A comparative life cycle assessment study with uncertainty analysis of cement treated base (CTB) pavement layers containing recycled asphalt pavement (RAP) materials

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ABSTRACT

Cement Treated Base (CTB) is a mixture of aggregates, Portland cement and water that hardens through curing to create a strong and durable material that is widely used as a base course in road pavement construction. This layer can be used in either flexible or rigid pavements, and the range of possible materials used in CTB has been recently expanded to include Reclaimed Asphalt Pavement (RAP). Despite the considerable use of CTB in road pavements, there is only limited information regarding its environmental performance, especially when RAP is added. This paper presents a comparative assessment of the environmental performance of sixteen CTB mixtures, with and without RAP, with different cement percentages, different production methods and different recycling procedures. The thickness of the pavement layers required for a given purpose was calculated for each CTB mixture using a pavement design tool (KENPAVE®) and data obtained from laboratory tests (both primary and secondary data). The environmental sustainability assessment used the Life Cycle Assessment (LCA) methodology combined with uncertainty analysis. The functional unit (FU) consisted of a road pavement structure corresponding to a 1 km stretch of 22 m wide major urban road including a CTB layer that would enable a specified volume of traffic to drive safely over a 20-year lifespan. A cradle-to-gate system boundary was adopted. The characterisation modelling to quantify the potential environmental impacts of each pavement structure was carried out using the CML v. 4.4 2015 impact assessment method at midpoint level. The analysis shows that having higher percentages of cement in the CTB mixture allows a thinner base-course layer, thereby compensating for the increased environmental burdens related to the production of cement and transport. The uncertainty analysis shows that including RAP in the mixture leads to greater spread in the LCA results. Further, the results of a real case study show, regardless of the CTB composition, that mixed-in-place production substantially reduces the environmental impacts compared to central-plant-mixed production. Overall, this research increases the knowledge on the environmental performance of CTB layers containing high percentages of recycled materials and produced using alternative construction methods.

1. Introduction

A decade ago, aware of the important role that the transport sector plays in a well-functioning economy and society, as well as the recognised need to drastically reduce greenhouse gas (GHG) emissions, the European Union’s Commission outlined a “roadmap to a single European Transport Area” known as the Transport White Paper (EU, 2011). This provided, for the first time, European targets for a reduction in GHG emissions from the transport sector. The challenge set in the Transport White Paper is to reduce GHG emissions by at least 60% by 2050 compared to 1990, with an intermediate target of reducing GHG emissions by 20% in 2030 relative to 2008 emissions (EU, 2011) (International Union of railways; Community of European railway and infrastructure companies, 2008). Despite the efforts and good intentions, the results to date are far from promising. According to preliminary estimates, the EU’s transport emissions (excluding shipping) increased by 0.8% in 2019. Furthermore, projections based on existing policy measures in EU Member States (an “existing measures” scenario)
Table 1
Characteristics of the studies involving the so-called sustainable pavement materials and strategies.

<table>
<thead>
<tr>
<th>Type of material</th>
<th>Mixture / maintenance and rehabilitation type</th>
<th>Type of analysis</th>
<th>Main data sources</th>
<th>Main results</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Warm mix asphalt (WMA)</td>
<td>Base course with WMA +30% RAP</td>
<td>Cradle-to-grave LCA</td>
<td>Material suppliers; contractors; literature; Ecoinvent database</td>
<td>The combination of RAP and WMA can reduce CO2eq emissions by 12%, energy consumption by 15% and water consumption by 15%.</td>
<td>(Giani et al., 2015)</td>
</tr>
<tr>
<td>WMA CECABASE +0% RAP</td>
<td>Cradle-to-grave LCA</td>
<td>Literature; Ecoinvent database; COPERTv5.0 emissions model (EMBIA, 2017); VTI’s rolling resistance model (Hammarström et al., 2012)</td>
<td></td>
<td>The foamed WMA +50% RAP option for the wearing course is the most environmentally friendly alternative throughout the pavement life cycle among all the competing solutions.</td>
<td>(Santos et al., 2018)</td>
</tr>
<tr>
<td>Foamed WMA +0% RAP</td>
<td>Cradle-to-grave LCA</td>
<td>Literature review</td>
<td>-</td>
<td></td>
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<tr>
<td>WMA CECABASE +50% RAP</td>
<td>Cradle-to-grave LCA</td>
<td>Literature review</td>
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<tr>
<td>Foamed WMA +50% RAP</td>
<td>Cradle-to-grave LCA</td>
<td>Literature review</td>
<td>-</td>
<td></td>
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<tr>
<td>WMA with synthetic zeolite + 0% RAP</td>
<td>Cradle-to-grave LCA</td>
<td>Asphalt mixtures producers; Ecoinvent database; EMF/EEA air pollutant emission inventory guidebook (EEA, 2009); literature</td>
<td></td>
<td>The reduced impact of WMA due to a lower manufacturing temperature is offset by the greater impacts of the materials used, especially of the synthetic zeolites. All endpoint impacts as well as climate change, fossil depletion and total cumulative energy demand were decreased by 13–14% by adding 15% RAP.</td>
<td>(Vidal et al., 2013)</td>
</tr>
<tr>
<td>RAC</td>
<td>Cradle-to-grave LCA</td>
<td>GaBi software professional database; literature</td>
<td>Up to 15% reduction of CO2 with full blending; marine ecotoxicity (34.09%); fossil depletion (27.04%); human toxicity (26.83%); and freshwater ecotoxicity (24.07%).</td>
<td>The impact categories scores for: Human Health, Ecosystem quality, Climate Change and Resources were reduced between 16 and 43% with increasing RAP percentages.</td>
<td>(Bressi et al., 2019)</td>
</tr>
<tr>
<td>Five maintenance and rehabilitation (M&amp;R) scenarios, each with different RAP incorporation rates: 0%, 25%, 50%, 75% and 100%</td>
<td>Cradle-to-grave LCA</td>
<td>National road authorities; construction companies; “technical experts”; Ecoinvent database</td>
<td></td>
<td>The impact categories scores for: Human Health, Ecosystem quality, Climate Change and Resources were reduced between 16 and 43% with increasing RAP percentages.</td>
<td>(Vandewalle et al., 2020)</td>
</tr>
<tr>
<td>Bituminous mixtures with 0, 30, 40, 50% RAP</td>
<td>Hybrid LCA: a combination of process-based LCA and economic input-output LCA (EIO-LCA)</td>
<td>Asphalt mixtures producers; Carnegie Mellon University Green Design Institute’s Economic Input-Output Life Cycle Assessment (EIO-LCA) (CMU, 2013); equipment manufacturers websites; PaLATE software; literature</td>
<td>Considering only the binder course, a reduction of up to 28% was observed in both energy consumption and GHG emissions. Also, the construction phase contributed very little (about 6-8%) to the total energy and GHG emissions. Reductions of 26%, 33% and 40% in feedstock energy were observed for the mixtures with 30%, 40% and 50% RAP, respectively.</td>
<td>(Aurangzeb et al., 2014)</td>
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<tr>
<td>Bituminous mixtures with up to 50% RAP percentages with different degrees of blending</td>
<td>Time-adjusted GHG emissions were compared with the results obtained from the traditional LCA</td>
<td>Literature; Ecoinvent database; NONROAD 2008 model</td>
<td>Decrease of up to 20% of GHG emissions due to RAP use. The environmental benefits of RAP decrease as the blending efficiency decreases or the moisture content of RAP increases.</td>
<td>(Chen and Wang, 2018)</td>
<td></td>
</tr>
<tr>
<td>Recycled HMA</td>
<td>Cradle-to-grave LCA</td>
<td>Literature</td>
<td>Using recycled HMA can reduce the eco-burden by 23%.</td>
<td></td>
<td>(Chiu et al., 2008)</td>
</tr>
<tr>
<td>Modified binder with 15% and 30% extracted RAP binders. Aged binder percentages of 15% and 30% in the binder blend.</td>
<td>Environmental performance evaluation in terms of energy consumption and GHG emissions</td>
<td>Literature review</td>
<td>-</td>
<td>The main advantage of using RAP is that it reduces the environmental impact by avoiding disposal in landfills.</td>
<td>(Xiao et al., 2019)</td>
</tr>
<tr>
<td>Crumb rubber modifier asphalt (CRM)</td>
<td>Warm +RAC</td>
<td>Literature review</td>
<td>-</td>
<td>Air quality: no definitive results indicating that CRM exposures are more hazardous than with</td>
<td>(Palaguera et al., 2018)</td>
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<td>Type of material</td>
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<tr>
<td>Dry technology 1.5 and 2.0% of crumb rubber, vulcanised and devulcanised rubber</td>
<td>Cradle-to-gate LCA</td>
<td>GaBi software professional database; literature</td>
<td>When compared with conventional methods, CIR reduced the acidification score by 18%, fossil fuel consumption by 15%, primary energy consumption by 16% and global warming score by 1%.</td>
<td>(Turk et al., 2016)</td>
<td></td>
</tr>
<tr>
<td>Asphalt rubber</td>
<td>Cradle-to-lay LCA</td>
<td>Literature</td>
<td>Asphalt rubber reduces the eco-burden by 23% over a 40-year lifetime.</td>
<td>(Chiu et al., 2008)</td>
<td></td>
</tr>
<tr>
<td>Comparison between Mill &amp; Overlay (M&amp;O) and CIR</td>
<td>Cradle-to-lay LCA</td>
<td>Equipment manufacturers websites; PaLATE software</td>
<td>The results show average environmental benefits of 23% in energy consumption and CO₂ emissions and 20% in water consumption when using CIR rather than M&amp;O for highway resurfacing. Further, CIR reduces virgin aggregate consumption by 37%. Environmental impact reductions achieved by using CIR were found to be directly related to the reduction in volume of new HMA used, and to the reduction in transportation of materials to and from the site.</td>
<td>(Pakes et al., 2018)</td>
<td></td>
</tr>
<tr>
<td>Cement treated case (CTB) and Hydrated cement treated crushed rock base (HCTCRB)</td>
<td>HCTCRB with 2% of cement and CTB with 0.75% of cement</td>
<td>Gate-to-gate and cradle-to-gate LCA</td>
<td>HCTCRB, compared to CTB, has a greater impact in terms of resource depletion (+0.9%) and energy consumption (+16.7%), while CTB imposes a higher environmental load in terms of GHG emissions (~2.6%).</td>
<td>(Yeo et al., 2009)</td>
<td></td>
</tr>
<tr>
<td>Recycled asphalt shingles (RAS)</td>
<td>Asphalt mixtures with different percentages of RAP (15-35%) and RAS</td>
<td>Cradle-to-gate LCA</td>
<td>Surveys; literature; NREL U.S. LCI</td>
<td>Impact reductions need to include several factors such as the distance and quantities of materials carried and the binder content.</td>
<td>(Mukherjee, 2016)</td>
</tr>
<tr>
<td>-</td>
<td>Eleven asphalt mixtures with different percentages of RAP and RAS</td>
<td>Cradle-to-gate LCA</td>
<td>US-Ecoinvent database; literature; MOVES software</td>
<td>Energy consumption reduction up to 46%.</td>
<td>(Yang et al., 2015)</td>
</tr>
<tr>
<td>Geopolymers</td>
<td>Four types of stabilised road base materials: waste glass-fly ash based geopolymer stabilised macadam (WFAG), fly ash based</td>
<td>Cradle-to-lay LCA</td>
<td>Ecoinvent database; literature; Chinese specifications</td>
<td>The use of geopolymer road bases reduces the climate change score substantially. Compared with CS, the CO₂-eq emissions of WFAG-1</td>
<td>(Zhang et al., 2021)</td>
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</table>

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Table 1 (continued)

<table>
<thead>
<tr>
<th>Mixture / maintenance and rehabilitation type</th>
<th>Type of analysis</th>
<th>Main data sources</th>
<th>Main results</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>geopolymer stabilised macadam (FAG), cement stabilised macadam (CS) and cement-fly ash stabilised macadam (CFAS)</td>
<td>Literature review</td>
<td>-</td>
<td>and FAG-1 declined by 17.9% per function unit.</td>
<td>(Balaguera et al., 2018) (Li et al., 2019)</td>
</tr>
<tr>
<td>Others Ash from the incineration of municipal solid waste, glass waste, steel slag, rubber, polymer, fly ash, RCA, industrial waste</td>
<td>-</td>
<td>-</td>
<td>The main advantage of the materials analysed is that they reduce the environmental impact by avoiding landfill disposal.</td>
<td>(Balaguera et al., 2018) (Li et al., 2019)</td>
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</table>


indicate that transport emissions will be 32% higher in 2030 than in 1990. If the additional measures indicated in national policies are included (the “with additional measures” scenario), the estimates for 2030 still indicate that GHG emissions will increase by 17% over 1990 levels. As such, if the sector as a whole is to contribute decisively to the goals set out in the European Green Deal, all transport modes will need to be more ambitious.

Of all transport modes, road transport contributes by far the highest proportion of overall transport emissions (around 72% in 2019) (EEA, 2021). The construction and regular road pavement maintenance activities require the consumption of considerable quantities of materials and energy resources. Further, contrary to common belief, the environmental impacts related to the pavement life cycle are not constrained to the above phases as they continue to be generated during the use phase, due to phenomena such as pavement–vehicle interaction, reflection or absorption of solar radiation (albedo), absorption of CO₂ (carbonation), lighting etc. (Harvey et al., 2016). Sometimes, the use phase can be responsible for the majority of the environmental impacts during a pavement’s life cycle, particularly in roads carrying high volumes of traffic. With roads carrying low volumes of traffic, the effects on the environmental performance of the extraction and production of materials and the construction processes of the road pavement are more pronounced (Santos et al., 2015a). Nevertheless, the overall environmental impacts associated with road pavements can be mitigated by fostering the adoption of synergetic efforts and initiatives that affect the different pavement life cycle phases (i.e., construction, use, maintenance and end-of-life). Such strategies could have as their main objective ensuring that the surface layer remains smooth throughout its service life, thus reducing rolling resistance (Santos et al., 2015a), but might also involve using and adopting recycled materials and in-place pavement recycling techniques (Praticò et al., 2020; J. Santos et al., 2015).

2. Background

2.1. Sustainable pavement systems: materials and practices

Sustainable pavement systems have been defined as networks of long-lasting pavements whose design, construction, use and management are guided by environmental, economic and social principles (Aurangzeb et al., 2014). Many so-called sustainable pavement materials and strategies have found widespread applications and their environmental sustainability has been assessed in various research studies (Balaguera et al., 2018; Li et al., 2019). Without claiming to be exhaustive, Table 1 presents the main findings from the existing literature on this topic.

As reflected in Table 1, RAP is clearly the most widely used recycled material. It is produced during asphalt pavement maintenance and rehabilitation (M&R) activities and often used in combination with other recycled materials. The various research studies show that RAP can be used as recycled aggregate in both bound and unbound pavement layers (Giani et al., 2015; Li et al., 2019). Several research studies have been conducted to estimate the potential benefits arising from the use of RAP in asphalt mixtures. Jullien et al. (2006) measured emissions to the atmosphere and other pollutants released during the asphalt-laying operations with different asphalt mixtures containing various quantities of RAP and concluded that emissions increase when the RAP content increases. However, this disadvantage is balanced by an increase in the beneficial effects of recycling large quantities of aggregates and bitumen, provided that the aged bitumen trapped in RAP is reactivated and blended efficiently with the virgin bitumen (Bressi et al., 2019). It has been widely demonstrated that bitumen production is one of the most environmentally burdensome and energy demanding process in the road paving activity (Bressi et al., 2018; Santero et al., 2011; Asphalt Institute, 2019). Other aspects that are important when dealing with RAP include the RAP percentage, its homogeneity and moisture content. The latter is particularly relevant because it contributes substantially to the total energy consumption during in-plant asphalt mixture production (Chen and Wang, 2018), the handling procedure at the plant (amount of crushing, sieving etc.) and the durability of the recycled material, which influences the pavement M&R strategy (Santos et al., 2017).

RAP has also been used in warm mix asphalt (WMA) technologies (Table 1). These mixtures tend to be environmentally beneficial by enabling reductions in CO₂ emissions and reducing the heating energy required for their production (up to 15% in some cases (Giani et al., 2015; Santos et al., 2018; Vidal et al., 2013)). Another notable aspect seen in Table 1 is that RAP is also used as a partial substitute for virgin aggregates in mixtures containing asphalt rubber, thereby combining the effects of different recycled materials. In this situation, the higher durability of the materials enables a thinner wearing course. Further, asphalt rubber produced using a wet technology combined with RAP leads to promising results in terms of energy savings, mitigation of environmental impacts, resource depletion and preservation of ecosystems (Farina et al., 2017).

Although several LCA studies have been conducted on road pavement recycling (Chiu et al., 2008), the majority of them consider the use of RAP, in HMA or WMA, only in the upper pavement layers (Cao et al., 2019; Chen and Wang, 2018; Farina et al., 2017; Giani et al., 2015; Santos et al., 2018; Tatari et al., 2012). Only a few studies have analysed from an environmental perspective the application of recycled materials in the deeper bound or unbound layers of road pavements (Sudarno et al., 2014; Birgisdóttir et al., 2006; Olsson et al., 2006).

2.2. Uncertainty in life cycle assessment studies of road pavement materials

Assessing the environmental sustainability of road pavement
construction and M&R practices is generally treated as a deterministic process. However, an LCA analysis requires a considerable quantity of input data, many of which have various sources and levels of uncertainty and, even when the same conditions apply, the models may provide surprisingly different results. Uncertainty is the term adopted by the International Organization for Standardization (ISO) 3534 to express the distribution of data within a population, due to either random variations or bias (Weidema et al., 2013). Variation is typically described statistically in terms of standard deviations, variance etc., while bias represents the systematic error in a measurement or observation (Weidema et al., 2013). Several LCA studies include a parametric sensitivity analysis where output variations are induced by varying one input factor at a time, holding all others at their default values. This method is labelled “One-Factor-at-a-Time” (OAT) sensitivity analysis (Larres-Gallegos et al., 2017; Olsson et al., 2006; Santos et al., 2019). In other cases, different performance scenarios are analysed for mixtures containing RAP on the basis that such mixtures are considered more susceptible to thermal and fatigue cracking than ‘normal’ virgin mixtures (Aurangzeb et al., 2014). The OAT method can be inefficient in considering the combined effects of different uncertainties affecting the various parameters because variations may occur simultaneously. For this reason, a more elaborated statistical analysis has been proposed for propagating the uncertainties in LCA results. For instance, Cao et al. (2019) performed an LCA on WMA with rubber that incorporated uncertainty composed of two contributions: basic uncertainty and additional uncertainty. Basic uncertainties, which can be incorporated in the LCA framework through Monte Carlo simulations, are related to the materials and processes, whereas additional uncertainties are related to data quality and appropriateness, and here one can follow the guidelines proposed by Weidema et al. (2013). This approach had already been adopted by (AzariJafari et al., 2018) and (Noshadravan et al., 2013) in comparative LCA studies of asphalt and concrete pavements. Yu et al. (2018) analysed different asphalt pavement maintenance projects to estimate energy consumption and CO₂ emissions from various recycling strategies. They considered two uncertainty categories (data quality uncertainty and model parameter uncertainty) and introduced the environmental burden comparison parameter R for testing the statistical significance of the results of different solutions. Bhat and Mukherjee (2019) developed a methodology based on Taylor’s first-order approximation to propagate parameter uncertainty through LCA outcomes and identify equivalence intervals that could be applied during material procurement decision-making. Uncertainty analyses have also been applied in developing a stochastic multi-objective optimisation model where environmental (LCA results) and socioeconomic objectives are simultaneously optimised (Kucukvar et al., 2014). Here, the optimisation model was coupled with uniformly distributed input variables to account for uncertainty.

Another approach to analysing uncertainties in the context of a pavement LCA study consists of describing how the different types of life cycle inventory data (i.e., background and foreground) are affected by uncertainties. Foreground data uncertainties can be related to diurnal variations in the quantification of the fuel consumed by construction equipment and hence can be categorised as aleatory uncertainty. Background data uncertainties may be the result of using data from different geographic, technological or temporal contexts than those specified in the goal and scope of the LCA study. (Bhat, 2020) provides an in-depth discussion of this subject.

3. Aim of the present study

Notwithstanding the efforts and the merits of the previous LCA studies discussed, research on the lifetime environmental impacts of pavement layers using materials other than bituminous mixtures is still very limited. In particular, only a few studies can be found regarding the use of CTB produced either in-plant or in-place with different quantities of RAP (see Table 1). Furthermore, when the material manufacturing aspect (either in-plant or in-place) and pavement construction are studied, the variability in results is usually overlooked, which could lead to misleading findings (Cao et al., 2019; Santero et al., 2011).

In order to overcome some of the above-mentioned shortcomings and gaps, the research study presented in this paper carried out a comparative attributional LCA analysis of different CTB technologies (mixed either in-plant or in-place) and mixture compositions with different RAP contents, along with an uncertainty analysis based on a real Italian case study. An attributional approach was used because the life cycle modelled is based on an existing supply chain (European Commission – Joint Research Centre – Institute for Environment and Sustainability, 2010). As such, it is beyond the scope of the study to identify the consequences that the decision to use RAP in CTB mixtures might have for other systems or sectors of the economy where RAP might be also used or processed.

Monte Carlo simulation was used to propagate the inputs uncertainties into the LCA outputs as a way to reduce the likelihood of drawing erroneous and misguided conclusions (which are often associated with a conventional deterministic analysis) provided the assumed distributions are representative of the actual conditions. Further, this random sampling method was used because it is the most common approach for uncertainty propagation in LCA studies (Larson Ivanov et al., 2019). Ultimately, including the consideration of uncertainties responds to the need to increase the pavement community’s capacity to make more strategic and better-informed decisions in increasing the sustainability of road pavement construction and M&R practices.

The remainder of the paper is organised as follows. Section 4 presents the characteristics of several alternative CTB mixtures as well as the design of the pavement structures. Following this, Section 5 describes the LCA methodology including definitions of the functional unit (FU), the system boundaries and data collection. Sections 6 then presents how the uncertainties were incorporated in the LCA analysis. The results from the application of the methodology to a real case study are presented and discussed in Section 7. Finally, a summary, conclusions, limitations and avenues for future research are offered in Section 8.

4. Materials and design

4.1. Cement treated base (CTB) mixtures with reclaimed asphalt pavement (RAP)

CTB is a term used for a mixture of crushed aggregates and specific amounts of cement and water that hardens during the curing period to become a strong paving material (Lim and Zollinger, 2003). An advantage of CTB is that it provides a stiffer and stronger base than an unbound granular base, therefore reducing the deflections caused by traffic loads, resulting in lower strains in the bituminous mixtures placed on top of the CTB. This has the effect of delaying the development of fatigue cracking distress and can lead to an extended pavement service life (Lim and Zollinger, 2003). Further, the CTB thickness required is normally lower than the thickness of granular material because the traffic loads are more evenly distributed over a larger area (Halsted and Luhr, 2006). A CTB also improves the rutting resistance of the pavement and the resistance to freezing and thawing cycles (Halsted and Luhr, 2006), thereby providing a durable and lasting base for a flexible pavement.

In this study, three scenarios were considered in the production of CTB mixtures (Garber et al., 2011):

1. Central-plant-mixed (CPM) where both virgin and recycled materials are taken from previously created stockpiles.

A mixed-in-place CTB is directly compacted after the in-situ mixing,
applies linear layered elastic theory to calculate pavement responses to (Halsted and Luhr, 2006). Finally, in both cases, a bituminous emulsion axle load applications given their specific configurations. The following statistics of the CTB alternatives are summarised in Table 2. Considerations were given giving a total of sixteen combinations. The characteristics of virgin materials. Further, different quantities of water and cement were considered and compared with the reference scenario corresponding to CTB mixtures with recycled materials, different percentages of RAP were added. The moisture content in the virgin aggregates and RAP material before mixing is null or negligible. Therefore, the water percentage required to achieve the optimal moisture content was completely added during the fabrication process. 

whereas the CTB mixed in a central plant is transported to the construction site by means of dumper trucks, spread and compacted (Halsted and Luhr, 2006). Finally, in both cases, a bituminous emulsion is spread to cover the material during the curing period prior to the top layers, of either bituminous mixtures or cement-based concrete, being added. To evaluate the potential environmental benefits related to the use of CTB mixtures with recycled materials, different percentages of RAP were considered and compared with the reference scenario corresponding to the production and placement of a traditional CTB composed exclusively of virgin materials. Further, different quantities of water and cement were considered giving a total of sixteen combinations. The characteristics of the CTB alternatives are summarised in Table 2.

The first step in comparing the alternative CTB mixtures in terms of their environmental performance involves determining the thickness required to achieve a satisfactory performance when included in a pavement structure.

In order to calculate the thickness of the different CTB alternatives, a pavement design analysis was performed. A mechanistic-empirical approach was adopted using KENPAVE® software (Huang, 2004). This applies linear layered elastic theory to calculate pavement responses to axle load applications given specific configurations. The following steps were followed:

1. Select an initial pavement structure based on a traffic value, type of road and soil bearing capacity.
2. Define input parameters: material characteristics (elastic moduli and Poisson’s ratio) of the layers, load configuration and layer thickness.
3. Run the analysis using the KENPAVE® software (Huang, 2004) for the different alternatives varying the CTB layer thickness (the material properties and thicknesses of the other layers are kept constant).
4. Define, for each alternative, the specific thickness that should provide the targeted service life (based on the tensile stress and vertical strain at the bottom of the CTB layer).

These steps are described in detail in the subsections below.

### 4.1.1. Input parameter for pavement design

#### 4.1.1.1. Initial pavement structure

For main and secondary urban roads with high traffic volumes (10 × 10^6 cumulative passages of commercial vehicles) and with a soil resilient modulus of approximately 90 N/mm², the Italian standard (CNR, 1995) suggests a flexible pavement composed of different layers and materials to provide an appropriate structural response to the high number of applied loads. A typical pavement section is composed of three layers of bituminous mixtures, namely a 5 cm thick wearing course, a 5 cm binder course and an 8 cm base course, laid

### Table 2

Summary of the characteristics of the different CTB mixtures analysed.

<table>
<thead>
<tr>
<th>Name of the mixture</th>
<th>Type of production</th>
<th>Description</th>
<th>Moisture content by mass of mixture (%)</th>
<th>Cement content by mass of aggregates (%)</th>
<th>RAP content by mass of mixture (%)</th>
<th>Virgin aggregates content by mass of mixture (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTB0RAP3.5CPM</td>
<td>Central-plant-mixed</td>
<td>Central-plant-mixed CTB without RAP (100% virgin aggregates) and 3.5% cement</td>
<td>6.0</td>
<td>3.5</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>CTB50RAP3.5CPM</td>
<td>Central-plant-mixed</td>
<td>Central-plant-mixed CTB with 50% RAP and 3.5% cement</td>
<td>8.5</td>
<td>3.5</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>CTB100RAP3.5CPM</td>
<td>Central-plant-mixed</td>
<td>Central-plant-mixed CTB with 100% RAP and 3.5% cement</td>
<td>7.8</td>
<td>3.5</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>CTB0RAP3.5MIP</td>
<td>Mixed-in-place</td>
<td>Mixed-in-place CTB withoutRAP and 3.5% cement</td>
<td>6.0</td>
<td>3.5</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>CTB50RAP3.5MIP-CPM</td>
<td>Mixed-in-place with RAP delivered from plant</td>
<td>Mixed-in-place CTB with 50% RAP and 3.5% cement</td>
<td>8.5</td>
<td>3.5</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>CTB100RAP3.5MIP-CPM</td>
<td>Mixed-in-place with RAP delivered from plant</td>
<td>Mixed-in-place CTB with 100% RAP and 3.5% cement</td>
<td>7.8</td>
<td>3.5</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>CTB0RAP5MIP</td>
<td>Mixed-in-place</td>
<td>Mixed-in-place CTB without RAP and 5.0% cement</td>
<td>6.5</td>
<td>5.0</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>CTB50RAP5MIP-CPM</td>
<td>Mixed-in-place with RAP delivered from plant</td>
<td>Mixed-in-place CTB with 50% RAP and 5.0% cement</td>
<td>8.8</td>
<td>5.0</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>CTB100RAP5MIP-CPM</td>
<td>Mixed-in-place with RAP delivered from plant</td>
<td>Mixed-in-place CTB with 100% RAP and 5.0% cement</td>
<td>8.2</td>
<td>5.0</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>CTB0RAP3.5MIP-RIS</td>
<td>Mixed-in-place</td>
<td>Mixed-in-place CTB without RAP and 3.5% cement</td>
<td>8.5</td>
<td>3.5</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>CTB50RAP3.5MIP-RIS</td>
<td>Mixed-in-place with RAP available in-situ</td>
<td>Mixed-in-place CTB with 50% RAP and 3.5% cement</td>
<td>7.8</td>
<td>3.5</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>CTB100RAP5MIP-RIS</td>
<td>Mixed-in-place with RAP delivered from plant</td>
<td>Mixed-in-place CTB with 100% RAP and 5.0% cement</td>
<td>8.2</td>
<td>5.0</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>CTB0RAP3.5MIP-RIS</td>
<td>Mixed-in-place</td>
<td>Mixed-in-place CTB without RAP and 3.5% cement</td>
<td>6.5</td>
<td>5.0</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>CTB50RAP3.5MIP-RIS</td>
<td>Mixed-in-place with RAP available in-situ</td>
<td>Mixed-in-place CTB with 50% RAP and 3.5% cement</td>
<td>8.8</td>
<td>5.0</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>CTB100RAP5MIP-RIS</td>
<td>Mixed-in-place with RAP delivered from plant</td>
<td>Mixed-in-place CTB with 100% RAP and 5.0% cement</td>
<td>8.2</td>
<td>5.0</td>
<td>100</td>
<td>0</td>
</tr>
</tbody>
</table>

Note: The moisture content in the virgin aggregates and RAP material before mixing is null or negligible. Therefore, the water percentage required to achieve the optimal moisture content was completely added during the fabrication process.
on top of an unbound 25 cm thick subbase layer that protects the sub-grade and helps distribute the loads (Domenichini and Di Mascio, 1993).

The input parameters required for a pavement design are as follows: characteristics of the materials used in each layer (i.e., elastic modulus and Poisson’s ratio), load characteristic and configuration, and thickness of the layers.

### 4.1.1.2. CTB elastic modulus

Primary data supplied by an Italian construction company were used to calculate the inputs necessary to run the pavement design. In particular, the elastic moduli were derived from laboratory tests in which the CTB mixtures were made of virgin aggregates mixed with 3.5% and 5% Portland cement. The results of compressive strength tests were also provided. These values were input into the American Concrete Asphalt’s empirical formulae to determine the elastic modulus of a mixture as follows (ACI Committee 209, 1998; Lim and Zollinger, 2003):

$$E(t) = 4.38 \times w^{1.5} \times f_c(t)^{0.75}$$  

Equations (1) and (2) were then used to calculate the elastic modulus at the seventh day using the previously measured value of the compressive strength. Table 3 summarises the characteristics of the materials used and the elastic moduli of the CTB mixtures composed exclusively of virgin aggregates.

For the CTB mixtures with RAP–virgin aggregate blends no laboratory tests were available. Therefore, the study conducted by Taha et al. (2002) was used as a reference to calculate the coefficients of the exponential relationships describing the evolution of the elastic moduli with the increase of the RAP content in the mixtures (see Figure 1).

The equations presented in Figure 1 (a and b) were used in the present case study to determine the evolution of the elastic modulus with increasing RAP percentages, using as a reference and initial value the case where no RAP has been added to the CTB mixtures. In this way it was possible to determine the initial elastic moduli for each combination of mixtures summarised in Table 2. However, the CTB mixtures show significant variations in their effective stiffness over their life cycle and it could be that the elastic modulus decreases due to chemical deterioration leading to the fragmentation of the cement matrix during the service life (Theyse et al., 1996). More specifically, the CTB mixtures can have two phases during their life cycle: pre-cracked and equivalent granular unbound.

The elastic modulus of the layer that forms a continuous slab during the pre-cracked phase can be above 3000 MPa (determined with Equation 1) and the exponential regression shown in Figure 1. This modulus value decreases rapidly to 800-2000 MPa when the CTB slab starts to crack forming large blocks. Over time, the number of blocks will increase, and the layer will increasingly act as a granular unbound material with an elastic modulus in the range of 200-400 MPa. Given that the pre-cracked phase is extremely short relative to the other phase, the corresponding modulus is not considered appropriate when predicting the service life of the cement layer (De Beer, 2008). Therefore, only the effective life phase represented by the equivalent granular unbound is considered when calculating the elastic modulus of the CTB mixtures (Theyse et al., 1996). The different states of the CTB mixtures create a problem in defining a unique elastic modulus that can be used for pavement design purposes. Consequently, the effective long-term stiffness (ELTS) concept was adopted in the case study as an indicator of the average long-term in-situ stiffness of the CTB layer (Ali, 2009). The ELTS does not represent the stiffness value at a specific time, rather it is an average value that takes into account the decreasing stiffness over time caused by traffic, seasonal variations etc. (Ali, 2009).

---

**Table 3**

Primary data related to the composition and characteristics of the CTB specimens with 3.5 and 5.0% cement.

<table>
<thead>
<tr>
<th>Cement content (%)</th>
<th>Specimen number</th>
<th>Wet mass (g)</th>
<th>Moisture content (%)</th>
<th>Density dry (g/cm³)</th>
<th>Unitary load (N/mm²)</th>
<th>w (pcf)</th>
<th>Ec(28) (pcf)</th>
<th>Ec(t) (MPa) at 7-day curing period</th>
</tr>
</thead>
<tbody>
<tr>
<td>3,5</td>
<td>1</td>
<td>7380</td>
<td>6.0</td>
<td>2.125</td>
<td>3.45</td>
<td>132.66</td>
<td>500.38</td>
<td>4882</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>7410</td>
<td>6.0</td>
<td>2.133</td>
<td>3.43</td>
<td>133.16</td>
<td>497.48</td>
<td>4888</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>7375</td>
<td>6.0</td>
<td>2.123</td>
<td>3.44</td>
<td>132.53</td>
<td>498.93</td>
<td>4904</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>7310</td>
<td>6.0</td>
<td>2.105</td>
<td>3.56</td>
<td>131.41</td>
<td>516.34</td>
<td>4928</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>7410</td>
<td>7.1</td>
<td>2.133</td>
<td>3.81</td>
<td>133.16</td>
<td>552.60</td>
<td>5289</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>7430</td>
<td>7.1</td>
<td>2.139</td>
<td>4.03</td>
<td>133.54</td>
<td>584.80</td>
<td>5539</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>7405</td>
<td>7.1</td>
<td>2.132</td>
<td>3.86</td>
<td>133.09</td>
<td>559.85</td>
<td>5337</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>7425</td>
<td>7.1</td>
<td>2.138</td>
<td>3.98</td>
<td>133.47</td>
<td>577.25</td>
<td>5484</td>
</tr>
</tbody>
</table>
The determining factors in calculating ELTS are the type of support (a high support stiffness leads to a higher ELTS) and the thickness of the CTB layer.

In the present case study, the subgrade that supports the CTB layer is a gravel-soil mixture belonging to material class G9 with a maximum stiffness of 90 MPa (Al., 2009). The average thickness of the CTB layer was considered to be 20 cm. Given these values, a reduction coefficient of 0.4 was applied to the pre-cracked modulus to calculate the ELTS (Al., 2009).

The pre-cracked elastic moduli obtained from Equation (1) and the equations presented in Figure 1 for CTB mixtures containing RAP are presented in Table 4. This table also presents the ELTSs obtained after the adjustments made related to the two factors outlined above. The Poisson’s ratios for all the CTB mixtures were taken as 0.15 (Halsted and Luhr, 2006; Maher and Bennert, 2008).

4.1.1.3. Elastic modulus of asphalt mixtures. The elastic moduli of HMA depends on temperature. This means that the response of the pavement significantly differs over a year due to the seasonal variations in its modulus and mechanical characteristics. The pavement design methods can take this aspect into account and, therefore, the elastic modulus of the HMA applied in each layer was calculated for each season. The steps undertaken to calculate the elastic modulus of the different types of HMA in different seasons are summarised as follow:

1. Calculate the temperature in the middle of each layer of bituminous mixture using the following equation (Yoder and Witczak, 1975).

\[ T(t) = (1.467 + 0.043 \times z) + (1.362 - 0.005 \times z) \times T_a \]  

Where \( z \) is the pavement layer depth (m) and \( T_a \) is the mean seasonal air temperature (°C).

2. Apply the Time-Temperature Superposition Principle (TTSP) (Nguyen et al., 2009) to determine the mechanical properties at different temperatures from known properties at a reference temperature.

3. Define a master curve for each material.

4. Calculate the stiffness of the bituminous materials from the master curve (Chailleux et al., 2006).

The calculated temperatures in the middle of each bituminous layer are reported in Table 5.

Having calculated the temperature in the middle of each layer, the Time-Temperature Superposition Principle (TTSP) was applied to determine the temperature-dependent mechanical properties of the linear viscoelastic materials from known properties at a reference temperature. The elastic modulus of typical bituminous mixtures increases with a higher loading frequency and lower temperature, and decreases at high temperatures and low frequencies. This pattern can be organically represented in a master curve (Chailleux et al., 2006). Indeed, by applying the TTSP, the construction of a master curve allows the mechanical behaviour to be obtained over a wide range of times and temperatures (Chailleux et al., 2006; Rowe et al., 2009). As such, the calculated master curve of the bituminous mixture enabled the elastic modulus to be determined for each analysis period as a function of temperature. Based on the abovementioned considerations, the elastic moduli for each layer are summarised in Table 6. For design purposes, the Poisson’s ratio was considered to be the same for each bituminous layer and set to 0.35.

4.1.1.4. Load configuration and calculation of the thickness of the required CTB layer. The vehicle loadings applied are simulated by considering a single axle load with dual tyres, a contact radius (CR) of the circular loaded areas equal to 10.53 cm and contact pressure (CP) on these circular loaded areas equal to 785 KPa (Huang, 2004). With the elastic modulus of each layer calculated, and the load characteristics and
configuration defined, several runs with CTB layer thicknesses ranging between 20 cm and 30 cm were performed while keeping the thickness of the bituminous layers constant. The results of this pavement design procedure are shown in the Subsection 4.1.2 below.

4.1.2 Outputs of the pavement design

The outputs of the layered elastic model consist of stresses, strains and deflections at several critical points in the pavement structure. The critical parameter in controlling the effective fatigue life of cemented layers is the maximum tensile strain at the bottom of the layer (Theyse et al., 1996). The pavement design solutions were required to ensure the same performance and therefore durability in terms of fatigue life of the layer. This was determined by comparing the maximum tensile strain at the bottom of the CTB layer with a reference value. This value was set at 125 µε and corresponds to the breaking strain of a cemented treated material composed of natural gravel with an elastic modulus varying between 2-10 GPa in the pre-cracked phase, and between 200-400 MPa in the subsequent granular phase (Theyse et al., 1996). The resulting pavement designs are summarised in Table 7. This shows the thicknesses of the different CTB layers that ensure the same effective fatigue life. The complete structure of the road pavement is depicted in Figure 2. The characteristics, composition and thicknesses of the alternative CTB layers were used in the LCA analysis described in the next section.

5. LCA methodology

LCA is a systematic methodology used to assess the potential environmental impacts of a product or service over its life cycle that includes the extraction of raw materials, production, transport, distribution, use and end-of-life management. Its principles, framework and requirements are defined by the ISO in standards ISO14040 and ISO 14044 (ISO, 2006a, 2006b). Apart from these ISO standards, the present study also took into account the guidelines and information provided in the Federal Highway Administration’s (FHWA) Pavement LCA Framework (Harvey et al., 2016) and in the ILCD Handbook (European Commission – Joint Research Centre – Institute for Environment and Sustainability, 2010) (Wolf et al., 2012). In this study the guidelines were used to support the execution of an attributional LCA study comparing different products in terms of their environmental performance (i.e., the identification of significant environmental aspects of the products) (Harvey et al. 2016). Therefore, and based on the supporting guidelines, the functional unit, the system boundaries and the cut-off approach were defined as explained in the following subsections.

5.1 Goal and scope definitions

The goal of the present study was to compare the environmental performance of different CTB mixtures used in a road pavement structure. The functional unit (FU) is a one-kilometre length of road pavement structure that includes a CTB layer that contributes to enabling a given volume of traffic to drive in safe, comfortable conditions over a twenty-year lifespan. This is part of a new urban road, located close to Città di Castello (Perugia), Italy, with two carriageways, four lanes and a total width of 22 m. Various CTB mixtures were compared on the basis of their primary function when used in a structural layer of a road pavement structure. This function consists of absorbing and distributing the traffic loads to the subgrade, thereby contributing to a durable performance of the pavement structure over a specified project analysis period (PAP). Given that the alternative CTB mixtures considered may not have the same performance, individual specific thicknesses were initially calculated to provide the same durability. Therefore, the quantity of each CTB mixture is that required to achieve the required thickness on a well-compactd and even subbase with the dimensions described above.

The system boundary incorporated two main stages: (1) a product stage comprising raw material extraction, transport and manufacturing, either at the plant or at the construction site; and (2) the construction stage, consisting of the in-situ processes for constructing the road pavement layer. However, in the life cycle inventory section, material transportation is considered as an individual stage for comprehensiveness.

As discussed previously, two types of CTB processing are analysed: (1) Mixed-in-Place (MIP); and (2) Central-Plant-Mixed (CPM). Further, for the MIP scenario, two conditions were analysed: (1) recycling at the plant; and (2) recycling in-situ. In the first scenario, the RAP is stockpiled at the plant where the crushing and screening operations take place. In the second, the RAP is directly available at the construction site after milling the old road pavement. Figures 3-5 shows all the processes considered in the materials’ production and construction stages of the layer using MIP and CPM processes.

A cut-off approach was adopted in evaluating the burdens and benefits associated with the use of RAP material. Adopting the cut-off approach as specified by the General Guide for Life-Cycle Assessment (Wolf et al., 2012), only the burdens directly associated with the product itself are accounted for. Therefore, only the environmental impacts related to RAP processing were considered (Bressi et al., 2018). Moreover, given that the thickness of the alternative CTB layers were specified to give the same durability, later maintenance and dismantling activities would take place at the same time and, therefore, these phases could be excluded from the system boundaries, an approach also applied in other recent studies (Bressi et al., 2019; Porot et al., 2017).
Finally, given that the use of recycled materials in the CTB is not expected to lead to large structural market changes, the decision context falls under Situation A of the ILCD Guideline (European Commission – Joint Research Centre – Institute for Environment and Sustainability 2010), i.e. micro-level, product or process-related decision-support studies. As such, in line with the information presented previously, an attributional approach, depicting the actual or forecast specific or average supply chain, was selected as the life cycle inventory (LCI) modelling framework (Hertwich, 2014).

5.2. Life cycle inventory

In modelling the system, the third phase of the LCA methodology consists of collecting primary, secondary and/or eventually proxy data (Wolf et al., 2012). Primary, or specific, data are related to the processes required for modelling the product or service studied in the LCA (European Commission – Joint Research Centre – Institute for Environment and Sustainability, 2010). Such data are mainly gathered from the manufacturing company, the suppliers and contractors. Specific data are obtained for the unit processes under analysis. In turn, secondary, or generic, data represent generic or average data related to the product or service to be analysed (European Commission – Joint Research Centre – Institute for Environment and Sustainability, 2010). The sources of such data include relevant literature and, in our case, the Ecoinvent database as discussed later in the paper. Generic data can be divided into identified secondary data that comply with the quality requirements for precision and completeness, and proxy data that do not comply with those requirements (Wolf et al., 2012).

In the present study, both primary and secondary data were incorporated as detailed in the following subsections. Primary data were collected from a manufacturing plant while secondary data were obtained from the most recent and appropriate datasets representing Italian processes. The quality requirements of the data collected describe the characteristics that the data must satisfy in order to ensure the credibility of the study and the validity of the interpretation of the results. Hence, data sources were selected that, as far as possible, were in line with the following principles (Wolf et al., 2012): (1) time-related representativeness, i.e. representative in terms of their time-related origin; (2) geographical representativeness, i.e. the data are representative in terms of their geographical origin and coverage; and, (3) technological representativeness, ensuring the data have sufficient technological accuracy.

The life cycle phases considered in the case study are now detailed.

5.2.1. Product stage: raw and recycled materials production

The virgin aggregates required for the CTB mixtures were modelled as crushed gravel and inventory data associated with their production were taken from the Ecoinvent database. These include all material and energy flows associated with their extraction from a quarry, and the cleaning and crushing stages of production. The finished product is crushed (dried) gravel at the factory gate. Inventory data for the Portland cement production were obtained from the Ecoinvent database. The data cover raw material extraction, kiln drying, finishing, grinding, blending, packaging and shipping. The production of the bitumen emulsion was also modelled using the Ecoinvent database and covers all the energy and material flows related to the extraction, transport and refinement of the crude oil. The finished product contains 40% bitumen.

In addressing RAP production, the milling of the old pavement and the transportation of the RAP materials were considered, in line with the cut-off approach, as EOL activities and part of the previous product system. In comparison, the processes that the RAP undergoes at the plant (i.e., storing, handling, screening and downsizing) were included in the...
current product system. The usual production rates of several machines were considered in determining the energy required for handling the RAP, and the Ecoinvent database was used for obtaining LCI data related to the production and distribution of these energy sources. Specifically, the energy required for sieving and crushing was set to 0.0212 MJ per kg of RAP (Zaumanis et al., 2011). Table 8 presents the density of the different materials required to calculate the total mass of the different CTB mixtures per FU (see Table 9).

### 5.2.2. Construction stage: mixture manufacture, compaction and curing

The CTB using the selected materials can be mixed in place or in a central plant. Mixed-in-place CTB is mixed and compacted directly in-situ, whereas central-plant-mixed CTB is prepared in a central plant and then transported to the construction site in dumper trucks and placed on the roadway using a grader and paver before being compacted with a compactor (Halsted and Luhr, 2006). The operations to be included depend on the fabrication process.

#### 5.2.2.1. Mixed-in-place CTB

In the mixed-in-place technology, the

<table>
<thead>
<tr>
<th>Table 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density of the various component materials.</td>
</tr>
<tr>
<td>Type of material</td>
</tr>
<tr>
<td>Virgin aggregate</td>
</tr>
<tr>
<td>RAP</td>
</tr>
<tr>
<td>Cement</td>
</tr>
<tr>
<td>Water</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quantities of the different materials required to produce each CTB mixture.</td>
</tr>
<tr>
<td>Mixture type</td>
</tr>
<tr>
<td>CTB0RAP3.5CPM and CTB0RAP3.5 MIP</td>
</tr>
<tr>
<td>CTB50RAP3.5 CPM and CTB50RAP3.5 MIP</td>
</tr>
<tr>
<td>CTB100RAP3.5 CPM and CTB100RAP3.5 MIP</td>
</tr>
<tr>
<td>CTB0RAP5.0 CPM and CTB0RAP5.0 MIP</td>
</tr>
<tr>
<td>CTB50RAP5.0 CPM and CTB50RAP5.0 MIP</td>
</tr>
<tr>
<td>CTB100RAP5.0 CPM and CTB100RAP5.0 MIP</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processes, datasets and respective quantities required to produce 1 tonne of CTB mixture.</td>
</tr>
<tr>
<td>Phase</td>
</tr>
<tr>
<td>Raw materials production</td>
</tr>
<tr>
<td>Gravel and sand quarry operation</td>
</tr>
<tr>
<td>Tap water production, conventional treatment</td>
</tr>
<tr>
<td>Bitumen emulsion production</td>
</tr>
<tr>
<td>CTB production</td>
</tr>
<tr>
<td>RAP crushing</td>
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<td></td>
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</table>

<table>
<thead>
<tr>
<th>Table 11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processes, datasets and respective quantities required for the construction phase (excluding transportation) of the CTB layer (entire FU).</td>
</tr>
<tr>
<td>Phase</td>
</tr>
<tr>
<td>Pavement layer construction</td>
</tr>
<tr>
<td>CBB placement</td>
</tr>
<tr>
<td>Motor-grader operation</td>
</tr>
<tr>
<td>CBB Paving</td>
</tr>
<tr>
<td>Compaction</td>
</tr>
</tbody>
</table>
cement is spread uniformly on the surface of the unbound materials using a mechanical cement spreader. Following this, the aggregates, cement and RAP (if used) are mixed in a mixing machine to create the CTB. A tanker truck supplies the water that is sprayed from a bar mounted in the mixing chamber. As the water comes in contact with the aggregates and cement, the materials must be appropriately blended to avoid the formation of clumps (Halsted and Luhr, 2006). Compaction commences after the CTB has been spread on the road surface.

5.2.2.2. Central-plant-mixed CTB. Adopting the central-plant-mixed approach requires mixing cement, aggregates, RAP (if used), and water. Specifically, the cement is metered into a main feeder belt before entering the pugmill mixer and water is added through spray bars mounted above the pugmill. After being mixed, the CTB material falls into a holding hopper and then into trucks to be transported to the construction site. On arrival at the construction site, the material is placed uniformly on the road surface using an aggregate spreader to avoid segregation (Halsted and Luhr, 2006). Compaction and slope finishing activities finalise the construction of the layer. The compaction starts immediately the CTB has been spread on the road surface. Vibratory steel-wheel rollers are used to achieve an adequate densification and a bituminous emulsion prime coat is then applied to act as curing membrane (Halsted and Luhr, 2006).

Tables 10 and 11 summarise the information included in the datasets for the material production and CTB construction phases and the main processes involved. Note that, when using mixed-in-place CTB, the manufacturing and the construction processes take place simultaneously at the construction site.

5.2.2.3. Transport. The virgin aggregates, Portland cement and all the other mixture components have to be transported to the mixing plant and/or to the construction site. All materials were assumed to be hauled by heavy duty vehicles (HDVs), and the “transport, freight, lorry 7.5-16 metric ton, EURO 5” and “transport, freight, lorry >32 metric ton, EUROS” processes were used to determine the environmental burdens associated with the emissions released by the transportation vehicles. The production of the fuel consumed by the HDVs was included in the system boundaries, whereas the production of the HDVs themselves was not. The transportation distances considered in the case study are displayed in Figures 3, 4 and 5 and also listed in Table 12.

5.3. Life cycle impact assessment

The characterisation modelling to quantify the potential environmental impacts was carried out using the CML v. 4.4 2015 impact assessment method at midpoint level (Guinée et al., 2002). Specifically, the following impact categories were considered: climate change (CC), acidification (Ac), depletion of abiotic resources – elements, ultimate reserves (DAR-E), depletion of abiotic resources – fossil fuels (DAR-FF), eutrophication (Eu), freshwater ecotoxicity (FAE), human toxicity (HT), marine ecotoxicity (MAE), ozone layer depletion (OLD), photochemical oxidation (PO) and terrestrial ecotoxicity (TE). The Open LCA software® v. 1.9 was adopted for modelling the processes analysed in this case study.

6. Uncertainty analysis

In this study, the uncertainties are considered to be the sum of two components: basic uncertainty and additional uncertainty. The basic uncertainty is related to the processes and the possible variations in quantities and construction methods. This aspect is modelled using a selected probability distribution and incorporated in the LCA analysis through a Monte Carlo simulation. After consultations with several Italian contractors, a triangular probability distribution was considered appropriate to model the uncertainties related to materials and construction parameters. The summary of the parameters (min, max and mean) of the triangular distributions for the transport distances,
operation times of construction machines and other construction-related items are summarised for the central-plant-mixed and mixed-in-place production alternatives in Tables 13 and 14 respectively. It should be noted that, with the material quantities, only additional uncertainties were considered because incorporating the basic uncertainties would require a probabilistic approach in all the stages related to the pavement design and this was beyond the scope of the present study.

In addition to the basic uncertainties included, additional uncertainties in the Ecoinvent database related to the appropriateness and quality of the data were incorporated in terms of five indicators: “reliability,” “completeness,” “temporal correlation,” “geographical correlation” and “further technological correlation”. Each of these indicators are defined as data quality indicators (DQIs) and further specified on one of five levels and together form the “Pedigree Matrix”. Each level of the quality indicator was converted into an uncertainty factor (variances of the underlying normal distributions) with higher scores corresponding to higher variances and lower quality data (Cao et al., 2019; Weidema et al., 2013). The total variance can then be calculated using Equation (4). The data quality assessment can be found in supplementary materials.

\[ \sigma^2_t = \sigma^2_b + \sum_{i=1}^{5} \sigma^2_i \]  

Where \( \sigma^2_t \) is the total variance, \( \sigma^2_b \) is the basic uncertainty, and \( \sigma^2_i \) is the additional uncertainty related to the data quality indicator \( i \).

7. Results and discussion

The comparison of the environmental performance of sixteen CTB alternatives was carried out by applying equivalent conditions in terms of functional unit, data quality, system boundary and allocations rules as defined in the previous sections. The impact of the data uncertainty was estimated and introduced into the LCA calculation procedure using the Monte Carlo simulation approach. The number of runs required was determined by assessing the evolution of the mean of the score for each indicator. Here, once there is no (or only a residual) change in the mean, one can conclude that stability in the outcome has been achieved. Figure 6 shows that this condition, with no significant changes in the mean value, was achieved for the Climate Change environmental impact indicator after approximately 500 runs (similar results were obtained for the other impact categories and CTB mixtures). Consequently, adopting a conservative approach, one thousand runs were carried out.

Figure 7 shows the mean and the 95% confidence intervals of the impact category scores for the mixed-in-place CTB alternatives, while Figure 8 presents similar results for the central-plant-mixed CTB alternatives transported to the construction site. The results presented in these figures show that the mixed-in-place CTB alternatives, for all the tested compositions and both production approaches (i.e., central-plant or in-place), have substantially lower environmental impacts than when using the central-plant-mixed approach to production. Reductions in impacts ranged from 78% (Ozone layer depletion (OLD) impact category) up to 96% (Freshwater aquatic ecotoxicity (FAE) and Marine aquatic ecotoxicity (MAE) impact categories).
Table 12: Transportation distances considered in the case study.

<table>
<thead>
<tr>
<th>Transport</th>
<th>Type of material</th>
<th>Origin</th>
<th>Destination</th>
<th>Dataset</th>
<th>Distance (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>RAP</td>
<td>Mixing plant</td>
<td>Construction site</td>
<td>transport, freight, lorry 7.5-16 metric ton, EURO5</td>
<td>150</td>
</tr>
<tr>
<td>T2</td>
<td>Virgin aggregates (VA)</td>
<td>Quarry</td>
<td>Construction site</td>
<td>transport, freight, lorry 7.5-16 metric ton, EURO5</td>
<td>57</td>
</tr>
<tr>
<td>T3</td>
<td>Cement</td>
<td>Cement supplier</td>
<td>Construction site</td>
<td>transport, freight, lorry 7.5-16 metric ton, EURO5</td>
<td>206</td>
</tr>
<tr>
<td>T4</td>
<td>Water</td>
<td>Mixing plant</td>
<td>Construction site</td>
<td>transport, freight, lorry &gt;32 metric ton, EURO5</td>
<td>150</td>
</tr>
<tr>
<td>T5</td>
<td>Bitumen Emulsion (BE)</td>
<td>BE factory</td>
<td>Construction site</td>
<td>transport, freight, lorry &gt;32 metric ton, EURO5</td>
<td>146</td>
</tr>
<tr>
<td>T6</td>
<td>Virgin aggregates (VA)</td>
<td>Quarry</td>
<td>Mixing plant</td>
<td>transport, freight, lorry 7.5-16 metric ton, EURO5</td>
<td>91</td>
</tr>
<tr>
<td>T7</td>
<td>Cement</td>
<td>Cement supplier</td>
<td>Mixing plant</td>
<td>transport, freight, lorry 7.5-16 metric ton, EURO5</td>
<td>57</td>
</tr>
<tr>
<td>T8</td>
<td>CTB</td>
<td>Mixing plant</td>
<td>Construction site</td>
<td>transport, freight, lorry 7.5-16 metric ton, EURO5</td>
<td>150</td>
</tr>
</tbody>
</table>

Table 13: Triangular distribution parameters for the FU for central-plant-mixed production.

<table>
<thead>
<tr>
<th>Item</th>
<th>Unit</th>
<th>Min</th>
<th>Mean</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance from the supplier to the mixing plant</td>
<td>km</td>
<td>50.4</td>
<td>56</td>
<td>61.6</td>
</tr>
<tr>
<td>Distance from the plant to the construction site</td>
<td>km</td>
<td>81.9</td>
<td>91</td>
<td>100.1</td>
</tr>
<tr>
<td>CTB from the plant</td>
<td>km</td>
<td>135</td>
<td>150</td>
<td>165</td>
</tr>
<tr>
<td>Bitumen emulsion (BE)</td>
<td>km</td>
<td>131.4</td>
<td>146</td>
<td>160.6</td>
</tr>
<tr>
<td>Construction operations</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hauling materials</td>
<td>km</td>
<td>0.9</td>
<td>1</td>
<td>1.1</td>
</tr>
<tr>
<td>Compaction time</td>
<td>min</td>
<td>16</td>
<td>20</td>
<td>24</td>
</tr>
<tr>
<td>Paving time</td>
<td>min</td>
<td>24</td>
<td>30</td>
<td>36</td>
</tr>
<tr>
<td>Sloping finishing time</td>
<td>min</td>
<td>8</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>Road geometry</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Road width</td>
<td>m</td>
<td>14.25</td>
<td>15</td>
<td>15.75</td>
</tr>
<tr>
<td>Road length</td>
<td>m</td>
<td>950</td>
<td>1000</td>
<td>1050</td>
</tr>
<tr>
<td>Other</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Amount of BE to cover the CTB surface</td>
<td>km/ m²</td>
<td>1.2</td>
<td>1.5</td>
<td>1.8</td>
</tr>
</tbody>
</table>

These results can largely be attributed to the reduction in the volume of materials that need to be transported and to the shorter transportation distances to the construction site. The large differences between the environmental profiles of the mixed-in-plant and mixed-in-place CTB alternatives can be linked to the quantity of diesel fuel consumed in the transportation of the mixed-in-plant CTB. It is the diesel combustion process that is responsible for a considerable proportion of the non-renewable energy consumption, terrestrial acidification, respiratory inorganics and organics, and ionising radiation. Moreover, the supply chain processes in diesel production and the emissions related to tyre and brake wear are known to be major contributors to several environmental impact categories: Ionising radiation and Non-renewable energy consumption, Ozone layer depletion, Non-carcinogenic effects, Marine aquatic ecotoxicity and Terrestrial ecotoxicity (AzariJafari et al., 2018).

When comparing the environmental performance of the mixed-in-place CTB alternatives based on the mean impact category scores, Figure 7 shows that the CTB100RAP3.5MIP-RIS mixture is the most environmentally friendly option, slightly ahead of the CTB100RAP5MIP-RIS alternative, despite the former requiring a thicker CTB layer. At the other end of the scale, the CTB100RAP3.5MIP-RIP mixture has the worst environmental performance. Compared to the best CTB100RAP3.5MIP-RIS alternative, it has significantly higher environmental impact scores that vary between 95% (Terrestrial eco-toxicity) and 787% (Depletion of abiotic resources). The fact that layers made of the CTB100RAP3.5MIP-RIP and CTB100RAP3.5MIP-RIS mixtures have the same thickness, and therefore require the same quantity of materials, while generating vastly different environmental impacts highlights once again the important role played by the transportation phase in driving the environmental performance of the alternative mixtures.

When analysing in more detail the effect on environmental performance of using RAP that is available in-situ in mixed-in-place CTB options, the results displayed in Figure 7 shows that, for the same percentage of cement, higher percentages of RAP are associated with lower environmental impacts, even if the required layer thickness is higher. For instance, comparing the CTB100RAP3.5MIP-RIS and CTB0RAP3.5MIP alternatives, the reduction in environmental impact scores can be as high as 204% (for Climate Change) despite the former requiring an 80 cm thicker layer. A similar pattern is observed with the higher 5% cement content. However, if the RAP has to be transported from a plant to the site, higher percentages of RAP are associated with higher environmental impacts, even if the CTB is mixed-in-place. The cause underlying these results is related to the transportation of RAP and the associated environmental impacts as explained earlier.
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50%. Further, the variability in the impact category scores for the layer depletion and Terrestrial ecotoxicity impact categories, are at least mixed-in-place CTB alternatives, the COVs, excluding for the Ozone alternatives exceed 50% (specifically 52%). In comparison, for the categories (Terrestrial ecotoxicity) does the COV of central-plant-mixed CTB ecotoxicity impact categories, only in one of the eleven impact categories (Terrestrial ecotoxicity) does the COV of central-plant-mixed CTB alternatives exceed 50% (specifically 52%). In comparison, for the mixed-in-place CTB alternatives, the COVs, excluding for the Ozone layer depletion and Terrestrial ecotoxicity impact categories, are at least 50%. Further, the variability in the impact category scores for the mixed-in-place CTB alternatives seems to be more sensitive to the use of RAP than with the central-plant-mixed CTB alternatives, with the differences between the COV values for mixtures with and without RAP greater in mixed-in-place CTB alternatives. For example, the difference in the COV values between alternatives with and without RAP is approximately only 1% in four out of eleven impact categories for central-plant-mixed CTB alternatives whereas, in the case of mixed-in-place CTB alternatives, this difference is never less than 14%.

8. Conclusions, limitations and recommendations for future research

8.1. Conclusions

The study presented in this paper has evaluated the environmental performances of sixteen CTB alternatives, with and without RAP, with different percentages of cement, different means of production (in-plant and in-place) and different sources of the RAP material (in-plant and in-situ). The required thicknesses of the CTB layers were determined for a specific road pavement using a pavement design tool, and the environmental sustainability assessment was performed through the LCA methodology including uncertainty analysis.

The following conclusions can be drawn from the results obtained:

- Regardless of the provenance of the RAP materials (in-plant or in-situ) and their percentages in the overall mixture, the use of mixed-in-place CTB mixtures can substantially reduce the mean environmental impact scores in all impact categories relative to in-plant produced mixtures. The reductions ranged from 78% (Ozone layer depletion) to 96% (Freshwater aquatic ecotoxicity and Marine aquatic ecotoxicity).
- Of the several mixed-in-place CTB alternatives considered, the alternative comprising 100% available in-situ RAP (by milling the old pavement) and 5.0% cement was found to be the most environmentally friendly.
- Of the central-plant-mixed CTB alternatives, the one consisting of 100% virgin aggregates and 5.0% cement was found to be the preferable option from an environmental standpoint.
- Overall, the effect of uncertainties is more pronounced in mixed-in-place CTB alternatives than in central-plant-mixed CTB alternatives.

Of the central-plant-mixed CTB alternatives, Figure 8 shows that the CTB0RAP5.0CPM option is the most environmentally preferable in the sense that the means of its impact category scores are the lowest in 8 out of 11 impact categories. The exceptions are the Depletion of abiotic resources – elements, the Depletion of abiotic resources – fossil fuels and the Ozone layer depletion impact categories, for which the alternative CTB100RAP5.0CPM was found to be less environmentally damaging. These results show that despite the fact that cement is generally recognised as one of the most environmentally burdensome construction materials, its use in some CTB alternatives improves the mechanical performance of the pavement layers, thereby allowing a reduction in the thickness of the CTB layer and consequently of the total quantity of materials used and the corresponding environmental impacts. Furthermore, from Figure 8, one can observe that all the alternatives with the higher percentage of cement (5.0%) are preferable to their counterparts with less cement (3.5%). This is true for all RAP percentages and is a consequence of the possible reduction in CTB thickness of at least 20 cm that mitigates the impacts of the higher quantity of cement by reducing significantly the quantities of other materials while maintaining the same performance level.

When analysing in more detail the effect on the environmental performance of the use of RAP in mixed-in-place CTB alternatives, the results displayed in Figure 8 show that no broad, widely applicable statements can be made about the superiority of alternatives containing higher or lower percentages of RAP.

In order to determine the influence of the uncertainties attached to the environmental impact category scores, coefficients of variation (COV) were calculated (Figure 9). These are presented as the ratio of the standard deviation to the mean, thereby representing the level of dispersion around the mean. The most striking result that emerges from the analysis shown in Figure 9 is that, overall, the COVs of mixed-in-place CTB alternatives with RAP are greater than those associated with central-plant-mixed CTB alternatives with RAP. Apart from the Freshwater aquatic ecotoxicity, Human toxicity and Marine aquatic ecotoxicity impact categories, only in one of the eleven impact categories (Terrestrial ecotoxicity) does the COV of central-plant-mixed CTB alternatives exceed 50% (specifically 52%). In comparison, for the mixed-in-place CTB alternatives, the COVs, excluding for the Ozone layer depletion and Terrestrial ecotoxicity impact categories, are at least 50%. Further, the variability in the impact category scores for the
Fig. 7. Means and 95% confidence intervals of the environmental impact scores for the mixed-in-place CTB alternatives: a) Acidification (AC); b) Climate change (CC); c) Depletion of abiotic resources – elements (DAE-E); d) Depletion of abiotic resources - fossil fuels (DAE-FF); e) Eutrophication (Eu); f) Freshwater aquatic ecotoxicity (FAE); g) Human toxicity (HT); h) Marine aquatic ecotoxicity (MAE); i) Ozone layer depletion (OLD); j) Photochemical oxidation (PO); k) Terrestrial ecotoxicity (TE).
Fig. 7. (continued).
Fig. 7. (continued).
The environmental impact categories are more uniformly affected by the effects of the uncertainties in mixed-in-place CTB alternatives than in central-plant-mixed CTB alternatives.

Based on the conclusions above, it can be asserted that the most environmentally sustainable solutions can be found in the appropriate compromise between the quantity of cement used and the RAP content. While a higher quantity of cement increases the environmental impacts due to its production, it also gives the CTB layer greater strength. This allows a thinner CTB layer, leading to a reduction of the environmental impacts deriving from material transportation, CTB layer production and in-situ operations. Finally, the considerable environmental impacts related to the transportation of materials highlight the importance of promoting the acquisition of local materials.

8.2. Limitations

Despite the value of the conclusions presented above, the research work presented in this paper is not without its limitations. The first important limitation lies in the assumptions made regarding the value of the elastic modulus of the CTB mixtures with RAP. Under current standards, the in-situ production and application of CTB does not require elastic modulus tests. Therefore, a number of assumptions had to be made in the LCA study as one could not combine reliable laboratory and in-situ tests and primary data. Similarly, data on laboratory tests of CTB mixtures containing RAP are limited. Consequently, additional assumptions had to be made which increase the uncertainties attached to the processes and subsequent results.

The second main limitation of this research work lies in the assumption that the quantities of materials to be used in the construction of the CTB layers are deterministic, thereby ignoring uncertainties associated with the pavement design parameters.
Fig. 8. Means and 95% confidence intervals of the environmental impact scores for the central-plant-mixed CTB alternatives: a) Acidification (AC); b) Climate change (CC); c) Depletion of abiotic resources – elements (DAE-E); d) Depletion of abiotic resources - fossil fuels (DAE-FF); e) Eutrophication (Eu); f) Freshwater aquatic ecotoxicity (FAE); g) Human toxicity (HT); h) Marine aquatic ecotoxicity (MAE); i) Ozone layer depletion (OLD); j) Photochemical oxidation (PO); k) Terrestrial ecotoxicity (TE).
Fig. 8. (continued).
Fig. 8. (continued).
8.3. Recommendations for future research

Based on the limitations identified above, several opportunities for future research can be identified that would enhance a decision-maker’s capacity to make better informed decisions. The first research line should aim to improve the knowledge of the mechanical characteristics of CTB mixtures, especially when containing recycled materials. Another possibility for future research work would be to develop a probabilistic pavement design approach that takes into account the uncertainties associated with the pavement design parameters, thereby improving the reliability of the pavement design process and the confidence in the results. A third research direction would be to quantify the costs associated with construction of CTB layers using different materials and construction modes. Finally, recognising that a decision-making process based on the results presented in the present paper could be labelled as a multi-criteria decision-making process due to the multiplicity of the impact categories and alternatives involved, the final suggestion offered for future research concerns the development of a stochastic multicriteria decision-making model that not only accounts for uncertainties related to the quantification of the impact category scores (and costs), but also for the uncertainties related to the role of human judgement in the weighing process.

CRediT authorship contribution statement

Sara Bressi: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization, Supervision. Michele Primavera: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation. João Santos: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization, Supervision.
Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2022.106160.

Fig. 9. Coefficients of variation of environmental impact categories scores of: a) mixed-in-place CTB alternatives, and b) central-plant-mixed CTB alternatives. Acronyms: Acidification (Ac), Climate change (CC), Depletion of abiotic resources – elements, ultimate reserves (DAR-E), Depletion of abiotic resources – fossil fuels (DAR-FF), Eutrophication (Eu), Freshwater ecotoxicity (FAE), Human toxicity (HT), Marine ecotoxicity (MAE), Ozone layer depletion (OLD), Photochemical oxidation (PO), and Terrestrial ecotoxicity (TE).

References


