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Improving the Environmental Sustainability of Low Noise Pavements: Comparative Life Cycle Assessment of Reclaimed Asphalt and Crumb Rubber Based Warm Mix Technologies

Monica Puccini *, Pietro Leandri, Andrea Luca Tasca, Lavinia Pistonesi and Massimo Losa

Department of Civil and Industrial Engineering, University of Pisa, Largo Lucio Lazzarino, 56126 Pisa, Italy; pietro.leandri@unipi.it (P.L.); andreasilstella@gmail.com (A.L.T.); l.pistonesi@outlook.it (L.P.); massimo.losa@unipi.it (M.L.)

* Correspondence: monica.puccini@unipi.it; Tel.: +39-050-221-7888

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Abstract: Increasing environmental awareness is pushing towards sustainable approaches to the design and management of transport infrastructures. A life cycle assessment of low noise pavements is carried out here, with the aim to evaluate and compare the use of warm mix asphalts containing crumb rubber (CR) from end-of-life tires (ELTs) and reclaimed asphalt pavement (RAP). Different scenarios have been considered, taking into account production, construction, maintenance activities, and end-of-life of the pavement, according to a cradle to grave approach. Hot mix asphalt (HMA) was used as a reference wearing course. Results show that the simultaneous implementation of warm asphalt technologies and recycled materials can lead to a 50% reduction of the environmental burdens, compared to the standard scenario. The difference is mainly ascribed to the material depletion, the energy consumption, and the emissions associated with the frequency of maintenance of the wearing course. The use of asphalt rubber is environmentally advantageous, if compared to polymer modified binders (PMB); moreover, rubberized open-graded mixtures require the lowest bitumen content and maintenance. The findings of this research support the use of recycled materials and warm technologies as a way to improve the environmental sustainability of low noise pavements.

Keywords: LCA; asphalt mixture; road; WMA; impact assessment

1. Introduction

In the recent years, significant efforts have been made to evaluate the environmental impacts of road construction and rehabilitation with the aim to introduce a more sustainable approach to the design and management of transport infrastructures [1–3]. The increasing environmental awareness, encouraged by government policies and regulations, has led the asphalt industry to look for production and construction processes able to improve pavement performance, saving the available natural resources.

The life cycle assessment (LCA) methodology has been recently identified by the asphalt industry as the most effective tool for measuring and comparing the environmental performances of road pavements throughout their whole design life. In this context, several studies have been published with the aim of comparing the environmental effects of different materials and technologies used in the construction and maintenance of pavements. However, due to limitations and uncertainties related to data availability and to the choice of system boundaries, functional unit, and impact categories, there is still no consensus regarding which type of material and technology is more sustainable [4,5]. The results of recent LCA studies on road pavement have shown that extraction and processing of virgin materials have the highest impact on the lifecycle, mainly due to the use of bitumen [6–8]. Therefore, the incorporation of recycled materials by reducing the demand for virgin materials contributes to the preservation of resources, as well as minimizes waste and landfill pressure [9].

Reclaimed asphalt pavement (RAP) is the removed and reprocessed pavement material typically generated from milling operations in rehabilitation projects [10]. Nowadays reuse of RAP is a common practice in many European countries [11–13], representing the most used material for replacing virgin raw materials (aggregates and bitumen) in asphalt mixtures [14]. However, the introduction of RAP to conventional hot mix asphalt (HMA) requires additional heating energy to achieve adequate levels of bitumen viscosity [15], with a consequent increase of air emissions during the production stage. Hence, in addition to reclaimed materials, warm mix asphalt (WMA) technologies have been developed to improve the environmental performance. The main advantage associated with WMA has been identified as its ability to incorporate high percentages of reclaimed asphalt paving, due to its improved workability at lower temperatures [7,16,17]. WMA is proven to increase the workability of the mixtures, allowing it to be hauled long distances and a quick turnover to traffic due to a shorter cooling time [17,18]. A recent life cycle cost analysis shows that addition of moderate amounts of WMA additives increases the fatigue life; moreover, a reduction of the mixing temperature may increase the likelihood of rutting [19]. The use of WMA leads to a reduction in mixing and compaction temperatures of about 20–40 °C, if compared to the traditional HMA [18] and the addition of zeolites has been shown to further decrease the temperature [20]. As the required heat is reduced, plant and site emissions are lowered [21]. Life cycle assessment (LCA) studies have shown that a reduction of processing temperature is associated with a reduction of air pollution, smog production, and fossil fuel depletion [22]; on the other hand, the production of required additives may counteract the reduced environmental impact [7,23,24]. The energy to produce WMA is less than that for HMA and the equipment required by the two technologies is basically the same, although some process-dependent modifications may be necessary at the mixing plant [25]. Zaumanis et al. [15] found that the energy saving associated with improved compaction is negligible, while a recent review of the available literature shows that generally the energy use is reduced [21]. Several LCA analysis have shown that the impacts of WMA are significantly reduced when RAP is added [6,7,15,23,26]. Therefore, asphalt production using RAP coupled with WMA technology is the key for the sustainable design of road pavements [6]. Despite these findings, the available reclaimed asphalt in Italy (nine million tons) is only used in hot and cold recycling, according to the annual report for asphalt [27], leaving a large room for improvement.

Besides WMA technologies, several materials such as recycled glass [28], fly ash derived zeolites [29], boron waste [30], recycled ceramic aggregates [31], desulphurization gypsum residues [32], and recycled polymers [33] have been investigated as asphalt additives or road base materials. Crumb rubber modified (CRM) represents a valuable solution to fulfill high environmental standards. CRM from end-of-life tires (ELTs) is a secondary material that has been widely investigated in road application, due to the associated reduced pressure on landfills. This material can be included in bituminous mixtures by wet or dry processes. In the wet process CRM is added to bitumen as a modifying agent, and the resulting modified binder is called asphalt rubber [34,35]. In the dry process CRM grains are added to the dry mixture as a replacement of a small portion of aggregates [36]. Crumb rubber modified mixtures have shown improved acoustic performances compared to traditional mixtures [37]. Moreover, recent LCA studies conducted on CRM wet mixtures shown a mitigation of the environmental impact in terms of reduction of the pavement thickness [38], or increased service life [8,39], due to improved mechanical performances. On the other hand, LCA results for dry CRM mixture do not show any significant environmental improvement compared with traditional HMA [38].

Recently the European Environmental Agency highlighted the impact of traffic noise on human health [40]. Several methods have been proposed with the aim to include traffic noise in LCA [41], but noise effects continue to be overlooked in pavement LCA studies [5]. Texture of the pavement surface plays a fundamental role in the generation of rolling noise [42]; furthermore, besides the fulfillment of environmental standards, adequate mechanical performances of the mixtures are required to achieve the desired pavement design life. However, a detailed planning of future maintenance activities is not a common practice in the LCA framework [4]. Indeed, the scheduling of the maintenance depends also on several factors that do not necessarily account for mixtures properties, such as: the variability of traffic loads, the weather conditions, the adequacy of the construction practice, and the financial policy followed by road agencies and authorities. Therefore, in the LCA method, the prediction of the residual pavement life becomes challenging especially in case of non-traditional asphalt mixtures [43].

An approach towards sustainability of bituminous mixtures should comprise limited usage of virgin non-renewable materials, the use of secondary materials to lower landfill pressure, and a reduction in the production temperatures (i.e., energy requirements), and provide adequate functional (e.g., acoustic) and mechanical performances. RAP and CRM technologies fulfill the first and the second requirements, while the use of WMA fits the latter scope. Hence, the combined effect of these three technologies/materials on the environmental impact of bituminous mixtures must be quantified. In this work a LCA analysis is carried out with the aim to evaluate the environmental impact of mixtures produced with RAP and CRM by using a WMA technology. Acoustic performances are included and discussed. Moreover, the results obtained are compared with the environmental assessment of traditional HMA.

2. Methodology

The LCA methodology is here used to evaluate and compare the environmental performances related to three road pavement wearing courses: open-graded, gap-graded, and dense graded mixtures. For such layers of the pavement, novel WMA mixtures composed of virgin materials (binder and aggregates), RAP, and CRM are analyzed and compared with traditional HMA (dense asphalt concrete 0–12). In each type of mixture, CRM was added by using both wet and dry technology; thus, six different bituminous mixes were compared to the reference one for the construction of the wearing course. Differences in the composition of the wearing courses provide layers with different structural capacities (e.g., different stiffness, different durability); therefore, the pavements will have a different structural capacity under loading, and thus, a different design life. Hence, for comparison purposes, the thickness of the layers has been adjusted in order to analyze the different pavements under the same level of structural capacity.

The analysis was conducted referring to a case study of an Italian urban road located in the municipality of Massarosa in the province of Lucca (Tuscany) and performed using a methodological framework based on the International Organization for Standardization (ISO) recommendations [44]. The data collected for the entire life cycle of the road were analyzed with the LCA software SimaPro 8.3.0 and the environmental impacts were estimated using the ecological scarcity method, by a midpoint approach.

2.1. Life Cycle Assessment

The LCA was the methodology chosen to investigate iteratively the environmental impacts associated with the studied systems. Each process was analyzed from the raw material extraction and acquisition, through the energy and material production/manufacturing, until the end-of-life treatment and final disposal, according to a cradle to grave approach. The methodology consisted of four phases: goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA), and life cycle interpretation (LCI). Goal and scope definition is the preliminary phase in which the objectives of the study, the functional unit, temporal and spatial boundaries, amount and quality of data, assumptions, and limits are defined. Within the LCI analysis, inputs and outputs associated with the processes included within the system boundaries are identified and quantified in relation to the functional unit and a model of the studied systems is developed. In the LCIA phase the inventory results are assigned to defined impact categories and the contribution to each impact category is quantified. Finally, system improvements are proposed in the life cycle interpretation phase, in order to reduce the environmental impacts.

2.2. Goal and Scope Definition

2.2.1. Goal

The main goal of the analysis was to quantify and compare the environmental performances of different road pavement rehabilitations carried out using RAP, CRM, and WMA technologies. To this end, six different production methods and methods for the laying of warm mix asphalt for the wearing course were designed and compared with the reference scenario.

2.2.2. Functional Unit

The functional unit is a measure of the performances of the analyzed system, a reference to which inputs and outputs are related. The pavement structure (i.e., the type and thickness of materials) is influenced by different factors, such as traffic, environmental conditions, design life, and other project-specific details; hence, several functional units have been proposed to assess road pavements [4]. In this study, the functional unit was defined as: 400 m and 464.5 m of pavement of an urban road, depending on the scenario considered. The reason of this choice is explained in Section 2.2.4. Such road section consisted of a single dual-lane carriageway (one lane per direction). The total width of the carriageway was 9.5 m; the width of the lane was 3.5 m with a shoulder of 1.25 m.

2.2.3. Pavement Design and Maintenance Planning

The pavement structures related to the different scenarios were designed according to a typical flexible pavement structure. For the sake of simplicity, the pavement thicknesses were calculated to provide a pavement design life of 20 years, applying the semi-empirical method of the AASHTO Guide for Design of Pavement Structures [45]. According to this method, the pavement performances are quantified as per the serviceability loss (present serviceability index, PSI) due to repeated traffic loading expressed in terms of equivalent single axle load (ESAL) (single axle-dual tire at 80). Based on the ESALs obtained by traffic analysis (8.9 million) and the resilient modulus of the subgrade, the thickness of the asphalt layers of each pavement section and the structural number (SN) were calculated (Table 1).

Table 1. Thickness of the asphalt layers (cm).

Scenario (Wearing Course Mixture)	Wearing Course	Binder Course	Base Course	SN
S (Standard dense-graded)	4	6	10	7.83
O_{WR} (Rubberized open-graded mixture with RAP)	4	6	11	7.83
O_{DR} (Dry rubberized open-graded mixture with RAP)	4	6	11	7.83
G_{WR} (Rubberized gap-graded mixture with RAP)	3	6	11	7.82
G_{DR} (Dry rubberized gap-graded mixture with RAP)	3	6	11	7.82
D_{WR} (Rubberized dense-graded mixture with RAP)	3	6	11	7.82
D_{DR} (Dry rubberized dense-graded mixture with RAP)	3	6	11	7.82

The binder course was designed with a constant thickness (6 cm) in all the scenarios, as shown in Table 1. Such a layer was designed considering a 20% RAP content in the mixture. The base course mixture included 30% RAP content and had a thickness of 10 and 11 cm in the reference scenario and in the other six scenarios considered, respectively. The major difference among the different scenarios was in the wearing course mixture. The traditional hot mixture of the reference wearing course was compared to six surface layers containing 25% RAP (by weight of dry aggregates), different percentages of crumb rubber (CR), and obtained using WMA technology. Table 2 includes the percentages of RAP and CR (added by wet or dry process) in the wearing course mixtures of the different scenarios:

Table 2. Percentages of crumb rubber (CR) and reclaimed asphalt pavement (RAP).

Scenario	% CR_{Wet} (%*w*/*w* Binder)	% CR_{dry} (%*w*/*w* Aggregates)	% RAP (%*w*/*w* Aggregates)
S	–	–	–
O_{WR}	20.0	–	25
O_{DR}	–	1.3	25
G_{WR}	20.0	0.0	25
G_{DR}	–	2.9	25
D_{WR}	20.0	–	25
D_{DR}	–	2.0	25

The mixture compositions presented as kg of the constituent materials per ton of mix are given in Table 3.

Table 3. Composition of 1 ton of bituminous mixtures.

Scenario	Aggregates (kg)	Bitumen (kg)	AR [1] (kg)	RAP (kg)	CR (kg)	Additive (kg)
Wearing course S	943.40	56.60	–	–	–	–
Wearing course O_{WR}	710.65	–	52.10	237.00	–	0.25
Wearing course O_{DR}	694.05	52.00	–	241.10	12.60	0.25
Wearing course G_{WR}	706.47	–	70.10	223.20	–	0.23
Wearing course G_{DR}	670.96	69.80	–	231.80	27.20	0.24
Wearing course D_{WR}	710.65	–	52.10	237.00	–	0.25
Wearing course D_{DR}	698.95	52.00	–	239.40	9.40	0.25
Binder course	765.35	35.41	–	199.04	–	0.20
Base course	672.78	26.92	–	300.00	–	0.30

[1]: Asphalt rubber (AR).

Alongside the definition of the final recommended pavement structure and the design of the mixtures to meet the expected performances, the schedule of the maintenance operations was conducted following three main criteria. These criteria consist of evaluating the degradation of friction levels provided by the wearing course, the acoustic performances of the wearing course, and the PSI provided by the overall pavement structure. Data related to the degradation of the functional characteristics of the wearing course (friction levels and acoustic performances) were gathered from the "Leopoldo" project dataset [46]. Within the "Leopoldo" project, the functional characteristics of wearing course mixtures similar to those used in this study case (dense-graded, gap-graded, and open-graded) were monitored over time and degradation curves of such properties versus the number of vehicle passes were developed. Regarding the friction degradation of the surface layer, the frequency of the interventions was calculated based on the time interval during which the friction level drops below the minimum acceptable values. The threshold limits of the minimum friction level expressed in terms of BPN (British portable number) were provided by the national standards in the gradations used for wearing course mixtures.

The noise levels generated through the tire-pavement interaction was measured through the close proximity method (CPX) as per the ISO/CD 11819-2 [47]. The index employed for this evaluation is the difference between the CPX level measured on a wearing course similar to those under study and the one obtained on a traditional dense asphalt surface. The time intervals between two consecutive maintenance interventions estimated on the basis of the described criteria are given in Table 4.

Table 4. Time interval between two consecutive maintenance interventions on the wearing course.

Time Interval (years)	Open-Graded	Gap-Graded	Dense-Graded
Levels of friction	8	6	6
Acoustic performance	4	3	3

The main function of the wearing course is providing adequate levels of tire–pavement friction to meet the safety requirements. Hence, the criterion related to the minimum allowable friction was selected to schedule the maintenance of the wearing course layer, although it provides a lower frequency of maintenance compared to the acoustic criterion. In the case of open-graded mixtures, in order to avoid the clogging of the air voids (that undermines drainability and acoustic performances), the open-graded mixtures are cleaned by pressurized water injection every four years. Based on experimental data collected on the pavements of the "Leopoldo" project, open-graded mixtures show higher durability of friction compared to gap-graded and dense-graded ones; this is related to the higher macrotexture, measured on the open-graded mixtures, that is less prone to be reduced by traffic.

The design life of the pavement is a function of the overall pavement structure, where each layer contributes to meeting the design life requirement. For this reason, after some years, maintenance limited to the wearing course only may not be enough to achieving the expected design life. According to the AASHTO method, the design value of the structural number is discounted by a condition factor (CF), calculated by referring to the remaining life to reach the terminal serviceability (PSI equal to 1.5). The degradation of PSI with time of standard, gap-graded, and dense-graded scenarios is shown in Figure 1, while Figure 2 refers to the open-graded scenarios.

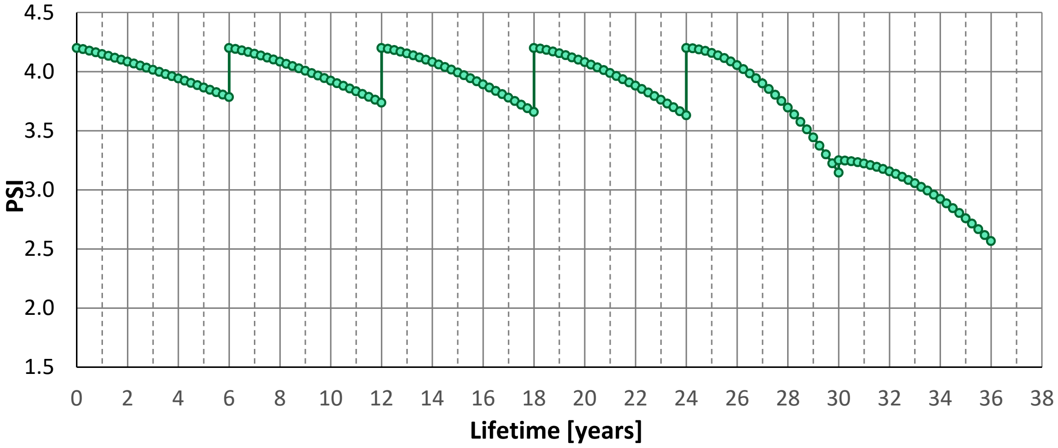

Figure 1. Present serviceability index (PSI) variation of S–G_{WR}–G_{DR}–D_{WR}–D_{DR} scenarios.

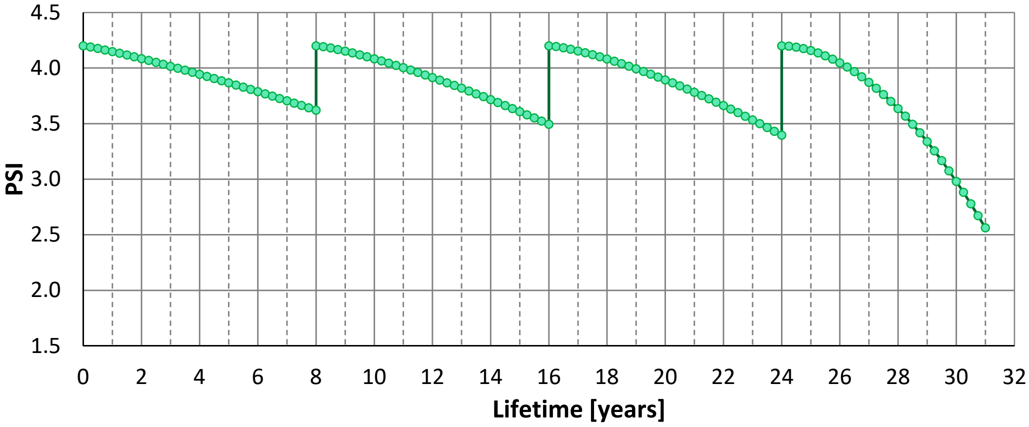

Figure 2. PSI variation of O_{WR}–O_{DR} scenarios.

As it can be seen in Figures 1 and 2, after each restoration, the value of PSI rises back to the original value of 4.2, typical of flexible pavements. The scheduling of the maintenance is given in Tables 5 and 6.

Table 5. Maintenance and planned operations of standard, gap-graded, and dense-graded scenarios.

S–G_{WR}–G_{DR}–D_{WR}–D_{DR} Scenarios	Time Post Construction (years)	Planned Maintenance Operation
wearing course	6	1st–milling
wearing course	12	2nd–milling
wearing course + binder course	18	3rd–milling
wearing course	24	4th–milling
wearing course	30	5th–milling
wearing course + binder course + base course	36	6th–milling (pavement rehabilitation)

Table 6. Maintenance and planned operations of open-graded scenarios.

O_{WR}–O_{DR} Scenarios	Time Post Construction (years)	Planned Maintenance Operation
wearing course	8	1st–milling
wearing course + binder course	16	2nd–milling
wearing course	24	3rd–milling
wearing + binder + base course	31	4th–milling (pavement rehabilitation)

2.2.4. System Boundaries

Road infrastructure has to be maintained in the best conditions of safety and efficiency as possible. Therefore, road maintenance is an on-going process, which aims to keep the infrastructure safe and efficient throughout its entire lifetime. Generally, once a road infrastructure has been constructed, it is not removed and its function lasts along with time of scheduled ordinary and extraordinary maintenance. For this reason, it becomes very difficult to define the end-of-life of a road unless it is removed, closed, or replaced with a new infrastructure. If different pavements have to be compared, the selected analysis period should cover at least the time between two major maintenance operations [47]. Hence, an analysis period of 72 years was selected for the present comparative assessment. Since the pavement analysis on the different scenarios provided different design life, the comparative LCA analysis of the 400 m stretch of pavement related to the G_{WR}, G_{DR}, D_{WR}, and D_{DR} scenarios was compared with 464.5 m stretch (72/62 = 1.16) of O_{WR} and O_{DR} scenarios [48].

Previous LCAs of road pavements divided the system boundaries into five major stages: processing of raw materials, construction, use, maintenance, and end-of-life [4]. The different stages were considered in the present LCA study as the following:

- Production stage, i.e., raw/secondary material processing, asphalt mix production, and transport between processes;
- Construction stage, which refers to all the processes and the pieces of equipment associated with the construction of the pavement;
- Maintenance stage, which includes the pavement rehabilitation;
- End-of-life stage (i.e., pavement removal and recycling).

System boundaries are shown in Figure 3. The usage stage, that is related to the interaction of the pavement with vehicles (e.g., variation in rolling) and environment (e.g., change in albedo), was not included in the system boundaries, due to the lack of reliable data and accurate estimation methods.

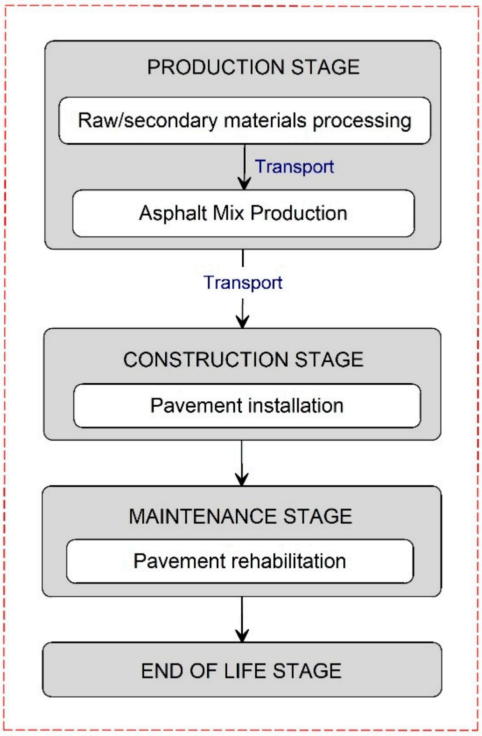

Figure 3. System boundaries.

2.3. *Life Cycle Inventory*

The life cycle inventory phase involves data collection and the calculation procedures related to the quantification of the relevant inputs (i.e., energy and raw materials) and outputs (i.e., emissions) associated with the life cycle of the pavement. The LCI dataset used to model the system was developed from interviews with contractors and experts, existing data available on specific literature on the topic, and the Ecoinvent database v3.2, considering European and Italian averages. The life cycle phases for the product system were grouped into three subsystems:

- Construction phase (which includes the raw material processing);
- Maintenance and rehabilitation phase (M and R);
- End-of-life phase.

2.3.1. Construction Phase

The construction phase includes the acquisition of raw and secondary materials, the transformation processes from the raw material to the finished product, mixing processes in the asphalt plant, pavement construction (i.e., laying and compaction), and the transport between the phases.

The first step of system modeling was the creation of processes related to raw and secondary materials. The data for modeling production of mineral aggregates, bitumen, and warm mix additives were taken from the Ecoinvent database. The production of virgin aggregates was modeled by considering the crushed gravel process, which includes the flow of materials and energy associated with rock blasting, crushing, and aggregate fraction separation in the quarry, while in the bitumen production process included were extraction, transportation, and refining of crude oil.

Processes related to the production of CRM and RAP are not available in the Ecoinvent database. Hence, the recycling processes of ELTs and existing pavements were modeled by using the available literature. A cut-off approach was chosen to account for burdens and benefits of recycled materials, as this was the advised allocation method in previous LCAs of road pavements [49]. According to this method, recycling benefits were attributed to the life cycle of the recycled product. Therefore, the production of CRM begins with mechanical size reduction of scrap tires in specialized plants. Similarly, the production of RAP starts with plant processing (i.e., crushing and screening), but the burdens of milling and transporting demolished pavement to recycling facilities were attributed to the end-of-life of the previous pavement. Data on CRM production were derived from a recent national study on carbon footprints carried out by Ecopneus [50]. According to this investigation, the production of 1 ton of CRM from 1.56 tons of ELTs requires the consumption of 435.3 kW h of electricity, 0.83 liters of diesel oil, and variable quantities of auxiliary materials (1.85 kg of bags for collection, 0.20 kg of steel for shredding blades, 0.21 m^3 of water). In addition, the transport from the collecting platform to the crushing plant (average distance of 100 km) and from the recycling plant to the asphalt plant (average distance of 350 km) has been considered. According to Zaumanis and co-workers, 21.20 MJ of energy were considered for the crushing and screening of 1 ton of milled material during pavement rehabilitation, assuming that these operations take place directly at the asphalt plant [15]. Data on modified bitumen employed in the dry rubberized mixture were taken from the Eurobitume report, which provides cradle to grave LCIs of bituminous materials [51]. The production process of the copolymer (styrene–butadiene–styrene, SBS) used for bitumen modification was modeled on the basis of manufacturer's datasheets, considering the production of 1 kg of SBS as associated with 0.55 kW h of electricity, 5.5 kg of steam, and 200 m^3 of cooling water. According to the data obtained from the LCA, 2.63 kW h of electricity were taken into account for the bitumen and CRM mixing required for the production of 1 ton of asphalt rubber [38]. In each process, the transport between the production site of the mixture constituents to the asphalt plant was considered (Table 7).

Table 7. Travelling distances.

Material	Transport (km)
Bitumen	100
Modified bitumen	110
Aggregates	200
RAP	0
CR	320
Additive	340

At the mixing plant, significant amounts of energy are required to heat and mix the materials. Data on the energy demand associated with the production of 1 ton of bituminous mixture in Italy were taken from the work of Leng and Al-Qadi [23]. According to this study, the HMA production demands about 6.3 KW h of electricity and 63.3 kW h from natural gas, while the WMA technology, thanks to reduced production temperatures, allows a savings of 35% of the energy consumption [17]. The traveling distance from the asphalt plant to the work site was assumed equal to 70 km.

The pavement construction involves the associated processes and equipments. The parameters chosen to assess the environmental loads associated to this stage are: the paving machineries, the emission of polycyclic aromatic hydrocarbons (PAHs), and the heat emissions generated during the paving of the mixtures. The estimation of the environmental impacts related to the operation of each machine involved was made by using the reference values of productivity of the construction equipment available in the Ecoinvent database and the reference values of productivity of the specific equipment used at the work site. The latter values of productivity were calculated based on the operating conditions of the case study equipment. Type and main operating conditions of the equipment were obtained from the technical specifications provided by the equipment's manufactures and complemented by interviews with contractors and the available literature. The main characteristics of the machinery are shown in Table 8.

Table 8. Paving and milling machine specifications.

Machine	Model	Effective Width (mm)	Speed (m/min)	Number of Passes
Asphalt paver	Vogele SUPER 1803	4750	18	1
Vibratory roller	HAMM HD + 110	1850	60	6
Milling machine	Wirtgen W200i	2000	8–30 [1]	1

[1]: Variable speed depending on the thickness of the pavement to be removed.

The amounts of PAHs and heat released to the environment during the mix paving were calculated. Data on PAHs concentration in ambient air, which are useful in order to understand the background contribution to the exposure of workers, were derived from a study carried out to evaluate the safety of the use of CRM from ELTs in bituminous mixtures [52]. According to this work, the air emissions from HMA pavements are about twice as high as those from WMA pavements. With regards to heat, it was observed that the WMA allows a reduction of heat released in the environment during the mix paving of approximately 35%, if compared to hot technologies, due to the smaller differential between the asphalt temperature and ambient temperature. Such amount was determined through an energy balance, by taking into account the different composition of the mixtures and the temperature variation. The final temperature was assumed to be equal to the ambient temperature of 25 °C for all the asphalt mixtures, whilst the paving temperature of the mixtures depends on the technology; the paving temperatures of HMA and WMA were set at 160 and 130 °C, respectively.

2.3.2. Maintenance Phase

In the maintenance phase, material production and all activities needed to ensure adequate levels of performance of pavement during its life cycle were included. Therefore, the milling of the different pavement thicknesses depending on the maintenance intervals set in the maintenance planning of the case study (Section 2.2.2), material acquisition and processing, asphalt mix production at the plant, equipment used at the work site for the pavement paving and dismantling, and all transportation were considered in the modeling of this phase. Hence, energy and materials associated with the construction phase were also included in the maintenance phase. In addition to this, the operation of the milling machine required to remove the asphalt pavement layers was included in the maintenance activities; the operating conditions are shown in Table 8. Moreover, a machine with pressurized water injection was considered, in order to preserve the drainability and the acoustic performances of the open-graded mixtures throughout the entire life cycle. Based on the data provided by the manufactures, its operation requires about 4500 L/h of water with a 95% recovery.

2.3.3. End-of-Life Phase

The end-of-life phase involved the dismantling of the pavement and the transport of the removed material to recycling facilities. According to the cut-off approach, no burdens were attributed to the recycling of the asphalt layer. However, the use of RAP for replacing a portion of the virgin materials entails environmental benefits as it avoids the disposal to the landfill, as well as the extraction of raw materials. The operating conditions of the milling machine are those reported in Table 8.

2.4. Life Cycle Impact Assessment

In the LCIA phase the inventory data were analyzed in terms of environmental impacts. Among the different methodologies available, the ecological scarcity method was chosen to investigate the environmental loads associated with the seven scenarios under study. With this method, results are reported in terms of eco-factors, expressed as eco-points per unit of pollutant emission or resource extraction. The eco-factors are normalized towards current emissions/levels and weighted according to national or international policy targets, then they are translated into the same unit (UBP) and implemented in 19 impact categories.

3. Results

The assessment of different scenarios was conducted to identify, quantify, and compare the environmental impacts associated with the use of hot mix asphalt and mixtures prepared with recycled materials and warm mix additives. Results show that the standard scenario implies major impacts in 15 of the 19 impact categories considered (Figure 4). The acoustic performances, which are rated by the noise impact category, improved by 66% for open-graded mixtures, 41% for gap-graded mixtures, and 29% for dense-graded mixtures, compared to the traditional mixture of the wearing course.

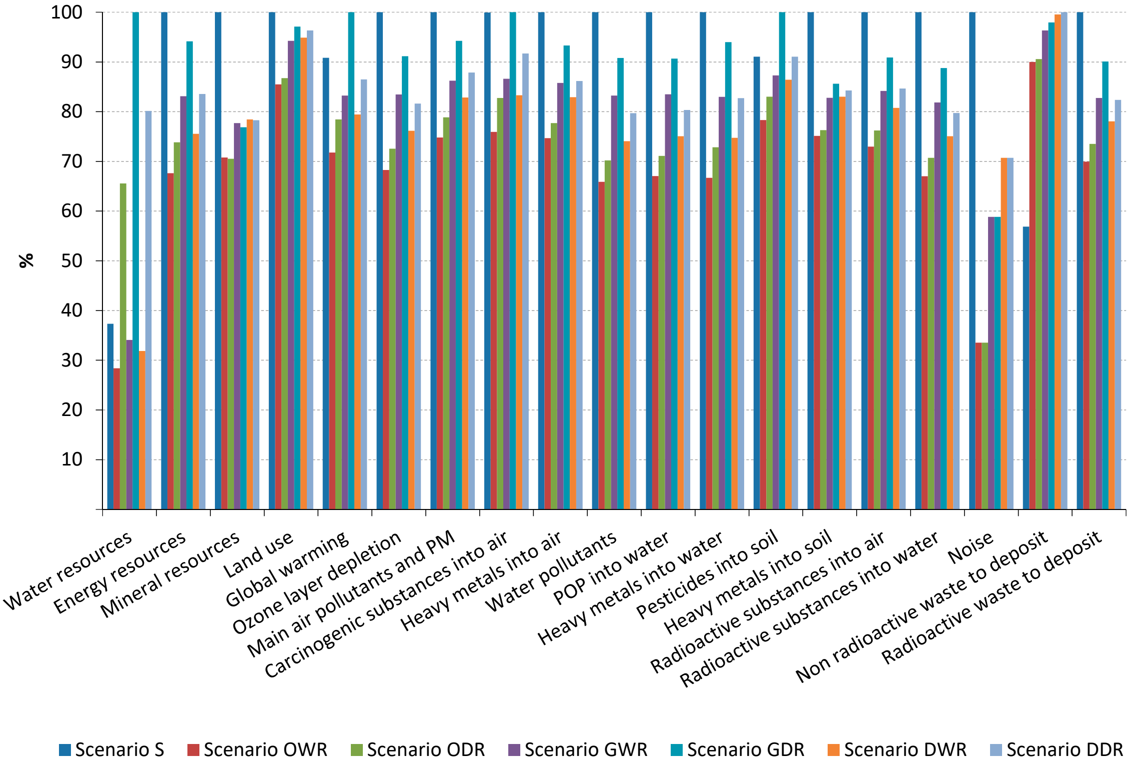

Figure 4. Impact assessment results: comparison between standard and alternative scenarios.

In order to understand which pavement layer gives the highest contribution to the entire pavement structure, the standard scenario was analyzed. The contribution analysis was conducted referring to four impact categories (i.e., energy resources, mineral resource, global warming, and ozone layer depletion) of the ecological scarcity method. As it can be seen in Figure 5, the wearing course was the layer with the highest impact on the standard scenario, despite it having the smallest thickness.

The wearing course contributed to the consumption of 60% of the energy resources and 55% of the mineral resources used in the life cycle assessment of the entire road pavement. Moreover, it was associated to 52% and 60% of the global warming emission and ozone layer depletion, respectively. These results are explained by the high frequency of maintenance interventions (every 6 years) required by the wearing course. Given the high impact of the top layer, focus has been made on the design of different surface mixtures. Secondary materials and warm technology were assessed, in order to minimize the environmental loads. The results of the comparative analysis of different wearing courses are shown in Figure 6 and listed in Table 9.

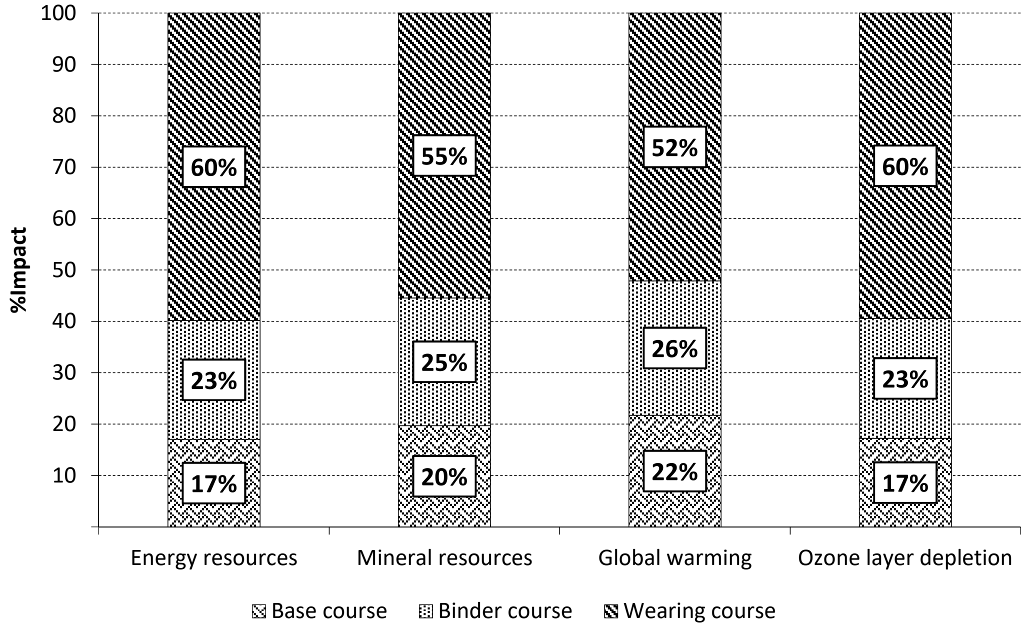

Figure 5. Contribution of the pavement layers to selected impact categories, scenario S.

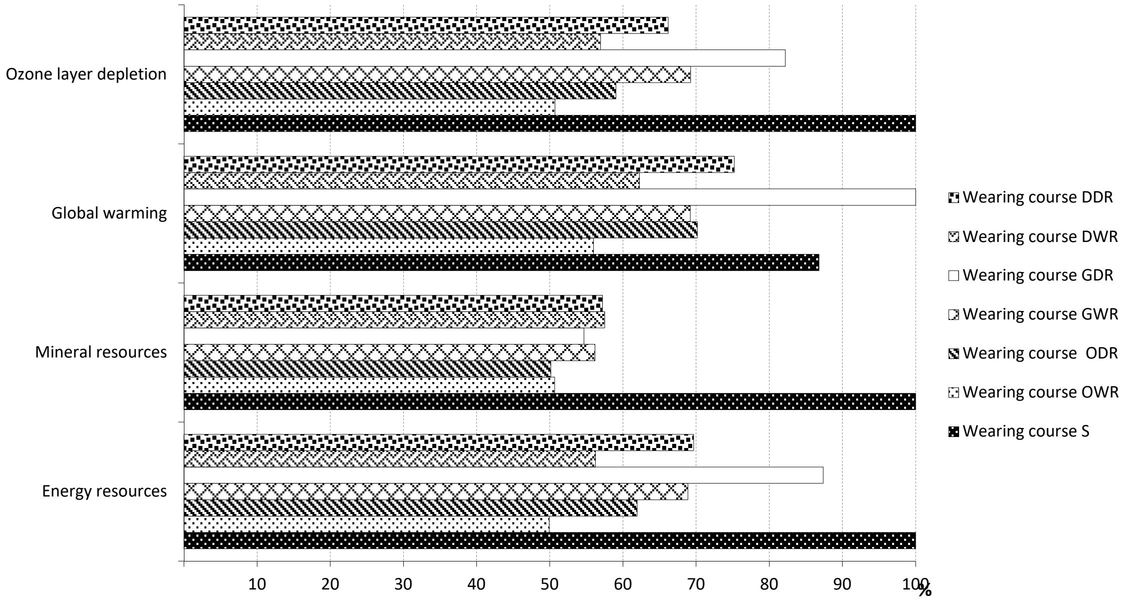

Figure 6. Comparison between the wearing courses on selected impact categories.

Table 9. Wearing courses: results of selected impact categories.

Impact category	**Unit**	**S**	**O_{WR}**	**O_{DR}**	**G_{WR}**	**G_{DR}**	**D_{WR}**	**D_{WR}**
Energy resources	UBP × 10^3	140.537	70.154	87.057	96.809	122.776	79.036	97.897
Mineral resources	UBP × 10^3	357.001	180.889	179.039	200.585	195.209	205.319	204.229
Global warming	UBP × 10^3	353.626	228.110	285.771	281.962	407.429	253.667	306.322
Ozone layer depl.	UBP × 10^3	2.476	1.256	1.462	1.715	2.035	1.410	1.639

As it can be seen in Table 9, warm mix asphalt containing secondary material for wearing course renovation leads to significant environmental advantages along the life cycle of the pavement. These benefits are highlighted by the results related to the depletion of mineral resources; hence, the use of the innovative mixture saves almost 50% of the available resources.

The environmental benefits associated with the alternative scenarios, with respect to the use of traditional mixtures, range between 50% savings of energy resources, relative to the rubberized open-graded mixture, to a 13% reduction of global warming, relative to the dry rubberized dense-graded mixture. The reduction of production and laying temperatures due to the use of WMA technologies involves a reduction of the energy consumption and related emissions. Moreover, the RAP used to replace a portion of virgin material (bitumen and aggregates) allows saving natural resources and reducing the impact associated with bitumen refining and aggregate mining.

Wet mixtures are associated with lower burdens than dry mixtures; this result has been ascribed to the use of modified bitumen with CRM (asphalt rubber), which is environmentally advantageous compared to polymer-modified bitumen. Furthermore, the results of comparative analysis highlight how the design mix and the frequency of maintenance affect resources depletion and pollutant releases. Figures 7 and 8 show the results of the comparison analysis carried out on the surface layers with mixtures containing CRM added by using dry and wet technology, respectively.

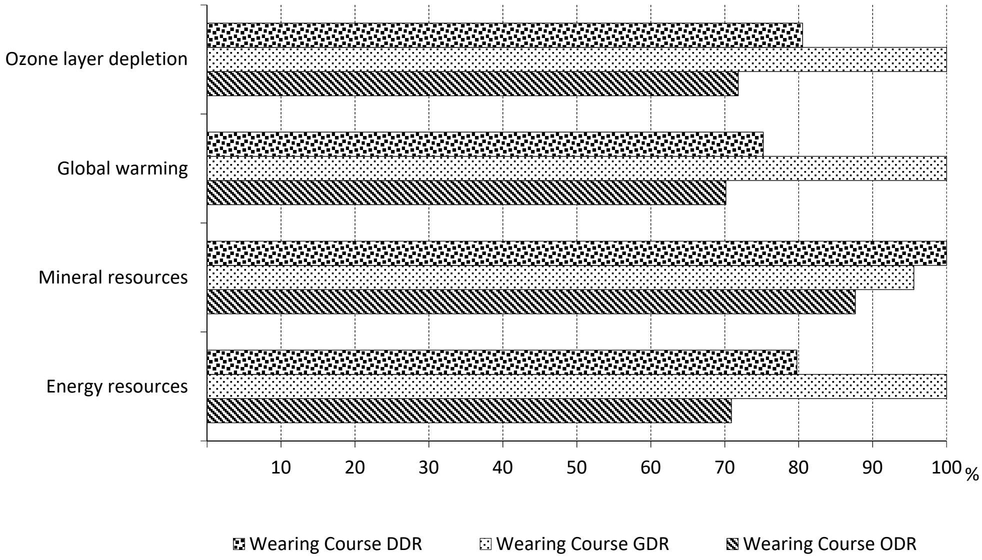

Figure 7. Comparison between dry rubberized wearing courses.

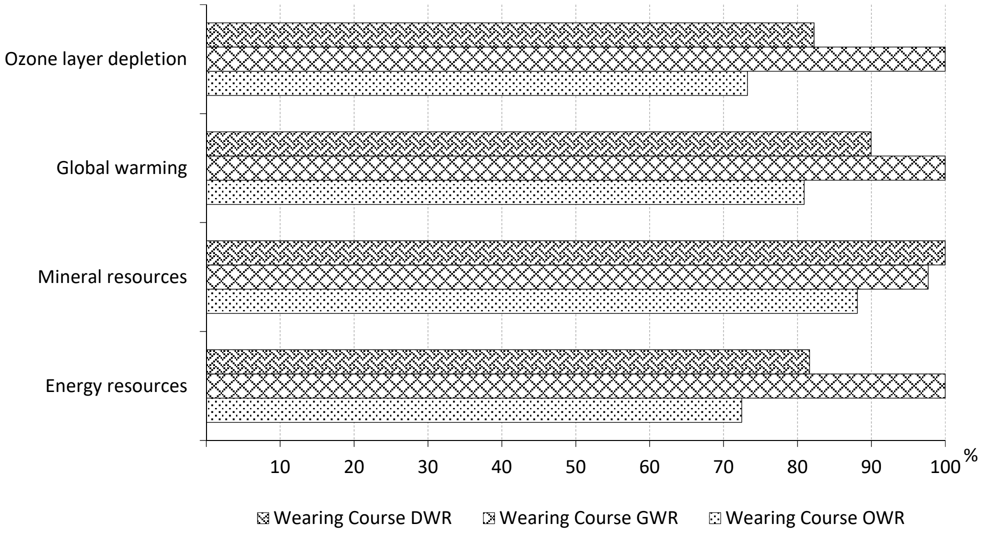

Figure 8. Comparison between wet rubberized wearing courses.

Results show that open-graded mixtures, which require the lowest frequency of maintenance, entail low environmental loads due to the reduced demand of raw materials and energy. On the other side, the high amount of bitumen used in the gap-graded mixtures causes a relevant impact, as the bitumen appears to be the mixture component with the highest environmental burden (e.g., highest temperature requirements, hydrocarbon emission, demand of non-renewable resources) compared with the other constituents. The environmental gap between open and gap-graded mixtures is highlighted by the global warming category. Indeed, the use of dry rubberized open-graded mixtures could reduce greenhouse gas emissions by about 30% compared to the dry rubberized gap-graded mixture. Dense-gap mixtures require maintenance intervals equal to the gap-graded mixture, but contain a bitumen percentage similar to those of open-graded mixtures.

4. Conclusions

Life cycle assessment is a precious tool for the selection of technologies able to lower the impacts associated with the construction and the maintenance of road pavements. In this study, the LCA methodology was applied to compare the environmental impacts related to the whole life cycle of seven types of pavements with different wearing course mixtures, with the aim to promote the use of low-noise pavement containing recycled materials and produced by warm mix technologies.

The results obtained confirmed the high impacts associated with the use of conventional HMA mixtures. As highlighted by the contribution analysis of the standard scenario, the wearing course causes the most severe impact, due to the high frequency of maintenance. However, the use of warm mix technologies and recycled material in the construction and rehabilitation of this layer may reduce the environmental burdens up to 50%, compared to the standard scenario. Indeed, the use of reclaimed materials is associated with a reduced demand for virgin non-renewable materials such as bitumen and mineral aggregates. Moreover, the use of warm mix technologies allows a reduction in mixing and compaction temperatures, resulting in reduced emissions of hydrocarbons.

The comparison of the wearing courses highlights how the design mix and the frequency of maintenance affect resource depletion and pollutant emissions to the environment. These findings can be summarized as follows:

- the use of wet mixtures was crucial in lowering the environmental burdens, due to the use of modified bitumen with CRM, instead of bitumen modified with polymers (typical of dry mixtures).
- Wearing courses with open-graded-mixtures allowed up to 30% reduction of the environmental impact, compared to the other mixtures here analyzed. This result has been ascribed to this mixture requiring the lowest frequency of maintenance (i.e., reduced material consumption and plant/field operations) and the lowest bitumen content. Rubberized open-graded mixtures is the technology responsible for the lowest environmental impacts associated with the rehabilitation of the pavement.
- The wearing courses with gap-graded mixtures present more severe environmental loads when compared with dense-graded and open-graded mixtures, due to the high bitumen content.

The findings of this research demonstrate that wearing course mixtures designed with recycled materials and produced with warm mix technologies represent a promising solution for the construction and rehabilitation of low-noise pavements.

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