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A comparative environmental impact analysis of asphalt mixtures containing Crumb Rubber and Reclaimed Asphalt Pavement using Life Cycle Assessment

The research work presented in this paper aims at evaluating the potential environmental impacts of asphalt mixtures containing crumb rubber (CR) (vulcanized or devulcanized) and reclaimed asphalt pavement (RAP) assuming different degree of blending between aged and virgin binder by means of a life cycle assessment (LCA). The LCA allows comparing distinct alternatives according to their environmental performance across a set of impact categories. The results of the case study showed that when compared with a traditional asphalt mixture, the CR modified (CRM) mixtures caused higher impacts due to the treatment of the rubber as well as the higher amount of bitumen employed in the mixture. In turn, for mixtures containing RAP the analysis revealed an improvement of all the environmental indicators considered. Moreover, the potential environmental benefits of all impact categories were found to increase linearly when the degree of blending between the aged and virgin bitumen increases.

Keywords: Life cycle assessment; crumb rubber; devulcanization; RAP; base course; road sustainable materials.

1. Introduction

Reclaimed Asphalt Pavement (RAP) and End-of-Life tires (EOLTs) are among the most popular recycling materials to be used in road construction and maintenance (Silva *et al.* 2012, Bressi *et al.* 2016). The massive use of these materials that have the potential to replace non-renewable resources, is very attractive because it may lead to the reduction of a set of environmental burdens, such as the greenhouse gas (GHGs) emissions and energy consumption (Farina *et al.* 2017). EOLTs are among the largest and most problematic sources of waste due to the large volume produced and their durability (Lo Presti 2013). While these characteristics are negative if EOLTs are considered as waste material, the fact that crumb rubber modifiers (CRM) obtained from the processing of EOLTs are very resistant and durable make them an interesting material for use in other products, such as asphalt mixtures.

Rubber grains obtained from the treatment of crushing scrap tires in specialized plants can be incorporated into the preparation of asphalt mixtures by the so-called “wet” and “dry” production processes. The wet process describes the dissolution of the CR in the bitumen as a modifying agent. The dry process describes the replacement of a small portion of aggregates with the same fractions as those of the rubber grains (FHWA 1997).

The re-use and recycling of RAP in the construction and maintenance of infrastructure is a well-known practice that has been object of several research efforts towards maximizing the quantity of RAP employed in the production of new asphalt mixtures (Bressi *et al.* 2016). The use of RAP avoids the land use change, since the landscape is often ruined by disused quarries (Puppala *et al.* 2012). Moreover, the aged binder contained in RAP can act as the virgin binder (VB), which allows reducing the addition of new binder. In this context, the quantification of the Degree Of binder Activation (DoA) defined as the amount of RAP binder that can be considered “active” in the new formulation of asphalt mixtures incorporating RAP, has raised the interest of the scientific community (Shirodkar *et al.* 2011, Castorena *et al.* 2016, Cavalli *et al.* 2016) because the increase of the aged binder mobilized in a new mixture can be seen as a potential way to reduce the consumption of non-renewable resources such as the bitumen.

1.1. Vulcanized and devulcanized rubber for asphalt mixtures

To produce tires, the rubber undergoes a vulcanization process by using sulfur, peroxides and other substances intended to prevent the tires from cracking and to improve their properties (Rafique 2012). Vulcanization therefore is a process where chemical bonds are created between sulfur and the carbon molecules of rubber. Devulcanization refers to the process in which the crosslink bonds in the vulcanized rubber are selectively broken, cleaving the sulfur-sulfur or carbon-sulfur bonds and shortening the molecular chains (Rader *et al.*

1995). Indeed, the three-dimensional network structure restrains the rubber from melting (Fukumori and Matsushita 2003, Mangili *et al.* 2015). Therefore, the reclamation of scrap tires is mainly related to shredding and devulcanization of CR (Rafique 2012). When rubber is intended for use as element in wet or dry process for asphalt mixture, the use of reclaimed rubber, i.e. devulcanized rubber that has regained its viscosity as well as the characteristics of the original compound (ChemRisk(LLC) 2009), is preferable. In this case, a more homogeneous blend with the binder may be obtained because the rubber acts mainly as a flexible filler (Giavarini 1994, Gawel *et al.* 2006) that can be stored at high temperatures for longer periods without having problems related to its sedimentation (Morrison *et al.* 1995).

The devulcanization process encompasses several steps. They can be summarized as follows: (i) shredding the tires to small particles of rubber; (ii) fibers and steel removal through the use of suitable separators, and; (iii) further grinding of the rubber to a finer size and then mixture with different reclaiming agents (Rajan *et al.* 2006). The most studied devulcanization strategies involve mechanical, chemical, physical, biological, microwave and ultrasonic processes (Adhikari *et al.* 2000, Rafique 2012, Isayev 2013, Mangili *et al.* 2015).

Shredding is the first stage of the entire process of rubber reclamation and it pulverizes the scrap tires into a fine powder from 10 to 30 mesh (Li *et al.* 2014). Specifically, ambient grinding is a multi-step technology where tire chips are crushed in mills at ambient temperature (Shu and Huang 2014). The chips are fed into a granulator that breaks them into small pieces. Afterwards, the remaining steel is removed magnetically, while for the fiber a combination of shaking screens and wind sifters are used. Other important shredding processes for producing CR are the cryogenic and water jet processes (CalRecovery 2004).

After shredding, the rubber could be used either directly in a vulcanized state, or it can undergo the devulcanization process. It should be noted that the size of the rubber particles is responsible for the effectiveness of the devulcanization processes. Certain process requires fine particles, other can tolerate coarser rubber particles (CalRecovery 2004).

1.2. RUMAC technology

When CR is used as a portion of aggregates in hot mixture asphalt (HMA), the resultant product is sometimes referred to as rubber-modified asphalt concrete (RUMAC). This type of mixture usually contains a rubber percentage that varies from 1 to 3 percent by weight of the total aggregate in the mixture and a target air voids content that varies from 2 to 4 percent (FHWA 1997). In the 1980's the mixture design and the technology were refined, given origin to the production of an asphalt mixture commercially called PlusRide (Kandhal and Hanson 1993).

The long-term performance of CRM using dry process need to be further studied (Cao 2007), because of the higher uncertainties characterizing the performance of dry process compared to the wet process (Santagata et al. 2016). Indeed, the use of CR for dry process contributes to create a complex scenario regarding the performance of the mixture because there are many variables affecting the results that could yield to an inconsistent performance record, with non-negligible problems related to homogeneity and compaction (Santagata et al. 2016, Bressi et al. 2018a). Nevertheless, controlling bitumen–CR interactions and other fabrication parameters in dry mixtures it is possible to obtain beneficial effects (Khalid HA and Artamendi I., 2002). Moreover, undoubtedly the dry process, using rubber particles much coarser than wet process, facilitates the industrial production. The amount of rubber can be significantly higher (the dry process can use from 2 to 4 times as much as the wet process), increasing the rate of the recycling material and the incorporation in the mixture is easier (in the dry process there is no need of special equipment, while in the wet process special mixing chambers, reaction and blending tanks, and oversized pumps are required) (Roberts *et al.*

1989). Referring to low noise pavements, according to some Authors, when using the dry process in experimental sections, the noise absorption can be significant and higher if compared to the wet process (Paje *et al.* 2010, Losa *et al.* 2012); it seems this effect is amplified by the devulcanization treatment (Zhang *et al.* 2013). The improvement of the acoustic absorption is attributed to the improved chain flexibility of the molecules after the devulcanization treatment (Liang 2013).

Several studies exist in the literature that compare the performance and the durability of CRM materials. However, only a few of them have analyzed the potential environmental benefits derived from the use of these recycled materials (vulcanized or devulcanized rubber) for road pavement construction.

For these reasons, in this paper different combinations of percentage of rubber and rubber treatments used in the dry process RUMAC technology for asphalt mixtures are compared in order to evaluate the potential reduction of the environmental burdens arising from the use of these material and technologies in the production of asphalt mixtures.

1.3. Degree of activated aged binder in RAP mixtures

Combining RAP with virgin materials introduces some unique challenges, as the RAP materials contain aged bitumen that often is considered as inactive (“black rock”). However, experience shows that “black rock” is not a priori inactive. The other scenario normally considered is the “full blending”. “Full blending” assumes that 100% of the RAP binder is reactivated, binding and covering aggregates in the new mix, whereas “black rock” considers that 0% of the binder will be active and the RAP behaves as a rock. In between these two extremes, more reasonably it is considered that the aged binder contained in RAP does not act in a new mixture just like a "black rock", and also not 100% reactivated at high temperatures. A more reasonable assumption is that the DoA is located between these two points.

Quantifying the level of DoA in RAP mixtures is important for mix design purposes because allows reducing the amount of VB employed in the mixture (Coffey *et al.* 2013) and would bring higher level of reliability in the overall process of design, production and compaction of asphalt mixtures containing high quantity of RAP.

Despite the research efforts dedicated to investigate the behavior of aged binder in recycled asphalt mixtures, there are not common and standardized procedure for determining the DoA (Lo Presti *et al.* under review) and the majority of the studies of the environmental benefits related to the use of RAP assumes full blending between aged and VB (Ventura *et al.* 2008, Giani *et al.* 2015).

The fact that a common and standardized procedure is not clearly defined leads to high level of uncertainties associated with the quantification of the DoA, which among other factors, also depends on the characteristics of the RAP and VB.

Therefore, in the framework of this paper several DoAs in an asphalt mixture containing 40% of RAP were considered to analyze the environmental benefits derived from the reactivation of the aged binder and the reduction of the use of VB.

As suggested by the traditional approach recommended by many authors for mixtures containing more than 25% of RAP (Kandhal and Foo 1997, McDaniel and Anderson 2001, Zhou et al. 2011), blending charts should be used for selecting the type and content of the VB or Recycling Agents (RA). Soleymani et al. (1999) and Shen et al. (2007) recommended the use of softer binders in mixtures with 30–40% of RAP, while rejuvenators should be used in mixtures with higher percentages of RAP. Therefore, in the study presented in this paper the rejuvenators were not considered, given that the RAP content of the mixtures studied was within the range of 40%.

Furthermore, controlling the mixture gradation with fractionation of RAP, asphalt mixture interaction and compatibility between RAP and virgin materials is important in producing consistent performing mixtures maximizing their durability (Colbert and You 2012).

2. Objectives and Methodology

A life cycle approach is crucial to identify and quantify the potential environmental benefits derived from the use of alternative materials in asphalt mixtures.

This need can be fulfilled with the support of the life cycle assessment (LCA) methodology, which is a data-driven, systematic methodology, that has proven to be effective in estimating the potential environmental burdens caused by a product, process, or service throughout its life cycle (Matthews *et al.* 2015). Among other capabilities, LCA does not only assesses the potential environmental impacts of the outputs released to the environment because of the energy and material consumed, but also identifies opportunities for environmental improvements.

The LCA study is performed taking into account as much as possible and suitable the ISO 14040 and ISO 14044 series (ISO 14040, ISO 14044), the Federal Highway Administration's (FHWA's) Pavement LCA Framework (Harvey et al., 2016) and the ILCD Handbook (European Commission - Joint Research Centre - Institute for Environment and Sustainability 2010).

The next sections thoroughly report the LCA study performed in the research work.

2.1. Goal and scope definition

2.1.1. Intended applications

This study aims to perform a comparative LCA of traditional Italian asphalt mixtures and certain innovative mixtures containing different percentages of recycled materials (i.e., RAP and CR), employed in the base course of flexible road pavements. Specifically, the CR obtained from processing EOLTs (ambient grinding and devulcanization process) and the RAP coming from the demolition of old road pavements considering different DoA were considered. The results are compared with those associated with the use of traditional mixtures and are intended to provide insights on the extent to which recycling based materials with similar features to those considered in this case study and employed in analogous situations, are efficient in contributing to greening the road pavement sector.

2.1.2. *Reasons for carrying out the LCA study and target audience*

The main reason underlying to the performance of this study has to do with the fact it is believed to provide valuable information to be incorporated at the early stages in the design of new or in the maintenance of existing pavement structures. The findings of this study are intended to be used by engineering experts and practitioners for evaluating the advantages and disadvantages associated with the use of emerging and commonly called sustainable strategies and practices for road pavement construction, maintenance and rehabilitation (M&R). Indeed, this study quantifies the potential benefits resulting from the consideration of different DoAs, by developing different equations that show the evolution of the reduction of the scores of each impact category indicator when different DoAs are assumed. Furthermore, the concerned audience is provided with the results of a comparative and seldom performed LCA study between the use of vulcanized and devulcanized rubber in the road pavement construction.

The system includes, within its boundaries, all the activities required to construct the asphalt base course layer. Specifically, the following phases are accounted for: (i) resources extraction and composite materials production; (ii) movement involved in hauling the materials between facilities and work site; and (iii) construction equipment operation during the construction of the base course layer.

2.1.3. Function, functional unit and reference flows

Function: The different asphalt mixtures are made of different materials and compared considering their main function when used in a structural layer of a road pavement structure. Their aim is to distribute loads to the layers beneath, thereby contributing to ensure safe, comfortable, economical, and durable driving conditions over a given project analysis period (PAP).

Functional unit: All the asphalt mixtures are compared on the basis for the following functional unit: Help to enable a given volume of traffic to drive with safe, comfortable, economical, and durable conditions in a 1 km-length principal Italian rural roadway, located in Empoli (Tuscany), with 2 carriageways and 4 lanes and a base course layer which is 10 cm-tick and 15 m-wide. The thickness is equal for all the alternatives since it is assumed that all the solutions have the same durability. The rationale behind this assumption is presented later in this paper with more detail.

Reference flows: Considering that all the alternative asphalt mixtures are assumed to have the same durability, The quantity of asphalt mixtures corresponding to a unitary application of such mixtures in the base course with the dimensions described above is considered as the reference flow.

In total, eleven types of asphalt mixtures intended to be applied in base course are considered in the case study: the traditional mixture, complying with the Italian standards, and ten alternative mixtures with recycled materials, i.e., different quantities of CR and RAP.

To understand the potential environmental advantages and disadvantages related to the use of asphalt mixtures with recycled materials, different percentages of RAP and CR are considered and compared with the reference scenario corresponding to the production and placement of a classical asphalt mixture named “Base” with 4.5% of bitumen by weight of mixture. The mixtures considered have the features described below (the percentages are given by weight of mixture):

- DRY1.5D - Rubberized asphalt mixture (RUMAC dry process) containing 1.5% of devulcanized CR and 5.5% of bitumen;
- DRY2.0D - Rubberized asphalt mixture (RUMAC dry process) containing 2.0% of devulcanized CR and 6.0% of bitumen;
- DRY1.5V - Rubberized asphalt mixture (RUMAC dry process) containing 1.5% of vulcanized CR and 5.5% of bitumen;
- DRY2.0V - Rubberized asphalt mixture (RUMAC dry process) containing 2.0% of vulcanized CR and 6.0% of bitumen;
- RAP40BR - asphalt mixture with 40% of RAP in partial substitution of virgin aggregates. This scenario considers that the bitumen trapped in RAP behaves as black rock (Shirodkar *et al.* 2011), and then it is not active in the new asphalt mixture. Therefore, the percentage of the VB to be added to the mixture cannot be reduced and was kept equal to 4.5%;
- RAP40DOA20, RAP40DOA50, RAP40DOA70, RAP40DOA80 - asphalt mixtures with 40% of RAP in partial substitution of virgin aggregates. This scenario considers that the bitumen trapped in RAP partially blends (DoA equal to 20, 50, 70 and 80%) with the VB.
- RAP40FB - asphalt mixture with 40% of RAP in partial substitution of virgin aggregates. This scenario considers 100% of aged bitumen trapped in the RAP being reactivated. The full blending between the RAP and VB allows reducing the portion of VB. The RAP binder content is 5.3%. Therefore, it is necessary to add 2.4% of VB in order to have a final content of 4.5% of total bitumen by weight of the mixture.

The bitumen selected for the RUMAC dry process mixture is similar to the one used for the traditional asphalt (FHWA 1997). The size of rubber grains ranges from 4.75 mm to 0.075 mm. The target air voids content of the asphalt mixture was defined to be equal to 3%.

The compositions of DRY1.5D, DRY1.5V, DRY2.0D and DRY2.0V mixtures were obtained from the mix design performed in previous studies in which were shown that higher amounts of rubber can inhibit a satisfactory compaction in the laboratory of dense graded asphalt mixtures due to the elastic behavior of the rubber (Bressi *et al.* 2018a). Due to this reason, higher percentages of rubber were not considered. Moreover, rubber absorbs the oil fraction of bitumen in the so-called maturation process (Dong *et al.* 2012); this causes the swelling of the CR particles and leads to the need of adding higher quantity of VB. Indeed, when the rubber is added to the asphalt mixture by means of the dry process, the grains of rubber swell up because they absorb part of the volatile parts of bitumen (paraffin and maltenes). This process of maturation, called "maceration", originates a stiffer bitumen (Dong *et al.* 2012), therefore increasing the quantity of bitumen necessary to achieve the optimal mix design of the CR mixtures. Tables 1-2 summarize the composition of each asphalt mixture used as alternative to the traditional asphalt mixture.

Table 1

Table 2

2.1.4. LCI modelling framework

Given that the eventual use of the new asphalt mixtures is not expected to have large structural changes in the market, the decision context falls into the situation A in the ILCD Guideline (European Commission - Joint Research Centre - Institute for Environment and Sustainability 2010), i.e. is micro-level, product or process-related decision support studies. As such, the attributional approach was chosen as the life cycle inventory (LCI) modelling framework. The attributional approach depicts the actual or forecasted specific or average supply-chain. Also, it assumes that the decisions made within the system that produces and uses the asphalt mixtures do not influence the "outside world" (Hertwich 2014).

2.1.5. *System boundaries*

The system boundaries tailored for the specific application considered in this research work took into account the existing literature on the durability and performance of asphalt mixtures containing CR (dry process) and/or RAP. In this context, according to several studies (McDaniel *et al.* 2000, Cao 2007, Farina *et al.* 2017), the performance of mixtures containing dry CR and RAP can be considered to be similar to that of traditional mixtures if they are properly designed to avoid non negligible problems related to homogeneity and compaction of the mixture (Santagata et al. 2016). A few others studies, instead, report higher performance (Airey *et al.* 2003, Huang *et al.* 2004, Hernandez-Olivares *et al.* 2009). In the particular case of the devulcanization process, it emerges that at low temperatures the asphalt mixtures containing devulcanized rubber perform better than traditional ones. Nevertheless, at high temperatures, the devulcanized rubber provides only a modest improvement, because the elastic properties of the rubber are damaged due to the devulcanization/depolimeration effect (Han *et al.* 2016). It should be also considered that a small amount of residual solvent used during the devulcanization process can have a significant effect on the binder properties at high and low temperatures (Morrison *et al.* 1995). Despite the potential benefits in terms of asphalt performance, derived from the use of devulcanized rubber at low temperature (Morrison *et al.* 1995), additional research is currently needed to improve the technology and the incorporation of the rubber into the asphalt mixture to ensure higher durability of the final product. These materials, in particular the RUMAC technology analysed in this paper, have also been tested several times in test sections showing contradictory results. For instance, the California Department of Transportation (CalTrans) has constructed four projects using the PlusRide dry process technology and the results showed that two of the four dry process projects improved the performance of traditional dense-graded asphalt, while a third project has performed comparably and the last one showed worse results (Kirk 1991). Moreover, the two dry process sections constructed by the Minnesota Department of Transportation (MNDOT) have not shown higher performance compared to traditional asphalt (Turgeon 1989). The Washington State DOT (Estakhri *et al.* 1992) concluded that the RUMAC dry process did not provide improved performance compared to conventional asphalt. Therefore, a conservative approach assuming the same durability for all the solutions was considered. That means that the maintenance, dismantling and disposal phases are scheduled at the same time for all the solutions and then were excluded from the system boundaries. Indeed, a cradle-to-gate model is appropriate when the materials do not differ in durability, i.e. they have same construction, transport implications, maintenance and EOL management (European Commission - Joint Research Centre - Institute for Environment and Sustainability 2010). Due to these facts, these phases were excluded from the compared systems. This approach has also been adopted in recent studies comparing the use of materials with RAP in infrastructures, when the durability was similar (Porot *et al.* 2016). Indeed, the use of RAP percentages below 30–40% do not require usually specific technologies, such as separate parallel drum or the use of additives to overcome technical issues. These percentages allow for achieving the same durability of traditional mixtures without the employment of particular technologies. Therefore, a cradle-to-gate approach could be considered (Porot *et al.* 2016). This approach was also preferable in this case study because it allows a better isolation and identification of the potential environmental benefits derived from the different DoA scenarios.

Notwithstanding the considerations presented previously, the modelling approach considered in this case study went beyond the cradle-to-gate, in the sense that the construction and transportation of materials phases were also considered. An elaborated description of the phases considered in this case study is provided next.

The resources extraction consists of the acquisition and processing of raw materials, such as the bitumen production at refinery; extraction, crushing and sieving of aggregates; acquisition of CR generated as a by-product of the scrap tires, ambient grinding, devulcanization and RAP processing.

The composite materials production phase consists of the production of the asphalt mixtures. It takes place in a batch-type hot mix production plant where the bitumen is heated and pumped. Virgin aggregates are washed, dried, heated and then added to the mixture. The CR is added at room temperature while RAP is heated at lower temperatures compared to the virgin aggregates. Indeed, it is important to heat the RAP as little as possible, as the heating process further ages the already aged binder (Cavalli et al., 2016). Next, once arrived at the construction site, the asphalt mixtures are laid down with specific construction equipment and machinery, such as standard pavers and rollers.

Finally, the transportation of materials phase refers to the hauling movements of materials, to and from the construction site and between intermediate facilities.

2.1.6. Basis for impact assessment

The life cycle impact assessment (LCIA) stage of the standardized LCA methodology comprises several steps, namely, classification, characterization, normalization, group and weighting (ISO, 2006). Among these steps, classification and characterization were undertaken in this study.

The characterization modelling to quantify the potential life cycle impacts was performed by applying the impact assessment method ReCiPe according to the hierarchist perspective (Goedkoop *et al.* 2013). Each perspective defined in the ReCiPe method (i.e., individualist, hierarchist and egalitarian) represents a hypothetical practitioner or decision maker that has differences in moral beliefs, concerns and/or interests. This corresponds to a specific set of preferences and contextual values that explains one's view on society and nature (Hofstetter, 1998). The hierarchist perspective is based on the most common policy principles with regards to time-frame and other issues (Goedkoop et al. 2013). The impacts were modelled at midpoint level, rather than at endpoint level, in order to keep the uncertainty as low as possible. Indeed, each aggregation step contributes to further increase the uncertainty in the results (Hauschild and Huijbregts, 2015)

The aggregation of the different impact categories with their relative weights and damage pathways was left to engineering experts and practitioners to make more assertive judgments based on their own beliefs. Moreover, no normalisation was performed, mainly because the existing reference values are thought to be underestimated for the toxicity-related impact categories due to the insufficient knowledge of total emissions of the thousands of different chemicals with toxicity potentials in Europe, thereby resulting in overestimation of normalised impact scores for the freshwater ecotoxicity and human toxicity impact categories (Laurent *et al.* 2011).

Summarizing, the following impact categories were considered: climate change, fossil depletion, freshwater ecotoxicity, freshwater eutrophication, human toxicity, marine ecotoxicity, marine eutrophication, particulate matter formation, terrestrial acidification, ozone depletion, terrestrial ecotoxicity and water depletion. The "land use" impact category was not considered in this analysis due to its high uncertainty (Latunussa *et al.* 2016).

The systems were modelled in Gabi Professional Academy LCA software® (GaBi ts Software 7.3.3). The impact scores were calculated using the original set of ReCiPe (version 1.05) characterization factors as implemented in GaBi.

2.2. Life Cycle Inventory

The life cycle inventory (LCI) phase consists of the primary and secondary data collection and the modelling of the system.

2.2.1. *Data collection and system modelling per life cycle phase*

Primary data are specifically related to the processes for obtaining the product or service studied in the LCA. In turn, secondary data represent generic or average data for the product or service subjected to an analysis. The provenience of that data includes literature, research groups, national and international database and expert's opinion (European Commission - Joint Research Centre - Institute for Environment and Sustainability 2010). In the present research work both primary and secondary data were considered as detailed in the following sub-paragraphs. The data sources were selected in order to be as much time, geographical and technological representative as possible. That means that the most recent and truthful data representing Italian processes and conditions were used as inputs when modelling the processes covered by the sub-components integrating the system boundaries. The Ecopneus document (Ecopneus 2013) was used as main reference for conducting the LCI of asphalt mixtures containing alternative materials. Reference values for the productivity and working hours of the machinery (pavers and rollers) considered for the laying down and compaction operations of the base course layers were collected from literature (Autostrade per l'Italia 2011). For completing the data set and modelling the background system, the *Construction materials* (CM) database extension of the Gabi software was used.

2.2.2. *Materials Extraction and Composite Materials in Production Phase*

2.2.2.1. ***Virgin aggregates and bitumen production sub-phase.***

The virgin aggregates required for the base course layer were modelled as crushed gravel and the inventory data associated with their production were obtained from the CM database considering the percentage of the material passing at different sieves in a typical grading curve of base course. The dataset crushed rock 16-32 mm (40% of aggregates), crushed stone 2-15 mm (30% of aggregates) and crushed sand 0-2 mm (30% of aggregates) were selected. It comprises all the flows of materials and energy associated with the extraction in the quarry, the cleaning, the two stages of crushing and organization of the production. The finished product is the crushed gravel (dried) at the factory gate. The CM database was also used as the data source for modelling the bitumen production. In this case the dataset “Bitumen at refinery; from crude oil; production mix, at refinery EU-27” was selected from the *Professional database in Gabi software*. This dataset covers the entire supply chain of the refinery products. That includes drilling, crude oil production and processing as well as the transportation of crude oil via pipeline to the refinery. The production includes several aspects, such as energy consumption, transport distances, crude oil processing technologies, feedstock that are individually considered for each crude oil production country. The inventory is mainly based on industry data and is completed, where necessary, by secondary data.

2.2.2.2. ***Crumb rubber production sub-phase.*** A “cut-off” approach was adopted for the evaluation of the burdens and benefits associated with the use of this recycled material. According to this approach, only the impacts of the recycling process are attributed to the second life cycle, while all the processes related to the production of the material before waste are attributed to the first life cycle (Schrijvers *et al.* 2016). Therefore, only the burdens directly associated with the product itself (crumb rubber) were accounted for. Two different rubber treatments were considered: (i) the ambient grinding without chemical treatment of the rubber, which produces vulcanized rubber, and; (ii) the devulcanization process, which includes the rubber powder preparation (shredding and granulating), devulcanization (mainly desulfurization) and refining of the rubber. All the stages of the rubber reclamation are schematically represented in Figure 1.

Figure 1

Based on Figure 1, new processes related to the CR recycling, such as rubber preparation (shredding and granulating), devulcanization and refining and collection in plastic big bag, were created specifically for this analysis by collecting information from recent studies conducted by Ecopneus (2013) and Li *et al.* (2014) and by using the *CM database*.

Shredding and granulating. The shredding and granulating is the first phase of the rubber reclamation process, where the tires are crushed and broken into small pieces and the remaining steel and fiber are removed magnetically. This process is performed with a combination of shaking screens and wind sifters, without any chemical treatment of the rubber.

In this phase the environmental impacts of the following processes were taken into account: (i) transport of materials from the collection platform to the crushing plant; (ii) crushing and separation of the fibers and metal from the rubber; and (iii) sieving of different fractions.

For shredding and granulating phase it was necessary to build another sub-process: *Steel blade* to crush the scrap tires conveyed in the batch through a conveyor belt for the shredding and granulating.

For the steel blade production, the processes selected were as follows: (i) steel production; (ii) hot rolling; and (iii) sheet rolling. The data set represents the steel production based on the main production steps that take place within an integrated steel plant. The LCI of the steel blade production process was collected from the recent study (Farina *et al.* 2017) and it is represented by the processes “IT: electricity mix [supply mix]” (0.00103 MJ), “Steel, converter, unalloyed, at plant”, “Sheet rolling, steel [processing]” present in CM database. The input/output flows of materials and energy sources were calculated as the average value of the data collected from the Italian crushing plants.

The CR production is a multi-output process. Indeed, from shredding and granulating the scrap tires in specialized plants, three main elements can be obtained: (i) CR (that will be used in the asphalt mixtures); (ii) scrap steel; and (iii) textile. Therefore, the allocation of all the outputs was conducted according to the mass approach by using the following percentages: 69% for the CR output; 20% for the scrap steel output; and 11% for the textile output (Farina *et al.* 2017). Despite the high market value of steel, steel scrap was not assumed to undergo recycling due to the high operational complexity of separating the scrap steel from residual rubber. Table 3 summarizes the input and output flows of the CR production process for producing 15 kg of rubber (1.5% of 1 ton of asphalt mixture).

Table 3

Devulcanization and refining. All the input and outputs of the devulcanization process were collected from literature (Li *et al.* 2014). Specifically, plasticizers (pine tar and rosin) were considered to be added to improve rubber plasticity after the shredding process. Pine tar is a viscous and sticky liquid obtained from pine through destructive distillation. Rosin is solid resin obtained from the oil of pine trunk. The desulfurization tank is kept at a high temperature (approximately 230°C) and under pressure (2.2 MPa). The waste gas discharged in two different moments was treated. The first gas steam is discharged from desulfurization tank, after it is cooled and decompressed. Finally, a gas absorber with sodium carbonate is used to remove almost entirely the contaminants from the steam. The other one is discharged from the heat conduction oil furnace and consists mainly of CO_2, NO_X and SO_2 (Li *et al.* 2014). A wet-flue gas desulfurization system, which rely on 96% efficiency in dust collection and 75% desulfurization efficiency, was used. After the devulcanization process, the rubber is reprocessed in the refining stage where non-methane volatile organic compounds (NMVOC) are collected and absorbed with an efficiency of 80%. After that, they are released to the atmosphere. Table 4 reports the input and output of the devulcanization and refining processes.

Table 4

Collection of rubber in plastic big bag. The last step is represented by the collection of rubber grains in plastic bag to be transported to the asphalt mix plant. It was assumed that the plastic big-bag used for collecting the different fractions of rubber grains are composed of 90% of polypropylene and 10% of polyethylene. The process contains all the operations and burdens for the transformation of raw plastic into the final product. The LCI data of the plastic big bag production was collected from recent studies (Ruban 2012) and summarized in Table 5.

Table 5

To collect 15 kg of rubber, i.e. final product to transport to the asphalt plant for producing 1 ton of asphalt mixture (DRY1.5D and DRY1.5V), 0.028 kg of plastic big bag is needed (Farina *et al.* 2017).

2.2.2.3.***RAP production sub-phase***. Also for the RAP production the “cut-off” approach was adopted. In this case study, it was considered that once removed from road pavement, the RAP is transported directly to the asphalt plant where it is stored in special sites and subjected to screening and down-sizing operations. For the RAP handling, the common production rates of the several machines were considered when determining the energy requirements. The LCI data related to the production and distribution of those energy resources was taken from the CM database. Moreover, the treatment of the RAP at the plant requires a certain amount of energy for sieving and eventually crushing of the recycled material. This amount of energy was considered to be equal to 0.0212 MJ per kg of RAP (Zaumanis *et al.* 2012).

2.2.2.4.***Asphalt mixtures production sub-phase.*** The asphalt mixture production activities take a place in the hot mix production plant. The processes CR production, aggregates production, RAP production and bitumen production already described were created and fed into the process for the production of the asphalt mixtures. The electricity for the production of 1 ton of any asphalt mixture was considered to be equal to 160 kWh (Ecopneus 2013) based on the assumption that the mixing temperature is the same regardless of the mixture being produced (Farina *et al.* 2017). In this case study the electricity was used to power a discontinuous batch with a gas burner with a power of 580 kW.

2.2.3. Construction Phase

To build a layer of asphalt mixture in a road pavement it is necessary to lay down the asphalt mixture with a paver and compact it in order to achieve the desired thickness of 10 cm. The fuel combustion-related emissions associated with the operation of each construction equipment were determined by combining the LCI data corresponding to the process "machine operation, diesel, >= 74.57 kW, high load factor" existing in the CM database with an hourly productivity of 200 ton/h for the operations of the paver and 150 ton/h for the roller involved in the pavement construction activities. By considering fuel consumption rates of 30 and 17 l/h (Autostrade per l'Italia 2011), respectively for a paver and a roller, the total fuel consumption was calculated as 585 l/km (paver) and 332 l/km for the roller. The consumptions were considered to be the same for all the alternatives proposed. Indeed, regardless to the fact that recent studies (Bressi *et al.* 2018a) demonstrate the need of higher compaction efforts of dry mixtures in the laboratory, there is no practical link between laboratory increased compaction efforts and in-situ compaction in terms of the number of roller passages.

The airborne emissions caused by the lay down and compaction operations of asphalt layers increases with recycling rate. Therefore, the data coming from measurements performed by Jullien *et al.* (2006) was considered when modelling the construction process of the base course layer depending on whether or not the RAP is included in the mixture formulation.

2.2.4. Transportation of Materials Phase

Scrap tires, crushed gravel limestone, bitumen as well as plastic big bag, steel blade and subsequently CR must be transported between the production facilities, whereas the asphalt mixtures must be transported from the asphalt plant to the construction site. It was assumed that the materials are hauled from the quarry and plants by truck. Therefore, the environmental impacts resulting from the transportation of materials were due to the emissions released by the combustion process of the transportation vehicles. The process "GLO: Truck, Euro 3, 20 - 26t gross weight / 17.3 t payload capacity ts <u-so>" existing in the CM database was used to determine the environmental burdens associated with the transportation of materials hauled by heavy vehicles on the road.

The different processes adopted for the case study are outlined in Figure 2 for the rubberized mixtures and for the RAP mixtures. The transport distances between different sites are reported in Table 6.

Figure 2

Table 6

2.3. *Life Cycle Impact Assessment*

The characterized LCIA results are shown in Figure 3 and Figure 4. They highlight different aspects of the environmental performance associated with each alternative considered for the construction of the base course layer. In particular, Figure 3 displays the potential relative life cycle environmental impacts of the asphalt base course mixture containing vulcanized or devulcanized CR (i.e., DRY1.5V, DRY2.0V, DRY1.5D and DRY 2.0D) calculated in relation to those of the traditional asphalt mixture. The results are to be understood as follows: negative relative numbers mean that the alternative asphalt mixtures worsen the potential life cycle environmental impact results in relation to those associated with the traditional asphalt mixture while positive numbers represent an improvement of the environmental profile.

Figure 3

It can be observed that not only all the rubberized solutions lead to an increase of the scores of the whole impact categories set but also that the type of rubber treatment influences the environmental performance of the different solutions. Indeed, the devulcanization process leads to a significant increase of the environmental burdens compared to ambient grinding, especially in the case of the impact categories freshwater ecotoxicity, terrestrial ecotoxicity and water depletion. This can be confirmed in Figure 4 that displays the relative contributions of the several life cycle phases and sub-phases to the total impact category scores of the two types of rubberized asphalt.

Figure 4

As detailed in Figure 4, the asphalt mixtures production and base course layer construction phases are the main source of impacts for 7 out of 11 impact categories, followed by the bitumen production (4 out of 11 impact categories). In turn, the production of CR (ambient grinding) is responsible by the lowest share of the impact scores. In the case of the asphalt mixtures production and base course layer construction, their contribution can be as high as 79.0% and 93.0% for the impact category particulate matter formation, respectively in the solutions DRY2.0D and DRY2.0V, while the maximum contribution given by the production of bitumen can amount to 69.3% and 73.2% for the impact category marine ecotoxicity respectively in the solutions DRY2.0D and DRY2.0V. Regarding the production of CR, its maximum contribution is observed for the impact category freshwater eutrophication, being equal to 20.3% as the sum of rubber preparation, devulcanization and refining for DRY2.0D and 3.0% for the ambient grinding for DRY2.0V in the case of particulate matter formation. The devulcanization and refining have the highest environmental burden in the rubber treatment because the desulfurization requires extensive heat from coal combustion (Li *et al.* 2014). In the present case study, the highest impact category scores are observed in the impact categories water depletion, freshwater eutrophication and climate change. Therefore, to obtain a cleaner production, the focus must be placed on the flue gas treatment in the devulcanization process. The results presented previously also confirm the findings of other studies that reported the production of VB to be one of the most environmental damaging and energy demanding processes in the road paving activity (Santero *et al.* 2011, Santos *et al.* 2015, Farina *et al.* 2017, Bressi *et al.* 2018b).

Another important remark emerging from the results presented previously is that the use of rubberized asphalt mixtures can only be justified (from an environmental perspective) if the durability of the final product is higher. This is mainly due to the fact that the rubber grains are obtained from crushing scrap tires in specialized plants where they are also separated from steel fibers and textile. All these operations are extra compared to those required for producing conventional asphalt mixtures while the associated environmental burdens are not compensated by the amount of recycled material employed (only 1.5 or 2% of

CR). From the analysis of Figure 4 it emerges that when only ambient grinding is considered, the CR production is not directly responsible of the higher impacts category scores of the alternatives proposed. Instead, the higher quantity of bitumen required for the optimal mixture design of the CR asphalt mixtures leads to considerable effects on the scores of all impact categories, especially those related to the impact category ecotoxicity.

On the contrary, when the rubber is devulcanized, the desulfurization process requires an extensive heat from coal combustion, and the emissions of the related flue gas contribute to further increase of the environmental burdens.

Given that there is no clear evidence in the literature that the durability of the dry mixtures is higher than that of traditional mixtures, it was assumed that the life cycle of the layer constructed with the alternative mixtures is equal to that implemented with the traditional solution. Therefore, the results in terms of durability of the layers and consequently the life cycle environmental profile might have been different if the wet process had been adopted to produce the alternative rubberized asphalt mixtures. In this case, the chemical treatment of the rubber can improve the rheology of the binder thereby increasing the performance of the overall mixture (Mangili *et al.* 2015).

Figure 5 shows the potential relative life cycle environmental impacts of the asphalt mixtures containing RAP (RAP40BR and RAP40FB) in relation to those of the traditional asphalt base course mixture. It can be observed that the solutions containing RAP reduce the impact category scores compared to the reference solution in all the impact categories. In particular, for the solution RAP40BR, which requires a lower quantity of virgin aggregates and the same content of bitumen as that of the reference mixture, the impact categories marine eutrophication (10.02%), freshwater eutrophication (6.59%), climate change (6.56%), terrestrial ecotoxicity (6.41%) and particulate matter formation (6.22%) show the highest benefits. It should be noted that when considering the full blending between the aged and VB and reducing the quantity of VB to be added to the RAP40FB mixture, the impact categories exhibiting the highest benefits are different: marine ecotoxicity (34.09%), fossil depletion (27.04%) human toxicity (26.83%), and freshwater ecotoxicity (24.07%). This means that the reduction by 40% of virgin aggregates has a greater effect on certain impact categories, while the bitumen reduction allows further reductions in all the impact categories, especially in the cases of the marine ecotoxicity, fossil depletion and human toxicity.

Figure 5

A more realistic assumption is made when the aged binder existing in RAP is considered to blend partially with the VB.

Figure 6 shows the potential life cycle impact category scores obtained when considering different DoA. From that figure it can be seen that as a consequence of the reduction in the use of VB, due to the increase in the DoA, the reduction of the potential life cycle impact scores derived from the incorporation of RAP in the production of asphalt mixtures are globally considerable for all the impact categories and follow a linear relationship. Table 7 displays all the numerical relationships derived from the potential life cycle impact category scores that relate the DoA of aged and VB with the potential relative benefit for each impact category.

Figure 6

Table 7

The table and figure introduced previously show that it is possible to define a ranking of improvement that depends on the VB to be added to the mixture. The ranking of the impact categories that have the highest benefits according to the equations derived from the analysis are reported in Table 8 along with their specific range of improvement. The impact category that benefits the most with the increase in the DoA is clearly the marine ecotoxicity, followed by fossil depletion and human toxicity. On the contrary, the impact categories ozone and water depletion are found to be almost insensitive to changes in the DoA (improvements inferior to 1%). Additionally, for DoA values approximately greater than 40% and lower than 10%, Figure 6 shows that the rankings of impact categories in terms of reductions in the scores remained generally stable. This trend is different from that denoted for DoA values ranging between approximately 10% and 40%, in which a change in the rankings is observed.

Table 8

Figure 7 shows the primary energy demand and climate change, expressed in terms of CO_2-eq. emissions, derived from the production of asphalt mixtures containing recycled materials in relation to those of the traditional asphalt base course mixture.

Figure 7

From Figure 7 it can be observed that the solutions containing RAP reduce the primary energy demand and the CO_2-eq. emissions per ton of material in relation to those associated with the reference solution. The energy required as well as the climate change score decreases when the active aged binder increases, because there is a further reduction of the VB needed to be added to the asphalt mixture. On the other side, as for all the other environmental impact categories, the energy required for producing CRM mixtures increases, especially if the rubber is treated with a devulcanization process before its use.

3. Summary, conclusions and perspectives

Currently, several research efforts are being undertaken to study the behavior of innovative mixtures produced with a high content of recycled materials. Nevertheless, the extent to which those mixtures are environmentally friendly remains to be assessed and quantified. Therefore, this paper presents a comparative LCA of a traditional asphalt mixture employed in the base course layer of a flexible road pavement and alternative asphalt mixtures containing different percentages of recycled materials, namely RAP and CR.

The LCA is performed from the resource extraction and composite materials production to the placement of the mixtures in the construction site, and including the movements of transportation of materials. The results obtained show that:

- without an increase in the durability, the use of CR in asphalt mixtures leads to an increase of the scores in all impact categories. For the CR mixtures, the amount of bitumen increases as the amount of rubber in the mixture increases. That is due to the fact that rubber absorbs the lighter parts of the bitumen in the so called process “maceration”. The highest impact category scores are more pronounced in the case of devulcanized rubber, because additional chemical treatments are required;
- due to the rubber elasticity, the rubberized asphalt usually recovers deformation after the compaction phase. Therefore, by using a standard re-use of CR in asphalt mixtures, the percentage of rubber in CR mixtures cannot be increased significantly. As such, the small amount of CR used in this application does not justify all the additional consumption of resources and emissions associated with its treatment;
- mixtures containing 40% of RAP reduce the scores of all the impact categories;
- further reductions of all the resources consumed and emissions released can be achieved if the aged binder was fully reactivated and considered as VB, thereby leading to a reduction of the amount of VB needed to be employed in a new mixture;
- the potential environmental benefits associated with all impact categories increase linearly when the DoA between aged and VB increases. The impact categories that showed the highest benefits when DoA increases are marine ecotoxicity, fossil depletion and human toxicity;

- it is recommended the development and the use of additives able to reactivate the aged binder trapped in RAP, provided that the environmental impacts of their production, transportation and use do not offset the benefits obtained with the reduction of the use of VB.

To sum up, this study evaluated the environmental consequences of implementing innovative asphalt mixtures containing different percentages of recycled materials. The results show the negative effect deriving from the use of CR in the RUMAC technology. Nevertheless, certain potential benefits associated with the use of this technology were not considered, such as the reduction of noise and vibration. Therefore, the next steps of this research work will evaluate the sustainability of those materials by using a holistic and integrated approach that considers the three pillars of sustainability (environmental, social and economic).

Moreover, this research work opens the way to extend the study to other materials, such as, for instance, the assessment of the possible benefits derived from the use of rejuvenators (industrial or natural) when high RAP contents are used. The case study described and the results presented in this paper represents a first step in the study of the environmental performance of materials containing RAP. However, further studies are being performed to ascertain the effects of the rejuvenator on the total environmental impacts.

Finally, the availability of data to be used in the assessment of the environmental performance of these type of materials is still very limited. Therefore, further research efforts should be employed to produce a more complete and robust LCI that will certainly improve the overall quality of the LCA.

Disclaimer

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Table 3. Input and output flows associated with the CR production process

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Table 5. Inventory referring to the production of 1 kg of plastic big-bag

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Table 7. Equations that provide the potential relative environmental improvement in each category depending on the degree of blending between aged and VB

Table 8. Ranking of the impact categories resulting from the differences in the degree of blending between virgin and aged binder and the consequent reduction of VB consumption

Figure 1. Rubber reclamation stages: rubber preparation, devulcanization, refining and collection of rubber in plastic big-bag

Figure 2. Schematic representation of the processes and transportation distances adopted for the production and placement of the asphalt mixtures with CR and the asphalt mixtures with RAP

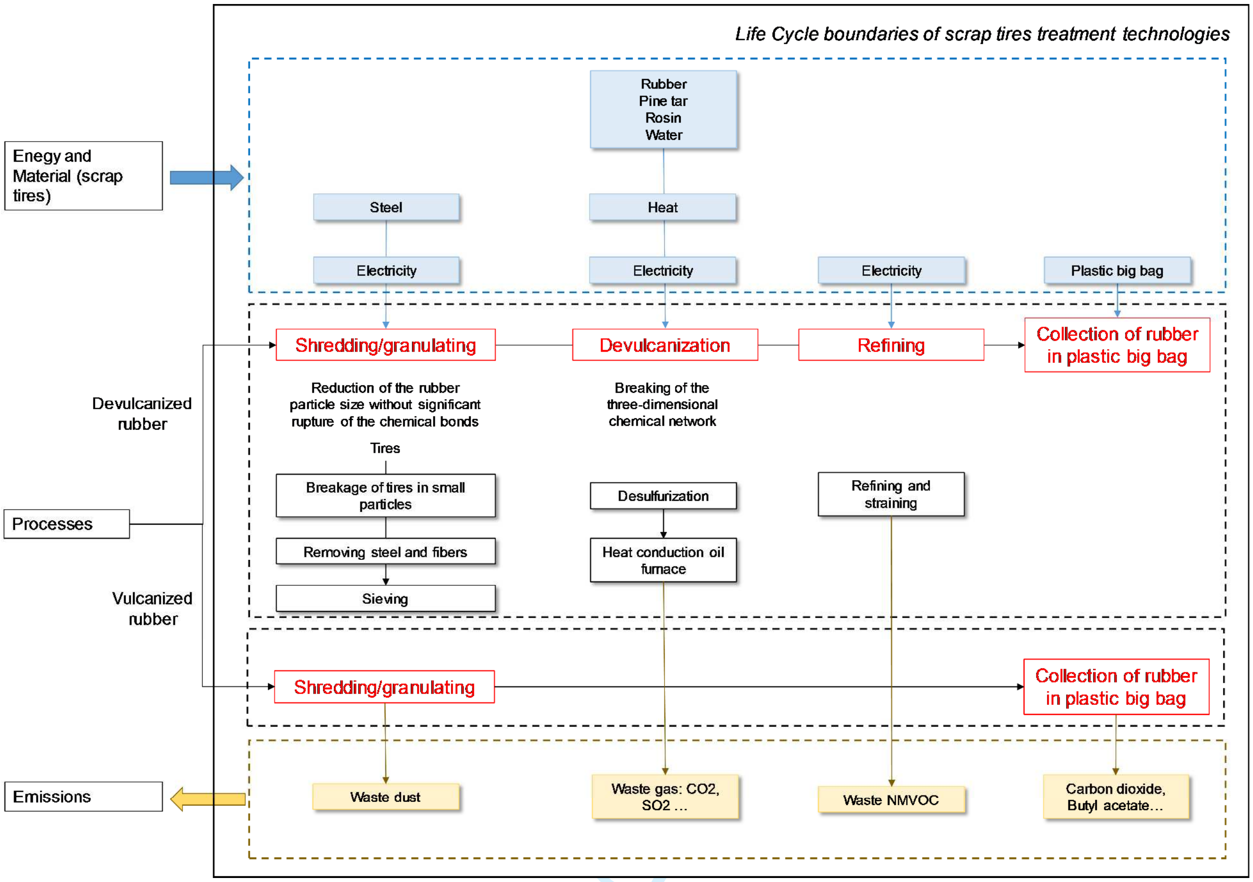
Figure 3. Potential relative life cycle environmental impacts of alternative asphalt mixtures

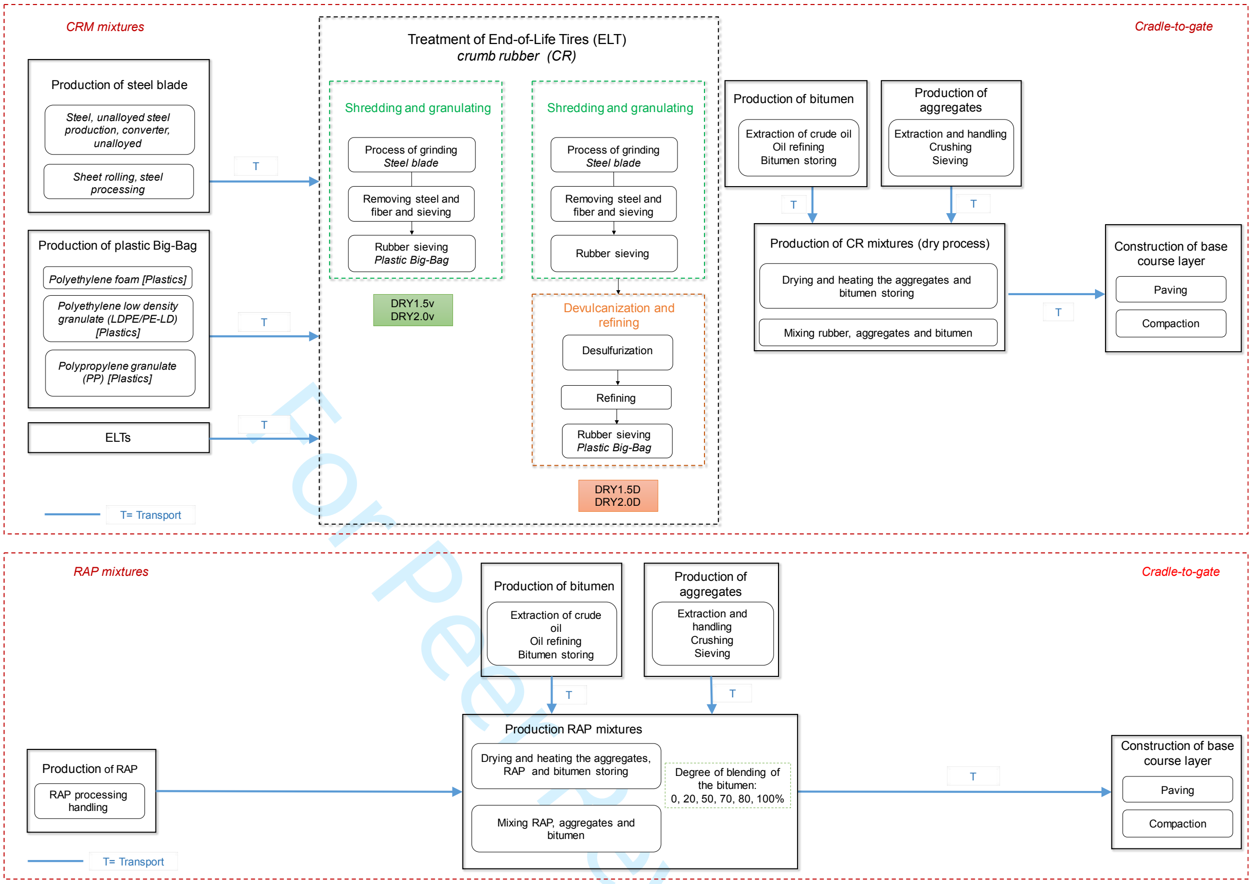
Figure 4. Relative contribution of different life cycle phases and sub-phases for the total environmental impacts due to the use of (a) asphalt mixture with 2.0% of vulcanized CR and (b) asphalt mixture with 2.0% of devulcanized CR

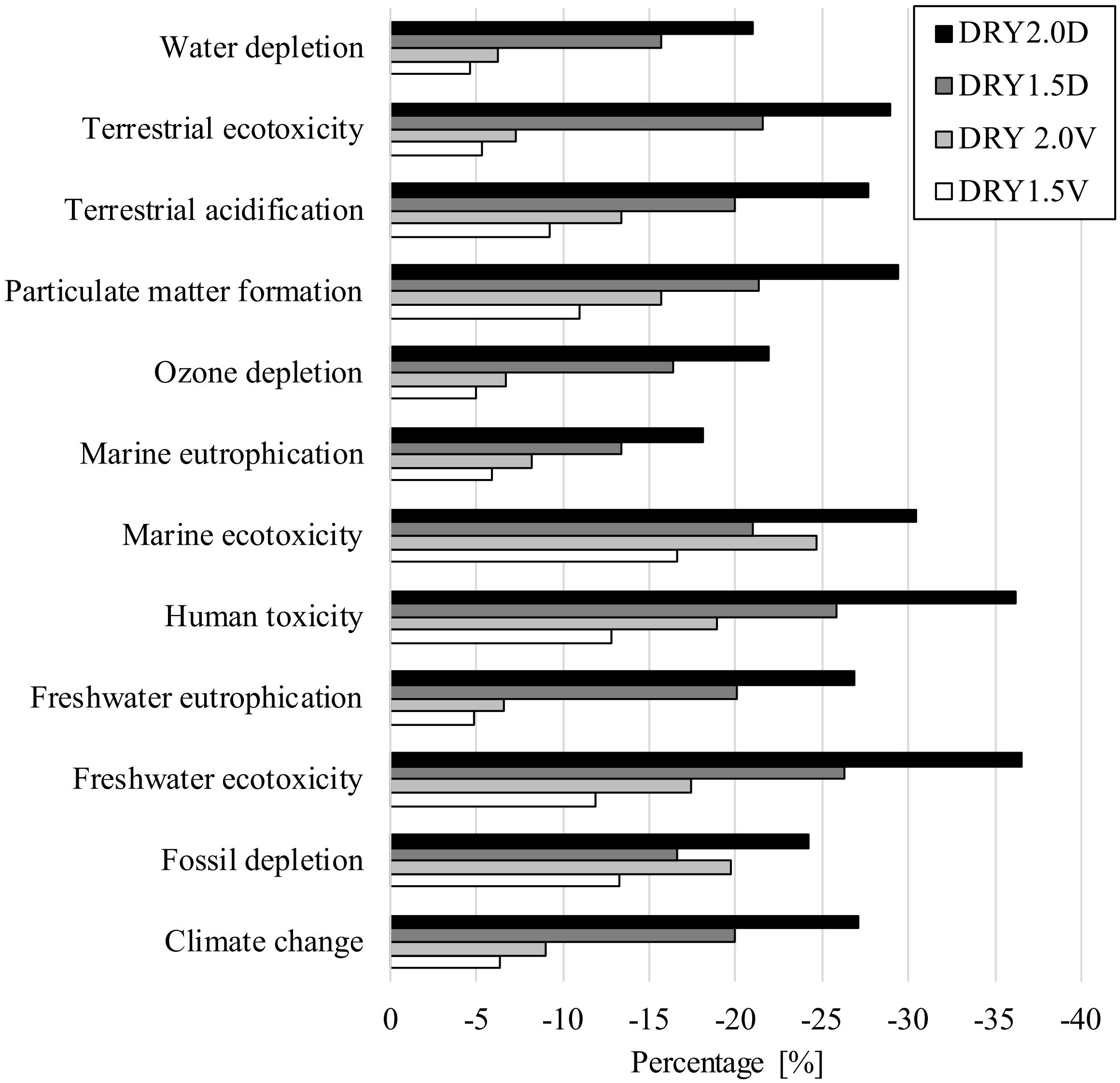
Figure 5. Potential relative life cycle environmental impacts of alternative asphalt mixtures (RAP40BR and RAP40FB) calculated in relation to those of the reference solution, i.e. the traditional asphalt mixture

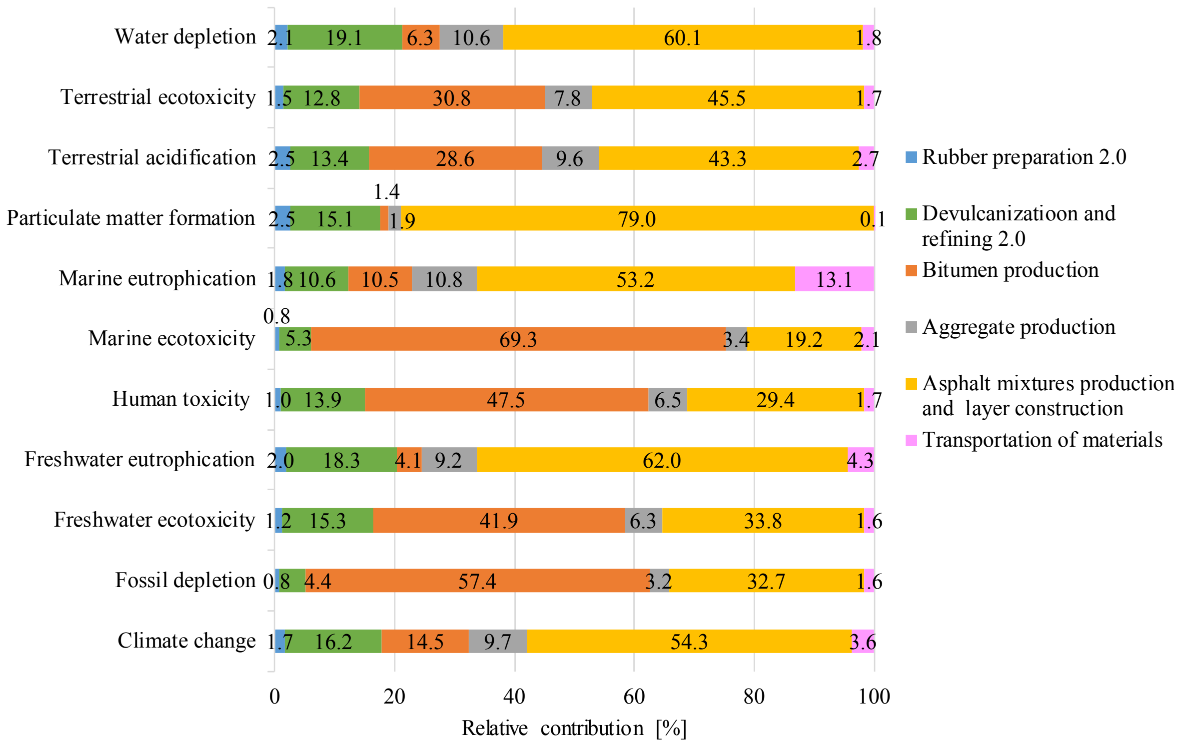
Figure 6. Relationships between degree of blending between aged and VB and the percentage of environmental benefits in all impact categories

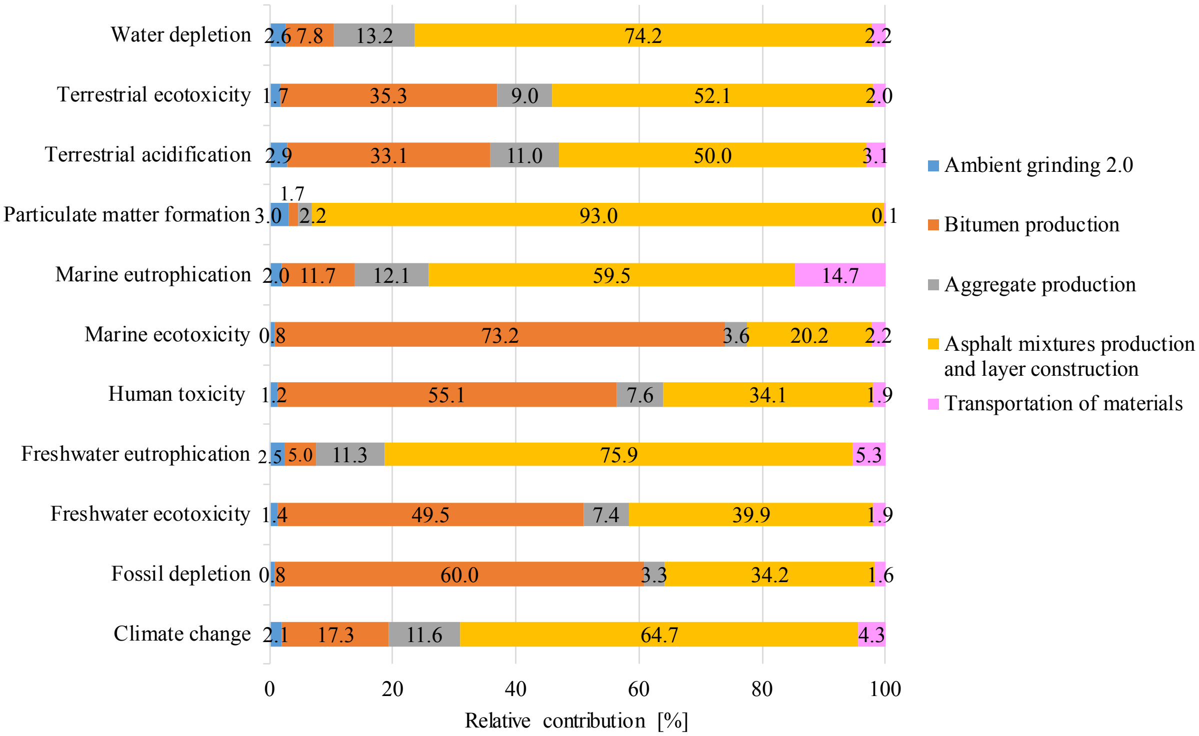
Figure 7. Primary energy demand and climate change derived from the production of asphalt mixtures containing CR and RAP in relation to those of the traditional asphalt base course mixture

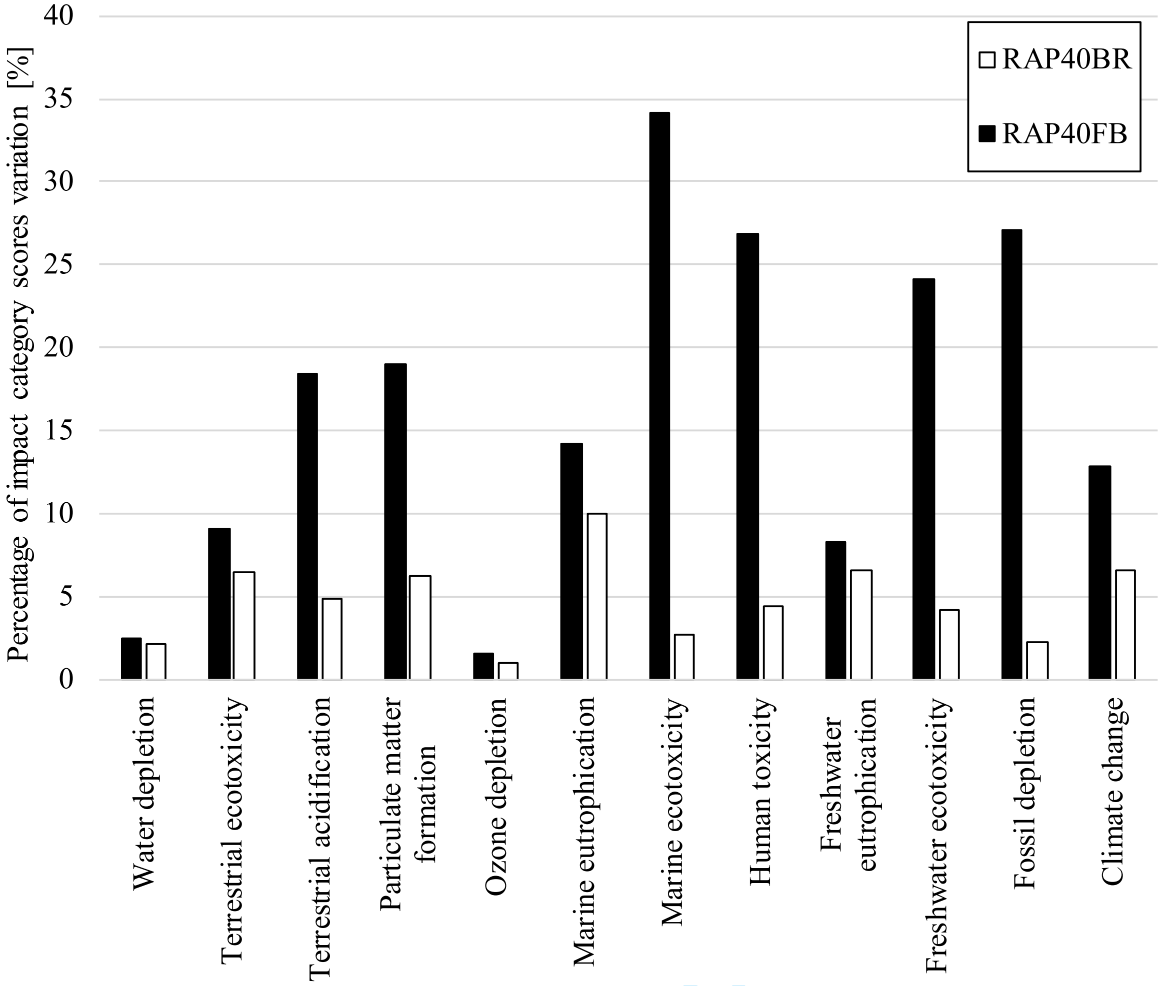

Life Cycle boundaries of scrap tires treatment technologies
Enegy and Material (scrap tires)
Rubber
Pine tar
Rosin
Water
Steel
Heat
Electricity
Electricity
Electricity
Plastic big bag
Devulcanized rubber
Processes
Vulcanized rubber
Shredding/granulating
Devulcanization
Refining
Collection of rubber in plastic big bag
Reduction of the rubber particle size without significant rupture of the chemical bonds
Breaking of the three-dimensional chemical network
Tires
Breakage of tires in small particles
Removing steel and fibers
Sieving
Desulfurization
Heat conduction oil furnace
Refining and straining
Shredding/granulating
Collection of rubber in plastic big bag
Emissions
Waste dust
Waste gas: CO2, SO2 …
Waste NMVOC
Carbon dioxide, Butyl acetate…

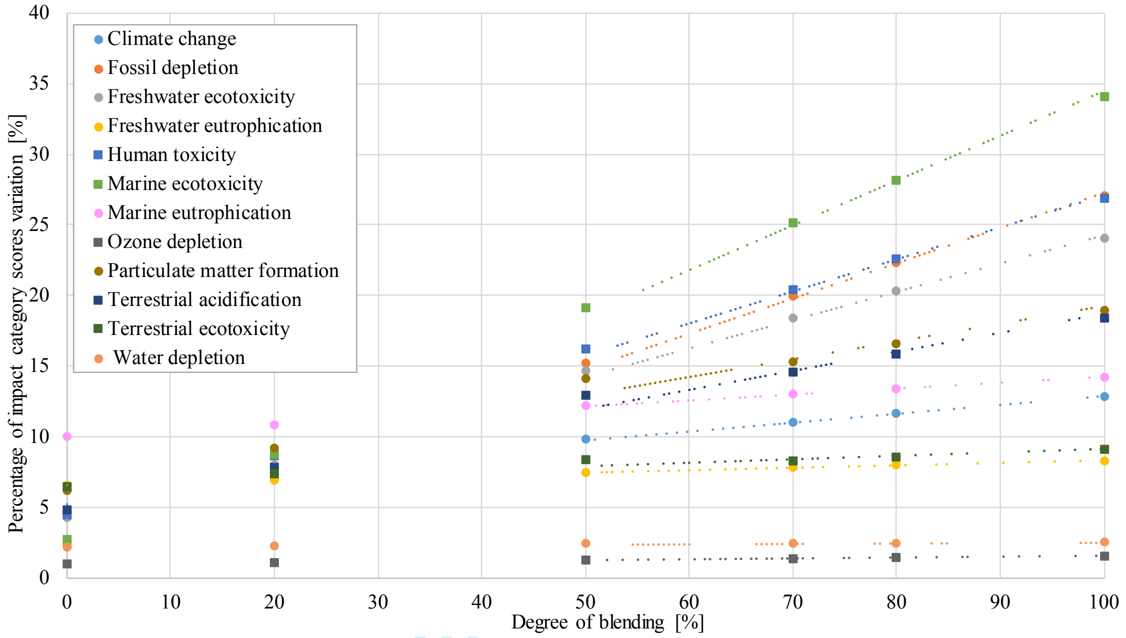

CRM mixtures
Cradle-to-gate
Production of steel blade
Steel, unalloyed steel production, converter, unalloyed
Sheet rolling, steel processing
Production of plastic Big-Bag
Polyethylene foam [Plastics]
Polyethylene low density granulate (LDPE/PE-LD) [Plastics]
Polypropylene granulate (PP) [Plastics]
ELTs
T
T
T
T= Transport
Treatment of End-of-Life Tires (ELT)
crumb rubber (CR)
Shredding and granulating
Process of grinding
Steel blade
Removing steel and fiber and sieving
Rubber sieving
Plastic Big-Bag
DRY1.5v
DRY2.0v
Shredding and granulating
Process of grinding
Steel blade
Removing steel and fiber and sieving
Rubber sieving
Devulcanization and refining
Desulfurization
Refining
Rubber sieving
Plastic Big-Bag
DRY1.5D
DRY2.0D
Production of bitumen
Extraction of crude oil
Oil refining
Bitumen storing
Production of aggregates
Extraction and handling
Crushing
Sieving
T
T
Production of CR mixtures (dry process)
Drying and heating the aggregates and bitumen storing
Mixing rubber, aggregates and bitumen
T
Construction of base course layer
Paving
Compaction
RAP mixtures
Cradle-to-gate
Production of bitumen
Extraction of crude oil
Oil refining
Bitumen storing
Production of aggregates
Extraction and handling
Crushing
Sieving
T
T
Production of RAP
RAP processing handling
T= Transport
Production RAP mixtures
Drying and heating the aggregates, RAP and bitumen storing
Mixing RAP, aggregates and bitumen
Degree of blending of the bitumen:
0, 20, 50, 70, 80, 100%
T
Construction of base course layer
Paving
Compaction


Water depletion
Terrestrial ecotoxicity
Terrestrial acidification
Particulate matter formation
Ozone depletion
Marine eutrophication
Marine ecotoxicity
Human toxicity
Freshwater eutrophication
Freshwater ecotoxicity
Fossil depletion
Climate change
■ DRY2.0D
▨ DRY1.5D
▨ DRY 2.0V
☐ DRY1.5V
0
-5
-10
-15
-20
-25
-30
-35
-40
Percentage [%]


Water depletion
2.1
19.1
6.3
10.6
60.1
1.8
Terrestrial ecotoxicity
1.5
12.8
30.8
7.8
45.5
1.7
Terrestrial acidification
2.5
13.4
28.6
9.6
43.3
2.7
Particulate matter formation
2.5
15.1
1.4
1.9
79.0
0.1
Marine eutrophication
1.8
10.6
10.5
10.8
53.2
13.1
Marine ecotoxicity
0.8
5.3
69.3
3.4
19.2
2.1
Human toxicity
1.0
13.9
47.5
6.5
29.4
1.7
Freshwater eutrophication
2.0
18.3
4.1
9.2
62.0
4.3
Freshwater ecotoxicity
1.2
15.3
41.9
6.3
33.8
1.6
Fossil depletion
0.8
4.4
57.4
3.2
32.7
1.6
Climate change
1.7
16.2
14.5
9.7
54.3
3.6
0
20
40
60
80
100
Relative contribution [%]
Rubber preparation 2.0
Devulcanizatioon and refining 2.0
Bitumen production
Aggregate production
Asphalt mixtures production and layer construction
Transportation of materials


Water depletion
2.6
7.8
13.2
74.2
2.2
Terrestrial ecotoxicity
1.7
35.3
9.0
52.1
2.0
Terrestrial acidification
2.9
33.1
11.0
50.0
3.1
Particulate matter formation
3.0
1.7
2.2
93.0
0.1
Marine eutrophication
2.0
11.7
12.1
59.5
14.7
Marine ecotoxicity
0.8
73.2
3.6
20.2
2.2
Human toxicity
1.2
55.1
7.6
34.1
1.9
Freshwater eutrophication
2.5
5.0
11.3
75.9
5.3
Freshwater ecotoxicity
1.4
49.5
7.4
39.9
1.9
Fossil depletion
0.8
60.0
3.3
34.2
1.6
Climate change
2.1
17.3
11.6
64.7
4.3
0
20
40
60
80
100
Relative contribution [%]
Ambient grinding 2.0
Bitumen production
Aggregate production
Asphalt mixtures production and layer construction
Transportation of materials


Percentage of impact category scores variation [%]
0
5
10
15
20
25
30
35
40
RAP40BR
RAP40FB
Water depletion
Terrestrial ecotoxicity
Terrestrial acidification
Particulate matter formation
Ozone depletion
Marine eutrophication
Marine ecotoxicity
Human toxicity
Freshwater eutrophication
Freshwater ecotoxicity
Fossil depletion
Climate change


Climate change
Fossil depletion
Freshwater ecotoxicity
Freshwater eutrophication
Human toxicity
Marine ecotoxicity
Marine eutrophication
Ozone depletion
Particulate matter formation
Terrestrial acidification
Terrestrial ecotoxicity
Water depletion
Percentage of impact category scores variation [%]
0
5
10
15
20
25
30
35
40
Degree of blending [%]
0
10
20
30
40
50
60
70
80
90
100

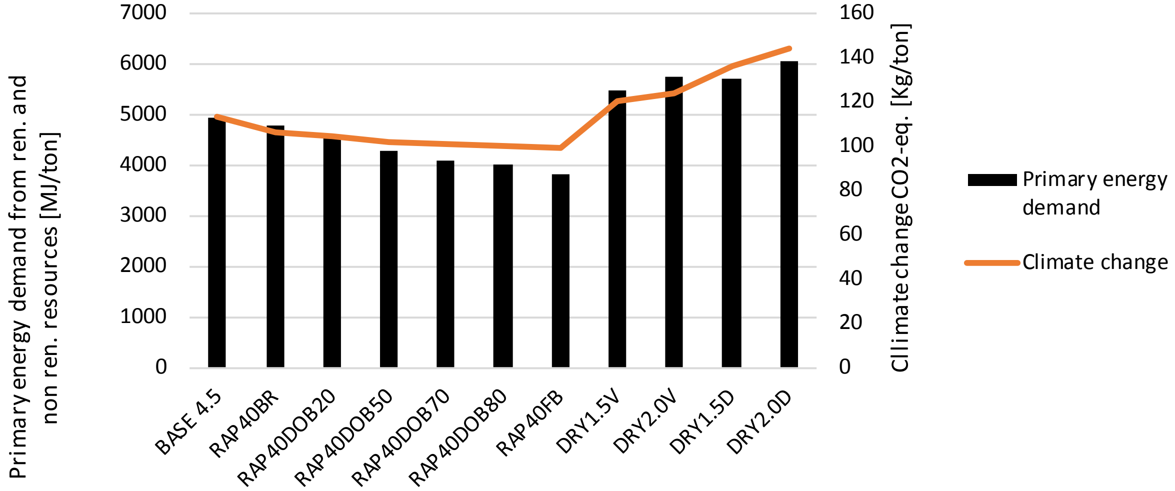

7000
6000
5000
4000
3000
2000
1000
0
Primary energy demand from ren. and non ren. resources [MJ/ton]
160
140
120
100
80
60
40
20
0
Climate change CO2-eq. [Kg/ton]
BASE 4.5
RAP40BR
RAP40DOB20
RAP40DOB50
RAP40DOB70
RAP40DOB80
RAP40FB
DRY1.5V
DRY2.0V
DRY1.5D
DRY2.0D
Primary energy demand
Climate change

Table 1. Composition of the different asphalt mixtures containing CR used in the base course layer

Name of mixture	**Description**	**Quantity of CR (kg per ton of mixture)**	**Quantity of bitumen (kg per ton of mixture)**
Base	Traditional asphalt mixture (4.5% of bitumen)	0	45
DRY1.5D	Rubberized asphalt mixture (dry process) with devulcanized rubber (1.5% of rubber and 5.5% of bitumen)	15	55
DRY2.0D	Rubberized asphalt mixture (dry process) with devulcanized rubber (2.0% of rubber and 6.0% of bitumen)	20	60
DRY1.5V	Rubberized asphalt mixture (dry process) with vulcanized rubber (1.5% of rubber and 5.5% of bitumen)	15	55
DRY1.5V	Rubberized asphalt mixture (dry process) with vulcanized rubber (2.0% of rubber and 6.0% of bitumen)	20	60

Table 2. Composition of the different asphalt mixtures containing RAP with different simulations of degree of blending used in the base course layer

Name of mixture	**Percentage of RAP (%)**	**Quantity of RAP (kg per ton of mixture)**	**Degree of blending (DOB) (%)**	**Activated old binder (%)**	**Percentage of virgin bitumen to add to the mixture (%)***	**Quantity of bitumen to add to the mixture (kg per ton of mixture)**	**Quantity of virgin aggregates (kg per ton of mixture)**
Base	0	0	0	-	4.5	45	555
RAP40BR	40	400	0	0	4.5	45	555
RAP40DOB20	40	400	20	0.4	4.1	41	559
RAP40DOB50	40	400	50	1.0	3.5	35	565
RAP40DOB70	40	400	70	1.5	3.0	30	570
RAP40DOB80	40	400	80	1.7	2.8	28	572
RAP40FB	40	400	100	2.1	2.4	24	576

*the total bitumen content active in the mixture is always 4.5%.

Table 3. Input and output flows associated with the CR production process

Input flow	**Quantity**	**Unit**
Diesel mix at refinery EU-28[a]	0.038	Kg
IT: Electricity mix grid production[b]	20.7	MJ
Lubricating oil	0.001	Kg
Tap water, at user	3.3	Kg
Steel blade	0.004	Kg
Conveyor belt, at plant	9.5E-005	m
Scrap tires	21.8	Kg
Output flows	**Quantity**	**Unit**
CR (module created)	15	Kg
Recycled fibers	2.4	Kg
Steel scrap product	4.35	Kg

Notes: [a] This module includes the steam treatment and allows quantifying all the output of the diesel production; [b] It refers to the production and importation of energy in Italy, including all types of energy. It includes also losses, calculated as average values

Table 4. Input and output flows associated with the devulcanization and refining processes. The quantities refer to the treatment of 15 kg of rubber

Process	Input items	Quantity	Unit
Devulcanization	Coal tar [Organic intermediate products]	0.15	kg
	IT: electricity, high voltage, production IT, at grid [production mix]	68.2	MJ
	Purchased rubber powder [Plastic parts]	7.35	kg
	RER: rosin size, at plant [organics]	0.15	kg
	RER: tap water, at user	0.15	kg
	Rubber [Consumer waste]	7.35	kg
	Output items		
	Devulcanized rubber	15	kg
	Charcoal (loaded) [Hazardous waste for recovery]	0.675	kg
	Carbon dioxide [Inorganic emissions to air]	5.63	kg
	Different pollutants [Other emissions to industrial soil]	0.0248	kg
	Nitrogen oxides [Inorganic emissions to fresh water]	0.0105	kg
	Sulphur dioxide [Inorganic emissions to air]	0.00675	kg
Refining	**Input items**		
	Devulcanized rubber	15	kg
	IT: electricity, high voltage, production IT, at grid [production mix]	14.4	MJ
	Output items		
	Crumb recycled rubber	15	kg
	NMVOC, non-methane volatile organic compounds, unspecified origin [ecoinvent long-term to air]	0.000555	kg

Table 5. Inventory referring to the production of 1 kg of plastic big-bag

Input Item	**Quantity**	**Unit**
Diesel [Refinery products]	6,81E-05	kg
Polyethylene foam [Plastics]	1	kg
Polyethylene low density granulate (LDPE/PE-LD) [Plastics]	0,1	kg
Polypropylene granulate (PP) [Plastics]	0,9	kg
Emissions to air and water	**Quantity**	**Unit**
Butyl acetate [ecoinvent long-term to air]	0,0097	kg
Carbon dioxide [Inorganic emissions to air]	0,00041	kg
Carbon monoxide [Inorganic emissions to air]	8,06E-06	kg
Ethanol [ecoinvent long-term to air]	0,00194	kg
Methane [Organic emissions to fresh water]	3,26E-08	kg
Nitrogen dioxide [Inorganic emissions to air]	4,10E-06	kg
Sulphur oxides [Inorganic emissions to air]	5,00E-07	kg
Toluene [ecoinvent long-term to air]	0,00399	kg

Table 6. Transportation distances considered in the case study and displayed in Figure 2 and Figure 3

Type of material	**Transport distance [km]**	**Origins/Destinations**
Bituminous mixtures with CR (Figure 2)		
Steel blade	286	Production of steel blade/Crumb rubber plant
Plastic big bag	286	Production of plastic big-bag/Crumb rubber plant
ELT	60	ELT stock/Crumb rubber plant production
Crumb rubber	532	Crumb rubber plant production/Asphalt plant
Bitumen	100	Refinery/Asphalt plant
Aggregates	75	Quarry/Asphalt plant
CR mixtures	80	Asphalt plant /Construction site
Bituminous mixtures with RAP (Figure 3)		
RAP	-	The RAP stock is present at the asphalt plant
Bitumen	100	Refinery /Asphalt plant
Aggregates	75	Quarry/Asphalt plant
RAP mixture	80	Asphalt plant/Construction site

Table 7. Equations that provide the potential relative environmental improvement in each category depending on the degree of blending between aged and virgin bitumen

Impact category and acronyms	**Potential relative life cycle environmental impacts improvements (%)**	**Coefficient of determination (R^2)**
Climate change (CC)	$\Delta CC = 0.063DoB + 6.569$	0.999
Fossil depletion (FD)	$\Delta FD = 0.250DoB + 2.283$	0.999
Freshwater ecotoxicity (FEc)	$\Delta FEc = 0.201DoB + 4.247$	0.999
Freshwater eutrophication (FEu)	$\Delta FEu = 0.017DoB + 6.591$	0.998
Human toxicity (HT)	$\Delta HT = 0.227DoB + 4.437$	0.999
Marine ecotoxicity (MEc)	$\Delta MEc = 0.317DoB + 2.741$	0.999
Marine eutrophication (MEu)	$\Delta MEu = 0.042DoB + 10.023$	0.998
Ozone depletion (OD)	$\Delta MO = 0.006DoB + 0.971$	0.998
Particulate matter formation (PM)	$\Delta PM = 0.125DoB + 6.697$	0.985
Terrestrial acidification (TA)	$\Delta TA = 0.135DoB + 5.197$	0.991
Terrestrial ecotoxicity (TE)	$\Delta TE = 0.025DoB + 6.724$	0.921
Water depletion (WD)	$\Delta WD = 0.003DoB + 2.211$	0.949

Table 8. Ranking of the impact categories resulting from the differences in the degree of blending between virgin and aged binder and the consequent reduction of virgin bitumen consumption

Ranking	**Impact category**	**Range of improvement between black rock and full blending [%]**
1	Marine ecotoxicity	31.70
2	Fossil depletion	25.03
3	Human toxicity	22.65
4	Freshwater ecotoxicity	20.05
5	Terrestrial acidification	13.48
6	Particulate matter formation	12.54
7	Climate change	6.33
8	Marine eutrophication	4.22
9	Terrestrial ecotoxicity	2.45
10	Freshwater eutrophication	1.72
11	Ozone depletion	0.59
12	Water depletion	0.31