Proceedings of the 13th International Scientific Conference

ENVIRONMENTAL ENGINEERING

April 23–24, 2026, Vilnius, LITHUANIA

eISSN 2029-7092
eISBN 978-609-476-444-8
Article ID: enviro.2026.2257
https://doi.org/10.3846/enviro.2026.2257

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LIFE CYCLE EVALUATION OF MATERIAL TRANSPORTATION IMPACTS IN ASPHALT MIXTURE PRODUCTION

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Received 19 January 2026; revised 29 January 2026; accepted 9 February 2026

Abstract. This study evaluates the effect of raw material transportation distance and mode – particularly of aggregates – on the Global Warming Potential (GWP) and related environmental indicators during the production stage of bituminous mixtures. Understanding how transport contributes to the life cycle impacts of asphalt mixtures is essential for improving resource logistics and minimising carbon emissions in pavement construction. A Life Cycle Assessment (LCA) was performed using SimaPro software in accordance with the ISO 14040 standards. The analysis considered a representative bituminous mixture composition, including aggregates, bitumen, and filler materials, with varying transport distances and modes (road, rail, and water). Sensitivity analysis quantified the effect of each transport scenario on total GWP at the manufacturing gate. Results indicate that transportation represents a substantial share of total GWP, with outcomes highly dependent on both hauling distance and vehicle type. Reducing aggregate transport distance yields substantial GWP reductions, as halving the road transport distance from 200 km to 100 km decreased total GWP by more than 9%, while long-distance road transport (≥800 km) increased total GWP by over 50%. Among the modes analysed, rail transport exhibited notably lower emissions per ton-kilometre compared with diesel trucking. These findings highlight the critical role of transport logistics in asphalt production and demonstrate that optimising sourcing distances and adopting low-carbon transport modes can significantly reduce the climate impact of road infrastructure.

Keywords: life cycle assessment, bituminous mixtures, transportation distance, global warming potential, environmental impact.

1. Introduction

The production of bituminous mixtures is associated with significant environmental impacts (European Asphalt Pavement Association, 2024), particularly in terms of Global Warming Potential (GWP), which are commonly assessed using Life Cycle Assessment (LCA) following a cradle-to-gate approach (modules A1–A3). Within this system boundary, the transportation of raw materials to the asphalt plant (module A2) can play a non-negligible role in the overall environmental performance of asphalt mixtures, especially when long transport distances or carbon-intensive transport modes are involved (Shacat et al., 2024).

Transportation of asphalt mix constituents from raw material extraction sites to the asphalt plant can significantly influence the final GWP impact of the product stage. This effect is particularly pronounced for aggregates, as they represent the dominant mass fraction of bituminous mixtures, typically exceeding 90% by weight. Consequently, even relatively small changes in aggregate transport distance or transport mode (road, rail, or sea) may lead to noticeable differences in the total cradle-to-gate GWP of asphalt mixtures (Kleizienė et al., 2025a).

Recent LCA studies have demonstrated that module A2 can contribute a substantial share of the total GWP of asphalt mixture production, with reported values ranging from a few percent up to approximately 20% of cradle-to-gate emissions, depending on supply chain configuration and transport distances (Moretti et al. 2017; Shacat et al., 2024). These findings underline the importance of explicitly analysing transport scenarios and avoiding the use of overly generic assumptions for raw material logistics in asphalt LCA studies.

Despite this, transport-related impacts are often simplified or treated as secondary in comparative assessments of asphalt technologies. A more detailed evaluation of transport distance and transport mode is therefore essential to improve the robustness of LCA results and to support informed decision-making aimed at reducing the environmental footprint of asphalt mixture production.

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The paper aims to assess how transport distance and transport mode of aggregates affect the Global Warming Potential (GWP) and other environmental impacts during the product stage of bituminous mixtures. To achieve this goal, several objectives need to be accomplished:

1) Identify typical aggregate supply distances and transport modes used in the production of bituminous mixtures.
2) Model transport scenarios with varying distances and transport modes (road, train, and sea).
3) Quantify the contribution of aggregate transport to the Global Warming Potential (GWP-total) of bituminous mixtures during the product stage.
4) Evaluate the influence of transport distance and mode on other relevant environmental impact indicators.
5) Compare alternative transport scenarios to determine conditions under which transport has a significant effect on overall environmental performance.
6) Provide recommendations for reducing environmental impacts through optimized aggregate transport strategies.

2. Life cycle assessment (LCA) methodology

2.1. Goal and scope of LCA

The goal is to determine the environmental impact of 1 ton of asphalt mixture (declared unit) and evaluate the influence of aggregate transportation mode and distance on the environmental impact at cradle-to-gate (system boundaries of A1-A3 modules). LCA was performed using SimaPro software in accordance with the ISO 14040 (International Organization for Standardization, 2006) and EN 15804:2012+A2:2019/AC:2021 (European Committee for Standardization, 2019) standards.

2.2. Life cycle inventory

Life Cycle Inventory (LCI) analysis involves the systematic collection and quantification of all material and energy inputs and outputs across a product's life cycle under system boundaries. It encompasses both data collection and the modelling of the product system.

2.2.1. Materials extraction (module A1)

This study was conducted by calculating a single reference asphalt mixture case, selecting the AC 16 AS asphalt base layer mixture. Main components and attributes of the asphalt mixture is presented in Table 1. Unmodified bitumen 50/70, supplied by the Mažeikiai oil refinery, is planned to be used for its production. Aggregates account for the largest share of asphalt mix, so this study focuses on aggregate transportation scenarios. The aggregate may be locally sourced if it is dolomite or gravel from Lithuanian quarries, or imported if it is granite aggregate. These types of materials can be used in the production of the selected asphalt mixture.

Table 1. Main components and attributes of the asphalt mixture

Material	Amount (unit)	Unit Process from Ecoinvent	Supply via road
Bitumen binder	39.8 kg	Bitumen adhesive compound, hot {RER} bitumen adhesive compound production, hot | Cut-off	280 km
Filler	10 kg	Lime {Europe without Switzerland}| lime production, milled, loose | Cut-off, S	25 km
Sand	113 kg	Sand {RoW}| gravel and sand quarry operation | Cut-off, S	40 km
Aggregates	837 kg	Gravel, crushed {RoW}| gravel production, crushed | Cut-off, S	200 km*
Additive	0.2 kg	Chemical, organic {GLO}|production|Cut-off, S	2050 km
	1000 kg		

Note: *This transportation distance applies to the reference mixture and is treated as a variable parameter, as explained in detail in Section 2.2.2.

2.2.2. Transportation to plant (module A2)

It is assumed that the asphalt plant is located near Vilnius. The fixed distances are presented in Table 1 for analysis, but the aim of this study was to assess the environmental impact depending on the supply chain of coarse aggregates. To this end, twelve coarse aggregate transport scenarios were initiated, as shown in Table 2. The reference scenario Tref-R includes a scenario where coarse aggregates are transported from the Akmenė region to Vilnius by truck. Scenarios T1-T4 R also include the road transport of aggregates over distances ranging from 50 km to 800 km. These scenarios are based on the assumption that the mixture can be produced from gravel or crushed granite, which can be supplied from both local and more distant quarries. Scenarios T5-T7 RT include the transport of raw materials partly by truck (road) and partly by rail (train). Rail transport distances are also modelled based on the possible location of quarries both in Lithuania and in neighbouring countries, such as Belarus and Ukraine. Although at the moment granite is not supplied from Belarus and Ukraine due to sanctions, as was the case before the war, the possibility that granite will again be supplied from these countries if the political situation changes cannot be ruled out, so these distances were included in the scenario analysis.

However, a survey of asphalt producers has shown that granite is most often supplied to the Lithuanian market from Scandinavian quarries, transported by sea containers and then by truck from the coast to the production site. Sometimes it is shipped from Sweden, when the distance is around 500 km, and also be shipped from

Norway with a distance of around 1000 km. This is modelled in scenarios T8-T9 RS. Sometimes, granite shipped to Klaipėda and then transported to Vilnius by train; this is modelled in scenarios T10-T11 RTS.

Default unit processes for the modelling transportation module (A2) is shown in Table 3.

Table 2. Transport scenarios of aggregate supply distances and transport modes

Scenario	Evaluated distances (km) and transport modes		
	Road	Train	Ship
Tref-R	200	–	–
T1-R	50	–	–
T2-R	100	–	–
T3-R	350	–	–
T4-R	800	–	–
T5-RT	50	200	–
T6-RT	50	350	–
T7-RT	50	800	–
T8-RS	350	–	500
T9-RS	350	–	1000
T10-RTS	50	350	500
T11-RTS	50	350	1000

Table 3. Default unit processes for the modelling transportation module (A2)

Process	Unit Process from Ecoinvent	Unit
Road transport	Transport, freight, lorry >32 metric ton, EURO5 {RER}| transport, freight, lorry >32 metric ton, EURO5 | Cut-off, S	tkm
Water (sea) transport	Transport, freight, sea, container ship {GLO}| transport, freight, sea, container ship | Cut-off, S	tkm
Railway transport	Transport, freight train {Europe without Switzerland}| transport, freight train, diesel | Cut-off, S	tkm

2.2.3. Production (module A3)

Hot mix asphalt is produced in dedicated asphalt plants where aggregates of different sizes, pre-blended and graded to meet specification requirements, are dried and heated before being mixed with a controlled amount of hot bitumen in a pugmill (batch plant). Heat is applied to remove moisture from the aggregates and to ensure sufficient bitumen fluidity for effective mixing and workability.

The analysis is based on a batch-type asphalt plant located in Lithuania, near Vilnius. Aggregate drying and heating are carried out using natural gas, while the production line, mixer, and bitumen storage tanks are powered by electricity. The energy consumption required to produce one tonne of asphalt mixture (module A3) is presented in Table 4, and these parameters are assumed to remain constant across all analysed scenarios.

Table 4. Energy consumption to produce one ton of asphalt mixture (A3)

Element	Energy source	Quantity and unit	Unit Process from Ecoinvent
Production line	Electricity	18.90 MJ	Electricity, low voltage {LT}|electricity, low voltage, residual mix|Cut-off, S
Burner	Natural gas	380.0 MJ	Heat, district or industrial, natural gas {Europe without Switzerland}|heat production, natural gas, at industrial furnace > 100 kW|Cut-off, S
Loader	Diesel	9.05 MJ	Diesel, burned in building machine {GLO}|diesel, burned in building machine|Cut-off, S

2.3. Environmental impact indicators

To assess the potential impacts on the environment of the asphalt mixture and the different scenarios, the 15804:2012+A2:2019/AC:2021 (European Committee for Standardization, 2019) method has been used, which was revised in 2019 and aligns with the Environmental Footprint EF 3.1 method. The calculation was carried out using the LCA software Simapro 10.2.0.3 and the Ecoinvent 3.9.1 database (Ecoinvent 3 – allocation, cut-off).

2.3.1. Global Warming Potential (GWP-total)

Global Warming Potential (GWP) quantifies the relative ability of a greenhouse gas to absorb heat in the atmosphere over a specific time horizon. The total GWP is the sum of three climate change sub categories: GWP-fossil, GWP-biogenic and GWP-luluc (land use and land use change global warming potential). GWP values enable the conversion of emissions of different greenhouse gases into carbon dioxide equivalents (CO_2-eq), thereby allowing their climate impacts to be compared and aggregated in climate change assessments.

2.3.2. Aggregated single score

The single-score (or aggregated single score) combines life cycle impact results by applying normalisation and weighting factors into one representative unit (Kleizienė et al., 2025b). The normalisation and weighting factors are presented in Table 5.

2.3.3. Environmental cost indicator (ECI)

Additionally, the Environmental Costs Indicator (ECI) impact method, which originally was developed for the construction sector of the Netherlands, was applied to calculate a single score measured in euros based on price weighting published in a 2020 report from Delft University (de Bruyn et al., 2020).

3. Results and discussion

3.1. Influence evaluation of transport distances and modes

Asphalt manufacturers often underestimate the environmental impact of the raw material supply chain when choosing cheaper raw materials, not considering transportation distances, so we sought to draw attention to this in our study. As usual, the environmental impact of the asphalt mix was determined by assessing raw material extraction (module A1), transportation (module A2), and mix production (module A3). The raw material and energy requirements for producing 1 ton of asphalt mix were fixed, but the transport distance and mode of transport for the aggregates were varied depending on the scenario.

A distance of 200 km was chosen as the starting point for the transport of coarse aggregates (Tref). In this case (Tref), the GWP-total indicator was 95.4 kg CO_2 eq., of which 44.7% was accounted for by raw materials (A1), 20% by transport (A2), and 35.3% by the production stage (A3). The impact of the GWP-total indicator, taking into account transport distances and modes, is shown in Figure 1.

Calculations show that by reducing the transport distance for coarse aggregates by half (to 100 km, T2-R), the total GWP of the asphalt mixture can be reduced by more than 9%. However, when transporting aggregates over a longer distance, say 350 km (T3-R), the GWP-total increases by 13.7%, and when transporting over a very long distance of 800 km (T4-R), it increases by over 54.7%. Percentage difference of GWP-total indicator compared to the research scenarios with Tref is presented in Figure 2.

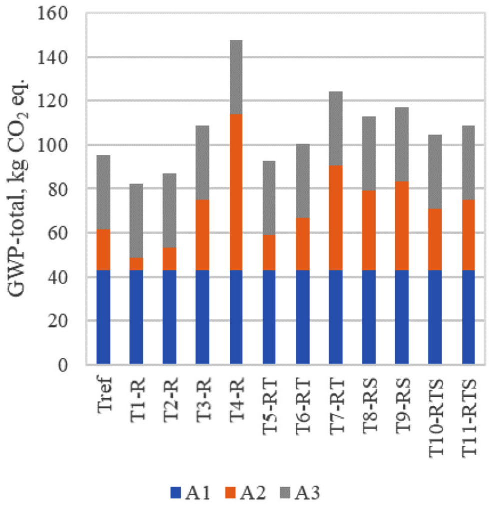

Figure 1. Impact of transport distance on transportation-related (module A2) GWP-total emissions

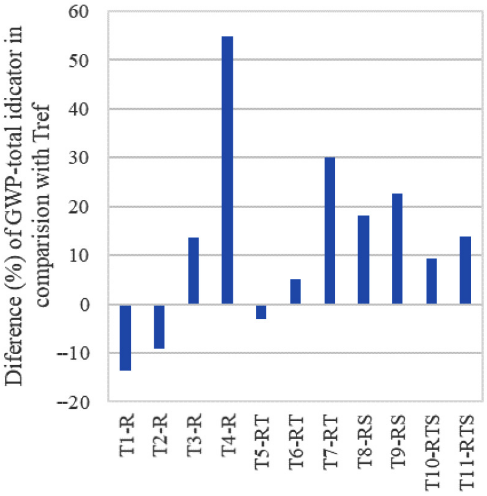

Figure 2. Percentage difference of GWP-total indicator compared to the research scenarios with Tref

3.2. Comparison of alternative transport scenarios

It is known that certain types of aggregates, such as granite or basalt, are not available in Lithuania, so they are transported from quarries in other countries over long distances. Two long distances were selected for analysis: 800–900 km when transported from quarries in Sweden and 1350–1400 km when transported from quarries in Norway.

To transport aggregates over a distance of 800-900 km (comparable to T4-R, T7-RT, T8-RS, and T10-RTS scenarios), the least polluting approach is T10-RTS, where the supply chain combines shipping (up to 500 km), rail transport (up to 350 km), and truck transport (up to 50 km). It has been determined that the GWP-total indicator for the asphalt mixture with the T10-RTS transport scenario is 104.4 kg. CO_2 eq., i.e. 29.3% lower than in the T4-R scenario, where transport is carried out only by road.

If it is not possible to transport the aggregates by rail when planning their delivery, then a good transport alternative would be the T8-RS scenario, where the aggregates are transported by ship (up to 500 km) and by road (up to 350 km). It has been determined that the GWP-total indicator for the asphalt mixture with the T8-RS transport scenario is 112.7 kg. CO_2 eq., i.e. 23.6% lower compared to the T4-R scenario.

When transporting aggregates over a distance of 1350–1400 km (comparing the T9-RS and T11-RTS scenarios). Again, the least polluting option is T11-RTS, where the supply chain combines shipping (up to 1000 km), rail transport (up to 350 km), and truck transport (up to 50 km). It has been determined that the GWP-total indicator for the asphalt mixture with the T11-RTS aggregates transport scenario is 108.7 kg. CO_2 eq., i.e. only 4% higher than the T10-RTS scenario, where transport is over a distance of 500 km shorter.

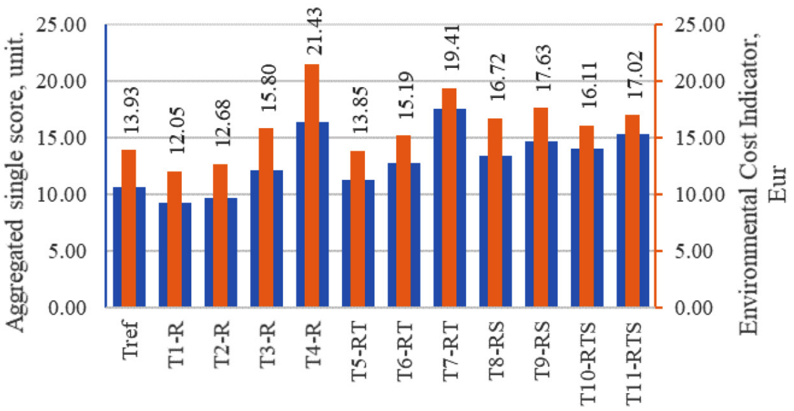

Figure 3. Comparison of alternative transportation scenarios based on the aggregated single score and environmental cost indicator

3.3. Environmental impact assessment using a single indicator and an environmental cost index

Comparison of alternative transportation scenarios based on the aggregated single score and environmental cost indicator is presented in Figure 3. Both the aggregated single score and the environmental cost index show similar trends to the GWP-total indicator. The highest ECI was for asphalt mix, whose raw materials were transported 800 km by road transport T4-R, reaching €21.43 per ton of asphalt. A similar ECI price of €19.41 per ton of asphalt mix was found in the T7-RT scenario, where raw materials were transported 800 km by diesel train.

A relatively lower price was found for mixtures whose aggregates were transported over long distances (850–1400 km) by sea. The price ranged from €16.11 to €17.63 per ton of asphalt (see Figure 3, T8-RS, T9-RS, T10-RTS, and T11-RTS). When comparing the asphalt mix (Tref), which was produced using local aggregates transported over a distance of 200 km, with the mix produced using imported aggregates transported from Scandinavia, it was found that the ECI is 15.6–26.6% higher.

Table 5. The normalisation and weighting factors

Impact category	Indicator	Abbreviation	Unit	EF 3.1 Single score		ECI
				Normalisation	Weighting (Pt/unit)	Weight score (€/unit)
Acidification	Acidification potential, Accumulated Exceedance	AP	Mol H+ eq	1.799	0.062	0.39
Climate change	Global Warming Potential total	GWP-T	kg CO_2 eq	1.324	0.2106	0.116
Ecotoxicity, freshwater	Potential Comitative Toxic Unit for Ecosystems	ETP-fw	CTUe	1.763	0.0192	0.00013
Particulate matter	Potential incidence of disease due to PM emissions	PM	disease inc.	1.679	0.0896	549.750
Eutrophication, marine	Eutrophication potential, fraction of nutrients reaching marine and compartment	EP-M	kg N eq	5.116	0.0296	3.28
Eutrophication, freshwater	Eutrophication potential, fraction of nutrients reaching freshwater and compartment	EP-F	kg P eq	6.223	0.028	1.96
Eutrophication, terrestrial	Eutrophication potential, Accumulated Exceedance	EP-T	mol N eq	5.657	0.0371	0.36
Human toxicity, cancer	Potential Comparative Toxic Unit for Humans	HTP-c	CTUh	5.796	0.0213	1096368
Human toxicity, non-cancer	Potential Comparative Toxic Unit for Humans	HTP-nc	CTUh	7.768	0.0184	147588
Ionising radiation	Potential Human exposure efficiency relative to U235	IRP	kBq U-235 eq	2.369	0.0501	0.049
Land use	Potential soil quality index	SQP	Pt	1.22	0.0794	0.000178

End of Table 5

Impact category	Indicator	Abbre-viation	Unit	EF 3.1 Single score		ECI
				Norma-lisation	Weighting (Pt/unit)	Weight score (€/unit)
Ozone depletion	Depletion potential of the stratospheric ozone layer	ODP	kg CFC11 eq	1.91	0.0631	32
Photochemical ozone formation	Formation potential of tropospheric ozone	POCP	kg NMVOC eq	2.447	0.0478	1.22
Resource use, fossils	Abiotic depletion for fossil resources potential	ADP-F	MJ	1.538	0.0832	0.00033
Resource use, minerals and metals	Abiotic depletion potential for non-fossil resources	ADP-MM	kg Sb eq	1.572	0.0755	0.30
Water use	Water (user) deprivation potential, deprivation-weighted water consumption	WDP	m^3 depriv.	8.719	0.0851	0.00506

3.4. Recommendations for reducing environmental impacts

Manufacturers' decisions on raw material sourcing must take into account transport emissions, not just costs, but the entire supply chain. Asphalt LCA consistently shows that module A2 accounts for at least 20% of the total GWP when assessing the environmental impact of asphalt mix within the cradle-to-gate system. It is important to note that in regions where there are no coarse aggregate production quarries, the transport module A2 may become more significant than the emissions from raw material (module A2) and production (module A3) (Mukherjee, 2016). In this case, raw materials should be delivered to asphalt plants using multimodal transport, with raw materials being transported over long distances by sea ship or rail. This holistic assessment of transport modes encourages the selection of raw material suppliers that reduce the environmental footprint of logistics, increasing overall sustainability without compromising the durability properties of the mixture.

Prioritising locally sourced (up to ~100–150 km) aggregates and alternative pavement materials application stands as a cornerstone strategy for confining the environmental burden of asphalt production, as transport distances bigger than 350 km profoundly dictate GWP. Within this distance, Module A2 (transport) becomes dominant and underscores the additional need for procurement policies to evaluate in the supply chain. And so the favouring local quarries, balancing environmental performance with emissions thresholds below 20% of total GWP per modules A1–A3 as well as application of alternative road construction materials like reclaimed asphalt, slags, reclaimed concrete and ect, which are burden-free by themselves, are accepted as the most rational strategy for production of asphalt (Kleizienė et al., 2025a; Oreto et al., 2021)

4. Conclusions

Based on analysis, the following conclusions can be drawn:

1) Transport distance and mode significantly influence the cradle-to-gate GWP-total of asphalt mixtures, with module A2 contributing around 20% of total GWP in reference scenarios and becoming the dominant module of life cycle for long-distance aggregate supply chains.
2) Reducing aggregate transport distance yields substantial GWP reductions, as halving the road transport distance from 200 km to 100 km decreased total GWP by more than 9%, while long-distance road transport (≥800 km) increased total GWP by over 50%. Road transport is environmentally optimal for aggregate supply over short distances (up to ~100–150 km), but for longer distances it should be restricted to last-mile delivery within multimodal transport chains to minimise GWP impacts.
3) Multimodal transport chains combining maritime, rail, and short-distance road transport substantially reduce environmental impacts compared to road-only transport, achieving up to 30% lower GWP for long-distance aggregate imports.
4) Local aggregate sourcing (up to ~100–150 km distance) remains the most effective strategy for minimising environmental impacts, and when local resources are unavailable, environmentally optimised multimodal logistics should be prioritised to limit the contribution of transport to overall asphalt mixture impacts.

Funding

This study has received funding from the Research Council of Lithuania (LMTLT), project agreement No S-REP-25-8.

References

de Bruyn, S., Bijleveld, M., & Korteland, M. (2020). *Milieuprijzen als weegfactor in de bepalingsmethode milieuprestatie bouwwerken* [Environmental prices as a weighting factor in the determination method for the environmental performance of buildings]. https://ce.nl/publicaties/milieuprijzen-als-weegfactor-in-de-bepalingsmethode-milieuprestatie-bouwwerken/

European Asphalt Pavement Association. (2024). *Towards net zero. A decarbonisation roadmap for the asphalt industry.* https://horizoneuropencpportal.eu/sites/default/files/2025-01/eapa-towards-net-zero-2024.pdf

European Committee for Standardization. (2019). *Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products* (EN 15804:2012+A2:2019/AC:2021). Brussels.

International Organization for Standardization. (2006). *Environmental management – Life cycle assessment – Principles and framework* (ISO 14040). ISO.

Kleizienė, R., Buttitta, G., Carreño, N., & Presti, D. L. (2025a). Enhancing the sustainability of asphalt mixtures: A focus on operational factors and dataset for environmental product declarations. *Sustainability*, *17*(20), Article 9349. https://doi.org/10.3390/su17209349

Kleizienė, R., van de Beek, M., Zofka, A., & Karbočius, M. (2025b). Application of single score methods for environmental impact assessment to compare pavement technologies. *Road Materials and Pavement Design*, *26*, 503–524. https://doi.org/10.1080/14680629.2025.2485335

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*(3), Article 400. https://doi.org/10.3390/su9030400

Mukherjee, A. (2016). *Life cycle assessment of asphalt mixtures in support of an environmental product declaration*. https://www.asphaltpavement.org/uploads/documents/EPD_Program/LCA_final.pdf

Oreto, C., Russo, F., Veropalumbo, R., Viscione, N., Biancardo, S. A., & Dell'Acqua, G. (2021). Life cycle assessment of sustainable asphalt pavement solutions involving recycled aggregates and polymers. *Materials*, *14*(14), Article 3867. https://doi.org/10.3390/ma14143867

Shacat, J., Willis, R., & Ciavola, B. (2024). The carbon footprint of asphalt pavements. In *Sip-109* (March). https://www.asphaltpavement.org/uploads/documents/Climate/NAPA-SIP109-TheCarbonFootprintOfAsphaltPavements-March2024.pdf