Action 5

Life cycle risk assessment

POLITECNICO DI TORINO

Project partners

Patrimonio s.r.l.

With the contribution of

Action 5 - Life cycle risk assessment

1. Methods

1.1 Life cycle assessment (LCA)

Life Cycle Assessment (LCA) is a scientific and comprehensive method, internationally standardized in ISO 14040 and 14044 (EC et al., 2010; ISO 14040-44, 2006), that quantifies consumption of resources, generation of emissions and other environmental and health impacts associated to any specific product. The methodology takes into account the full life cycle of the analysed system, “from cradle to grave”, thus including all phases which comprise extraction of resources, production, use and recycling, disposal of waste.

In general terms, LCA is constituted by four parts:

- definition of goal and scope;
- life cycle inventory (LCI);
- life cycle impact assessment (LCIA);
- interpretation and analysis of results.

In this project, the goal is highlight the environmental advantages and disadvantages related to construction and future maintenance of pavements containing crumb rubber (CR) from end-of-life tires. The analysis was carried out by considering scenarios of courses containing CR which were compared to those of a standard bituminous mixture.

It was assumed that system boundaries of the LCA analysis include all the processes and activities which encompass raw materials’ sourcing, construction and maintenance operations during service life of the wearing course. Environmental impacts associated to the so-called “use phase” (e.g. related to rolling resistance, de-icing, albedo) were not considered in the evaluation.

The functional unit employed in the LCA analysis was 1 m of built surface layer and the software used for life cycle modelling was SimaPro 7.3 (SimaPro7, 2006).

The methodology was developed including the selection of two 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 (Boustead and Hancock, 1979), whereas GWP quantifies climate change expressed in kg of equivalent released CO_2 (IPCC, 2006). In order to expand the analysis and cover more areas of environmental and resource-use interest, the ILCD 2011 Midpoint method (EC et al., 2011) was also used in the analysis since it considers a wider array of categories of environmental impact, such as human toxicity, water and terrestrial toxicity, natural land transformation.

Retrieval of Life Cycle Inventory (LCI) data for the analysis was, as usual, a rather complex task. Main data used to model the foreground system were collected from interviews with contractors and experts involved in road works. In order to complete the data set, reference was then made to the Ecoinvent 2.2 database (Ecoinvent, 2007) and to information contained in a Eurobitume report (Eurobitume, 2012) which provides from-cradle-to-gate LCIs of bituminous materials representative of the European scenario. Data for aggregates production were extracted from available studies (Blengini and Garbarino, 2010), who considered the case of quarries located in the Piedmont region. CR production data were derived from information contained in an ongoing national study on carbon footprint carried out by Ecopneus (2013).

1.2 Risk assessment (RA)

Sanitary-Environmental Risk Assessment (RA) is an approach which deals with the evaluation of impacts due to the use of a specific chemical or physical agent in a particular site and time, with the aim of protecting human health at the local level.
In this project, the methodology was employed to the monitoring of paving works and for the corresponding evaluation of toxicological and carcinogenic risks to which workers are exposed on site as a result of the presence of gaseous emissions coming from hot bituminous mixtures (Zanetti et al., 2014).
Given that both the contaminant source (i.e. bituminous mixture) and the potential receptors (i.e. paving workers) were clearly identified and that direct measurements were performed (i.e. fume sampling and analysis), risk evaluation was developed by analytically modelling experimental data in each local scenario and by comparing obtained results with threshold values (Zanetti et al., 2013; Zanetti et al., 2014). In particular, adequate models were chosen and used for exposure evaluation and of reliable dose-response curves, relative to toxic and carcinogenic substances, retrieved from literature.
Dose-response curves are obviously different in the case of toxic (non-carcinogenic) and carcinogenic substances.
In the first case, a dose threshold can be identified below which it has been experimentally verified that there are no harmful effects of that substance. However, risk calculations require the use of a “reference dose” (RfD) which is obtained by reducing the threshold in order to take into account uncertainty in the extrapolation of dose levels from animals to humans and to consider specific characteristics of human response.
In the case of carcinogenic substances, the concept of a threshold is no longer valid since health of human beings is damaged at any considered dose. For the description of such effects it can therefore be assumed that in a wide dose range the response curve is linear, with the consequent identification of a single gradient value, also known as “slope factor” (SF).

1.3 Life cycle risk assessment (LCRA)

Several studies considered and compared advantages and disadvantages resulting from the combined use of LCA and RA (Olsen et al., 2001; Carpenter et al., 2007; Barberio et al., 2010; Mazzi et al., 2013). These clearly indicate that the main asset of this type of combined process is to obtain a more comprehensive environmental assessment, inclusive of evaluations performed both at the global and local scale.
In order to expand LCA analysis and to include RA as subset to LCA (Flemström et al. 2004), ILCD recommendations were considered in the analysis of environmental sustainability of the full-scale trial sections (EC et al., 2011). Moreover, with the main intention of promoting the current best practice, the ILCD 2011 Midpoint method (EC et al., 2011) was employed, with the use of recommended methods for each impact category. In ILCD recommendations the human toxicity category is split in two in order to differentiate carcinogenic and non-carcinogenic effects, which are assessed by means of the USEtox model (Huijbregts et al., 2010).
LCA results were supplemented by those of Sanitary-Environmental Risk Assessment (RA), which considers the exposure of workers to asphalt fumes during construction.
During construction of trial sections, gaseous emissions were sampled at the driver’s seat of the paver and at the screed for the subsequent analysis of their content of polycyclic aromatic hydrocarbons (PAHs). Sampling operations were carried out by employing a pump (0.5 l/min flow rate, 5 minutes total sampling time) by means of which fumes were

adsorbed on active granular carbon cartridges that were then stored at freezing temperature until laboratory analysis. These matrixes are subjected to solvent extraction (with methylene chloride) in an ultrasound bath for a period of 60 minutes (EN 13649, 2002; Lindberg et al., 2008). Subsequent analyses were carried out in a gas-chromatographic apparatus Agilent 7890/5975, equipped with a HP5-MS capillary column (30m x 0.25mm x 0.25m).

2. Trial section

2.1 Baio Dora and San Giorgio Canavese

Case studies subjected to analysis as part of the TYREC4LIFE project were those of two full-scale trial sections constructed on two extra-urban roads located, respectively, at Baio Dora and San Giorgio Canavese in the Province of Turin. In both cases 18% CR (b.w. of total binder) was added to base bitumen as a modifying agent by means of the “wet” technology. The trial section located at Baio Dora was characterized by a length of 1000 m and a total carriageway width of 9.5 m. The wearing course mixture, of the gap-graded type, was designed with a target binder content of 8% and was laid with a thickness of 3 cm. In the course of the project, the scenario corresponding to this trial section was indicated as “scenario Wg”.

The trial section located in San Giorgio Canavese had a similar extension (1000 length, 9.0 m width), but the employed wearing course mixture was of the dense-graded type, characterized by a design binder content of 5.2% and laid with a thickness of 4 cm. The scenario associated to this trial section was indicated as “scenario Wd”.

In order to highlight advantages and disadvantages related to the use of CR in pavement wearing courses, scenarios corresponding to the two paving projects were compared to reference scenarios (indicated as “standard”, “Sbd” and “Ssg”, respectively referred to the Baio Dora and San Giorgio Canavese sites), in which wearing courses were considered composed by traditional dense-graded hot mix asphalt. In both cases laying thickness was assumed equal to 5 cm, while considered paving length and width were identical to those of actual trial sections.

2.2 Borgaro Torinese - Brillada plant

Anothers case studies subjected to analysis as part of the TYREC4LIFE project were those of trial sections constructed at Brillada bituminous mixtures plant, located in Borgaro Torinese in the Province of Turin. In this case 3 different types of bituminous mixtures designed for base courses and 2 for wearing courses are built by means of the “dry” technology. Thus, in all cases 1% CR (b.w. of dry aggregates) was employed as partial substitution of aggregates.

The trial sections were characterized by a thickness of 10 cm and were designed with a target bitumen content in according to Table 1.

Instead, the wearing trial sections laid with a thickness of 3 cm and were designed with a target bitumen content in according to Table 2.

In order to highlight advantages and disadvantages related to the use of CR in pavement courses, foreground scenarios were compared to reference scenarios, in which bituminous mixtures were considered composed by traditional hot mix asphalt.

Table 1. Content of bitumen in base courses

BASE COURSE MIXTURES	%B
Standard	4.1
Coarse CR	4.2
Ultrafine CR	4.3
Ultrafine CR + LVA	4.3

Table 2. Content of bitumen in wearing courses

WEARING COURSE MIXTURES	%B
Standard	4.8
Coarse CR	4.9
Ultrafine CR	5.0

The functional unit was referred to 0.1 m^3 and 0.3 m^3 of laid layer respectively in case of base and wearing courses, considering 1 m^2 of pavement and the given thicknesses.
In this specific case, LCA was carried out following the process cradle-to-gate; in fact, the system boundaries regarded only the raw and processed materials and the construction phase, while use phase, maintenance and end of life weren't taken into account.
The impact assessment was developed considering energy and environmental indicators: Gross Energy Requirement (GER) and Global Warming Potential (GWP). In order to cover more areas of environmental impacts the Impact 2002+ method (Humbert et al., 2012) was also used in the analysis. In this case, it was convenient to choose above mentioned method instead of ILCD 2011 to highlight the saving of resources-use by the impact called "Mineral extraction", regarding the mineral depletion.

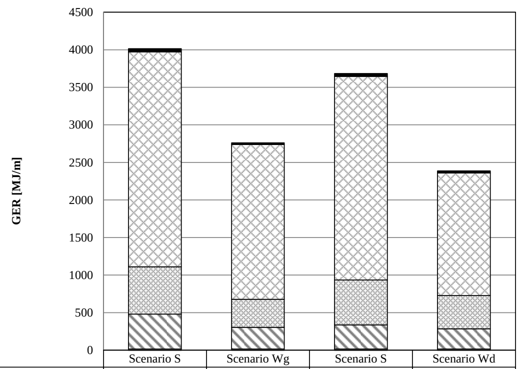
3. Results

3.1 Baio Dora and San Giorgio Canavese

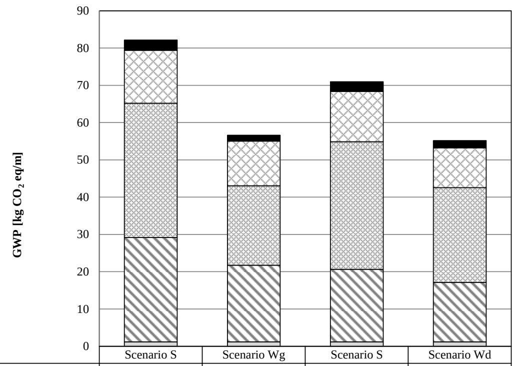
Table 3 shows the GER and GWP values that are associated to wearing course construction and maintenance operations during service life.
It can be observed that the choice of the materials which include CR causes a reduction of the overall spent energy (i.e. GER) and of carbon dioxide emissions (i.e. GWP), with percentages equal to the values given in parentheses.
Figure 1 shows the contributions of GER and GWP associated to raw materials' sourcing and construction. The production of bitumen and modified binder is the most energy intensive process, while production and transport of bituminous mixtures are the highest contributors to CO_2.

Table 3. GER and GWP associated to wearing course construction and maintenance operations

	Scenario Sbd		Scenario Wg		Scenario Ssg		Scenario W_d	
	GER [MJ/m]	GWP [kg CO_2 eq/m]	GER [MJ/m]	GWP [kg CO_2 eq/m]	GER [MJ/m]	GWP [kg CO_2 eq/m]	GER [MJ/m]	GWP [kg CO_2 eq/m]
Construction	4,016	82.2	2,763	56.64	3,686	71.0	2,390	55.19
Maintenance	16,800	377	7,980	175	15,200	310	6,890	168
Total	20,816	459	10,743 (-48.4%)	232 (-49.6%)	18,886	381	9,280 (-50.9%)	223.2 (-41.4%)



	Scenario S	Scenario Wg	Scenario S	Scenario Wd
Aggregates	43	24	40.1	29.7
Bitumen/Asphalt Rubber	2,860	2,060	2,710	1,630
Bituminous mixtures plant	631	373	597	444
Transport	464	288	321	268
Work equipment	18	18	18	18



	Scenario S	Scenario Wg	Scenario S	Scenario Wd
Aggregates	2.77	1.59	2.62	1.94
Bitumen/Asphalt Rubber	14.20	12.00	13.50	10.70
Bituminous mixtures plant	36	21.30	34.20	25.40
Transport	28	20.55	19.46	15.95
Work equipment	1.20	1.20	1.20	1.20

Figure 1. GER and GWP associated to raw materials' sourcing and construction

In Figure 2 results according to the midpoint method are shown, where, for comparison purposes, the value of the highest marker is set equal to 100%. The superior environmental performance of wearing courses containing rubberized binder (scenarios W_g and W_d) is confirmed, with the exception of a single case. In fact, the non-carcinogenic human toxicity score is lower in the case of standard scenarios because of the regeneration process of steel, that it is considered only in W_g and W_d scenarios due to the presence of CR in bituminous mixtures. In addition to usual environmental impact categories, Figure 2 and Table 4 show the results of LCRA in terms of human toxicity (carcinogenic and non-carcinogenic effects) of pavement workers exposed to asphalt fumes during hot mix asphalt laying operations. Thus, it is possible to analyse the values concerning the effects of fumes due to hot mix asphalt (S scenario) and to bituminous mixtures containing CR (Wg and Wd scenarios). This integrated approach and gathered results need to be considered preliminary, because of a certain level of uncertainty observed in the method applied for the evaluation of human toxicity and in some risk analysis assumptions.

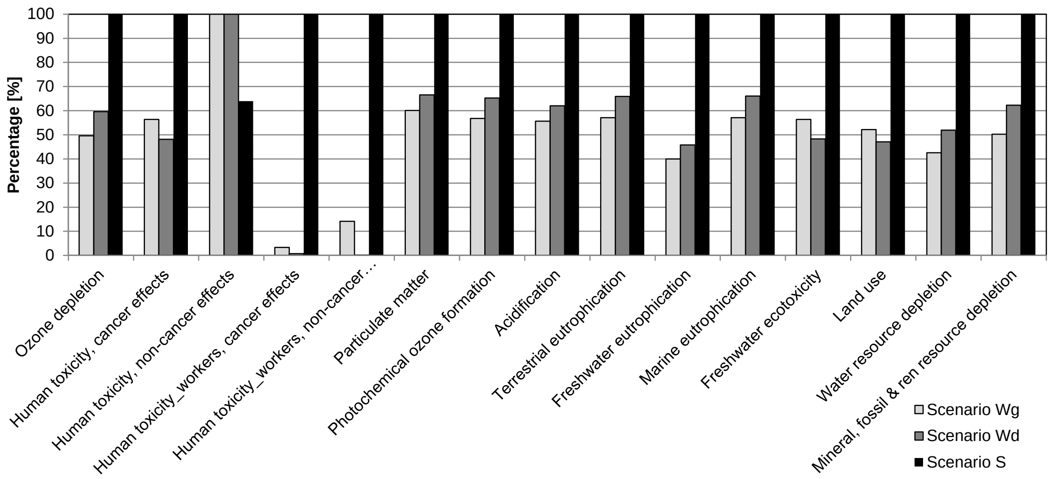


Figure 2. Results according to ILCD midpoint method and LCRA (in percentage)

Table 4. Results according to ILCD midpoint method and LCRA

Impact category	Unit	Scenario S	Scenario Wg	Scenario S	Scenario Wd
Ozone depletion	kg CFC-11 eq	6,2E-02	3,1E-02	5,0E-02	3,0E-02
Human toxicity, cancer effects	CTU	6,9E-01	3,9E-01	6,5E-01	3,1E-01
Human toxicity, non-cancer effects	CTU	2,0E-02	3,1E-02	1,6E-02	2,6E-02
Human toxicity_workers, cancer effects	CTU	4,3E-05	1,4E-06	4,3E-05	3,3E-07
Human toxicity_workers, non-cancer effects	CTU	5,8E-06	8,2E-07	5,8E-06	7,5E-09
Particulate matter	kg PM2.5 eq	1,4E+02	8,3E+01	1,1E+02	7,5E+01
Photochemical ozone formation	kg NMVOC eq	2,5E+03	1,4E+03	1,9E+03	1,2E+03
Acidification	molc H+ eq	2,3E+03	1,3E+03	1,8E+03	1,1E+03
Terrestrial eutrophication	molc N eq	8,5E+03	4,9E+03	6,4E+03	4,2E+03
Freshwater eutrophication	kg P eq	3,0E+01	1,2E+01	2,4E+01	1,1E+01
Marine eutrophication	kg N eq	7,8E+02	4,5E+02	5,9E+02	3,9E+02
Freshwater ecotoxicity	CTUe	6,9E+06	3,9E+06	6,5E+06	3,1E+06
Land use	kg C deficit	4,6E+06	2,4E+06	4,3E+06	2,0E+06
Water resource depletion	m^3 water eq	1,4E+02	6,0E+01	1,0E+02	5,3E+01
Mineral, fossil & ren resource depletion	kg Sb eq	7,2E-05	3,6E-05	5,2E-05	3,2E-05

3.2 Borgaro Torinese - Brillada plant

Tables 5 and 6 show the GER and GWP values that are associated to base and wearing course respectively.
Figure 3 shows a comparison between the results obtained for scenario standard and those which involved the use of CR by means of the “dry” technology.
It can be observed that the scenarios are approximately equivalent in terms of overall energy spent, with GER values, and of carbon dioxide emissions (i.e. GWP).
Figure 4 and 5 present the results in terms of a several environmental impacts such as ozon depletion, land occupation and mineral extraction. Properly in the last one, it is possible to note the difference between the reference scenario and “dry” scenarios, regarding the saving of raw materials in favor of bituminous mixtures containing CR.

Table 5. GER and GWP associated to base courses

	BASE Standard	BASE Coarse CR	BASE Ultrafine CR	BASE Ultrafine CR + LVA
GER [MJ]	1050	1048	1063	1066
GWP [kg CO_2 eq]	40,7	40,6	40,8	40,8

Table 6. GER and GWP associated to wearing courses

	WEARING Standard	WEARING Coarse CR	WEARING Ultrafine CR
GER [MJ]	669	666	672
GWP [kg CO_2 eq]	34,7	34,6	34,7

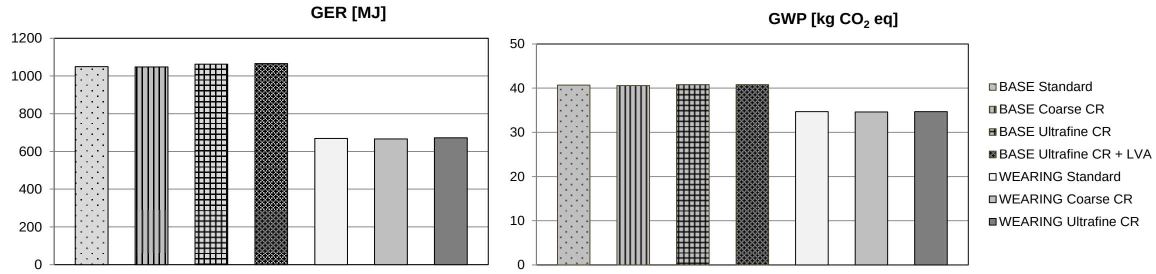


Figure 3. GER and GWP associated to base and wearing courses

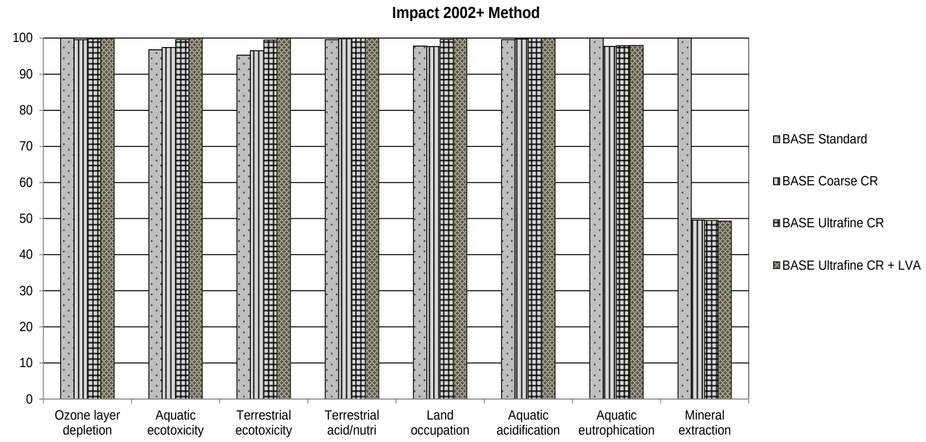


Figure 4. Imapct 2002+ method associated to base courses

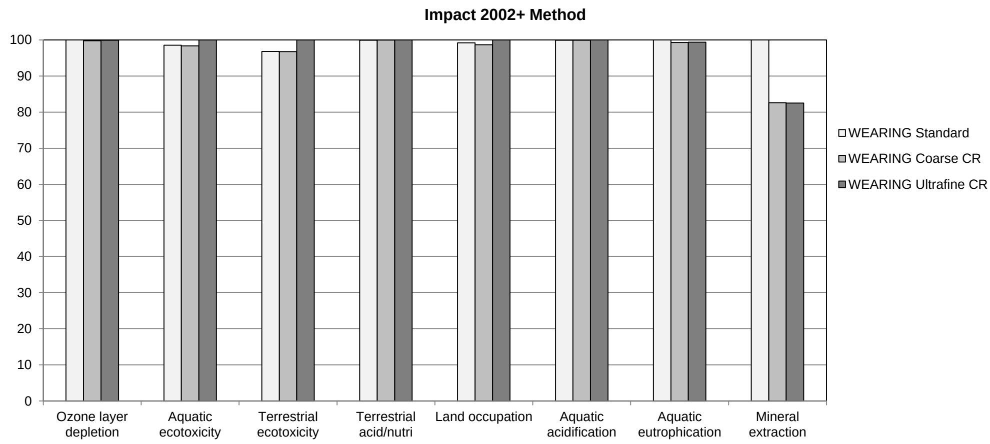


Figure 5. Imapct 2002+ method associated to wearing courses

4. Conclusions

Results obtained from the LCA analysis show that use of CR in gap- and dense-graded mixtures 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.

RA is included in ILCD midpoint method results as part of the human toxicity category, regarding the health safety of pavement workers in the Turin area.

Although the integrated method is very promising, results should be considered as preliminary due to a certain level of uncertainty in the USEtox method applied for the evaluation of human toxicity (classified by the Joint Research Centre as "recommended but in need of some improvements") and in some risk analysis assumptions.

In the case of the so-called "dry" technology, incorporation of crumb rubber from end-of-life tires in the base and wearing course mixture does not necessarily produce the same benefits. In fact, for the case study considered, the eco-profile of the corresponding pavement was found to be approximately equivalent to that of a standard cross section.

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