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A preliminary life cycle assessment – based environmental assessment of asphalt mixtures containing crumb rubber and reclaim asphalt pavement

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ABSTRACT

The road construction sector is significantly material- and energy-consuming. In recent years, the pursuit of sustainable practices has led to growing interest in the use of recycled materials to reduce the environmental impacts of asphalt mixtures. However, there is a lack of comprehensive LCA-based evaluations of such materials under region-specific conditions, particularly in the context of Polish road construction. This study addresses this gap by presenting a preliminary life cycle assessment (LCA) of selected asphalt mixtures modified with crumb rubber (CR) and reclaimed asphalt pavement (RAP), used in wearing and/or binder courses. The environmental evaluation was performed using two methods: IMPACT 2002+ and 100-year Global Warming Potential (GWP 100a), supported by Monte Carlo uncertainty analysis. The results indicate that the incorporation of recycled materials contributes to the reduction of environmental burdens by decreasing raw material extraction and avoiding waste disposal in landfills. The most notable effects were observed for binder course mixtures containing 10–20% RAP, which achieved significant reductions of up to 17.7% in the IMPACT 2002+ single score and up to 24.8% in GWP 100a. For CR additives in the wearing course (2–3%) and binder course (1–2%), the results were modest but consistent, with reductions of up to 0.3% in IMPACT 2002+ and up to 1.7% in GWP 100a.

Keywords: life cycle assessment, asphalt mixtures, crumb rubber, reclaimed asphalt pavement.

INTRODUCTION

In recent decades, growing concern for the natural environment and the efficient use of resources has been gaining significance across many sectors of the economy. This applies, among others, to the road construction industry, which is particularly resource- and energy-intensive, due to the large volumes of aggregates, bitumen, and energy required for material production and processing (Grossegger et al., 2024).

Consequently, the recycling and reuse of waste materials hold great promise for reducing environmental impacts (Poulikakos et al., 2017; Vishnu et al., 2021). Currently, the use of recycled aggregates is common in asphalt mixture production. These include bituminous waste (Bańkowski et al., 2018; Mariyappan et al., 2023), recycled concrete aggregates (Mohammed and Ismael, 2024), waste from the mining and energy industries (Calandra et al., 2022; Jura, 2017), rubber (Alsheyab et al., 2023; White et al., 2023), and plastic waste (Ma et al., 2021; Xu et al., 2021). These materials have been extensively studied in terms of mechanical properties and durability. Numerous studies have demonstrated that such materials, when properly processed and incorporated into asphalt mixtures, can achieve performance comparable to the traditional materials, while also minimizing environmental impacts. Moreover, their use supports the principles of circular economy (Czerwionka et al., 2025; Mrad and Frölén Ribeiro, 2022).

Among the mentioned additives, reclaimed asphalt pavement (RAP) and crumb rubber (CR) are widely available and increasingly used in the production of mineral-asphalt mixtures. RAP obtained during the milling of the road surface can be successfully reused as a component of new mineral-asphalt mixtures (Bańkowski et al., 2018; Mariyappan et al., 2023; Milad et al., 2020) or as a road base (Guerrero-Bustamante et al., 2025). When appropriate processing and mixture design practices are applied, the use of RAP typically has no adverse effect on the mechanical properties of the asphalt mixtures. In fact, research has shown that incorporation of RAP into asphalt mixtures can achieve comparable or, in some cases, even improved properties in comparison to conventional mixtures (Milad et al., 2020). Additionally, it contributes to reducing the demand for new mineral components and the energy consumption associated with the extraction and transportation of raw materials. Research shows that RAP can be incorporated in amounts of up to 50% in binder and base courses, and up to 30% in wearing courses, without compromising compliance with technical requirements (Bańkowski et al., 2018).

CR from used tyres or post-production rubber waste is used as a component of mineral asphalt mixtures to improve their properties. This results in better mix properties at low ambient temperatures and increased resistance to ageing (Jurczak and Marczak, 2023; Picado-Santos et al., 2020). Furthermore, the incorporation of CR significantly enhances resistance to permanent deformation, improves fatigue life, and reduces the temperature susceptibility of asphalt mixtures (Alsheyab et al., 2023). These improvements contribute not only to the extended pavement durability but also to the more sustainable road construction practices. Some studies report beneficial effects with more significant addition of CR, particularly in binder course and road base applications, where increased stiffness and rutting resistance are advantageous (Chegenizadeh et al., 2021). However, other publications recommend more conservative additions (even in wearing courses) typically in the range of 1–3% by total mixture weight, to avoid adverse effects on surface durability and performance (Trzaska, 2010; White et al., 2023).

In order to fully assess whether these environmentally motivated modifications deliver real ecological benefits, it is essential to apply comprehensive evaluation tools such as life cycle assessment (LCA). LCA enables a holistic analysis of environmental impacts across the entire life cycle of asphalt mixtures – from raw material extraction through production, use, and disposal.

In the context of road construction, the use of LCA can enable the comparison of different modification options for asphalt mixtures or the evaluation of the applied technology, thereby supporting the decision-making process (Balaguera et al, 2018; Szabat, 2011).

In this study, the LCA methodology was applied in order to determine the environmental impacts associated with the use of RAP and CR in typical asphalt mixtures used in wearing and/or binder courses. Although the mechanical properties of such mixtures have been widely investigated, comprehensive LCA studies addressing their environmental performance – especially in the context of commonly used technologies in Polish road construction – remain scarce. This highlights a significant research gap and reinforces the relevance of applying LCA in this case.

METHODOLOGY

Objective of the analysis and system boundaries

The aim of this preliminary analysis was to assess, using the LCA approach, the environmental impact of selected asphalt mixtures used in wearing and binder courses, containing CR and RAP additives, in comparison to conventional reference mixtures.

The analysis was performed using the SimaPro v8.0.5.13 program and the Ecoinvent and the USLCI databases. The scope of the analysis covered the production of mineral-asphalt mixtures, including the extraction phase of the raw materials necessary for their production. The environmental impacts related to the transportation of the final product to the construction site, as well as the road construction and end-of-life (EoL) phases, were excluded from the system boundaries. This decision was based on the assumption that these stages are identical or very similar for all compared mixtures – in terms of transport distances, equipment used, and road service life. Consequently, including them would not significantly affect the relative comparison of environmental performance. The functional unit in this analysis was defined as 1 tonne of a specific type of ready asphalt mixture.

Methods for the environmental assessment

To ensure a comprehensive evaluation of the environmental performance of the analyzed asphalt mixtures, two complementary impact assessment methods were selected: IMPACT 2002+ and 100-year Global Warming Potential (GWP 100a). The use of both methods allows for a more comprehensive interpretation of the results, combining a broad, multi-impact environmental perspective with a targeted emissions indicator – particularly relevant in the context of the ongoing energy transition.

The IMPACT 2002+ method enables the assessment of environmental impact based on the analysis of input and output data related to the studied process (Jolliet et al., 2003). At the final stage, the results are presented in four categories of damage: human health, ecosystem quality, reduction of natural resources and climate change. Individual values can be summarized to obtain a collective impact indicator (a single score) expressed in points (Pt). The higher the result obtained in the assessment, the greater the environmental pressure associated with the analyzed product.

The second method applied in the analysis was GWP 100a , as defined by the Intergovernmental Panel on Climate Change (IPCC, 2013), which considers climate impact over a 100-year time horizon. This method is based on an inventory of atmospheric emissions, in which the reference substance is the main greenhouse gas: carbon dioxide. All emissions recognized as having the potential to trap heat in the atmosphere are converted to carbon dioxide equivalent.

In order to estimate the impact of uncertainty in the inventory data on the life cycle assessment results, a statistics simulation based on Monte Carlo method was performed with 1,000 iterations for each analyzed asphalt mixture variant. The simulations were conducted using SimaPro v8.0.5.13 software, based on the default uncertainty distributions assigned to the inventory data in databases employed in the research. The outputs of the analysis are presented in the form of descriptive statistics, including minimum and maximum values, mean, median, and standard deviation, calculated for the 95% confidence interval.

Asphalt mixtures

In the performed analysis, two typical wearing and binder courses were included as a reference mixtures: AC 11 S (wearing course) and AC 16 W (binder courses). The input data for the analyzed mixtures were obtained from GR Development Group, a company located in Krasnystaw (Eastern Poland) and involved in the application of asphalt mixtures in road projects. The dataset is based on operational records from 2023, representing real-world use of conventional mixtures. While the company does not produce asphalt mixtures itself, the data provided reflect actual material usage and performance in field conditions. The dataset was partially complemented by the author's own estimations and calculations, as well as by secondary data from Ecoinvent and USLCI databases. The selected modification scenarios, described in the following paragraphs, are indicative and are intended to provide illustrative assumptions for the comparative environmental assessment.

The modification of the wearing course involved the addition of CR at levels of 2% and 3%, replacing the fine aggregate fraction. The assumed modification method for the study was the 'dry' method, which consists of introducing rubber granulate directly into the mineral mixture before mixing it with the asphalt binder. Quantitative modification variants were established based on literature reports (Alsheya et al., 2023; Trzaska, 2010). The qualitative composition of the reference and modified mixtures of wearing courses are presented in Table 1.

In case of the modifications in the binder course, two kinds of additives were taken into account: CR and RAP. The addition of CR at levels of 1% and 2% was carried out in the same way as in the wearing course (using the 'dry method'). The addition of RAP was set at 10% and 20%, in accordance with Polish road construction guidelines (General Directorate for National Roads and Motorways [GDDKiA], 2014). In the study, the 'cold' modification method was assumed, according to which cold granulate is fed directly into the mixer and heated by the hot aggregate. The qualitative composition of the reference and modified binder course mixtures is presented in Table 2.

RESULTS

IMPACT 2002+ results

The application of the IMPACT 2002+ method allowed for a detailed environmental assessment of asphalt mixtures modified with CR for wearing course and CR and RAP for binder course. The results, expressed as a single score (aggregated results for IMPACT 2002+) per 1 tonne of mixture (mPt), indicate different levels

Table 1. Quantitative composition and energy demand of asphalt mixtures in wearing course

Components	Unit	AC 11 S	AC 11 S + 2% CR	AC 11 S + 3% CR
Limestone filler	kg/Mg	70.8	70.8	70.8
Natural glacial fine aggregate 0/2	kg/Mg	151	148	146.5
Dolomite aggregate 0/2	kg/Mg	151	148	146.5
Dolomite aggregate 2/8	kg/Mg	434.2	434.2	434.2
Dolomite aggregate 8/11	kg/Mg	136.9	136.9	136.9
Asphalt 50/70	kg/Mg	56	56	56
Rubber granulate 0/2	kg/Mg	-	6.0	9.1
Energy demand	MJ/Mg	203	205	205

Table 2. Quantitative composition and energy demand of asphalt mixtures in binder course

Components	Unit	AC 16 W	AC 16 W + 1% CR	AC 16 W + 2% CR	AC 16 W + 10% RAP	AC 16 W + 20% RAP
Limestone filler	kg/Mg	38.2	38.2	38.2	36	33
Natural glacial fine aggregate 0/2	kg/Mg	152.8	151.3	149.7	137.5	122
Dolomite aggregate 0/2	kg/Mg	171.9	170.2	168.5	155	135
Dolomite aggregate 2/8	kg/Mg	305.6	305.6	305.6	272	245
Dolomite aggregate 8/11	kg/Mg	286.5	286.5	286.5	257	225
Asphalt 50/70	kg/Mg	45	45.0	45.0	42.5	40
Rubber granulate 0/2	kg/Mg	-	3.2	6.5	-	-
Asphalt granulate 0/16	kg/Mg	-	-	-	100	200
Energy demand	MJ/Mg	182	184	184	182	182

of environmental burdens depending on the type and amount of additive.

The final score for the base variant and the assumed modifications in the wearing course mixtures is presented in Figure 1. The addition of CR at 2% and 3% resulted in a slight but consistent reduction of the final environmental indicator by approx. 0.2% in each case.

A more detailed presentation of the results for the damage categories is provided in Figure 2. The most significant environmental impacts of the evaluated mixtures arise in the Resources and Human Health categories and are mainly related to the bitumen production and extraction of non-renewable resources (including natural aggregates). The contribution of those categories to the final score for all mixtures is approximately as following 50% and 30%. Contribution of 15% can be observed for Climate Change and 5% is related to the Ecosystem Quality.

The final results for the mixtures in the binder course are presented in Figure 3. The results

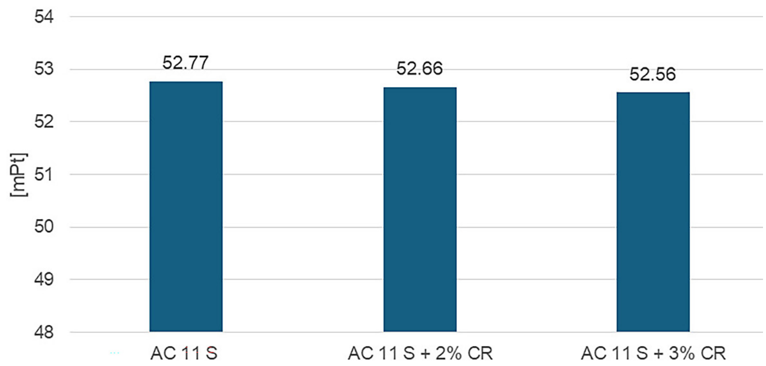

Figure 1. IMPACT 2002+ single score for wearing course mixtures, expressed per functional unit (mPt/tonne)

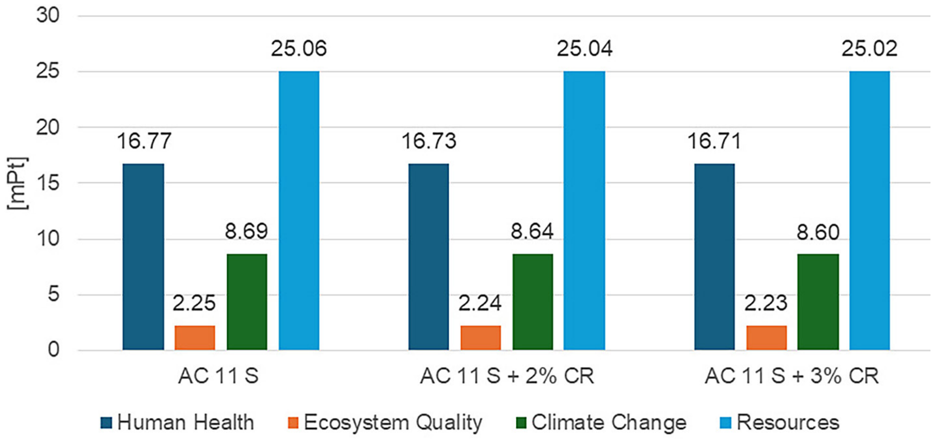

Figure 2. IMPACT 2002+ scores in damage categories for wearing course mixture, expressed per functional unit (mPt/tonne)

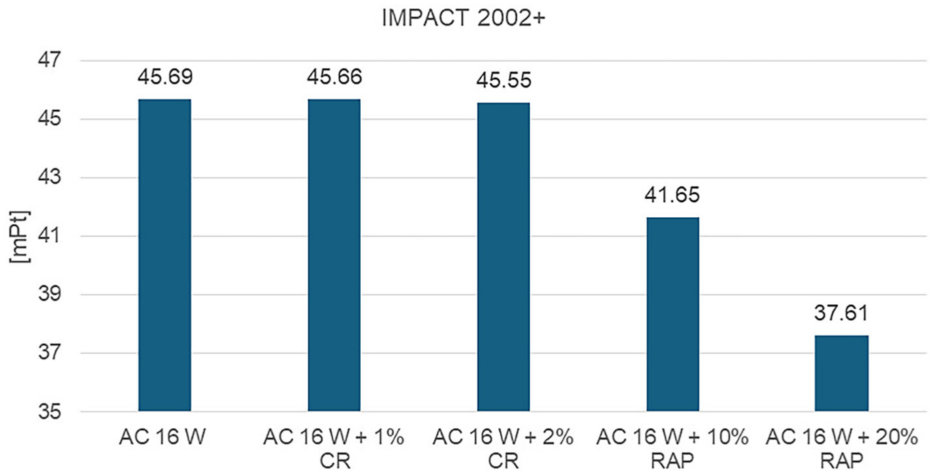

Figure 3. IMPACT 2002+ single score for binder course mixtures, expressed per functional unit (mPt/tonne)

indicate greater differences for the modification with RAP. As a comparison with the base mixture, the final score reductions for the modifications range from 8.8% to 17.7%, depending on the amount of RAP content. In contrast, asphalt mixtures incorporating CR show negligible reductions (approx. 0.3%) due to the significantly lower additive content. The results for each damage category are presented in Figure 4. Similarly to the results for the wearing course, in all binder course mixtures, the final IMPACT 2002+ score is predominantly influenced by Resource depletion (46-47%) and Human Health (around 32%), with smaller contributions from Climate Change (16-17%) and Ecosystem Quality (5%).

The results of Monte Carlo simulations indicate that all analyzed variants of asphalt mixtures have relatively narrow variety of environmental indicator values obtained in the IMPACT 2002+ method, indicating low sensitivity to uncertainty in the input data (Table 3). This limited variability is primarily due to the use of input data with minimal or undefined uncertainty ranges, particularly for values obtained from the industrial partner and default settings in secondary databases.

For all mixtures, the minimum-maximum ranges and standard deviations are highly comparable. For the wearing course, the lowest mean and median values are observed for the mixture with 3% CR (52.51/52.47 mPt), thereby confirming the observed trend from Figure 1. For the binder course, the differences between the variants are more pronounced. The average mean and median values decrease systematically with the increase in the share of recovered materials achieving the lowest values for the mixture with 20% RAP (37.63/37.64 mPt), which also confirms the trend presented in Figure 3.

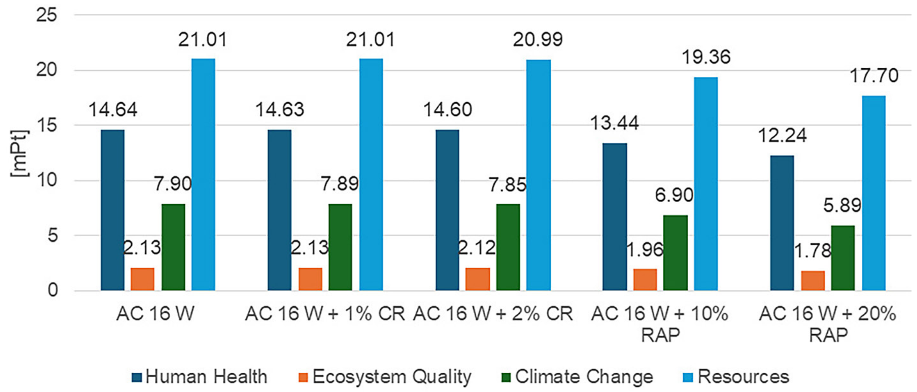

Figure 4. IMPACT 2002+ scores in damage categories for binder course mixtures, expressed per functional unit (mPt/tonne)

Table 3. Summary statistics of IMPACT 2002+ results per functional unit (mPt/tonne)

Asphalt mixture		Min.	Max.	Mean	Median	SD
Wearing course	AC 11 S	47.40	59.42	52.81	52.81	3.00
	AC 11 S + 2% CR	46.82	58.83	52.58	52.45	2.97
	AC 11 S + 3% CR	46.39	58.31	52.51	52.47	2.94
Binder course	AC 16 W	39.23	51.47	45.64	45.60	3.21
	AC 16 W + 1% CR	39.12	51.94	45.56	45.52	3.29
	AC 16 W + 2% CR	39.70	51.58	45.55	45.50	3.09
	AC 16 W + 10% RAP	36.11	47.57	41.61	41.64	2.84
	AC 16 W + 20% RAP	32.64	42.69	37.63	37.64	2.52

GWP 100a results

The GWP 100a method provided a complementary view by evaluating the climate change potential of emissions related to the asphalt mixtures. The results confirm a trend similar to the IMPACT 2002+ method.

The results of GWP 100a calculations for the wearing course are shown in Figure 5. Depending on the amount of CR additive used in the wearing course, the results achieved with this method indicate a potential reduction in final carbon dioxide equivalent emissions of between 1% and 1.7%.

The results for the binder layer, presented in Figure 6, also indicate that the use of additives has a positive effect on environmental performance. For mixtures with 1% and 2% CR additives, the

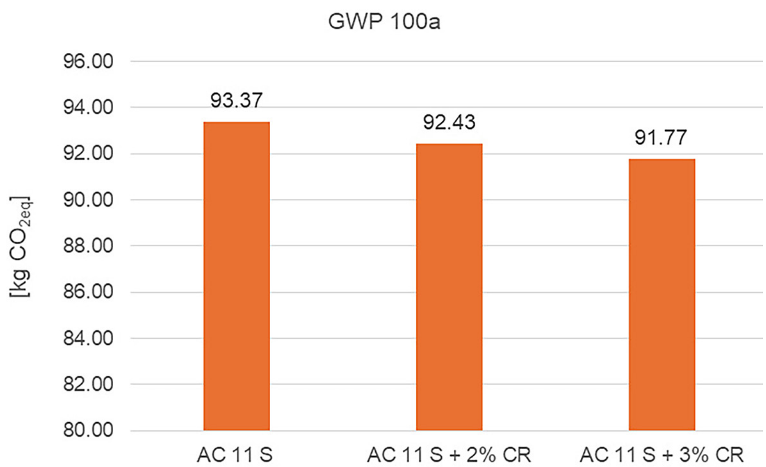

Figure 5. GWP 100a results for wearing course mixtures, expressed per functional unit ($kgCO_{2eq}$/tonne)

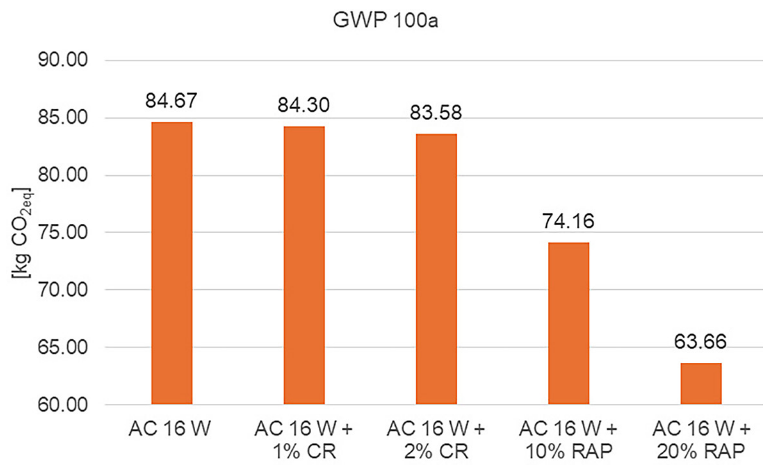

Figure 6. GWP 100a results for binder course mixtures, expressed per functional unit (kg CO_{2eq}/tonne)

reductions in the final score are 0.4% and 1.3%, respectively. In contrast, the incorporation of RAP at levels of 10% and 20% results in more substantial reductions of 12.4% and 24.8%, respectively. The GWP reductions observed for RAP-modified mixtures are more pronounced than for CR, primarily due to the higher percentage of RAP incorporated into the mixtures, which leads to a more substantial replacement of raw materials and bitumen.

In both wearing and binder courses, the major contributors to the final result are carbon dioxide emissions from fuels and methane emissions.

The Monte Carlo simulations for GWP 100a results also indicate low sensitivity to uncertainty in the input data (Table 4). Similarly to the results obtained for IMPACT 2002+, the limited variability observed in the GWP 100a outcomes is mainly attributable to the use of input data with narrow or undefined uncertainty ranges. For all mixtures, the ranges of minimum and maximum values and standard deviations are comparable and consistently low, confirming the reliability of the results. The results support the trends presented in Figures 5 and 6 – the incorporation of CR and RAP additives into asphalt mixtures appears to have a beneficial impact on their global warming potential. For the wearing course, the lowest mean and median of GWP 100a values are observed for the mixture with 3% CR (91.76/91.63 kg CO_{2eq}), while for the binder course, the lowest values are noticed for the mixture with 20% RAP (63.69/63.61 kg CO_{2eq}).

RESULTS AND DISCUSSION

The performed LCA-based analysis focused on the environmental effect of the incorporation of CR and RAP into asphalt mixtures, considering production phase (cradle-to-gate). This phase, according to Aurangzeb et al. (2014), accounts for over 90% of total energy use and greenhouse gas (GHG) emissions throughout the asphalt pavement lifecycle. The substantial contribution to the overall environmental results highlights the pronounced impact of the asphalt mixture production stage and emphasizes the need to optimize

Table 4. Summary statistics of GWP 100a results per functional unit (kg CO_{2eq} /tonne)

Asphalt mixture		Min.	Max.	Mean	Median	SD
Wearing course	AC 11 S	90.48	97.36	93.40	93.26	1.70
	AC 11 S + 2% CR	89.58	95.85	92.41	92.33	1.58
	AC 11 S + 3% CR	88.86	95.50	91.76	91.63	1.68
Binder course	AC 16 W	81.86	88.36	84.68	84.56	1.65
	AC 16 W + 1% CR	81.34	87.92	84.32	84.23	1.63
	AC 16 W + 2% CR	80.64	87.16	83.61	83.54	1.62
	AC 16 W + 10% RAP	71.44	77.22	74.12	74.05	1.46
	AC 16 W + 20% RAP	61.36	66.40	63.69	63.61	1.26

their composition to minimize environmental burdens. In this study, the environmental benefits of incorporating RAP were clearly demonstrated. The reference asphalt mixture (without RAP) in binder course had an IMPACT 2002+ single score of 45.69 mPt and a GWP 100a value of 84.67 kg CO_{2eq} referring to 1 tonne of asphalt mixture. The incorporation of 10% and 20% RAP led to reductions in the IMPACT 2002+ single score by 8.8% and 17.7%, and in GWP 100a by 12.4% and 24.8%, respectively. These results highlight the substantial potential of RAP to lower the environmental impact of asphalt mixture production.

Similar trends were reported by Bressi et al. (2019), where the reference mixture had a climate change impact of approx. 115 kg CO_{2eq}/tonne during the production phase – a higher value than that obtained in this study. In comparison, mixtures with 40% RAP showed notably lower emissions, ranging from 80 to 110 kg CO_{2eq}/tonne, indicating potential reductions between 4% and 30%, depending on the specific mixture formulations and assumptions. These percentage reductions are consistent with the findings of this study.

Aurangzeb et al. (2014) also confirmed the environmental advantages of RAP, showing that incorporating 30–50% RAP can reduce GHG emissions in the asphalt mixture production phase by approximately 38–63 kg CO_{2eq} per kilometer of asphalt pavement, corresponding to a 7–13% decrease as compared to mixtures without RAP.

Vandewalle et al. (2022) conducted an LCA for a 1 km asphalt road within a broader framework encompassing the combination of production, construction, and rehabilitation activities. Their findings also confirmed the positive environmental effects of incorporating RAP into asphalt mixtures. The study reported average reductions across all environmental impact categories (human health, ecosystem quality, climate change, and resources) by 19%, 23%, 31%, and 33%, respectively, as the RAP content in the mixture was increased to 25%, 50%, 75%, and 100%.

The incorporation of CR into asphalt mixtures also shows potential, though with more variable results. In this research, the IMPACT 2002+ single score for the reference mixtures without CR ranged from 45.69 to 52.77 mPt/tonne, depending on the course type, while the GWP 100a values ranged from 84.67 to 93.37 kg CO_{2eq}/tonne. The addition of 2-3% CR to the wearing course and 1–2% to the binder course resulted in relatively modest reductions: up to 1.7% in GWP 100a and up to 0.3% in the IMPACT 2002+ single score. The outcomes indicate that the environmental benefits associated with CR incorporation into asphalt mixtures are moderate and less significant than those observed for RAP.

However, evidence from other studies reveals that the environmental benefits of CR depend strongly on the LCA scope and time frame. For instance, Siverio Lima et al. (2022), analyzing asphalt mixtures with 34% CR in a cradle-to-grave LCA of sidewalk pavements, found that production-phase GHG emissions reached 156 kg CO_{2eq}/tonne – significantly higher than the 90 kg CO_{2eq}/tonne for the reference mixture without CR. While the levels of GHG emissions for the reference mixtures are very close to the results obtained in this analysis, the results for the CR mixtures diverge and indicate an opposite trend in the production phase. Nevertheless, as it was noted by Siverio Lima et al. (2022), the incorporation of CR into mixtures could lead to a 4–7% lower GWP and energy savings of 14–17% over a long-term period of 45 years, as considered in their analysis.

Similarly, Bressi et al. (2019) observed that for asphalt mixtures containing 1.5–2% CR slightly increased emissions can be observed, ranging from 125 to 135 kg CO_{2eq}/tonne, compared to 115 kg CO_{2eq}/tonne for the reference mixture for the asphalt mixture production phase. These results indicate that although additives of CR can improve pavement performance and potentially offer long-term environmental benefits, its immediate impact during the production phase is often less favorable compared to that of RAP. This is due to the increased demand for energy and bitumen resulting from rubber processing and its interaction with the binder – in this preliminary assessment study, the increased energy demand was taken into account, whereas the bitumen content was kept constant due to the simplifying assumptions made.

Despite differences in LCA methodologies across the reviewed studies, a clear trend emerges: RAP additives effectively reduces the environmental impact of asphalt mixtures by significantly lowering raw material demand. While CR additives may offer additional benefits when optimized across the full pavement lifecycle.

The scope of this preliminary LCA assessment can be expand beyond the production phase to include construction, use, maintenance, and end-of-life stages. Particular attention should be paid to the long-term performance of CR- and RAP-modified asphalt mixtures used in road construction under varying climatic conditions, as these can significantly influence durability and environmental outcomes. More region-specific data on material processing and transport, as well as integration with Life Cycle Cost Analysis (LCCA) would further support more accurate assessments. Moreover, individual processes within the life cycle should be thoroughly examined, as certain assumptions in this preliminary assessment – such as constant bitumen content in CR mixtures – may overlook relevant environmental impacts.

CONCLUSIONS

In the preliminary LCA-based study, IMPACT 2002+ and GWP 100a environmental assessment methods were applied, supported by Monte Carlo uncertainty analysis, in order to assess the use of CR and RAP as additives in asphalt mixtures. The main conclusions of the assessment are as follows:

- The results achieved in the analysis indicate that the incorporation of CR and RAP additives contributes to a reduction in environmental impact, in both applied methods.
- In the case of wearing courses, the addition of 2% and 3% CR leads to a slight but consistent decrease in impact values across both assessment methods.
- For binder courses, the incorporation of 20% rap results in a significant reduction in environmental indicators, with up to 24.8% lower GWP values and nearly 18% lower impact 2002+ single scores compared to the base mixture.
- The monte carlo analysis confirmed the reliability and consistency of the results for all mixture variants in both assessment methods.
- In general, the use of recycled additives such as CR and RAP in road pavement construction offers two key environmental benefits: it reduces emissions related to the production and transport of raw materials and avoids the environmental burdens resulting from landfilling.
- Even moderate incorporation of recycled materials can yield measurable environmental advantages and represents an effective strategy for reducing the carbon and resource footprint of road construction.
- In addition to emission reductions, the utilization of waste materials in road construction can reduce construction costs and promote the development of a circular economy.

The insights provided by this type of analysis may inform future developments in Polish road construction policy and support the achievement of national sustainability goals, particularly those related to climate neutrality and waste reduction.

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