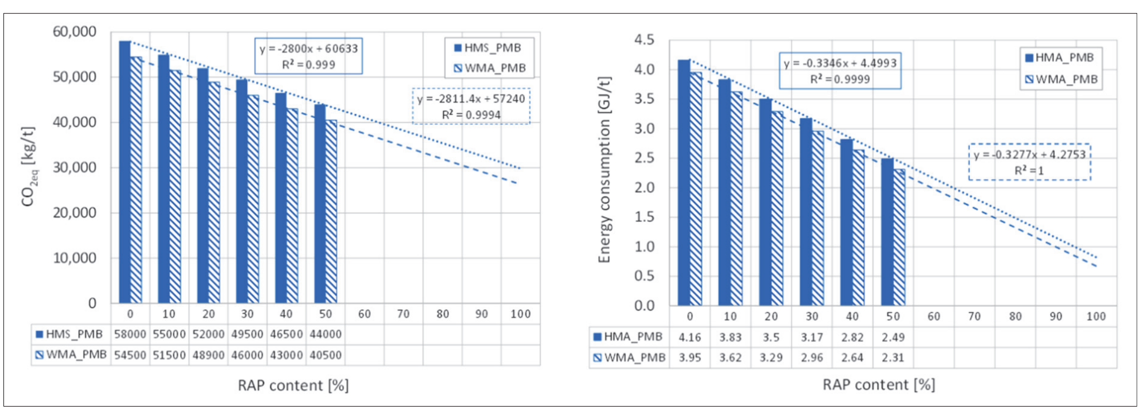
A further critical consideration pertains to the characteristics and intended applications of the asphalt mixtures under investigation (NB, PMB, and PC). NB mixtures, typically employed in low-traffic road infrastructures, can contain up to 100% RAP, provided that a suitable rejuvenating additive is incorporated to restore the aged binder's functional properties. In contrast, PMB and PC mixtures are generally designed for high-traffic pavements, where enhanced mechanical performance and long-term durability are required (although they require a higher initial investment, these mixtures offer long-term cost savings due to their reduced maintenance needs). PMB mixtures rely on the wet modification process, where polymers are blended directly with the raw binder.

This approach inherently limits the feasible incorporation of RAP to a maximum of 50%, beyond which the performance characteristics tend to deteriorate due to the reduced influence of the modified raw binder on the overall mix.



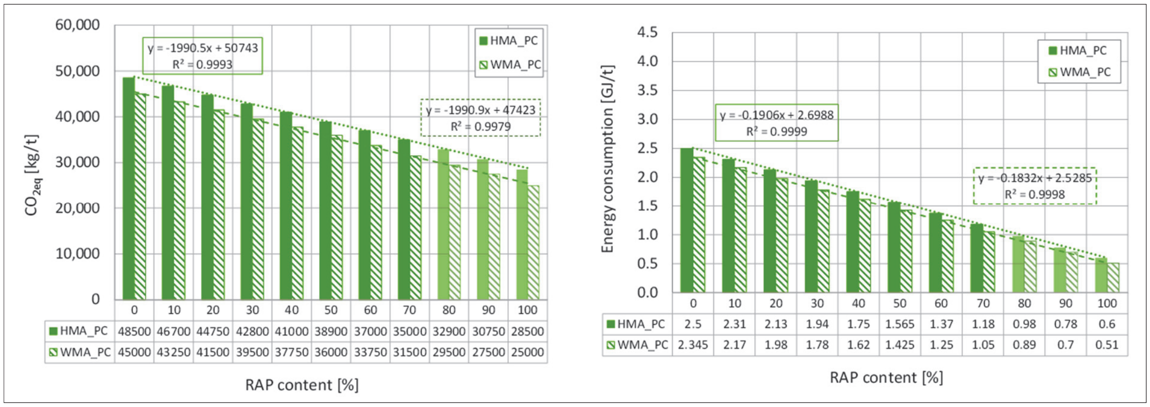
(a) (b)

Fig. 7. (a) Environmental and (b) energy impact of WMA as the RAP content varies (NB)



(a) (b)

Fig. 8. (a) Environmental and (b) energy impact of WMA as the RAP content varies (PMB)



(a) (b)

Fig. 9. (a) Environmental and (b) energy impact of WMA as the RAP content varies (PC)

Conversely, PC mixtures utilize the dry modification technique, whereby the polymeric compound is introduced directly into the asphalt mixture, enabling more effective performance control even at higher RAP contents.

Based on these technical considerations, the analysis of PMB mixtures was therefore restricted to RAP contents not exceeding 50%. However, it should be noted that even for PC mixtures, incorporating more than 70% RAP may lead to a significant reduction in mechanical performance. Therefore, the results presented in this study for RAP contents above 70% are to be considered theoretical and should be interpreted with appropriate caution.

5. Conclusions

The objective of this paper was to quantify the environmental and energy consumption impact of WMA containing different RAP percentages. Several LCA analysis (from cradle to laid) were carried out, which first confirmed that WMA technology allows a slight reduction of the carbon footprint and energy consumption (5-7% and 5-6% respectively), as confirmed by other international studies already carried out for this purpose.

Secondly, the use of RAP within AC mixtures has been shown to be very positive both environmentally and energetically (up to 30% and 54% less CO_{2eq} and energy considering a RAP content of up to 70%). This is because the use of RAP (suitably treated with rejuvenators) results in a consequent decrease of raw aggregates and bitumen in the mixture. However, it is important to emphasize that when the quantities of RAP are very high, the asphalt plant management (e.g. the management of RAP, aggregate moisture, and the use of additive) is of crucial importance to guarantee AC performance according to the level of traffic on the road. Nowadays, this is only feasible with modern asphalt plants (i.e. with double drum).

The final step in the analysis was to assess the impact of WMA+RAP technology, which allows old pavements to be recycled while reducing asphalt concrete production and laying temperatures. In this case, WMA-RAP synergies reduce CO_2eq by 35-50% and energy consumption by 54-80%. These results support the EU's 2035 emissions targets. Moreover, these technologies also greatly simplify the management of the asphalt plant as it only needs to handle one product instead of two. Finally, an additional aspect that emerged is that wet AC modification (PMB) involves higher energy consumption than dry modification (PC), due to the different production processes of the different materials.

This LCA study considered only the material supply, production, and construction phases; therefore, future research will focus on more comprehensive analyses (cradle-to-grave LCA), taking into account the actual performance of the different technologies, as well as the impacts related to durability and the number of maintenance operations.

References

Abdalla A., Faheem A.F., Walters E., (2022), Life cycle assessment of eco-friendly asphalt pavement involving multi-recycled materials: A comparative study, *Journal of Cleaner Production*, **362**, https://doi.org/10.1016/j.jclepro.2022.132471.

Akimov A.E., Yadykina V.V., Lebedev M.S., Denisov V.P., Inozemtcev S.S., Inozemtcev A.S., Korshunov A.V., Pilipenko A.S., (2024), Development of an energy-efficient method of obtaining polymer-modified bitumen with high operational characteristics via polymer–bitumen concentrate application, *Journal of Composites Science*, **8**, https://doi.org/10.3390/jcs8090337.

Araujo D.L.V., Santos J., Martinez-Arguelles G., (2023), Environmental performance evaluation of warm mix asphalt with recycled concrete aggregate for road pavements, *International Journal of Pavement Engineering*, **24**, https://doi.org/10.1080/10298436.2022.2064999.

Aurangzeb Q., Al-Qadi I.L., Ozer H., Yang R., (2014), Hybrid life cycle assessment for asphalt mixtures with high RAP content, *Resources, Conservation and Recycling*, **83**, 77-86.

Baghaee Moghaddam T., Baaj H., (2016), The use of rejuvenating agents in production of recycled hot mix asphalt: A systematic review, *Construction and Building Materials*, **114**, 805-816.

Bizarro D.E.G., Steinmann Z., Nieuwenhuijse I., Keijzer E., Hauck M., (2021), Potential carbon footprint reduction for reclaimed asphalt pavement innovations: Lca methodology, best available technology, and near-future reduction potential, *Sustainability*, **13**, 1382, https://doi.org/10.3390/su13031382.

Bocci E., Carpani C., Prosperi E., (2024), *Use of Highly Modified Asphalt and Rejuvenators to Restore the Rheological and Mechanical Properties of Aged Polymer-Modified Bitumen*, 14th Intern. Conf. on Asphalt Pavements ISAP2024 Montreal, https://doi.org/10.1007/978-3-031-67252-1_3.

Bonoli A., Degli Esposti A., Magrini C., (2020), A case study of industrial symbiosis to reduce GHG emissions: Performance analysis and LCA of asphalt concretes made with RAP aggregates and steel slags, *Frontiers in Materials*, **7**, 572955, http//doi.org/ 10.3389/fmats.2020.572955.

Bruno S., Carpani C., Loprencipe G., Venturini L., Vita L., (2024), Modified asphalt with graphene-enhanced polymeric compound: A case study, *Infrastructures*, **9**, https://doi.org/https://doi.org/10.3390/infrastructures9030039.

Bueche N., Probst S., Eskandarsefat S., (2024), Warm-mix asphalt containing reclaimed asphalt pavement: A case study in Switzerland. *Infrastructures*, **9**, https://doi.org/10.3390/infrastructures9050079.

Caputo P., Abe A.A., Loise V., Porto M., Calandra P., Angelico R., Rossi C.O., (2020), The role of additives in warm mix asphalt technology: An insight into their mechanisms of improving an emerging technology, *Nanomaterials*, **10**, 1202, http://doi.org/10.3390/nano10061202

Caputo P., Eskandarsefat S., Porto M., Loise V., Rossi C.O., Scarpelli F., De Santo M.P., Venturini L., (2021), *Towards Advances in Differentiating Recycling Agents: Softening Agents vs. Rejuvenating Agents*, Proc. of the 7th EE Congress Eurasphalt Eurobitume, On line at: https://repo.pw.edu.pl/info/book/WUT89a0861e94034d5998d8dddc9e603ce0/Proceedings+of+the+7th+Eurasphalt+&+Eurobitume+Congress+v1.0?ps=20&lang=en&pn=1&cid=584168

Caputo P., Eskandarsefat S., Porto M., Loise V., Abe A.A., Calandra P., Venturini L., Rossi C.O., (2023), Effect and mechanism of rejuvenation of field-aged bitumen extracted from reclaimed asphalt pavement, *Transportation Research Procedia*, **69**, 863-870.

Chen X., Wang H., Horton R., DeFlorio J., (2021), Life-cycle assessment of climate change impact on time-dependent carbon-footprint of asphalt pavement, *Transportation Research Part D: Transport and Environment*, **91**, 102697 https://doi.org/10.1016/j.trd.2021.102697.

Cheraghian G., Cannone Falchetto A., You Z., Chen S., Kim Y.S., Westerhoff J., Moon K. H., Wistuba M.P., (2020), Warm mix asphalt technology: An up to date review, *Journal of Cleaner Production*, **268**, 122128, https://doi.org/10.1016/j.jclepro.2020.122128.

D'Angelo J., Harm E., Bartoszek J., Baumgardner G., Corrigan M., Cowsert J., Harman T., Jamshidi M., Jones W., Newcomb D., Prowell B., Sines R., Yeaton B., (2008), *Warm-Mix Asphalt: European Practice*, Federal Highway Administration.

Diab L., Al-Qadi I.L., (2024), Life Cycle Assessment for the use of waste plastics in asphalt concrete mixes, *Transportation Research Record*, https://doi.org/10.1177/03611981241245674.

EAPA (2022), *Technical Aspects of the use of Warm Mix Asphalt,* EAPA Technical Review, On line at: https://eapa.org/technical-aspects-of-the-use-of-warm-mix-asphalt-view-online/

Elkashef M., Saboori A., Ostovar M., Harvey J.T., Butt A.A., Jones D., (2020), *Sensitivity Analysis of the Benefits of Replacing Virgin Materials with RAP Considering Rejuvenator Type and Hauling Distance*, In: *Pavement, Roadway, and Bridge Life Cycle Assessment*, Harvey J., Al-Qadi I.L, Ozer H., Flintsch G. (Eds.), CRC Press, https://doi.org/10.1201/9781003092278-39.

Elliot T., Carter A., Ghattuwar S., Levasseur A., (2023), Environmental impacts of road pavement rehabilitation, *Transportation Research Part D: Transport and Environment*, **118**, 103720, https://doi.org/10.1016/j.trd.2023.103720.

EPD International, (2023), Environmental product declaration of Gipave, On line at: https://api.environdec.com/api/v1/EPDLibrary/Files/7735f1ad-5308-40fc-0496-08db8d1ef4eb/Data.

Eurobitume, (2011), Life cycle inventory: Bitumen, Eurobitume report, On line at: https://eurobitume.eu/bitumen-life-cycle-assessment/.

Eurobitume, (2019), The Eurobitume Life-Cycle Inventory for bitumen, Version 3.0, 3rd edition, On line at: https://eurobitume.eu/bitumen-life-cycle-assessment/.

Ferrotti G., Mancinelli E., Passerini G., Canestrari F., (2024), Comparison of energy and environmental performance between warm and hot mix asphalt concrete production: A case study, *Construction and Building Materials*, **418**, 135453, https://doi.org/10.1016/j.conbuildmat.2024.135453.

Forton A., Ciutina A., Marc P., (2021), Environmental impact of bituminous mixtures produced with reclaimed asphalt pavement and rejuvenator, *IOP Conf. Series: Earth and Environmental Science*, **664**, 012010, https://doi.org/10.1088/1755-1315/664/1/012010.

Grael P.F.F., Oliveira L.S.B.L., Oliveira D.S.B.L., Bezerra B.S., (2021), Life cycle inventory and impact assessment for an asphalt pavement road construction-a case study in Brazil, *International Journal of Life Cycle Assessment*, **26**, 402-416

Guo M., Liu H., Jiao Y., Mo L., Tan Y., Wang D., & Liang M., (2020), Effect of WMA-RAP technology on pavement performance of asphalt mixture: A state-of-the-art review, *Journal of Cleaner Production*, **266**, 121704, https://doi.org/10.1016/j.jclepro.2020.121704

Harvey J.T., Butt A.A., Saboori A., Lozano M.T., Kim C., Kendall A., (2020), *Life cycle assessment and life cycle cost analysis for six strategies for GHG reduction in caltrans operations*, Technical Memorandum: UCPRC-TM-2019-02, https://doi.org/10.7922/G22R3PZG.

Hassan M., (2010), Evaluation of the environmental and economic impacts of warm-mix asphalt using life-cycle assessment, *International Journal of Construction Education and Research*, **6**, 238-250.

Ingrassia L.P., Cardone F., Ferrotti G., Canestrari F., (2021), Monitoring the evolution of the structural properties of warm recycled pavements with Falling Weight Deflectometer and laboratory tests, *Road Materials and Pavement Design*, **22**, 69-82.

Keymanesh M.R., Amani S., Omran A.T., Karimi M.M., (2023), Evaluation of the impact of long-term aging on fracture properties of warm mix asphalt (WMA) with high RAP contents, *Construction and Building*

Materials, **400**, 132671, https://doi.org/10.1016/j.conbuildmat.2023.132671.

La Macchia J.N., Baglieri O., Dalmazzo D., Santagata E., (2024), Engineering properties of road paving mixtures with high content of reclaimed asphalt and recycled waste plastics, *Materials*, **17**, 5681, https://doi.org/10.3390/ma17235681.

Lu D.X., Saleh M., (2016), Laboratory evaluation of warm mix asphalt incorporating high RAP proportion by using evotherm and sylvaroad additives, *Construction and Building Materials*, **114**, 580-587.

Lvel J., Watson R., Abbassi B., Abu-Hamatteh Z.S., (2020), Life cycle analysis of concrete and asphalt used in road pavements, *Environmental Engineering Research*, **25**, 52-61.

Ma F., Dong W., Fu Z., Wang R., Huang Y., Liu J., (2021), Life cycle assessment of greenhouse gas emissions from asphalt pavement maintenance: A case study in China, *Journal of Cleaner Production*, **288**, 125595, https://doi.org/10.1016/j.jclepro.2020.125595.

Ma H., Zhang Z., Zhao X., Wu S., (2019), A comparative life cycle assessment (LCA) of warm mix asphalt (WMA) and hot mix asphalt (HMA) pavement: A case study in China, *Advances in Civil Engineering*, https://doi.org/10.1155/2019/9391857.

Mallick R.B., Kandhal P.S., Bradbury R.L., (2008), Using warm-mix asphalt technology to incorporate high percentage of reclaimed asphalt pavement material in asphalt mixtures, *Transportation Research Record*, **2051**, 71-79.

Mariyappan R., Palammal J.S., Balu S., (2023), Sustainable use of reclaimed asphalt pavement (RAP) in pavement applications-a review, *Environmental Science and Pollution Research*, **30**, 30, 45587–45606.

Martinez-Soto A., Calabi-Floody A., Valdes-Vidal G., Hucke A., Martinez-Toledo C., (2023), Life Cycle Assessment of natural zeolite-based warm mix asphalt and reclaimed asphalt pavement, *Sustainability (Switzerland)*, **15**, 1003, https://doi.org/10.3390/su15021003.

Mazumder M., Sriraman V., Kim H.H., Lee S.J., (2016), Quantifying the environmental burdens of the hot mix asphalt (HMA) pavements and the production of warm mix asphalt (WMA), *International Journal of Pavement Research and Technology*, **9**, 190-201.

Mazzoni G., Bocci E., Canestrari F., (2018), Influence of rejuvenators on bitumen ageing in hot recycled asphalt mixtures, *Journal of Traffic and Transportation Engineering*, **5**, 157-168,

Moins B., Hernando D., Buyle M., France C., Audenaert A., (2021), Quantifying the environmental and economic impact of adding RAP and rejuvenators in asphalt pavements using LCA and LCCA, Final report for the users committee, https://doi.org/10.13140/RG.2.2.33684.83849.

Monu K., Ransinchung G.D., Singh S., (2019), Effect of long-term ageing on properties of RAP inclusive WMA mixes, *Construction and Building Materials*, **206**, 483-493.

Moretti L., Mandrone V., D'Andrea A., Caro S., (2017), Comparative "from cradle to gate" life cycle assessments of Hot Mix Asphalt (HMA) materials, *Sustainability*, **9**, 1-16.

Prakash G., Suman S.K., (2022), An intensive overview of warm mix asphalt (WMA) technologies towards sustainable pavement construction, *Innovative Infrastructure Solutions*, **7**, 110, https://doi.org/10.1007/s41062-021-00712-9.

Praticò F.G., Giunta M., Mistretta M., Gulotta T.M., (2020), Energy and environmental life cycle assessment of sustainable pavement materials and technologies for urban roads, *Sustainability*, **12**, 704, https://doi.org/10.3390/su12020704.

Prosperi E., Bocci, E., (2021), A review on bitumen aging and rejuvenation chemistry: Processes, materials and analyses, *Sustainability*, **13**, 6523, https://doi.org/10.3390/su13126523.

Saltan M., Khaliqi M.H., (2024), Effects of utilization of rejuvenator in asphalt mixtures containing recycled asphalt pavement at high ratios, *Case Studies in Construction Materials*, **20**, e03095, https://doi.org/10.1016/j.cscm.2024.e03095.

Santos J., Bressi S., Cerezo V., Lo Presti D., Dauvergne M., (2018), Life cycle assessment of low temperature asphalt mixtures for road pavement surfaces: A comparative analysis, *Resources, Conservation and Recycling*, **138**, 283-297.

SETAC, (1993), Guidelines for Life-Cycle Impact Assessment: Code of Practice, SETAC Workshop, Sesimbra (Portugal), On line at: https://www.setac.org/resource/guidelines-lca-code-practice-1993.html%0Ahttps://www.setac.org/resource/resmgr/books/lca_archive/guidelines_for_life_cycle.pdf.

Shacat J., Willis R., Ciavola B., (2024), *The Carbon Footprint of Asphalt Pavements: A Reference Document for Decarbonization*, NAPA, National Asphalt Pavement Association, March, On line at: https://www.asphaltpavement.org/uploads/documents/Climate/NAPA-SIP109-TheCarbonFootprintOfAsphaltPavements-March2024.pdf.

Sogno E., Ottonelli I., Carpani C., Venturini L., (2024), Structural and environmental assessment of high-performance asphalt mixes with a high reclaimed asphalt pavement content: a case study, *Environmental Engineering and Management Journal*, **10**, 2125-2138.

Spadoni S., Ingrassia L.P., Mariani E., Cardone F., Canestrari F., (2022), Long-term performance assessment of a warm recycled motorway pavement, *Case Studies in Construction Materials*, **17**, e01451, https://doi.org/10.1016/j.cscm.2022.e01451.

Suchismita A., Singh D., (2023), Rheological performance of bitumen mixed with laboratory simulated polymerized RAP binders, *Construction and Building Materials*, **400**, 132706, https://doi.org/10.1016/j.conbuildmat.2023.132706.

Sukhija M., Saboo N., (2021), A comprehensive review of warm mix asphalt mixtures-laboratory to field, *Construction and Building Materials*, **274**, 121781, https://doi.org/10.1016/j.conbuildmat.2020.121781.

Tao M., Mallick R.B., (2009), Effects of warm-mix asphalt additives on workability and mechanical properties of reclaimed asphalt pavement material, *Transportation Research Record*, **2126**, 151–160.

Tarsi G., Tataranni P., Sangiorgi C., (2020), The challenges of using reclaimed asphalt pavement for new asphalt mixtures: A review, *Materials*, **13**, 4052, https://doi.org/10.3390/ma13184052.

Tushar Q., Santos J., Zhang G., Robert D., Giustozzi F., (2025), Recycled used cooking oil (UCO) as a rejuvenator in high content reclaimed asphalt pavement (RAP) mixes: A life cycle assessment (LCA), *Science of the Total Environment*, **961**, 178376, https://doi.org/10.1016/j.scitotenv.2025.178376.

UNI EN ISO 14040, (2021), Environmental management - Life cycle assessment - principles and framework, On line at: https://www.iso.org/standard/37456.html.

UNI EN ISO 14044, (2021), Environmental management - life cycle assessment - requirements and guidalines, On line at: https://www.iso.org/standard/38498.html.

Vaitkus A., Čygas D., Laurinavičius A., Vorobjovas V., Perveneckas Z., (2016), Influence of warm mix asphalt technology on asphalt physical and mechanical properties, *Construction and Building Materials*, **112**, 800-806.

Vandewalle D., Antunes V., Neves J., Freire A.C., (2020), Assessment of eco-friendly pavement construction and maintenance using multi-recycled rap mixtures, *Recycling*, **5**, 17, https://doi.org/10.3390/recycling5030017

Vega AD.L., Santos J., Martinez-Arguelles G., (2022), Life cycle assessment of hot mix asphalt with recycled concrete aggregates for road pavements construction, *International Journal of Pavement Engineering*, **23**, 923–936.

Vidal, R., Moliner E., Martínez G., Rubio M.C., (2013), Life cycle assessment of hot mix asphalt and zeolite-based warm mix asphalt with reclaimed asphalt pavement, *Resources, Conservation and Recycling*, **74**, 101-114.

Vishal U., Chowdary V., Padmarekha A., Murali Krishnan J., (2020), Influence of moisture damage on fatigue of warm mix and hot mix asphalt mixture, *Journal of Materials in Civil Engineering*, **32**, https://doi.org/10.1061/(asce)mt.1943-5533.0003321.

Wang F., Hoff I., Yang F., Wu S., Xie J., Li N., Zhang L., (2021), Comparative assessments for environmental impacts from three advanced asphalt pavement construction cases, *Journal of Cleaner Production*, **297**, https://doi.org/10.1016/j.jclepro.2021.126659.

Wang W., Cheng H., Sun L., Sun Y., Liu N., (2022), Multi-performance evaluation of recycled warm-mix asphalt mixtures with high reclaimed asphalt pavement contents, *Journal of Cleaner Production*, **377**, 134209, https://doi.org/10.1016/j.jclepro.2022.134209.

West R.C., (2010), *Reclaimed Asphalt Pavement Management: Best Practices*, National Center for Asphalt Technology of Auburn University, On line at: https://thelibraryofcivilengineer.wordpress.com/wp-content/uploads/2015/09/rap-best-practices.pdf.

Wu S., Qian S., (2014), *Comparative Study of Warm Mix Asphalt and Hot Mix Asphalt Pavement Based on LCA*, In: *Life-Cycle of Structural Systems*, Furuta H., Frangopol D., Akiyama M. (Eds.), CRC Press, Boca Raton, USA, 1719-1724.

Xiao F., Su N., Yao S., Amirkhanian S., Wang J., (2019), Performance grades, environmental and economic investigations of reclaimed asphalt pavement materials, *Journal of Cleaner Production*, **211**, 1299-1312.

Yaro N.S.A., Sutanto M.H., Baloo L., Habib N.Z., Usman A., Yousafzai A.K., Ahmad A., Birniwa A.H., Jagaba A.H., Noor A., (2023), A comprehensive overview of the utilization of recycled waste materials and technologies in asphalt pavements: Towards environmental and sustainable low-carbon roads, *Processes*, **11**, 2095, https://doi.org/10.3390/pr11072095.

Zaumanis M., Mallick R.B., (2014), Review of very high-content reclaimed asphalt use in plant-produced pavements: State of the art, *International Journal of Pavement Engineering,* **16**, 39-55.

Zaumanis M., Mallick R.B., Frank R., (2016), 100% hot mix asphalt recycling: challenges and benefits, *Transportation Research Procedia*, **14**, 3493-3502.

Zhang S., Wang D., Guo F., Deng Y., Feng F., Wu Q., Chen Z., Li Y., (2021), Properties investigation of the SBS modified asphalt with a compound warm mix asphalt (WMA) fashion using the chemical additive and foaming procedure, *Journal of Cleaner Production*, **319**, 128789, https://doi.org/10.1016/j.jclepro.2021.128789.