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INVITED PAPER

Eco-efficient asphalt recycling for urban slow mobility

Salvatore Bruno[1] · Giuseppe Loprencipe[1] · Paola Di Mascio[1] · Giuseppe Cantisani[1] · Nicola Fiore[1] · Carlo Polidori[2] · Gennaro Riccio[1] · Antonio D'Andrea[1] · Laura Moretti[1]

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Abstract
Cycling infrastructures contribute to advancing zero-impact transport systems, aligning with the European Commission's proactive climate change mitigation policies. This paper explores the potential of innovative and sustainable pavements for cycling paths with mixtures composed of road-milling materials. This investigation involves low-environmental-impact bituminous-based mixtures differing from recipe, mixing method, and laying. Up to 100% secondary aggregates are used as alternative materials to design the Grande Raccordo Anulare delle Biciclette (GRAB), a 44-km cycling ring in Rome. According to the European standard EN 15804, their "from cradle to gate" life cycle analysis allows a comprehensive assessment and comparison of the environmental impact. Core and additional environmental impact categories and resource use indicators were quantified using primary data from asphalt producers and secondary data from the Ecoinvent database in the SimaPro software. Within the H2020 InfraROB project (grant agreement no. 955337), which aims at enhancing road infrastructure integrity, performance, and safety through autonomous robotic solutions and modularization, experimental sections have been constructed using a cold-mixed asphalt composed entirely of recycled asphalt and a rejuvenating additive. The results underscore the potential of the examined low-impact approach in conserving Earth's resources, ensuring long-lasting infrastructure for vulnerable urban populations and fostering sustainable environmental management.

Keywords Sustainability · Cycle path · Urban pavements · Rejuvenator · Reclaimed asphalt · Life cycle assessment

Introduction

The European Green Deal has marked a new era in sustainable development, promoting sustainable mobility solutions and emphasizing the role of zero-impact transport systems (Machin and Tan 2024). This transformative approach toward green mobility is based on the necessity to mitigate the effects of global warming, which have increased in recent years (De Luca et al. 2024). The European Union has set ambitious sustainability targets to reduce greenhouse gas emissions to at least 55% below 1990 levels by 2030 and achieve climate neutrality by 2050 (European Commission 2019). A 90% reduction by promoting more economical, accessible, healthy, and environmentally friendly transportation alternatives supports the strategy for decreasing transport-related emissions (Schwanen 2021). According to Winkler et al. (2023) a significant approach to reduce emissions in the short term is countering large-scale car use.

Pavement engineering can contribute to sustainable development goals (Bayoumy et al. 2024), and life cycle assessment (LCA) is an indispensable tool (Liu et al. 2024). It is a comprehensive, standardized methodology for appraising the environmental burdens of a product or activity throughout its lifecycle—from extraction of raw materials to processing, manufacturing, distribution, usage, repair, maintenance, and disposal or recycling (Aryan et al. 2023). This approach is particularly significant in assessing the use of recycled materials in road pavement, enabling quantifying environmental benefits in terms of greenhouse gas emission reduction (Picardo et al. 2023), nonrenewable resource consumption (Moins et al. 2024), and climate change impact (Trunzo et al. 2019). Reusing road materials promotes more sustainable use of raw resources, contributing actively to

Responsible Editor: Agnieszka Szmelter-Jarosz.

Salvatore Bruno
salvatore.bruno@uniroma1.it

[1] Department of Civil, Constructional and Environmental Engineering, Sapienza University of Rome, Via Eudossiana 18, 00184 Rome, Italy

[2] AIPSS-Associazione Italiana Professionisti della Sicurezza Stradale, Piazza del Teatro di Pompeo 2, 00186 Rome, Italy

a circular economy (Thom and Dawson 2019). Recycling pavement materials provides a strategy against nonrenewable resource extraction while reducing waste generation and reliance on landfills (Abdalla et al. 2022). In the USA, the acceptance of reclaimed asphalt pavement (RAP) materials by asphalt plants has led to considerable environmental gains: the use of RAP has saved an estimated 46.7 million cubic meters of landfill space in a single year, underscoring its potential in waste reduction efforts (NAPA 2018). Polo-Mendoza et al. (2022) further support the environmental advantages of incorporating RAP materials. Their findings indicate that introducing 15% RAP material into asphalt mixtures can reduce climate change impacts by 13% and decrease the depletion of fossil sources by 14%. Recycled asphalt mixtures can reduce CO_2 emissions—approximately 18 kg less per ton—and save 20% energy per ton (Zaumanis et al. 2014). Moreover, the production cost of RAP asphalt mixture is significantly lower than virgin mix: depending on the RAP content and market availability, the cost could be 50–70% less.

On the other hand, sustainable mobility is another strategy for minimizing environmental impact (Galambos et al. 2024). In this regard, governments should aim to reverse the transport pyramid, place less emphasis on private cars, and prioritize alternative transportation modes (Taillandier et al. 2023). This trend should include an increased focus on public transportation and less energy-consuming vehicles such as bikes (Cantisani et al. 2019a). Brand et al. (2021) illustrate that substituting bicycles for cars in daily commutes can save approximately 8 kg of CO_2 emissions per person per day. Additionally, recent studies indicate that bicycling is one of the most sustainable forms of transportation (Batool et al. 2024). Electric bicycles, extending and easing mobility, have attracted growing users to this low-impact transport mode (Mina et al. 2024). However, the choice of transport mode is heavily influenced by the availability of adequate and safe cycling networks (Hsu et al. 2023). Thus, it is crucial to invest in the construction and maintenance of bicycle infrastructures to ensure a high standard of service and safety for cyclists (Adsule and Kadali 2024). Constructing a bituminous bicycle path typically involves several layers, including the wearing, binder, and subbase layers, which may vary depending on the subgrade load-bearing capacity (Regione Lombardia 2002). The Boussinesq multilayer theory is the most common method for determining layer thickness from stress–strain analysis. It allows fatigue and rutting verifications for bound and unbound material layers, respectively (Sahis and Biswas 2021). The pavement design should consider the expected traffic (not just pedestrians but also vehicles for cleaning, maintenance, and emergency services), environmental factors, and ground characteristics over no less than a 20-year service life. Although several materials are employed in construction, asphalt is frequent because of its straightforward construction process, maintenance activity, and rapid availability for use by traffic. In particular, the top layer should be safe, durable, smooth, regular, slip-resistant, dust-resistant, and protective (Government of South Australia 2015).

This study focuses on the environmental performance of six asphalt mixtures designed to pave the Grande Raccordo Anulare delle Biciclette (GRAB) in Rome (Fig. 1), an urban cycling infrastructure project to preserve biodiversity and establish green corridors, contributing to the ecological health of the urban environment. The GRAB is a 44-km-long, easily accessible cycling and pedestrian ring to facilitate connections across districts, subway stations, and regional railway networks. This project reflects a modern urban planning strategy that offers multiple functions, including sustainability and support for tourism and local mobility (Caravaggi et al. 2022). The route traverses historical areas and contemporary landmarks, and green spaces border it.

A comparative analysis of the environmental impact of the mixtures designed to pave the GRAB by varying virgin aggregate, RAP, asphalt sheath waste (ASW), rejuvenator additives, flux oils, and bitumen content has been conducted. All the mixtures are an eco-efficient asphalt recycling solution for urban slow mobility. The life cycle assessment (LCA) methodology—"from cradle-to-gate"—has been applied to assess the environmental impact of these materials using the SimaPro software, according to EN 15804:2021 standards (EN 2021a). The outcomes underscore the feasibility of sustainable pavements for cycle paths, highlighting innovations such as the regeneration of old pavements, production at lower temperatures, and low-emission laying techniques.

Materials and methods

The methodology of the GRAB project incorporated a multicriteria analysis to evaluate its implementation across six main sections, focusing on cycle demand, network connectivity, urban accessibility, and cycle safety (Transform Transport 2024). For instance, the analysis of cycle demand utilized specific data on seasonal fluctuations, which was not detailed for the GRAB traffic: the emphasis on connecting diverse urban areas suggests an expectation of varied use throughout the year, accommodating both daily commuters and recreational cyclists. Network connectivity was assessed on the basis of the size of the local cycle network connected to each GRAB section, indicating that certain sections boasted higher connectivity and could attract more cyclists. This approach allowed for a systematic evaluation of the GRAB's potential impact on urban mobility and safety. Urban accessibility constituted another

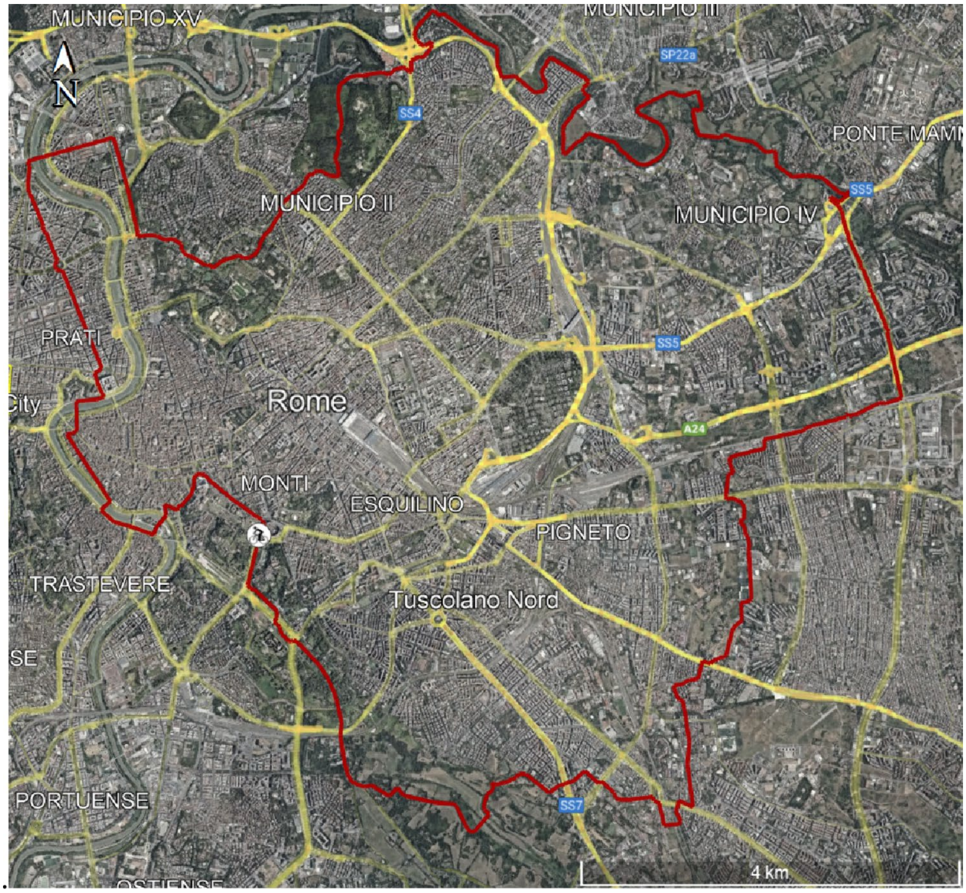

Fig. 1 GRAB

significant evaluation criterion within the GRAB project's methodology, quantifying the accessibility to essential services—including public transportation and healthcare facilities—within a radius allowing for a 10-min bicycle ride from each delineated section of the project according to the urban model growth (Galiano et al. 2021). The safety criterion within the GRAB project framework was informed by bicycle crash data to evaluate the safety of each section and identify crucial branches (Cantisani et al. 2019b). The cycle safety criterion addressed six mixtures designed to pave GRAB with high-performance materials.

The study presents a "from cradle to gate" LCA study of asphalt mixtures according to EN (2021a). The standard UNI EN ISO 14044 (EN 2021b) identifies four main phases to carry out an LCA: definition of objectives and the scope of the study; collection of the inventory of input data (life cycle inventory, LCI); impact assessment (life cycle impact assessment, LCIA); and interpretation and evaluation of the results.

Table 1 presents the system boundaries that include A1–A3 modules related to the product stage:

- A1 covers energy and materials for extraction and production of raw materials and fuels, and primary energy. It also includes the reuse of products from previous systems and processing of secondary materials, excluding disposal and end-of-life waste.
- A2 covers transportation within the production site and up to the end of the production stage, including transportation of raw materials.
- A3 covers production of auxiliary materials, semi-finished products, byproducts, and packaging.

The declared unit of the analysis is 1 Mg of each asphalt mixture. The reference year for the analysis is 2022. LCI involves primary and secondary data. The former is selected data provided by producers through on-site surveys, and the latter is selected generic data from Ecoinvent 3.8 (Wernet et al. 2016). No tertiary data have been used in this study. Table 2 lists the inventory data to produce 1 Mg (i.e., declared unit) of the asphalt recipes (R1 to R6). They consist of raw materials and energy consumption, emissions into air, transportation, and waste production. All the mixtures have physical and mechanical properties suitable for laying bike lanes. R1 (natural bitumen and virgin aggregates) and R3 (natural bitumen with 30% RAP and a hot mix asphalt rejuvenator agent) are hot asphalt mixtures (Fiore et al. 2023).

Table 1 Declared modules of LCA

Stage	Production				Construction				Use				End of life				Potential benefits
Phase	Raw material supply	Trans-port	Produc-tion	Trans-port	Installa-tion	Use	Mainte-nance	Repair	Replace-ment	Refur-bishment	Opera-tional energy use	Opera-tional water use	Demoli-tion	Trans-port	Waste process-ing	Waste disposal	Net ben-efits
Module	A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Declared module	X	X	X	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND

X declared module, *ND* not declared module

R2 is a warm repair-specific asphalt concrete with natural aggregates and flux oil, and R4 is a warm mix composed of ASW with 30% RAP and a rejuvenator and WMA additive. The cold mix R5 has only RAP and a cold mix asphalt rejuvenator agent; it was designed within the framework of the H2020 InfraROB project that focuses on pothole repair using 3D printing technology (Bruno et al. 2023). According to Di Mascio et al. (2023), R1 and R5 ensure comparable performances during the service life. Additionally, R6 represents a proposal for a hot mix containing 100% RAP and a hot mix asphalt rejuvenator agent. It has a 1.5‰ by weight of bitumen from the additive. It is a technical green solution designed to minimize the burden and balance often-conflicting technical and environmental goals. All the aggregates used in these recipes are wet, and the average moisture content is 3% by weight.

Transportation distances (Euro V 16–32 Mg freight lorry trucks) were 510 km for bitumen, 35 km for natural aggregates and secondary raw materials, and 600 km for chemicals.

The SimaPro ver. 9.3.0.3 (Pre Consultants 2016) software allowed LCA calculation with Ecoinvent ver. 3.8 (Wernet et al. 2016) library. Data from LCI were modeled with characterization factors according to EN (2021a) (Eq. 1):

$$\mathrm{IC} = \sum_{x} \mathrm{CF}_{\mathrm{ic}}(x) \cdot \mathrm{INV}(x) \tag{1}$$

where IC is the impact category obtained from the inventory of the substance x (i.e., INV(x)), and $\mathrm{CF}_{\mathrm{ic}}(x)$ is the characterization factor assigned to the substance x for the calculation of IC.

The outputs of LCIA consist of 22 parameters about core environmental impact, additional environmental impact, and resource use. Waste categories have been omitted because input and output data were comparable and insignificant for the analysis.

Results

Table 3 lists the core environmental impact categories of the modeled mixtures. All data refer to the declared unit (i.e., 1 Mg of asphalt mixture).

The results in Table 3 highlight the increasing green technology from R1 to R6. Climate change total is the sum of fossil, biogenic, and land use contributions. It reveals significant differences between the mixtures because the lowest value is 26 kg CO_2 eq (R6), and the highest is 68 kg CO_2 eq (R2). All the mixtures reveal the contribution from land use is negligible, and the fossil data drive the total result. In R1 to R3, the most impacting data is bitumen, which accounts for 40%, 32%, and 44%

Table 2 Input data

Input	Inventory	R1	R2	R3	R4	R5	R6
Materials	Bitumen (Mg)	0.041	0.036	0.041	0	0	0
	Natural aggregate (Mg)	0.902	0.953	0.613	0.658	0	0
	Filler (Mg)	0.057	0	0.058	0	0.009	0.058
	Reclaimed asphalt pavement (Mg)	0	0	0.287	0.278	0.926	0.901
	Tap water (Mg)	0	0	0	0	0.037	0
	ASW (Mg)	0	0	0	0.051	0	0
	Chemical (Mg)	0	0.011[a]	0.001[b]	0.013[c]	0.028[d]	0.003[b]
Energy	Electricity (kWh)	4.3	4.3	4.3	4.3	0.16	4.3
	Heat from natural gas (MJ)	230	180	230	190	0	230
	Diesel (kWh)	4.93	4.93	4.93	4.93	4.93	4.93

[a]Flux oil

[b]Hot mix asphalt rejuvenator agent

[c]Rejuvenator and WMA additive

[d]Cold mix asphalt rejuvenator agent

Table 3 LCA output—core environmental impact categories

	R1	R2	R3	R4	R5	R6
Climate change—total (kg CO_2 eq)	60.281	68.023	56.001	65.357	40.522	26.235
Climate change—fossil (kg CO_2 eq)	60.055	67.769	55.795	89.636	61.451	29.548
Climate change—biogenic (kg CO_2 eq)	0.196	0.223	0.185	−45.145	−27.820	−4.464
Climate change—land use (kg CO_2 eq)	0.026	0.020	0.017	11.128	6.846	1.137
Ozone depletion (kg CFC11 eq)	6.56E−06	5.59E−06	5.57E−06	8.52E−06	1.92E−05	4.48E−06
Acidification (mol H^+ eq)	0.355	0.439	0.327	0.723	0.496	0.122
Eutrophication, freshwater (kg P eq)	2.80E−03	1.57E−02	2.62E−03	2.20E−02	1.35E−02	3.07E−03
Eutrophication, marine (kg N eq)	0.103	0.114	0.091	0.445	0.278	0.059
Eutrophication, terrestrial (mol N eq)	1.152	1.233	1.008	2.430	1.525	0.394
Photochemical ozone formation (kg NMVOC eq)	0.416	0.432	0.378	0.761	0.508	0.127
Resource use—minerals and metals (kg Sb eq)	9.10E−05	1.80E−04	1.21E−04	4.10E−04	6.35E−04	1.27E−04
Resource use—fossils (MJ)	2604	2537	2555	1627	1613	530
Water use (m^3 depriv.)	17.228	26.932	15.419	185.419	113.292	20.234

of climate change-total and climate change-fossil, respectively. In R4, the amine oxide in the rejuvenator and WMA additive contributes to 43% of climate change-total and 65% of climate change-fossil. The negative contribution to climate change-biogenic (i.e., −45 kg CO_2 eq) justifies such a difference. In R5, the cold mix asphalt rejuvenator agent is responsible for 54% of climate change-total, 70% of climate change-fossil, and 99% of (negative) climate change-biogenic. From R1 to R6, the percentage contribution of transport and diesel burned in building machines increases. The burden from freight lorry is 16% in R1 and 29% of R6, while the impact from earthmoving machines is 1% of R1 and 4% of R6. Ozone depletion ranges between 4.48E−06 kg CFC11 eq (R6) and 1.92E−05 kg CFC11 eq (R5), and its average value is 8.32E−06 kg CFC11 eq. Whatever the investigated recipe, transport, building machines, and natural gas to produce the mixture affect ozone depletion. Their total contribution is 78% of R1, 59% of R2, 81% of R3, 43% of R4, 12% of R5, and 91% of R6. The results of R4 and R5 are affected by the chemicals in the mixtures (i.e., 47% and 87% of the total ozone depletion, respectively). Bitumen affects acidification that is at an average of 0.410 mol H^+ eq. It is responsible for 54% of R1, 40% of R2, and 60% of R3. In R4 and R5, the chemicals contribute to 80% and 85% of acidification, respectively. Fuel combustion for transport and heat contributes to the eutrophication of R1 and R3. On the other hand, chemicals in R2, R4, R5, and R6 account for 67–88% of freshwater eutrophication. The use of minerals and metals depends on natural raw materials (44%) and transport by lorry (50%) in R1, which is the most impacting recipe (i.e., 9.10E−05 kg SB eq). The decreasing content of raw materials and the increasing dosage of chemicals affect the results of R2 to R6 recipes. Additives account for up to 91% of the consumption of minerals and metals in R5, and natural raw materials are not used in R6. The fossil resource use reveals significant differences between the mixtures as their climate change-total performances. In particular, the highest fossil consumption is 2604 MJ of R1, and the lowest is 530 MJ of R6; the average value is 1911 MJ. In R1 to R3, the bitumen accounts for about 65%; in R4 and R5 the chemicals contribute 80% on average, and in R6 natural gas to produce the mixture gives the highest contribution. Concerning the water use of R1 to R3, quarry activities to extract raw materials cause up to 86% of the results. In R4 to R6, the chemicals are responsible for up to 96% of water use.

Table 4 lists all the additional impact categories according to EN (2021a). Their values shall be used with care as the uncertainties on them are high and there is limited experience with them.

Bitumen and chemicals affect the additional impact categories of R1 to R3 and R4 to R6, respectively. R6 ensures the best performances in Table 4. In particular, it implies the lowest values of particulate matter (i.e., 1.57E−06 disease inc.), ionizing radiation (i.e., 1.262 kBq U-235 eq), ecotoxicity (i.e., 770.63 CTUe), human toxicity-cancer (i.e., 2.57E−08 CTUh) and human toxicity-noncancer (i.e., 4.21E−07 CTUh). For each parameter, it accounts for 12–19% of the maximum value. R3 has the best performance in terms of land use (i.e., 375 Pt); the rejuvenator and WMA additive and the cold mix asphalt rejuvenator agent affect the results of R4 and R5 (i.e., 6176 and 2705 Pt).

Table 5 lists the resource use in terms of energy and water consumption. Since renewable primary energy is not used as raw material, the total use of renewable primary energy coincides with the use of renewable primary energy excluding renewable primary energy used as raw material. Bitumen is responsible for the use of nonrenewable primary energy as raw material.

The results of primary energy consumption require a correct interpretation.

R6 has a low consumption of total renewable primary energy (i.e., 130 MJ versus 1201 MJ of R4 and 735 MJ of R5) but is not the best because R1, R2, and R3 range between 13 and 21 MJ. However, the consumption of nonrenewable primary energy awards R6. Its total use of nonrenewable primary energy is 534 MJ, and the mixtures R1 to R3 range between 3927 and 4199 MJ due to the mixing procedure and mix design with bitumen. Therefore, the overall consumption of primary energy for R6 production (i.e., 723 MJ) confirms the sustainable performances compared with the traditional hot mixture R1 (i.e., 4213 MJ) and the innovative warm and cold mixtures R4 and R5 (i.e., 1871 and 2734 MJ, respectively). Finally, the net use of freshwater complies with the water use in Table 3: R6 (i.e., 0.936 m^3) is not the best option because the mixtures R1 to R3 have less impact (i.e., 0.421, 0.674, and 0.376 m^3, respectively).

Conclusions

The increasing use of light transport modes in urban areas is justified by their low impact but requires an objective and quantitative analysis of the environmental benefit. Improving bicycle infrastructures and promoting cycling as a primary mode of transportation are fundamental strategies for advancing sustainability, as confirmed in the main targets set out by the European Commission. In Rome, GRAB represents an innovative approach to sustainable urban mobility

Table 4 LCA output—additional impact categories

	R1	R2	R3	R4	R5	R6
Particulate matter (disease inc.)	3.64E−06	3.66E−06	2.99E−06	8.74E−06	5.38E−06	1.57E−06
Ionizing radiation (kBq U-235 eq)	1.938	2.940	1.552	4.577	6.517	1.262
Ecotoxicity, freshwater (CTUe)	6039.04	4853.08	5536.09	6383.49	3467.01	770.63
Human toxicity, cancer (CTUh)	3.35E−08	4.13E−08	3.29E−08	2.08E−07	1.31E−07	2.57E−08
Human toxicity, noncancer (CTUh)	2.84E−06	2.83E−06	2.84E−06	2.20E−06	1.47E−06	4.21E−07
Land use (Pt)	910	492	375	6176	2705	508

Table 5 LCA output—resource use

	R1	R2	R3	R4	R5	R6
Total use of renewable primary energy (MJ)	14	21	13	1201	735	130
Use of nonrenewable primary energy non as raw material (MJ)	2604	2537	2555	1670	1639	534
Use of nonrenewable primary energy as raw material (MJ)	1595	1400	1595	0	359	58
Total use of nonrenewable primary energy non as raw material (MJ)	4199	3937	4150	1670	1999	593
Net use of freshwater (m^3)	0.421	0.674	0.376	1.021	5.410	0.936

and covers approximately 44 km. It emphasizes the integration of cycling infrastructure into the city's environmental and historical heritage. However, the proper implementation of international sustainability efforts requires the impact assessment of transport infrastructures.

This study compares the environmental impacts of six asphalt mixtures suitable for bike paths. The adopted calculation methodology is life cycle assessment according to the 14,000 series of harmonized European standards. The calculation complies with the product category rules for construction products EN 15804. This study investigates a "from cradle to gate" system because it includes inventory data about raw materials, energy, fuels, transport, and processes to produce (production stage) 1 Mg of each bituminous mixture. They differ in recipe, mixing method, and laying procedure. In particular, R1 is a hot mixture composed of 100% natural bitumen, R2 is a warm repair-specific asphalt concrete with natural aggregates and flux oil, R3 is a hot mixture composed of natural bitumen with 30% RAP and a hot mix asphalt rejuvenator agent, R4 is a warm mix composed of ASW with 30% RAP and a rejuvenator and WMA additive, R5 is a cold mix composed of RAP and a cold mix asphalt rejuvenator agent, and R6 represents a proposal for a hot mix containing 100% RAP and a hot mix asphalt rejuvenator agent.

Primary and secondary inventory data have been used in SimaPro software ver. 9.3.0.3 with the Ecoinvent library ver. 3.8 to model the functional unit. The main results of the A1–A3 modules confirm the green performances of the sustainable recipe R6 proposed by the authors. It is a hot mix containing 100% RAP and a hot mix asphalt rejuvenator agent containing 1.5‰ by weight bitumen. Using recycled aggregates improves the climate change-total performances compared to the other recipes (i.e., 26 kg CO_2 eq versus 41–68 kg CO_2 eq). Concerning the primary energy consumption, R6 implies the total consumption of 593 and 130 MJ of renewable and nonrenewable primary energy, respectively. The hot mixtures R1 and R3 and the warm R2 imply the highest consumption (not less than 3937 MJ) and the lowest contribution from renewable resources (up to 21 MJ). These results comply with the fossil, mineral, and metal resource use. Therefore, the eco-friendly mixture saves energy and reduces greenhouse gas emissions and pollution. Conversely, the high content of the hot mix asphalt rejuvenator agent affects water use and net freshwater consumption of R6 (i.e., 20 m^3 deprive and 0.9 m^3, respectively).

The quantitative results highlight which variables of the production process can increase the sustainability of the bike lane. The results encourage holistic approaches that consider technical and environmental issues to design bike paths in temperate zones. Alternative power mix, transport system, and secondary raw materials may ensure environmental benefits to assess with a comparative LCA. Moreover, a "cradle to grave" analysis shall complete the study with the construction, maintenance, dismantling, and end-of-life stages to calculate the overall burdens of a cycling infrastructure.

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Data availability The data presented in this study are available on request from the corresponding author. The data are not publicly available due to confidentiality reasons.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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