LIFE CYCLE ASSESSMENT OF ROAD PAVEMENTS CONTAINING CRUMB RUBBER FROM END-OF-LIFE TIRES

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ABSTRACT

Management of the huge quantity of end-of-life tires (ELTs) collected every year leads to several options among which the preferable ones seem to be recycling and reuse, that allow the high quality of component materials to be fully exploited. In the area of road pavements a good example of this type of approach is provided by the technologies ("wet" and "dry") which consist in the production of bituminous mixtures containing crumb rubber (CR) derived from ELTs. While mechanical properties of such mixtures have been thoroughly assessed, quantification of the environmental impact of the use of CR is still a subject of debate. Thus, in the study presented in this paper a Life Cycle Assessment (LCA) was carried out by considering different scenarios corresponding to the construction and maintenance of pavements containing CR and of the standard type. By comparing the results obtained from the LCA model in terms of selected environmental indicators, it was found that the use of rubberized binders produced by the "wet" technology leads to significant benefits, while in the case of the "dry" technology no significant differences can be identified with respect to standard pavements.

INTRODUCTION

Until a few years ago, the majority of end-of-life tires (ELTs) were either stockpiled or illegally dumped, thus causing a serious threat to public health and to the environment. Although landfill disposal is now banned in most countries, management of ELTs is still a critical issue. In the year 2012, more than 200,000 tons of tires were collected in Italy, of which 59% employed for energy production (47% in Italy and 12% in other Countries) and 41% processed to retrieve reusable component materials (27% rubber, 10% steel and 4% textiles) *(1)*. Similar scenarios are reported in other countries, with a general trend which shows a constant increase of processing for reuse and recycling *(2)*.

In the case of recovered tire rubber, several alternatives for reuse have been explored, including its incorporation, in granular or powder form, in artificial turf *(3,4)*, mortars and concrete *(5,6)*, plastic/rubber products *(7)* and bituminous mixtures for road pavements *(8,9)*. In all cases, it has been proven that benefits can be obtained by exploiting the high-quality of the material which results from a careful selection of its components.

Use of crumb rubber (CR) derived from end-of-life tires (ELTs) in bituminous mixtures is considered especially attractive since it allows the production of high-performance composite materials employed for the construction and maintenance of road pavements *(8,9)*. In Italy, although this type of reuse is currently chosen for only 3% of total ELTs, there has been in the last 10 years a steady growth of interest for CR paving applications, possibly as a result of the diffusion of Green Public Procurement (GPP) policies and of several strategic actions and research projects *(10)*.

Methods currently available for the inclusion of CR in bituminous materials are associated to the so-called "wet" and "dry" production processes, in which CR is respectively added to base bitumen as a modifying agent ("wet" technology) or in hot mix plants as an additional aggregate fraction ("dry" technology) *(11-13)*. In the "wet" process, CR is added to bitumen in a percentage which is typically higher than 15% (b.w. of total binder). During mixing, which takes place at temperatures usually higher than 180°C, a time-dependent interaction develops between the two components, leading to the creation of a modified high-viscosity binder also known as "asphalt rubber" (AR) *(14)*. Such a binder is then combined with aggregates in the hot mix plant for the production of bituminous mixtures which are generally of the gap-graded or open-graded type, with a non-continuous particle size distribution that allows the use of very high binder contents (about 8-9% b.w. of dry aggregates) *(15)*. According to field and laboratory experience documented worldwide, AR mixtures exhibit excellent performance properties with respect to the main pavement distresses *(16)* in a wide range of climatic conditions *(9)*.

In the "dry" method, CR substitutes part of the aggregates which constitute the load-bearing skeleton of the mixture, thus providing an improvement of elastic response *(8,17)*. Mixtures produced with this technology are usually of the dense-graded type, with a continuous particle size distribution, while employed CRs can be characterized by different size distributions, ranging from "ultrafine" to "coarse" *(18)*. In all cases, typical dosages of CR are comprised between 1% and 3% of the weight of dry aggregates. CR particles are not preliminarily digested in bitumen but they do absorb part of the available aromatic fractions during mixture production and laying. For this reason, optimal binder content is often slightly higher than that adopted for standard mixtures containing no recycled rubber *(19)*.

Unfortunately, laboratory and in-situ tests performed on these mixtures show an inconsistent performance, with the frequent occurrence of early raveling phenomena and moisture-related damage *(18,20)*. This explains the limited diffusion of the technology, with full-scale applications that have been generally carried out locally rather than at the network level.

In this paper, the use of CR in bituminous mixtures is analyzed from a novel viewpoint, focusing on aspects related to the environmental performance of pavements in which such a material can be incorporated. By referring to the case study of an extra-urban road, advantages and disadvantages resulting from the use of CR were identified by means of a Life Cycle Assessment (LCA) methodology *(21,22)* which was developed and used to measure the eco-profile of a pavement unit length. Detailed analysis of results was carried out in order to highlight the elements which have the highest influence on selected environmental indicators.

MATERIALS AND METHODS

Pavement

The case study considered in this paper is that of an Italian extra-urban road, constituted by two lanes for each direction, with a total carriageway width of 21.9 m. Based on predicted total heavy traffic (4 million vehicles) and on the required minimum bearing capacity of the subgrade (resilient modulus equal to 90 MPa), the following pavement cross section was selected from the Italian Catalogue for Pavement Design *(23)*:

- 5 cm surface (wearing) course;
- 6 cm binder course;
- 10 cm base course;
- 20 cm unbound foundation layer.

The top three layers are constituted by dense-graded bituminous mixtures complying to Italian Technical Specifications *(24)* and contain neat (unmodified) bitumen. The foundation layer is made of crushed granular material. In order to highlight advantages and disadvantages related to the use of CR in the pavement, in the life cycle analysis described in the following paragraphs the reference scenario described above (indicated as "standard", "S", in the paper) was compared to two different cases in which the wearing course was respectively constituted by the following materials:

- A gap-graded mixture produced by employing an asphalt rubber binder containing 20% CR (b.w. of total blend) ("wet" scenario, "W");
- A dense-graded mixture containing 1% CR (b.w. of dry aggregates) incorporated by means of the "dry" production process ("dry" scenario, "D").

Given the reference thickness of the standard surface course mixture (5 cm), in the case of scenario W (wearing course with asphalt rubber) a reduced thickness was considered (4 cm) coherently with structural equivalency factors documented in literature *(15,25)*. In the absence of any reliable equivalency relationship, thickness of the "dry" mixture was kept equal to that of the standard material considered in scenario S (5 cm).

Table 1 synthesizes the composition of the various pavement layers after compaction (binder content [%B] and void content [%v]) and shows the employed unit quantities (in kg/m^3) produced and laid on site, expressed in terms of bitumen (pedex "B"), aggregates ("A") and crumb rubber ("CR").

Table 1: Composition of Mixtures and Quantities of Employed Materials

Layer	Composition [%]		Quantity [kg/m^3]		
	%B	%v	Q_B	Q_A	Q_{CR}
Wearing "S"	5.3	4.5	119.9	2,262	-
Wearing "W"	8.0	6.5	134.0	2,093	33.5
Wearing "D"	5.7	4.5	127.8	2,220	22.0
Binder	5.0	5.0	113.2	2,266	-
Base	4.5	5.5	102.7	2,282	-
Foundation	-	5.2	-	2,201	-

Life Cycle Assessment

Methodology

The definition of a sector-specific LCA procedure for road paving applications is still largely under debate *(26-31)*. In this study a methodology was therefore developed for the assessment of two main energy and environmental indicators: Gross Energy Requirement (GER) and Global Warming Potential (GWP). GER shows the life cycle energy extracted from the earth's crust *(32)*, whereas GWP quantifies climate change expressed in kg of equivalent released CO_2 *(33)*. In order to expand the analysis and cover more areas of environmental and resource-use interest, the *ReCiPe* method was also used in the analysis *(34)*, since it considers a wide array of categories of environmental impact, such as human toxicity, water and terrestrial toxicity, natural land transformation.

It was assumed that system boundaries of the LCA analysis include all the processes and activities (from-cradle-to-the-end) which compose construction and maintenance operations during the service life of the pavement. The functional unit employed in the analysis was 1 m of built pavement, adjusted in order to take into account the differences in terms of service life. The software used for life cycle modelling was *SimaPro* 7.3 *(35)*. Input data were retrieved from the sources described below.

By taking into account the performance records of the three wearing course types considered in the study, the LCA analysis was carried out by making different assumptions with respect to pavement service life and frequency of maintenance cycles of surface courses (Table 2) *(41)*. The analysis of each maintenance stage scheduled during the pavement service life considers milling of the old damaged surface layer, transportation of the removed material to landfill and reconstruction of the wearing course adopting the same composition and volumetric characteristics of the removed layer.

Table 2: Service Life and Maintenance Frequency

Parameter	Scenario S	Scenario W	Scenario D
Service life [years]	18	20	18
Maintenance frequency [1/years]	1/5	1/8	1/5

Data Sources

In the area of road pavements it is generally recognized that Life Cycle Inventory (LCI) data related to materials and construction activities are still incomplete, with the consequence that LCA analysts have to face complexities in data retrieval and are often forced to rely on estimate methodologies in order to make reasonable assumptions for the missing data *(36)*.

For the case study described in this paper, LCI data used to model the foreground system *(21)* were collected from available literature and through interviews with contractors and experts involved in road works. In order to complete the data set and model the background system, reference was made to the *Ecoinvent* 2.2 database *(37)* and to information contained in a Eurobitume report *(38)* which provides from-cradle-to-gate LCIs of bituminous materials and includes the feedstock energy value attributable to bitumen according to ISO 14044 *(43)*.

Data Processing

LCA modelling was carried out starting from the creation of processing units relative to raw materials (i.e. quarried aggregates, crumb rubber, bitumen) for which energy consumption, expressed in liters of fuel, was calculated on the basis of equipment and vehicles employed for production and transport.

Data for aggregate and bitumen production were extracted from available studies, respectively due to Blengini and Garbarino *(39)*, who considered the case of quarries located in the Piedmont region, and to Eurobitume *(38)*, that globally analyzed the European scenario. Data on CR production was not readily available and was derived from information contained in an ongoing national study on carbon footprint carried out by Ecopneus *(40)*. Fuel consumption due to transport of ELTs was computed by separately considering the initial collection phase (with an average of 75 km) and the second phase of delivery to the shredding plant (with an average of 150 km which for a small fraction, equal to 0.34%, is done by ship). When focusing on plant processing, it was found that the typical production yield can be assumed to be equal to 1 ton of CR from 1.45 tons of ELTs, with the corresponding consumption of 384 kWh of electric power, 2.99 liters of diesel oil and variable quantities of auxiliary materials (1.85 kg of big-bags, 0.29 kg of steel for shredding blades, 0.22 m^3 of water and 0.04 kg of lubricant oil). Analysis also considered the fate of co-products (0.29 tons of steel and 0.16 tons of textiles) which can either be landfilled or recycled. Given its high market value, steel was assumed to be recycled by 90%, while a lower percentage, equal to 50%, was considered for textiles, which can be employed as substitutes of non-renewable fuels in cement kilns.

In the framework of the LCA model, processing units were created also for the production of composite materials (asphalt rubber and bituminous mixtures) and for the laying and milling operations carried out during construction and maintenance. Data on asphalt rubber production was obtained from the only Italian plant which adopts such a technology *(41)*. Thus, a consumption of 18 liters of diesel oil was considered for the production of 1 ton of binder.

In the case of production activities carried out in hot mix plants, fuel consumption data were taken from available technical literature *(42)*. In particular, it was found that average consumption for the production of 1 ton of a standard bituminous mixture is given by the combination of 4.87 kg of fuel oil with low sulfur content, 1.9 m^3 of methane and 0.94 kg of liquefied petroleum gas (LPG). In the case of mixtures containing asphalt rubber, a greater energy is required for production as a result of the higher working temperature. In the absence of direct data on this specific point, a 10% increase was hypothesized for calculation purposes.

Analysis of pavement construction in the three scenarios outlined above required consideration of the quantities of the different component materials constituting the layers of a section of unit length and of the average haul distances which were estimated from the production/supply site (quarry, refinery, ELT shredding plant, AR plant) to the contractor’s premises. These data, which are synthesized in Table 3, were used together with the previously discussed LCI data for the calculation of total energy consumption.

For both construction and maintenance activities, fuel consumption associated to transport of composite materials from the plant to the laying site was computed by considering an average distance of 50 km.

In order to implement the contribution of laying operations in the LCA model, hourly fuel consumption (FC_h) of construction equipment was considered together with the typical productivity of each operation involved in pavement construction and maintenance. By referring to a unit length of each pavement and by hypothesizing a standard composition of the construction fleet, results were then expressed in terms of total fuel consumption (FC_t) (Table 4).

Table 3: Quantities and Transport Distances of Component Materials

Layer	Material	Scenario S		Scenario W		Scenario D	
		Q [kg]	D [km]	Q [kg]	D [km]	Q [kg]	D [km]
Wearing	Asphalt rubber	-	-	147	50	-	-
	Bitumen	131	100	-	-	140	100
	Crumb rubber	-	-	-	-	24.5	100
	Aggregates	2,477	30	1,834	30	2,431	30
		All scenarios					
		Q [kg]			D [km]		
Binder	Bitumen	149			100		
	Aggregates	2,977			30		
Base	Bitumen	225			100		
	Aggregates	4,998			30		
Foundation	Aggregates	9,641			30		

Table 4: Fuel Consumption of Construction Equipment

Layer	Equipment	FC_h [l/h]	Scenario S	Scenario W	Scenario D
			FC_t [l/h]		
Wearing	2 pavers	30	1.25	0.95	1.25
	4 rollers	17	1.42	1.07	1.41
			All scenarios		
			FC_t [l/h]		
Binder	2 pavers	30	1.50		
	4 rollers	17	1.70		
Base	2 pavers	30	2.50		
	4 rollers	17	2.84		
Foundation	1 grader	20	0.96		
	2 rollers	17	1.64		

In maintenance operations, fuel consumptions caused by wearing course reconstruction were added to those deriving from milling of the old damaged surface layer and to transportation of the removed material to a landfill (or storage site) located at a distance of 50 km. Total consumption in the service life of the pavement was thereafter computed by considering assumed frequencies of maintenance cycles discussed above (Table 2).

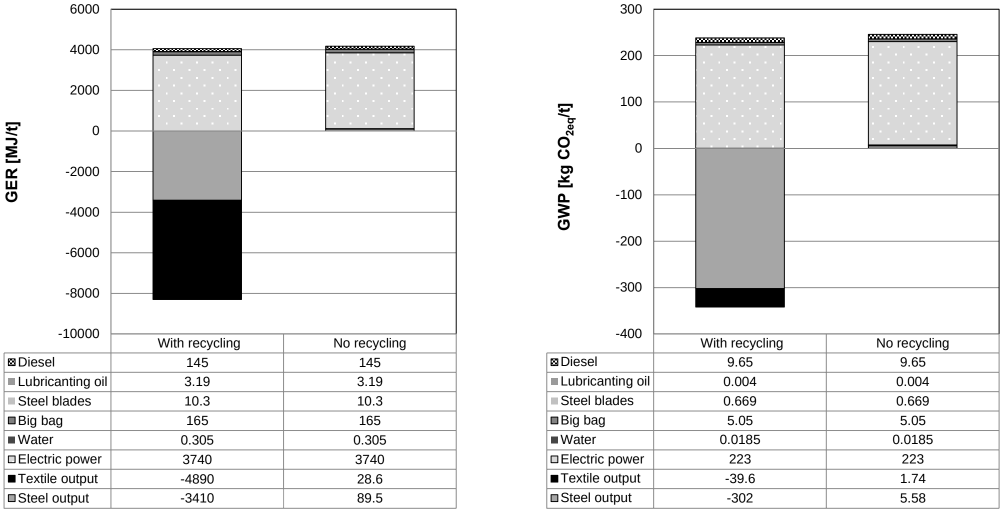
RESULTS AND DISCUSSION

Results of the LCA are shown in the following paragraphs, which highlight different aspects of environmental performance associated to the three considered pavement scenarios. The impact of CR on the case study described in this paper can therefore be assessed in differential terms. Moreover, a paragraph is exclusively dedicated to the LCA of CR, which can be of interest when comparing the processing of ELTs for reuse to other possible destinations (e.g. energy production).

Crumb Rubber

By making use of the developed LCA model and of the data presented above it was possible to quantify all contributions to energy consumption and gaseous emissions that are associated to CR production (Figure 1).

It can be observed that in the case of no recycling of co-products, the CR production chain leads to greenhouse emissions (GWP) of 307 kg CO_{2eq}/t and to a life cycle energy (GER) of 5,200 MJ/t. The main contribution to these values of GWP and GER, respectively equal to 223 kg CO_{2eq}/t and 3,740 MJ/t, comes from electric power used for shredding operations (which makes up for 72-73%).



	With recycling	No recycling
⊠ Diesel	145	145
▪ Lubricanting oil	3.19	3.19
▪ Steel blades	10.3	10.3
▨ Big bag	165	165
■ Water	0.305	0.305
□ Electric power	3740	3740
■ Textile output	-4890	28.6
▤ Steel output	-3410	89.5

	With recycling	No recycling
⊠ Diesel	9.65	9.65
▪ Lubricanting oil	0.004	0.004
▪ Steel blades	0.669	0.669
▨ Big bag	5.05	5.05
■ Water	0.0185	0.0185
□ Electric power	223	223
■ Textile output	-39.6	1.74
▤ Steel output	-302	5.58

Figure 1: GER and GWP associated to CR production.

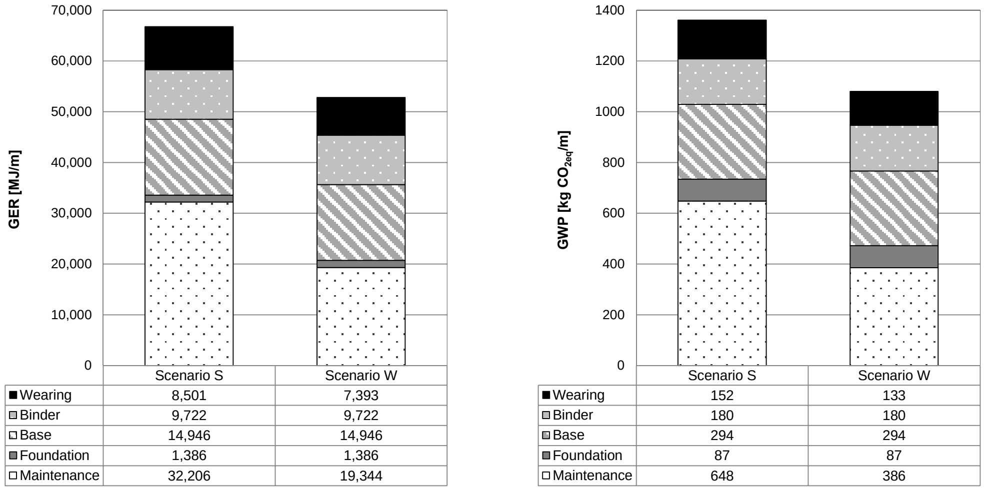
However, if recycling of co-products is considered, the overall environmental impact of CR production is significantly reduced. Total GWP decreases by 113%, assuming a negative value (-41.6 kg CO_2eq/t), which mainly derives from the reduction of steel production (-302 kg CO_2eq/t), and only marginally from the contribution of recycled textiles (-39.6 kg CO_2eq/t). Moreover, an energy saving effect is also obtained as proven by the total GER, equal to -3,220 MJ/t, which corresponds to a 162% reduction. This is due to the combined effects of recycling the two recovered materials which in this case are comparable (-3,410 MJ/t for steel, -4,890 MJ/t for textiles).

Pavements

“Wet” Technology

Figure 2 shows the GER and GWP values which are associated to pavement construction and maintenance operations during service life. In particular, results of scenario W, which involves the use of CR in the wearing course by means of the “wet” technology, are compared to those of the reference standard scenario (“S”). It can be observed that the choice of the pavement cross-section which includes CR causes a reduction of the overall energy spent (i.e. GER) and of carbon dioxide emissions (i.e. GWP), respectively equal to 20% and 21%. In particular, total GER and GWP values decrease from 66,761 to 52,791 MJ/m and from 1,361 to 1,080 kg CO_{2eq}/m. These data were obtained by hypothesizing recycling of CR co-products (steel and textiles). However, if co-product recycling is excluded, the two scenarios are approximately equivalent, with an almost negligible increase of GER and GWP, respectively equal to 1.6% and 3.2%.

Finally, from the data given in Figure 2 it is interesting to observe that the main contribution to total GER and GWP values comes from maintenance operations, which depending upon the considered scenario have a relative weight comprised between 35% and 48%.



	Scenario S	Scenario W
■ Wearing	8,501	7,393
▨ Binder	9,722	9,722
▧ Base	14,946	14,946
▩ Foundation	1,386	1,386
□ Maintenance	32,206	19,344

	Scenario S	Scenario W
■ Wearing	152	133
▨ Binder	180	180
▧ Base	294	294
▩ Foundation	87	87
□ Maintenance	648	386

Figure 2: GER and GWP associated to pavement construction and maintenance (scenarios S & W).

The key role played by maintenance frequency in LCA can be more clearly understood by analyzing the GER and GWP values reported in Table 5, obtained for scenario W and for the further three cases derived from it by:

- Increasing the thickness of the wearing course containing CR (from 4 cm to 5 cm, scenario "Wt+");
- Hypothesizing a higher maintenance frequency (from 1/8 to 1/5 years^{-1}, scenario "Wf+");
- Considering both variations to occur jointly (scenario "Wtf+").

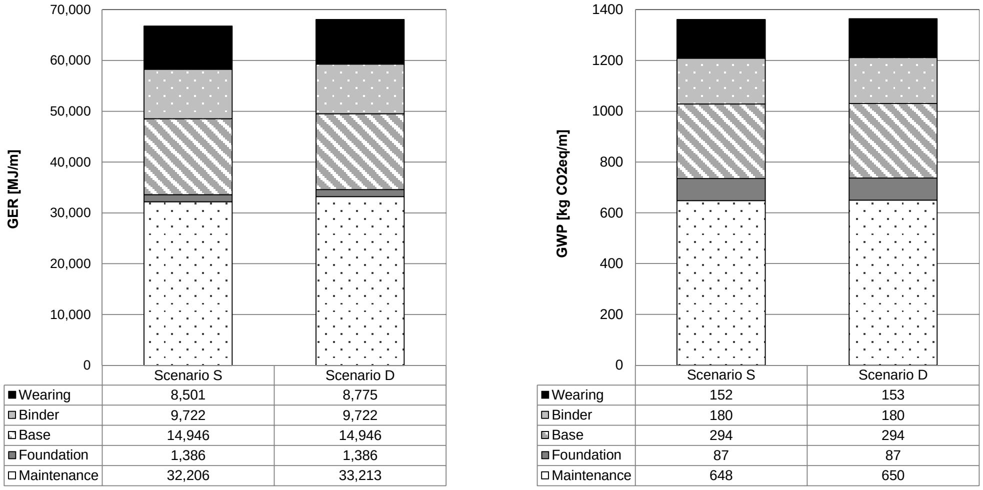
Table 5 also contains data of reference scenario S and, in parentheses, percent differences of GER and GWP with respect to it. It can be observed that if the wearing course containing CR had the same thickness and maintenance characteristics of the standard dense-graded surface course (5 cm and maintenance every 5 years, scenario Wtf+), its environmental performance benefits highlighted in Figure 2 would be compromised, with an 11% and 10% increase of GER and GWP, respectively. However, results of cases Wt+ and Wf+ show that starting from such a situation, significant improvements can be obtained if durability of the surface mixture is increased, with the consequent delay of scheduled maintenance (from a frequency of 1/5 to 1/8 years^{-1}), while almost negligible effects are produced by a 1 cm thickness reduction.

Table 5: GER and GWP as a Function of Thickness and Maintenance Frequency (Scenario W)

Scenario	W	Wt+	Wf+	Wtf+	S
Thickness [cm]	4	5	4	5	5
Maintenance frequency [1/years]	1/8	1/8	1/5	1/5	1/5
GER [MJ/t]	52,791 (-21%)	59,446 (-11%)	64,397 (-4%)	73,984 (+11%)	66,761
GWP [kg CO_{2eq}]	1,080 (-21%)	1,208 (-11%)	1,311 (-4%)	1,499 (+10%)	1,361

"Dry" Technology

Figure 3 shows a comparison between the results obtained for reference scenario S and those yielded by the analysis carried out on scenario D, which involves the use of CR in the surface course by means of the "dry" technology. It is interesting to observe that the two scenarios are approximately equivalent in terms of overall energy spent, with GER values, respectively equal to 66,761 and 68,042 MJ/m, that exhibit a relative difference of 1.9%. No changes are recorded for carbon dioxide emissions (i.e. GWP), with a common value equal to 1,364 kg CO_{2eq}/m.



	Scenario S	Scenario D
■ Wearing	8,501	8,775
▨ Binder	9,722	9,722
▨ Base	14,946	14,946
■ Foundation	1,386	1,386
□ Maintenance	32,206	33,213

	Scenario S	Scenario D
■ Wearing	152	153
▨ Binder	180	180
▨ Base	294	294
■ Foundation	87	87
□ Maintenance	648	650

Figure 3: GER and GWP associated to pavement construction and maintenance (scenarios S & D).

<u>Assessment with the *ReCiPe* Method</u>

In addition to GER and GWP, in the LCA analysis performed on the three scenarios, environmental indicators of the *ReCiPe* method were calculated *(34)*. They are shown individually in Figure 4 (midpoint method, where, for comparison purposes, the value of the highest marker is made equal to 100%) and divided into homogeneous groups in Figure 5 (endpoint method, i.e. human health, ecosystems and resources). In both cases, the superior environmental performance of the pavement containing rubberized binder (scenario W) is confirmed, while the pavement with the wearing course produced with the "dry" technology (scenario D) is found to be equivalent to the reference case (scenario S).

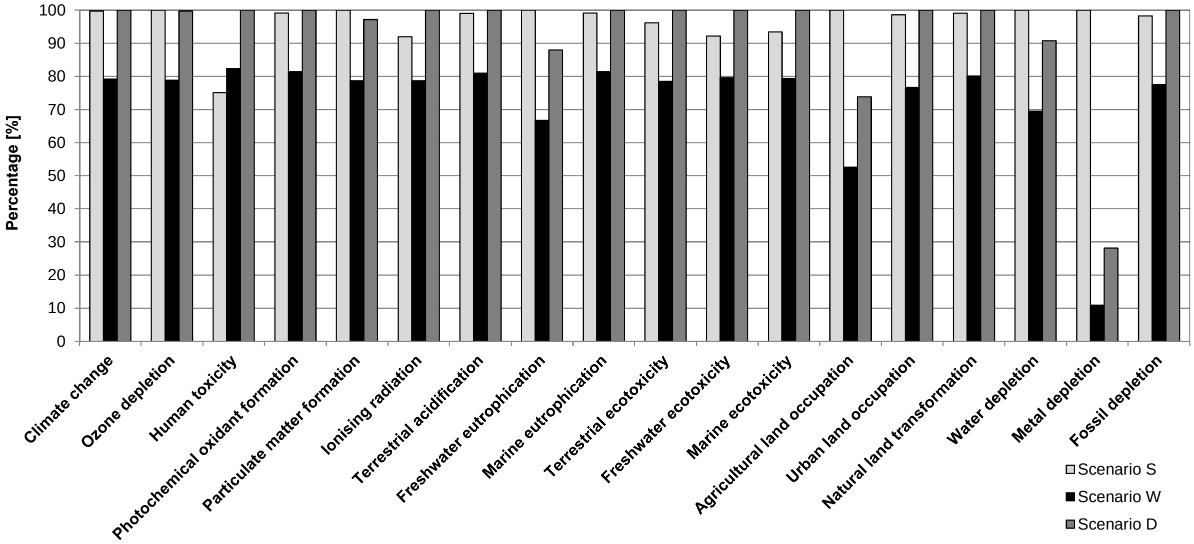


Figure 5: Results of the *ReCiPe* midpoint method.

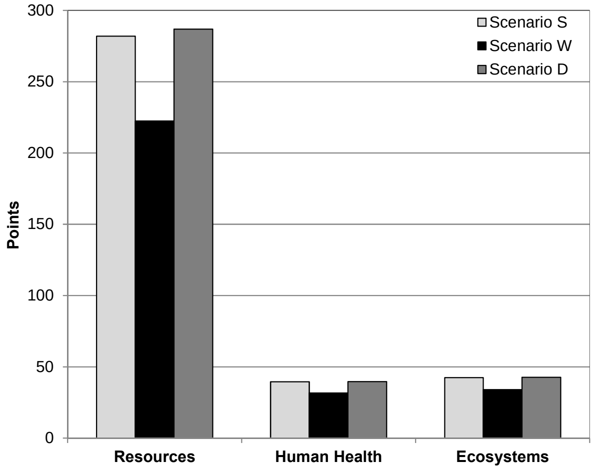


Figure 6: Results of the *ReCiPe* endpoint method.

CONCLUSIONS

Results obtained from the LCA analysis described in this paper show that use of wearing courses containing asphalt rubber produced by means of the “wet” technology can lead to significant benefits in terms of energy saving, environmental impact, human health, preservation of ecosystems and minimization of resource depletion. However, these advantages are guaranteed only if mixtures are properly designed and laid, with the corresponding possibility of reducing surface course thickness and maintenance frequency.

In the case of the so-called “dry” technology, incorporation of crumb rubber from end-of-life tires in the wearing course mixture does not necessarily produce the same benefits. In fact, for the case study considered in this paper, the eco-profile of the corresponding pavement was found to be approximately equivalent to that of a standard cross section. These findings are however influenced by the conservative assumptions which were made on the expected service life and maintenance needs of the surface course.

Even though obtained results are very promising, the work presented in this paper needs to be considered as preliminary, since calculations were based on several hypotheses and estimates. It is envisioned that in future studies these problems will be overcome by directly monitoring production and construction activities and this will likely fill the gaps of Life Cycle Inventory (LCI) data which are an essential component of Life Cycle Assessment (LCA).

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