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Life Cycle Assessment of Environmentally Friendly Solutions for the Construction of Unpaved Rural Roads †

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Abstract: In recent decades, the international community has recognized the detrimental impact of the construction industry on the environment. In recent years, the use of recycled aggregates has attracted increasing interest as a sustainable and cost-effective solution for the construction and maintenance of road pavements. The life cycle assessment (LCA) represents a valuable methodology for evaluating the environmental sustainability of technologies involving the use of such materials. This study deals with the LCA of alternative solutions for the construction and maintenance of unpaved rural roads. Different scenarios using recycled materials, such as reclaimed asphalt and mineral sludge, are analyzed and compared to a reference solution that employs only virgin aggregates. The environmental sustainability of the proposed alternatives is assessed by considering the global warming potential (GWP), energy requirements, and water consumption. The LCA analysis is performed using SimaPro software (version 9.1.1.7). The obtained results demonstrate that solutions involving the use of recycled materials represent a more sustainable and environmentally friendly option. In particular, a significant reduction in water depletion was found for the alternative scenarios, with savings between 56% and 99%. For GWP and energy, the total savings ranged from approximately 20% to 40%.

Keywords: life cycle assessment; sustainability; reclaimed asphalt; mineral sludge; unpaved roads; rural roads

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1. Introduction

The construction and maintenance activities of transportation infrastructures involve the use of large amounts of natural and non-renewable resources (including aggregates, water, and petroleum-based products), and dramatically contribute to climate change [1,2].

Increasing concerns regarding environmental issues have led the pavement construction industry to move towards more sustainable solutions that are conceived to preserve these natural resources [3]. In such a context, recycling by-products in paving mixtures represents a valuable option, since it allows large volumes of virgin aggregates to be replaced, with a consequent reduction in the depletion of raw materials [4–6].

Recycled materials of different origins, such as construction and demolition waste [7–13], plastics [14–20], rubber [21–26], reclaimed asphalt [10,19,24,25,27–37], and mineral sludge [38–44], have the potential for recycling in road pavement materials, making the performance of the corresponding mixtures in which they are employed comparable to those obtained with totally virgin components.

Reclaimed asphalt (RA), obtained from the milling of existing asphalt pavements, and mineral sludge (MS), derived from the industrial washing of natural aggregates in crushing plants, may be effectively used as alternative aggregates in the construction of pavement layers as a consequence of their high availability and due to the possibility of solving problems concerning their stockpiling and/or disposal [39,45,46]. In particular, a previous research study conducted by the authors showed that RA and MS could be successfully employed in large quantities in the production of emulsion-based cold recycled mixtures (CRMs) for the surface finishing of unpaved rural roads [47,48].

Although the technical feasibility of the abovementioned sustainable solutions has been widely proven in the literature, the corresponding environmental benefits still need to be properly identified. Over the last two decades, the life cycle assessment (LCA) methodology has attracted increasing interest as a method to evaluate the environmental sustainability of road infrastructures [4,49,50]. According to ISO 14040 [51], the LCA *"addresses the environmental aspects and potential environmental impacts throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal"*.

The application of the LCA methodology mainly focuses on the environmental impact of major infrastructures, where innovative materials and recycling solutions are generally compared to conventional practices [49,52–62]. In particular, Farina et al. [56] and Landi et al. [60] found that the use of crumb rubber (CR) from end-of-life tires resulted in a reduction in GWP between 30% and 45%. Puccini et al. [58] investigated the environmental benefits of different recycled materials (RA and CR) and technologies (hot-mix and warm-mix asphalts). They observed that the use of warm-mix technology together with recycled materials resulted in a 50% savings of energy resources. The benefits of using RA, in combination with other industrial by-products, were also evaluated by Giani et al., Bonoli et al., and Praticò et al. [53,59,61]. Their results all led to a significant reduction in CO_2 equivalent.

Only a few LCA studies focus on minor infrastructures, such as unpaved and low-traffic-volume roads [63,64]. However, these type of roads may represent a more fruitful and cost-effective sector for the implementation of recycling processes [65], since a reduced performance is generally required in comparison to high-volume highways and arterials [66].

The main goal of the study described in this paper is to compare the environmental benefits related to the adoption of different sustainable alternatives for the construction of unpaved rural roads. For this purpose, a full LCA is conducted, analyzing different alternatives that entail the use of large volumes of recycled components. A reference scenario, constituted by only virgin materials, is also considered for comparative purposes. The environmental features of the proposed alternatives are discussed in terms of the global warming potential (GWP), energy requirement, and water consumption involved in the production, construction, and maintenance stages.

The life cycle inventory (LCI) is based on both primary and secondary data. The LCA is performed using SimaPro, which is a commercially available software that incorporates several impact assessment methods and can be used for environmental and water footprinting.

The present paper is structured following the typical framework of an LCA analysis. Following the presentation of the analyzed scenarios, the life cycle inventory, impact assessment, and interpretation are provided in the following paragraphs. The main outcomes achieved from the study are finally presented in the concluding section.

2. LCA: Materials and Scenarios

Different construction and maintenance scenarios were considered in the present study for rural roads. The corresponding cross-sections (4.50 m width and 30 cm total thickness) are displayed in Figure 1.

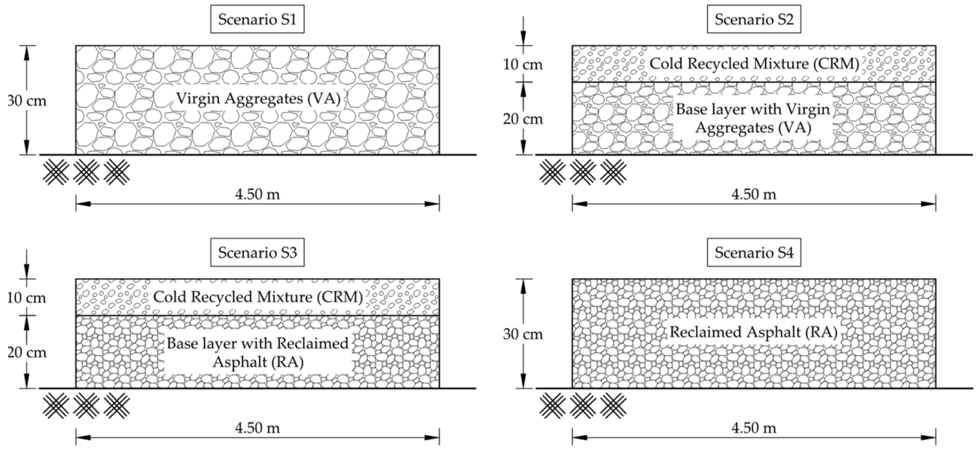

Figure 1. Cross-sections corresponding to the considered scenarios.

Scenario S1 refers to the typical solution currently adopted in northern Italy for low-volume unpaved rural roads, consisting of a single 30 cm-thick crushed aggregate layer (hereafter UB-VA). This unbound layer is composed of 0/45 Ga 90 virgin aggregates [67] with a particle density (ρ_a) of 2.700 g/cm^3 [68]. Based on the information provided by the contractor involved in the construction of the reference scenario and on previous studies conducted on similar materials, the optimum moisture content used in the mixing and compaction operations of this layer was assumed to be equal to 6.5% (by the dry mass of the aggregates).

As observed in the field, distresses occurring in unpaved rural roads included dustiness, erosion, raveling, potholing, corrugation, and rutting [69–71]. Since these distresses may have a direct effect on the comfort and safety of users, the functionality of unpaved rural roads needs to be preserved by using bound mixtures for road surface finishing. In fact, appropriate surfacing prevents material loss, eliminates dust, improves skid resistance, and reduces the risk of water seeping into the pavement structure. However, the environmental benefits of any adopted technical solution have to be carefully evaluated since they strongly depend on the materials employed in surface finishing operations.

Two alternative scenarios (S2 and S3), where an innovative solution was adopted for the surface finishing layer, were included in the study.

The proposed solution, derived from a previous study conducted by the authors [47], consisted of emulsion-based cold recycled mixtures (CRMs) containing large quantities of recycled components, including reclaimed asphalt (RA) obtained from the milling of existing asphalt pavements, and mineral sludge (MS) derived from the washing of natural aggregates in crushing plants.

The composition of the proposed solution for the finishing CRM layer is presented in Table 1.

Table 1. Composition of the proposed CRM.

Component	Value
Reclaimed asphalt	68.3%
Mineral sludge	16.4%
Silica sand	6.4%
Bituminous emulsion	3.5%
Water (added)	5.4%

It should be mentioned that active fillers (Portland cement or lime), typically adopted by this type of cold mixture to accelerate the curing process and improve the mechanical resistance [72], were not used to avoid further environmental burdens [73] and manufacturing costs.

In scenario S2, the CRM finishing layer was envisioned to be laid on a 20 cm crushed aggregate layer (UB-VA), while in scenario S3, to further enhance the environmental benefits, virgin aggregates used for the formation of the base layer were replaced by reclaimed asphalt (RA).

The RA used for the construction of the unbound base layer (hereafter UB-RA) in scenario S3 was identified as 20 RA 0/14 (in accordance with EN 13108-8 [74]), with a particle density (ρ_a) of 2.501 g/cm^3 [68]. Based on the information provided by previous studies conducted on similar materials, the optimum moisture content used for mixing and compaction operations for this layer was hypothesized to be the same adopted for the UB-VA layer (6.5% with respect to the dry mass of the RA particles).

Finally, the last scenario considered in the study (S4) consisted of a single 30 cm UB-RA composed of the same RA adopted for scenario S3.

In terms of the maintenance plans, different strategies were considered for the various solutions, as described below.

For reference scenario S1, the common practice adopted by local contractors involved in the maintenance activities of the rural road network was referred to. According to such a practice, during a service life of 10 years, the pavement is subjected to 2 maintenance cycles consisting of the laying and compaction of a new 9 cm layer of 0/45 Ga 90 on the existing distressed surface. As a result of its single-layer composition, the same maintenance plan and activities were considered for scenario S4. In this case, the only difference consisted of the fact that 20 RA 0/14 was used instead of the virgin aggregates.

Due to the lack of direct information or field experience, the maintenance operations for the remaining scenarios (S2 and S3) were hypothesized based on the mechanical characteristics of the adopted materials. In particular, due to the presence of the CRM mixture, it was deemed appropriate to consider a reduction in the number of maintenance cycles, referring to a single intervention in the 10 years of service life, with the laying and compaction of the existing surface of 3 cm of newly produced CRM.

The assumed maintenance operations are summarized in Table 2.

Table 2. Maintenance plan for the considered scenarios.

	S1	**S2**	**S3**	**S4**
Service life	10 years			
Number of maintenance interventions	2	1	1	2
Employed material	0/45 Ga 90	CRM	CRM	20 RA 0/14
Thickness of the new layer	9 cm	3 cm	3 cm	9 cm

The functional unit for the LCA analysis was set as equal to 1 km of road with a service life of 10 years. System boundaries included raw materials and production (MP), transportation (T), and construction and maintenance activities (C&M). The in-service phase was left out of the analysis due to its negligible impact in comparative terms and uncertainty in the forecast of traffic spectra. The end-of-life stage was also excluded from the LCA since all the employed materials could be fully reclaimed, re-mixed, and laid without requiring landfill disposal.

The impact assessment protocols adopted in this study were *ILCD 2011 Midpoint+* for the computation of water resource depletion and GWP, and the *Cumulative Energy Demand* (*LHV*) for the assessment of energy consumption levels.

3. LCA: Life Cycle Inventory (LCI)

The LCI phase was conducted to define the inputs (in terms of energy requirements and resource consumptions) and outputs (in terms of air emissions) for each unit process included in the system boundaries. This inventory was based on both primary (p) and secondary (s) data. Primary data were collected through interviews with local contractors, while the secondary data were obtained from the literature [75–77] and the Ecoinvent 3.6 database, already available in SimaPro.

When considering the materials' production, an inventory analysis was first performed for virgin aggregates (VA), reclaimed asphalt (RA), bituminous emulsion (BE), and mineral sludge (MS). Based on the corresponding outcomes, the production of the emulsion-based cold recycled mixture (CRM) and preparation of the unbound granular mixtures containing VA and RA (UB-VA and UB-RA, respectively) were then analyzed.

The inventory of equipment used for the materials' production was based on the information regarding fuel type, hourly production, and fuel consumption. These data are presented in Table 3 for the mobile crushing device (used for the crushing and screening of RA), the wheel loader (used for aggregate loading), and the blender machine (used for both bound and unbound mixture preparations). Only in the case of the crushing device used for the crushing and screening of virgin aggregates was detailed information excluded, since the data used for the inventory of VA production were extracted in an aggregated form from a study focusing on quarries located in the Piedmont region of Italy [75].

Table 3. Equipment, type of fuel, hourly production (P), fuel consumption (Fc), and data origin (p: primary data; s: secondary data).

Equipment	Activity	Fuel Type	P (t/h)	Fc (L/h)	Data
Crushing device	VA crushing and screening	-	-	-	s
Mobile crushing device	RA crushing and screening	Diesel	220	30.0	p
Wheel loader	Aggregate loading	Diesel	220	19.0	p
Blender machine	Mixture preparation	Diesel	132	19.0	p

The inventory related to the production of VA considered all activities occurring in the quarry. These included the extraction (such as the mining and transportation of coarse aggregates) and crushing of gravel. The impacts included those related to the infrastructures (construction, land occupation, and land transformation) along with those related to the equipment used during quarry activities. All operations were modeled in SimaPro by using the process "*Diesel, burned in building machine {GLO}|market for|Cut-off, U*". This process considered the impacts related to the production of fuel, diesel combustion, the production of the building machine, and the use of lubricating oil. The input used for modeling was the energy (obtained from fuel combustion) required by the machine to process 1 ton of material.

For the production of RA, a mobile crushing device located in the plant was considered for crushing and screening operations. At the end of the process, RA was assumed to be directly stockpiled in the plant for further use. The impacts related to the milling of pavements from which RA was obtained were allocated to the end-of-life stage of original pavements. The production of RA was modeled through the same SimaPro process used for the virgin aggregates, with the specific input data of the mobile crushing device. This could be achieved by knowing the hourly production and fuel consumption rates of the equipment, together with the density and heating values of specific fuels [78,79].

The data for the bituminous emulsion (BE) were collected from the Eurobitume report [60], which defined the LCI with a cradle-to-gate approach, starting from crude oil extraction and considering all the processes that occurred inside the refinery, as well as the impacts directly attributable to the refinery itself.

MS did not undergo any treatment before use. The impacts related to its production were allocated to the crushing of aggregate operations from which this by-product was derived.

The mass of CO_2eq, the volume of water consumption, and the energy required to produce 1 metric ton of VA, RA, and BE are listed in Table 4. Based on the allocation hypotheses presented above, the impacts related to the production of MS were assumed to be equal to zero.

Table 4. Impacts for the production of 1 ton of virgin aggregates VA, reclaimed asphalt RA, and bituminous emulsion BE.

Impact Indicator	VA	RA	BE
Global warming potential (kg of CO_2eq)	2.372	0.458	142.7
Water resource depletion (m^3 of H_2O)	1.218	1.251×10^{-4}	0.103
Cumulative energy demand (MJ)	38.140	6.411	2443

The production of the CRM was modeled according to the operative steps presented in the following section. The granular components were assumed to be placed in three different stockpiles, RA and MS were considered to be already inside the plant, while silica sand (SS) was unloaded from a dump truck. First, the wheel loader merged the stockpiles into a fourth stockpile; then, it tapped into the latter stockpile and poured the aggregate blend into the blender machine. Finally, the blender mixed the RA, MS, and SS with emulsion and water. The quantities considered to produce 1 ton of cold recycled mixture are presented in Table 5.

Table 5. Quantities for the production of 1 ton of CRM.

Component	Quantity (t)
RA	0.683
MS	0.164
SS	0.064
BE	0.035
Added water	0.055

Added water represents the water that must be added to the mixture to reach the optimum water content. This did not include the contributions of the bituminous emulsion and wet MS. Considering the typical natural moisture content of sludge (25% by the dry mass of MS), the use of wet MS saved of 0.041 tons of water during CRM production.

The production of UB-VA and UB-RA, which occurred in the mixing plant, was modeled considering the following operative steps. First, the granular components (0/45 Ga 90 and 20 RA 0/14 for UB-VA and UB-RA, respectively) were unloaded from a dumper truck and organized into a single stockpile. A wheel loader tapped into the stockpile and poured the aggregates into a blender, which mixed the aggregates with water. The quantities of the wet granular component and water required to produce 1 ton of UB-VA and UB-RA are indicated in Table 6.

Table 6. Quantities for the production of 1 ton of UB-VA and UB-RA.

Component	Quantity (t)
0/45 Ga 90 or 20 RA 0/14	0.958
Added water	0.042

Using these values, the impacts of the production of CRM, UB-VA, and UB-RA were calculated. The obtained results are presented in Table 7.

Table 7. Unitary impacts for the production of 1 ton of CRM, UB-VA, and UB-RA.

Impact Indicator	CRM	UB-VA	UB-RA
Global warming potential (kg of CO_2eq)	6.396	3.028	1.194
Water resource depletion (m^3 of H_2O)	0.087	1.174	7.18×10^{-3}
Cumulative energy demand (MJ)	105.3	47.117	16.718

By focusing on the material transportation, the use of dump trucks was assumed for both bound and unbound granular materials, while a tanker truck was considered for the transportation of the bituminous emulsion.

Modeling was conducted by considering Euro III diesel engines and the maximum technically admissible laden masses comprised between 16 and 32 tons. In the case of the dump and tanker trucks, only secondary data were taken into consideration. These were obtained from the Ecoinvent database [80]. An in-built SimaPro process was used, called "*Trasport, freight, lorry 16–32 metric ton, euro3 {ReR}| market for transport, freight, lorry 16–32 metric ton, EURO3 | Cut-off, U*". This process considered the impacts related to the combustion of diesel fuel, lorry production, and maintenance (proportionally attributed based on use), and a portion of the impacts associated with road construction and maintenance. The results for the unitary input (1 tkm) are reported in Table 8.

Table 8. Unitary impacts for 1 tkm transported.

Impact Indicator	Transportation
Global warming potential (kg of CO_2eq)	0.165
Water resource depletion (m^3 of H_2O)	5.27×10^{-5}
Cumulative energy demand (MJ)	2.569

When considering the travel distances, it was assumed that virgin aggregates (0/45 Ga 90 and SS) were hauled from the quarry to the plant facility. Reclaimed materials, both RA and MS, were processed at the plant where they were stored; hence, the distance between the recycling and mixing plant facilities was set as equal to zero. In the case of RA, the impacts related to the materials' transportation from the milling site to the recycling plant were allocated to the end-of-life stage of the original pavements. Regarding the fluid materials, BE was assumed to be hauled from the refinery to the mixing plant. No transportation distances were ascribed to water since water was directly available from the mixing plant, and the impacted related to its distribution were not included in the system boundaries of this study. All bound and unbound mixtures used for the pavement construction were hauled from the mixing plant to the construction site.

Table 9 presents details about the travel distances.

Table 9. Transportation distances for materials.

Material	Production/Extraction Sites to Plant (km)	Plant to Construction Site (km)
0/45 GA 90, SS	14.5	-
20 RA 0/14, RA, MS	0.0	-
BE	372	-
Water	0.0	-
UB-VA	-	43.8
UB-RA	-	43.8
CRM	-	43.8

The inventory of equipment refers to asphalt pavers, motorgraders, and roller compactors used for both pavement construction and maintenance activities. These activities were modeled by using the process "*Diesel, burned in building machine {GLO}|market for|Cut-off, U*". Although more specific processes on the use of construction equipment are available in SimaPro, the adoption of this generic process allowed the use of precise technical data for each machine type, according to the information reported in Table 10.

Table 10. Equipment, type of fuel, hourly production (P), fuel consumption (Fc), and data origin (p: primary data; s: secondary data).

Equipment	Activity	Fuel	P	Fc (L/h)	Data
Asphalt paver	CRM laying	Diesel	661 t/h	25	s
Motorgrader	UB-layer preparation	Diesel	2500 m^3/h	40.0	s
Roller compactor	UB and CRM-layer compaction	Diesel	500 m^3/h	37.6	s

Construction and maintenance operations were modeled according to the operative steps described in the following section. In scenarios S1 and S4, the unbound mixture was laid using a motorgrader, while a roller was used for compaction. This procedure was adopted for both the construction of the new pavement (30 cm thickness) and the placement of overlays during maintenance operations (9 cm thickness). In scenarios S2 and S3, during the initial construction stage, the unbound mixture of the base layer was laid and compacted employing a motorgrader and a roller (20 cm thickness). A paver and roller were then used for the laying and compaction of the bound surface layer during both the initial construction (10 cm thickness) and maintenance stages (3 cm thickness).

Unitary impacts, computed for 1 MJ consumption for each machine, are presented in Table 11.

Table 11. Unitary impacts for 1 MJ consumption of equipment.

Impact Indicator	Equipment
Global warming potential (kg of CO_2eq)	0.090
Water resource depletion (m^3 of H_2O)	2.47×10^{-5}
Cumulative energy demand (MJ)	1.267

4. LCA: Life Cycle Impact Assessment (LCIA)

The LCIA phase was conducted by taking into account both the overall outcomes and individual contributions made by the materials' production, transportation, and road construction and maintenance activities. This provided straightforward information about the influence of each stage, thus allowing for a proper comparison of the different solutions and further optimization of the possible alternatives.

Material production concerns the activities related to the production of all materials used for the initial construction and maintenance of the road. The quantities were computed considering the volumetric characteristics of the mixtures, road geometry (0.30 m × 4.50 m × 1 km, per the selected functional unit), and maintenance plan.

Transportation considers the movement of materials needed for the preparation of construction materials, for the initial construction, and for additional maintenance stages. These operations include transportation required for the preparation of the construction materials in the plant (from production/extraction sites to plant) and those required for construction and maintenance operations on site (from the plant to the construction site).

The construction and maintenance stages include the activities related to the on-site use of equipment for both initial construction and maintenance activities.

The analysis was repeated for all four scenarios considered in this study. Obtained results are reported in both aggregated (total) and disaggregated (MP, T, and C&M) forms in Table 12.

Table 12. GWP, energy requirements, and water consumption for the considered scenarios.

Stage	S1	S2	S3	S4
		GWP (t of CO_2eq)		
MP	14.2	14.2	10.4	5.2
T	44.6	30.8	25.3	31.3
C&M	0.7	0.6	0.6	0.7
Total	**59.4**	**45.6**	**36.3**	**37.2**
		Energy (GJ)		
MP	220.9	228.2	166.4	72.6
T	695.0	479.9	394.0	488.8
C&M	9.3	8.2	8.2	9.3
Total	**925.1**	**716.3**	**568.6**	**570.7**
		Water (m^3)		
MP	5500.6	2408.0	129.1	31.2
T	14.2	9.8	8.1	10.0
C&M	0.2	0.2	0.2	0.2
Total	**5515.0**	**2418.0**	**137.3**	**41.4**

5. LCA: Life Cycle Interpretation

The results of the impact assessment phase are presented in Figure 2. The outputs obtained for each impact category were normalized with respect to those obtained for reference scenario S1. Relative contributions provided by material production, transportation, and construction and maintenance activities are also highlighted in the plot.

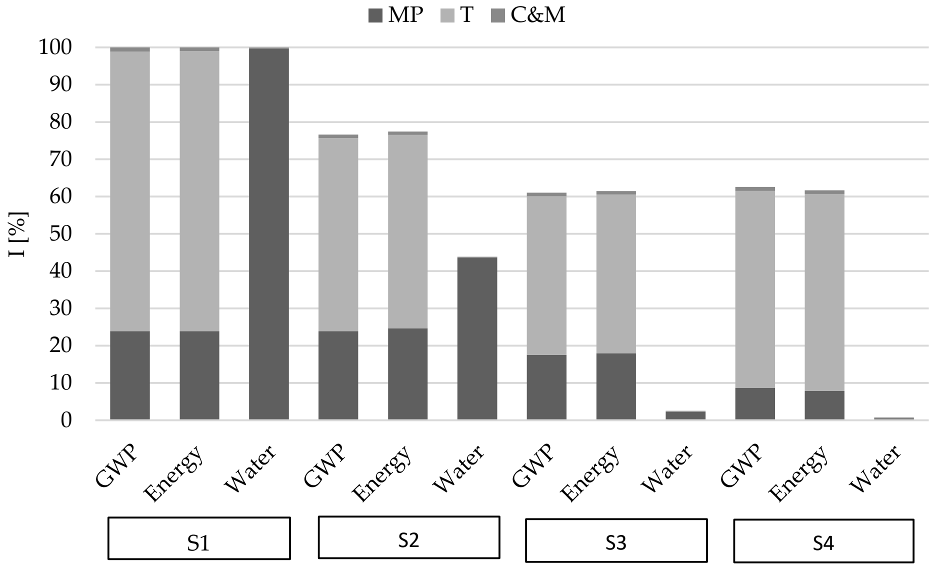

Figure 2. Normalized impacts (I) for GWP, energy, and water, expressed as a percentage of the results of reference scenario S1, with relative contributions of material production (MP), transportation (T), and use of equipment during construction/maintenance (C&M) stages.

In general, the adoption of all alternative options resulted in a reduction in environmental burdens when compared to the reference solution of scenario S1. Such a reduction was quite significant when considering water depletion. While for GWP and energy the total savings were observed to range from around 20% to 40%, savings of between 56% and 99% were achieved for the indicator based on water consumption.

When the three alternatives are compared, it can be observed that the least effective solution is that presented in scenario S2, which still entails the use of large volumes of VA in the base layer. The environmental impacts related to the use of VA are dramatically higher than those related to RA (used in all the other scenarios), in particular when considering water depletion. The advantages of adopting recycled materials were maximized in the third scenario (S3), where replacing the unbound layer of virgin aggregates with reclaimed asphalt caused the highest decrease in two of the three analyzed impact categories (GWP and energy). However, the solution proposed in S4 was found to be almost comparable to that found for S3, with relative impacts that were slightly higher in the cases of GWP and energy, and slightly lower in the case of water.

Focusing on the relative impacts of material production, transportation, and construction and maintenance operations, it is worth noting that the use of equipment for pavement construction and maintenance activities played a marginal role, as evidenced by contributions that were found to be always lower than 2%, regardless of the analyzed scenario.

The most relevant stage was found to be that related to material transportation. This was influenced by travel distances and the amount of materials transported over the service life of the pavement. As a result, the adoption of a bound mixture for the surface finishing of the road seemed to be a particularly valuable solution since it allowed a reduction in both the number of maintenance cycles required during the service life of the pavement and the quantity of materials that needed to be transported for each maintenance cycle.

When focusing on the impacts related to material production, different findings may be obtained by analyzing water consumption, GWP, and energy values.

Savings for water consumption were achieved by the decrease in the use of virgin aggregates, thus implying that the most effective solutions were those that maximized the amount of recycled materials. From a comparison of the outcomes obtained for S1 and S2, it is interesting to observe that the impacts of water needed to produce the cold recycled mixture (in terms of water added to the mixture and water derived from the emulsion) is still negligible concerning the production of virgin aggregates. In this regard, the presence of water in mineral sludge plays a beneficial role in reducing the volume of added water. By comparing the scenarios that resulted in the highest contents of recycled materials (S3 and S4), it was found that S4 was the best solution to reduce water consumption since the production of RA required a lower amount of water with respect to that needed for CRM.

By referring to GWP and energy requirement, significant reductions in the impacts related to material production were found for S3 and S4 (for which virgin aggregates were substituted by CRM and RA for S3, and by RA only in the case of S4). By comparing S1 and S2, it was finally shown that the savings related to the use of a reduced amount of virgin aggregates in the top layer of the pavement were offset by the use of CRM. This was mainly due to the environmental burdens caused by the industrial production of BE, and, to a lesser extent, by the treatments to which RA was subjected before use.

6. Concluding Remarks

In the present study, the environmental performances of four technical solutions developed for low-volume rural roads were evaluated using an LCA conducted using SimaPro software.

To this purpose, a technical solution largely adopted in northern Italy and consisting of a single thick layer of virgin aggregates was compared to alternative solutions that relied on the use of large amounts of recycled materials.

The outcomes of the performed LCA demonstrated the environmental benefits associated with the use of large quantities of recycled materials in road construction and maintenance operations. This was proven by the least impacts (in terms of GWP, energy requirement, and water consumption) observed when virgin aggregate layers were replaced by bound and/or unbound layers containing either reclaimed asphalt and mineral sludge or reclaimed asphalt only (scenarios S3 and S4, respectively). Comparable results were obtained when an emulsion-based cold recycled mixture was used for the surface finishing of the road laid on a reclaimed asphalt base layer (scenario S3) or by considering a single thick layer of reclaimed asphalt (scenario S4). Nonetheless, scenario S3 appears to be the most valuable option because it allows the recycling of relevant quantities of mineral sludge, thereby solving a serious environmental concern associated with the management of this type of waste material. Moreover, the presence of a bound surface layer can control, or at least reduce, several of the major distress types affecting unpaved roads, with direct impacts on the maintenance operations. The solution based on the use of an emulsion-based cold recycled mixture laid on a virgin aggregate base layer (scenario S2) produced minor environmental benefits with respect to the solutions proposed for scenarios S3 and S4. This was due to the relevant environmental burdens derived from the production of virgin aggregates.

In conclusion, the results of this research demonstrate the environmental advantages related to the use of recycled materials in unpaved low-volume roads. It is believed that this outcome can contribute to fill the gap in the existing technical literature, which mainly focuses on the LCA of major roads carrying high-volume traffic. However, further studies are certainly needed to extend the analysis to other impact categories and to validate the outcomes of this study by means of real-scale test sections.

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