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Life Cycle Risk Assessment Applied to Gaseous Emissions from Crumb Rubber Asphalt Pavement Construction

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Abstract: Asphalt mixtures for road pavements are produced and laid at high temperatures, producing gaseous emissions that contain polycyclic aromatic hydrocarbons and volatile organic compounds that paving workers are exposed to. This paper aims to combine the effects of gaseous emissions on human health with the life cycle impacts of wearing courses. The results of sanitary-environmental risk analysis and life cycle assessment were combined in an integrated approach, the life cycle risk analysis, to evaluate the environmental performance of road pavements and local cancer and toxicological effects on workers. Two asphalt mixtures modified with crumb rubber (CR) from end-of-life tires (gap and dense graded) were compared to standard, unmodified asphalt mix. Air samples were collected at the screed and the driver's seat of a paver during the construction of a full-scale trial section in Turin, Italy. The CR wearing course with a higher asphalt binder content (gap-graded) had a cancer effect on workers 3.5 and 2.9 times higher than the CR mixture with a lower asphalt binder percentage (dense-graded) and the standard mixture, respectively. Instead, the toxicological effects were 1.3 and 1.2 times higher for the gap-graded mixture than the dense-graded and the standard mix, respectively.

Keywords: life cycle assessment; sanitary-environmental risk assessment; life cycle risk assessment; road pavements; gaseous emissions; crumb rubber

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1. Introduction

Hot mix asphalt (HMA) is the most used asphalt mixture for road pavements worldwide. HMAs are produced and laid at high temperatures (150–190 °C) and are durable, weather-resistant, cost-effective, cool down quickly during construction, and let the traffic open in a short period [1]. Besides the standard hot mixtures composed of aggregates and asphalt binder, several other types of asphalt mixtures have been developed. Asphalt mixtures modified with synthetic or recycled polymers (e.g., styrene-butadiene-styrene, crumb rubber from end-of-life tires) are widely used and have better mechanical performance than standard mixes [2–11].

Crumb rubber (CR) from end-of-life tires is used in granular or powder form as a modifying agent for HMAs [12,13]. CR can be used to modify asphalt mixtures through wet technology by preliminarily mixing the CR with the asphalt binder to obtain a ductile, elastic, high-viscosity binder, also known as asphalt rubber [14]. CR is added to asphalt binder in a percentage typically higher than 15% by weight of the total binder, and the mixing process is at temperatures usually higher than 180 °C. The modified asphalt binder can then be combined with aggregates in the hot mix plant to produce asphalt mixtures that are generally of the gap-graded type, with a noncontinuous particle size distribution, and the dense-graded type, with a continuous particle size distribution.

The high temperatures at which HMAs are produced and laid lead to issues such as the gaseous emissions being released by road paving asphalt workers during the construction phase. The exposure of workers to asphalt fumes has been investigated in the literature from the technical and medical points of view. Exposure to dust, particulates, nitrosamines, benzothiazole, polycyclic aromatic hydrocarbons (PAHs), and volatile organic compounds (VOCs) were evaluated by performing medical tests on workers and collecting air samples at the asphalt plant and the paver [15–19]. Total particulate, PAHs, VOCs, and benzothiazole were measured by collecting air samples from the asphalt plant during the production of standard and CR HMAs and at the paver during the paving phase. These constituents were higher in gaseous emissions from rubberized asphalt mixtures [16]. The highest exposure was at the paver vehicle and the asphalt delivery truck [16]. However, the concentrations of the constituents at the screed and the driver's paver seat may be different. At the driver's seat, which is the point closest to the discharge of the HMA from the truck, the fumes can be affected by external factors, such as the wind speed and direction; instead, at the screed, the emissions are more uniformly distributed [18]. Performing self-reported symptoms, spirometry tests, and blood sampling pre- and post-work on workers employed in paving standard and rubberized asphalt mixtures, dust, PAH, and nitrosamine exposure was not different between standard and asphalt mixtures modified with CR [15]. However, benzothiazole was higher in workers exposed to fumes from rubberized asphalts, because this chemical is used for the vulcanization process of the rubber for tires [15,16]. Sanitary-Environmental Risk Assessment (RA) is an approach used to evaluate impacts due to the use of specific chemicals or physical agents in a specific site and time to protect human health at the local level. In the case of road pavements, RA assesses toxicological and carcinogenic risks to which workers are exposed on site because of the presence of gaseous emissions coming from hot bituminous mixtures laying operations [17,20].

Life Cycle Assessment (LCA) is a comprehensive methodology to quantify the environmental performance of goods and services [21–23]. In the case of the road pavements, the adoption of the LCA is especially useful in the case of innovative materials containing recycled products, which may be attractive for applications because of their contribution to the reduction of raw materials and nonrenewable resources [24–29].

LCA and RA can be used to assess the effects of chemicals and pathogenic agents emitted into the environment on humans and other species. Both tools require similar data, such as emissions, fate, and exposure of receptors [30]. The LCA impact category on human toxicity and ecotoxicity was developed based on mathematical relationships established by chemical RA [30]. LCA and RA can be combined to obtain a more comprehensive environmental assessment, inclusive of evaluations performed both at the global and local scales [30–34]. There are different ways to link LCA and RA in a life cycle risk assessment (LCRA). For instance, RA could be considered a subset of LCA or the opposite, and they could be used as complementary tools to create a comprehensive picture of a specific case [34].

The main hypothesis of this work is that HMAs expose paving workers to asphalt fumes containing contaminants, such as PAHs and VOCs, during construction operations. The human toxicity calculated for workers can be included in the life cycle impact assessment of the LCA of road pavements. The use of CR in asphalt mixes may not increase the concentration of the contaminants in the gaseous emissions. Instead, the percentage of the asphalt binder could change this factor. The environmental impact of road pavements built with asphalt mixtures using CR can be lower than that of standard, unmodified pavements.

This paper aims to combine the effects of asphalt fumes on human health during the construction phase of road pavements with the life cycle impacts of CR asphalt mixtures used as wearing course, as compared to standard asphalt mix for reference. Results of the RA were implemented in the LCA, considering the RA ad subset of LCA. We collected air samples at the screed and driver's seat of a paver during the construction of a full-scale trial section of a wearing course. The air samples were then analyzed to quantify the content of PAHs and VOCs, and the results were used to calculate the human toxicity related to the workers. We calculated the characterization factors (CF) for the human toxicity based on the chemicals detected in the gaseous emissions and then multiplied them by the mass content of PAHs and VOCs measured on site to quantify the human toxicity impact. The workers' toxicity impact category was added to the other impacts included in the ILCD (International

Reference Life Cycle Data System) 2011 midpoint method, assessed using the LCA tool SimaPro [35]. The quantification of the asphalt fumes from standard and rubberized hot mix asphalts and the calculation of their impact on human health has not been assessed in the literature. This paper represents a contribution to the construction phase of LCA applied to road pavements. LCA practitioners can use these results to consider the health impact of gaseous emissions during the construction phase of asphalt pavements.

2. Materials and Methods

2.1. Case Studies

In this study, a full-scale trial section constructed on an urban road located in Settimo Torinese, Province of Turin, Italy, in 2015 was considered. The trial section had a total carriageway width of 12.5 m, a length of 1680 m, and a thickness of 3 cm. The section was divided into three segments with different wearing course mixtures. Two segments were built using asphalt mixtures modified with 18% CR by weight of the total binder by means of wet technology, and the third one was unmodified. The asphalt mixture placed in the first segment was a gap-graded mix designed with an asphalt binder content of 7.06% by weight of the aggregates. The asphalt mixture in the second segment was a dense-graded mixture with 5.02% modified asphalt binder by weight of the aggregates. In order to highlight the advantages and disadvantages of the use of CR in pavement wearing courses, the two asphalt mixtures were compared to a standard, unmodified, dense-graded blend with an asphalt binder content of 5.72% by weight of the aggregates.

2.2. Gaseous Emissions Sampling

During the construction of the trial section, we sampled the gaseous emissions by using a pump with active granular carbon cartridges that absorb the fumes (Figure 1a). The pump had a flow rate of 0.5 L/min, and we collected the fumes for 5 min per sample, with two replicates. The samples were taken at the driver's seat of the paver and the screed (Figure 1b). At the same time, we measured the temperature of the air and the wind speed by using a Kestrel weather tracker anemometer, and asphalt mixtures, at the driver's seat of the paver and the screed (Table 1). The cartridges were then stored at freezing temperature until laboratory analysis. The matrixes were subjected to solvent extraction by using methylene chloride in an ultrasound bath for 60 min [36,37]. Subsequently, we carried out the analyses in a gas-chromatographic apparatus Agilent 7890/5975, equipped with an HP5-MS capillary column (30 m $\times$ 0.25 mm $\times$ 0.25 m), in order to analyze the content of PAHs and VOCs.

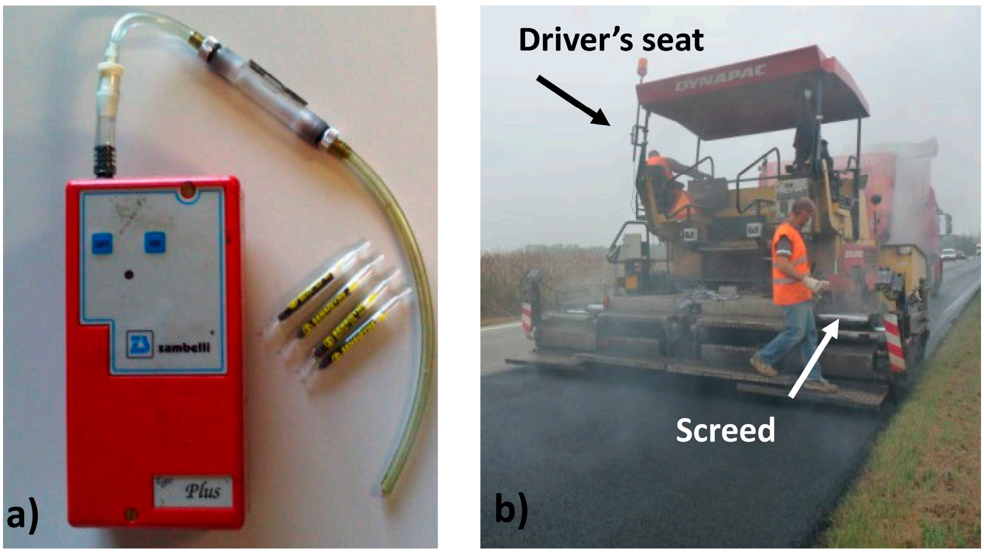


Figure 1. (**a**) Pump and cartridges used to collect the asphalt fumes, (**b**) positions where the fumes were collected at the paver.

Table 1. Weather conditions and temperature of the HMAs during construction.

	Standard		Gap		Dense	
	D	**S**	**D**	**S**	**D**	**S**
Temperature air (°C)	34.00	32.00	37.00	29.50	32.00	28.50
Temperature asphalt mix (°C)	140.00	139.00	162.00	166.00	163.00	161.00
Wind speed (km/h)	1.45	1.50	4.75	4.00	4.25	3.55

2.3. Life Cycle Assessment

The system boundaries included the raw material and asphalt mixture production phase, the construction and maintenance operations during the service life of the wearing course (Figure 2). Activities included in the raw materials production were rock blasting, milling and aggregate fraction separation in quarries, asphalt binder production in refineries, and tire processing in specific plants to produce crumb rubber. The construction phase included operations to lay asphalt mixtures using a paver and rollers. Maintenance activities consisted of removing the damaged wearing course, transporting the reclaimed asphalt pavement to the asphalt plant, and repaving. The reconstruction of the wearing course was assumed by adopting the same composition and volumetric characteristics of the removed layer. The service life of the pavements of standard and rubberized segments was considered to be equal to 20 years. The expected maintenance frequency of the surface courses was 1/7 years^{-1} for the asphalt mixtures modified with CR and 1/5 years^{-1} in the case of the standard mix [28]. The use phase (e.g., rolling resistance, noise, leaching, de-icing, albedo) was not considered due to a lack of data.

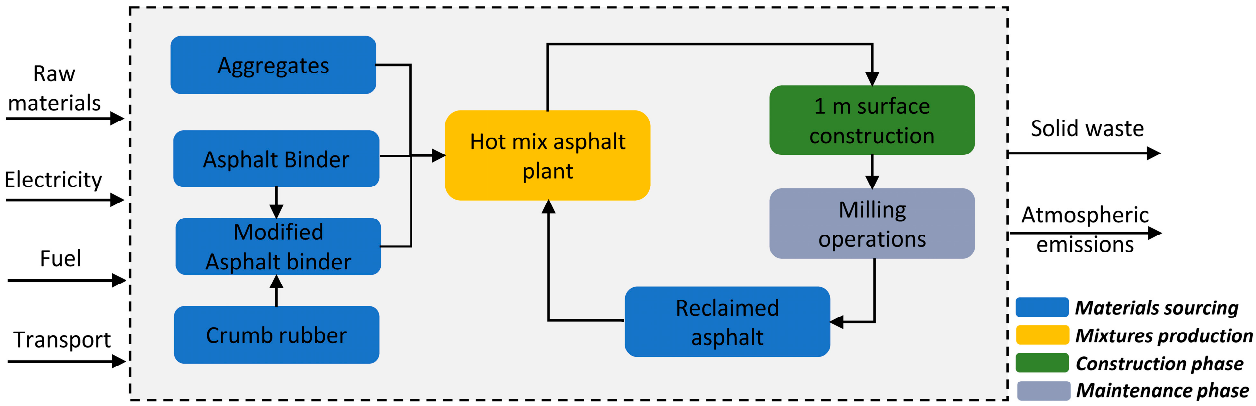


Figure 2. System boundaries for 1 m of the road wearing course construction.

The functional unit was 1 m of built surface layer for each mixture type. The software used was SimaPro 7.3 (PRé Sustainability B.V., Amersfoort, The Netherlands) [38]. The impact assessment evaluated the environmental indicators included in ILCD 2011, gross energy requirement (GER), and global warming potential (GWP). We used data collected from interviews with contractors and experts involved in roadworks, as well as the Ecoinvent 2.2 database and Eurobitume report for bituminous materials [39,40]. Data for the raw materials, as well as for the production of the asphalt mixtures, were reported in our previous work [28].

2.4. Sanitary-Environmental Risk Assessment

The method used for the Sanitary-Environmental Risk Assessment (RA) was an approach initially developed for contaminated sites and successively refined for its application to the monitoring of paving works [17,41,42]. The risk evaluation of the paving workers (potential receptors) exposed to the asphalt fumes from the asphalt mixture (contaminant source) was performed by analytically modeling experimental data in each local scenario and comparing obtained results with threshold values [17,20]. Risk analysis required the use of a specific model for exposure evaluation and dose-response curves relative to toxic and carcinogenic substances. These two key elements of risk assessment are provided in Equation (1).

$$EM = \frac{CR \times EF \times ED}{BW \times AT} \quad (1)$$

where EM is the calculated exposure (or effective exposure flow, in m^3/kg·day), CR is the so-called contact factor (dependent on the type of exposure, in this case, inhalation and therefore assumed equal to 3.6 m^3/day), EF is exposure frequency (in days/year, hypothesized equal to 250 for construction workers), ED is exposure duration (in years, assumed equal to 25 years), BW is average body weight (in kg, fixed at 70 kg), AT is the average mediation period of exposure. For the noncarcinogenic substances, AT corresponds to a exposure duration of 25 years. Instead, for the carcinogenic substances, AT is 70 years.

Figure 3 shows that the shape of the dose-response curves is different for toxic (non-carcinogenic) and carcinogenic substances. For the toxic substances, the dose threshold is considered because there are no harmful effects from that substance. In this case, the risk evaluation requires the use of a reference dose (RfD). By comparison, for carcinogenic substances, the concept of a threshold is no longer valid since the health of human beings is damaged at any considered dose. We can assume that, in a wide dose range, the response curve is linear, with the consequent identification of a slope factor (SF). We used RfD and SF values from the database of the Italian National Health Service Istituto Superiore di Sanità (ISS) [43]. The dose value (D, in $mg \cdot kg^{-1} \cdot d^{-1}$) used as an input was calculated for each compound, using Equation (2), where C is the compound concentration (in mg/m^3) in the fumes sampled on site.

$$D = C \times EM \quad (2)$$

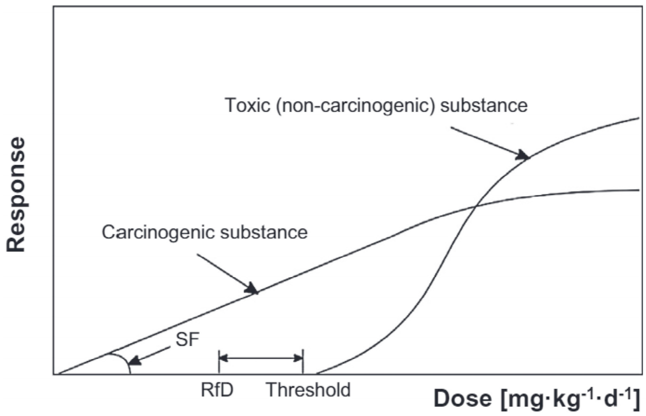


Figure 3. Shape of the dose-response curve for toxic and carcinogenic substances [17].

The toxicological and carcinogenic risks were quantified by considering, respectively, the so-called Hazard Quotient (HQ) and the Individual Excess Life Cancer Risk (IELCR), calculated as indicated in Equations (3) and (4).

$$HQ = D/RfD \quad (3)$$

$$IELCR = D \times SF \quad (4)$$

HQ or IELCR contributions due to each compound (or group of compounds) were summed together, thus obtaining final HQ or IELCR values, which provide a synthetic description of the potential impact of a specific paving site on workers' health, both from a toxicological and carcinogenic viewpoint. According to ASTM recommendations, for the working conditions to be acceptable, it is required that HQ must be lower than one and IELCR be lower than 1×10^{-4} [41,42].

2.5. Life Cycle Risk Assessment

In this study, the RA was considered a subset of LCA, integrating the toxicological model in the life cycle impact assessment [34]. Environmental impact was assessed using the ILCD 2011 Midpoint method. This method typically considers the urban and continental impact categories associated with the process materials under analysis. In the ILCD method, the human toxicity category is split into two different impacts. The first considers the carcinogenic effects, and the second impacts the noncarcinogenic effects. Both were assessed using the USEtox model [44]. As shown with Equation (5), the human toxicity impact score (IS) is calculated in comparative toxic units [CTU] by summing the contributions due to substances that can have an effect on urban air, rural air, fresh water, etc., and that can be inhaled, drunk, or eaten, expressed as the products of appropriate characterization factors ($CF_{x,i}$) [cases/kg] and the mass of emission expressed in kg ($M_{x,i}$) of each generic substance.

$$IS = \sum_i \sum_x CF_{x,i} \cdot M_{x,i} \tag{5}$$

In this study, to develop the LCRA combined procedure, the human toxicity impact score for pavement construction workers was obtained by making use of CF values derived from the mathematical equations of the USEtox model and by considering the results of laboratory analyses performed on gaseous emissions sampled onsite (RA local effect).

Equation (6) shows how to calculate the CF, which includes a fate factor (FF), an exposure factor (XF), and an effect factor (EF). In order to explain each factor, the FF [days] coefficient links the quantity released into the environment to the chemical masses or concentrations in a given compartment. It is equal to the residence time of a chemical. Table 2 shows the fate factors employed in the case study described in this paper. The exposure factor is equal to XF_{inh} [$days^{-1}$] and represents exposure via inhalation of air, as described in Equation (7), in which INH is the average inhalation rate of a person and, in the case considered in this paper, pavement workers, the parameter was set equal to 3.6 m^3/day (0.9 m^3/h and 4 h/day) [17,20]. The considered population was the pavement construction workers (2000, i.e., on the urban scale). The effect factor EF [$cases \cdot kg_{intake}{}^{-1}$] is the coefficient that reflects the change in lifetime disease probability due to changes in lifetime intake of pollutants, and it is calculated as indicated in Equation (8). For carcinogenic and noncarcinogenic effects, Equation (9) calculates the value of ED50 for humans related to inhalation, where $ED50_{a,t,j}$ represents the RfD and the SF, respectively, in the cases of toxicological (Equation (10)) and carcinogenic substances (Equation (11)), multiplied for specific extrapolation factors [45].

Based on indications provided by the ISS, RfD and SF related to inhalation of chemicals are reported in Table 3. The BW is the average body weight of humans (70 kg), LT is the average years working (25 years), and N is the number of days working per year (250 $days \cdot year^{-1}$ for pavement workers) [17,20]. Emission masses ($M_{x,i}$) were obtained from the results of laboratory analyses by multiplying detected concentrations of carcinogenic and noncarcinogenic PAHs and VOCs (expressed in µg/m^3) shown in the following, Table 3.

$$CF = FF \cdot XF \cdot EF \tag{6}$$

$$XF_{inh} = INH \cdot POP / VOLUME_{air} \tag{7}$$

$$EF = \frac{0.5}{ED50} \tag{8}$$

$$ED50_{h,j} = \frac{ED50_{a,t,j} \cdot BW \cdot LT \cdot N}{10^6} \tag{9}$$

$$ED50_{a,t,j} = RfD \cdot 9 \text{ (toxicological case)} \tag{10}$$

$$ED50_{a,t,j} = SF^{-1} \cdot 0.8 \text{ (carcinogenic case)} \tag{11}$$

Table 2. Fate factors [FF] from the Usetox model.

Emission to Continental Urban Air	
Chemical Substance	**[Days]**
Benzo[b]fluoranthene	4.90×10^{-2}
Benzo[a]pyrene	4.46×10^{-2}
Naphtalene	5.00×10^{-2}
Fluoranthene	4.81×10^{-2}
Dibenzo[a,h]antracene	4.57×10^{-2}
Pyrene	4.53×10^{-2}
Benz[a]anthracene	4.50×10^{-2}
Benzo[ghi]perylene	4.11×10^{-2}
Anthracene	4.70×10^{-2}
Indeno[1,2,3-cd]pirene	4.33×10^{-2}
Benzene	5.36×10^{-2}
Toluene	5.27×10^{-2}
Ethylbenzene	5.25×10^{-2}
p-Xylene	5.12×10^{-2}
Styrene	4.47×10^{-2}
Benzene, 1,3,5-trimethyl-	4.48×10^{-2}
Benzene, 1,2,4-trimethyl-	4.83×10^{-2}
p-isopropiltoluene	5.11×10^{-2}
Benzene, butyl-	5.22×10^{-2}
Benzene, 1,3,5-trichloro-	5.37×10^{-2}
Benzene, 1,2,4-trichloro-	5.37×10^{-2}

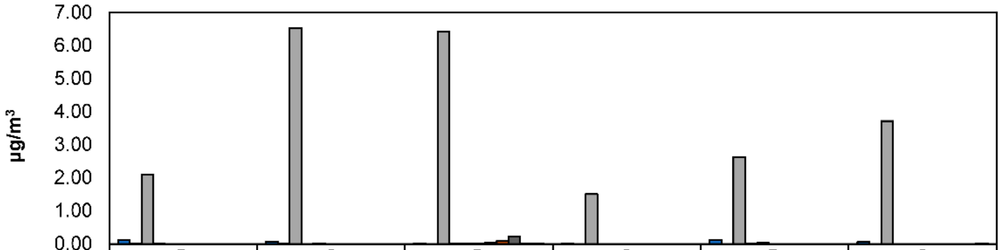
Table 3. Reference dose (RdF) and slope factors (SF) based on the Istituto Superiore di Sanita' (ISS).

PAHs	CAS-Number	RfD Inal. [mg/kg-day]	SF Inal. [mg/kg-day]$^{-1}$
Pyrene	129-00-0	0.000857	-
Benz[a]anthracene	56-55-3	-	0.385
Benzo[b]fluoranthene	205-99-2	-	0.385
Benzo[ghi]perylene	191-24-2	0.000857	-
Naphtalene	91-20-3	0.000857	0.119
Others	-	0.0143	-
VOCs	**CAS-Number**	**RfD Inal. [mg/kg-day]**	**SF Inal. [mg/kg-day]$^{-1}$**
Benzene	71-43-2	0.00857	0.0273
Toluene	108-88-3	1.429	-
Ethylbenzene	100-41-4	0.286	0.00875
p-Xylene	106-42-3	0.029	-
Styrene	100-42-5	-	0.286
Benzene, 1,2,4-trichloro-	120-82-1	-	0.000571
Others	-	0.285	-

3. Results and Discussions

3.1. Gaseous Emissions Sampling

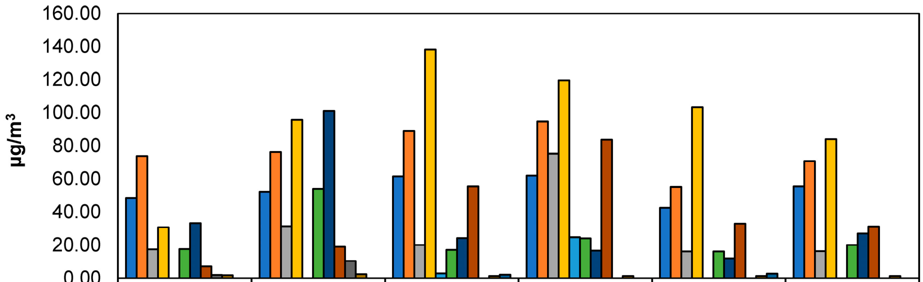
The chemical analyses of the gaseous emissions sampled at the trial section were performed to measure the concentrations of the toxic and carcinogenic compounds among substances potentially detectable using gas-chromatographic techniques. Listed data in Figures 4 and 5 belong to the examined cases because the composition of fumes is affected by several materials and site-specific factors, for example, mixture composition, CR type and base asphalt binder, temperature and laying temperature, wind, and air pressure.



	Standard D	Standard S	Gap graded D	Gap graded S	Dense graded D	Dense graded S
Benzo[b]fluoranthene	0.11	0.06	0.02	0.01	0.11	0.06
Benzo[a]pyrene	0.01	0.01	0.00	0.00	0.00	0.00
Naphtalene	2.10	6.53	6.42	1.50	2.63	3.72
Fluoranthene	0.01	0.00	0.02	0.00	0.01	0.00
Dibenzo[a,h]antracene	0.00	0.01	0.00	0.00	0.03	0.00
Pyrene	0.00	0.00	0.01	0.00	0.00	0.00
Benz[a]anthracene	0.00	0.00	0.03	0.00	0.00	0.00
Benzo[ghi]perylene	0.00	0.00	0.09	0.00	0.00	0.00
Anthracene	0.00	0.00	0.22	0.00	0.00	0.00
Triphenylene	0.00	0.00	0.02	0.00	0.00	0.00
Indeno[1,2,3-cd]pirene	0.00	0.00	0.01	0.00	0.00	0.01

Note: PAHs equal to zero represent values either not detected or below the detection limit

Figure 4. PAHs of gaseous emissions (µg/m^3) at the paver (D: driver's seat; S: screed).



	Standard D	Standard S	Gap D	Gap S	Dense D	Dense S
Benzene	48.38	52.30	61.71	62.11	42.68	55.43
Toluene	73.87	76.27	88.86	94.69	55.14	70.77
Ethylbenzene	17.52	31.41	20.10	75.31	16.16	16.33
p-Xylene	30.73	95.71	138.11	119.41	103.47	84.15
Styrene	0.00	0.00	2.98	24.75	0.00	0.00
Benzene, 1,3,5-trimethyl-	17.55	54.02	17.21	24.11	16.22	20.16
Benzene, 1,2,4-trimethyl-	33.36	101.22	24.28	16.74	12.01	26.90
p-isopropiltoluene	7.17	18.97	55.51	83.90	33.07	31.19
Benzene, butyl-	2.17	10.44	0.00	0.00	0.00	0.00
Benzene, 1,3,5-trichloro-	1.94	2.51	1.48	1.48	1.43	1.52
Benzene, 1,2,4-trichloro-	0.00	0.00	2.30	0.00	2.86	0.00

Note: VOCs equal to zero represent values either not detected or below the detection limit

Figure 5. VOCs of gaseous emissions (µg/m^3) at the paver (D: driver's seat; S: screed).

In RA methodology, these data are the starting point to calculate hazard quotient and Individual Excess Life Cancer Risk, assessing the health of workers exposed to asphalt fumes on paving site. In LCRA, the chemical concentrations are used to calculate the human toxicity impact score at the local scale.

3.2. Life Cycle Assessment and Risk Analysis

Results related to the asphalt mixtures modified with CR by means of wet technology were compared to those of the reference standard mixture. Table 4 shows the GER and GWP results that are associated with the life cycle of the wearing courses built with the CR and standard mixtures. It can be observed that asphalt mixtures containing CR cause a reduction of the overall spent energy (i.e., GER) and carbon dioxide emissions (i.e., GWP), with percentages equal to the values given in parentheses. These environmental benefits can be attributed to the asphalt rubber that confers better mechanical performance to bituminous mixtures, with the corresponding possibility of reducing the quantity of asphalt mixture during the service life of the pavement and maintenance frequency [2,46].

Table 4. GER and GWP associated with wearing course construction and maintenance operations.

Standard		CR Gap Graded		CR Dense Graded	
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]
1.78×10^4	348	1.09×10^4 (−63.3%)	256.00 (−35.9%)	1.13×10^4 (−57.5%)	263.00 (−32.3%)

Table 5 shows the results of RA concerning Hazard Quotient (HQ) and the Individual Excess Life Cancer Risk (IELCR) for asphalt workers. It can be observed that the adoption of the gap-graded technology determines an increase of HQ and IELCR coefficients. This fact may be explained by the higher binder quantity employed in gap-graded mixtures with CR (7.06%) in comparison with dense-graded mixtures with CR (5.02%) and standard dense-graded mixtures (5.72%). Particularly, the IELCR value for gap-graded mixtures is about equal to the foreseen ASTM limit value.

Table 5. HQ and IELCR values associated with wearing course.

	Standard	CR Gap Graded	CR Dense Graded	ASTM Limits
HQ	0.48	0.61	0.46	1.00
IELCR	2.47×10^{-5}	9.02×10^{-5}	2.38×10^{-5}	1.00×10^{-4}

3.3. Life Cycle Risk Analysis

We implemented the human toxicity associated with paving workers in the ILCD method. Characterization factors calculated to quantify the impact category related to workers are reported in the Supplementary Materials. Figure 6 shows the results of the LCRA in terms of human toxicity (carcinogenic and noncarcinogenic effects) of pavement workers exposed to asphalt fumes during hot mix asphalt laying operations, in addition to the other environmental impact categories already included in the ILCD method. In Figure 6, the highest value was set as equal to 100% and the others were calculated as a proportion. The asphalt mixture modified with CR containing the higher percentage of asphalt binder had cancer effects on workers 3.5 times and 2.9 times higher than the CR mixture with lower asphalt binder content and the standard mix, respectively. By comparison, the toxicological effects were 1.3 and 1.2 times higher for the CR mixture with the higher binder with respect to the other CR mixture and the standard blend, respectively.

Results showed that the human toxicity noncarcinogenic effects for workers were more significant than the human toxicity for the urban population, calculated using the characterization factors already implemented in the model (Table 6). The opposite occurs for the human toxicity carcinogenic effects indicator, even if the absolute value concerning workers is rather significant (Table 6). The higher environmental impact of wearing course containing rubberized asphalt binder for the noncarcinogenic human toxicity score was due to the recycling process of steel removed from the end-of-life tires, which was considered only in the gap and dense-graded mixtures [28].

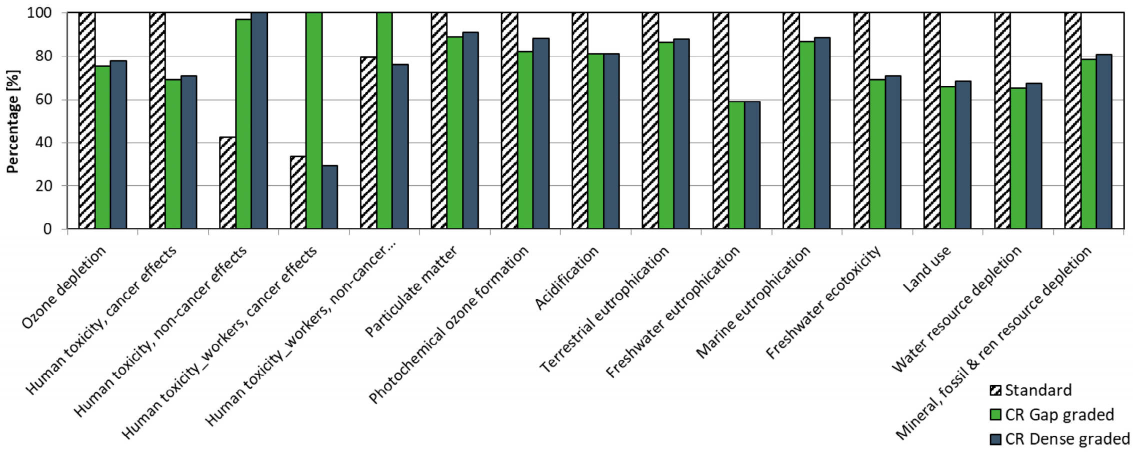


Figure 6. Results according to the ILCD midpoint method and LCRA (in percentage).

Table 6. Human toxicity results for population and paving workers' health.

Impact Category	Unit	Standard	CR Gap	CR Dense
Human toxicity, cancer effects	CTU	5.8×10^{-4}	4.0×10^{-4}	4.1×10^{-4}
Human toxicity, non-cancer effects	CTU	1.4×10^{-5}	3.2×10^{-5}	3.3×10^{-5}
Human toxicity—workers, cancer effects	CTU	1.2×10^{-6}	3.5×10^{-6}	1.0×10^{-6}
Human toxicity—workers, non-cancer effects	CTU	6.5×10^{-4}	8.1×10^{-4}	6.2×10^{-4}

4. Conclusions

Results obtained from the LCA analysis described in this paper show that the use of wearing courses containing asphalt rubber produced using wet technology (gap-graded and dense-graded) can lead to significant benefits in terms of energy saving, environmental impact, human health (human toxicity noncancer effects excepted), preservation of ecosystems and minimization of resource depletion. However, these advantages are only guaranteed if mixtures are adequately designed and laid, possibly reducing surface course thickness and maintenance frequency. Risk Assessment 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. Based on the gathered results, workers' cancer and noncancer effects were more elevated from asphalt mixtures containing a higher binder content (gap-graded) than the dense-graded and the standard wearing course. Therefore, the integrated method, LCRA, may allow a complete evaluation of global (regional, urban) impacts and local impact (in the examined case, pavement workers) and may be a valuable tool in making decisions considering all the involved aspects.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su14095716/s1. Table S1: Coefficients used to calculate the characterization factors (CF) for the human toxicity for the PAHs. Table S2: Coefficients used to calculate the characterization factors (CF) for the human toxicity for the VOCs. Table S3: Results of the life cycle and risk assessment implemented in the ILCD midpoint method.

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