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# Integrated and Comparative Structural-LCA Analysis of Unbound and Cement-Stabilized Construction and Demolition Waste Aggregate for Subbase Road Pavement Layers Formation

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**ABSTRACT**

A more extensive use of recycled aggregate in road construction is key to meeting the ambitious targets of the EU circular economy action plan. However, scepticism among designers, contractors and road agencies remains a bottleneck. This integrated structural-environmental study demonstrates the advantages of using recycled construction and demolition waste aggregate (CDW-RA) in substitution of primary natural aggregate (NA) for the formation of subbase layers in both flexible and semi-rigid road pavements. The structural responses of different pavements with a 0.30 m subbase layer made up of four materials, i.e., two unbound and two cement-stabilized obtained including NA and CDW-RA, were compared. The environmental-related impacts were also assessed by means of a life cycle assessment (LCA).

Laboratory tests and structural design led to pavement structures with the same thickness for the upper hot-mix asphalt layers, i.e., 0.26 and 0.28 m for the two unbound and the two cement-stabilized subbase materials respectively. The pavement with unbound CDW-RA subbase showed the best LCA outcomes because of the more favourable environmental performance of CDW-RA compared to NA. Although the stabilization of NA and CDW-RA reduces the thickness of the top hot-mix asphalt layers by 0.02 m, the environmental benefits are outweighed by the impact associated with the usage of cement. This study encourages the use of CDW-RA in road subbase layers with similar characteristics to those investigated here. The LCA results also support the use of alternative and more environmentally friendly binders that can enhance the environmental sustainability of stabilized materials in road construction.

**KEYWORDS:** Construction and demolition waste, pavement structural design, life cycle assessment, road subbase construction, recycled aggregates

## HIGHLIGHTS

- An integrated and comparative structural-LCA analysis of flexible and semi-rigid road pavements
- Construction and demolition waste aggregate (CDW-RA) in lieu of natural aggregate (NA) for subbase layer formation
- Unbound CDW-RA shows the most favourable LCA outcomes for the same pavement service life
- The thickness reduction in cement-stabilized materials offset by the negative environmental impact of the use of cement
- Subbase with CDW-RA used in substitution of NA results in a reduction of 9% in pavement costs

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## 1. INTRODUCTION

The use of recycled aggregate is strategic for the sustainability of the construction sector and the preservation of natural resources (Peng et al., 1997; Ghisellini et al., 2018). The recycling of construction and demolition waste (CDW) is among the priorities of the European Circular Economy Action Plan (European Commission, 2020). At present, the production of secondary aggregate from CDW is increasing and, together with primary aggregates from quarrying activities, it is able to meet the needs of the construction industry. In 2018, around 80% of the 850 million tons of CDW generated in EU-28 was sent for recovery and recycling (Villoria Sáez and Osmani, 2019), while 2.45 billion tons of primary aggregates coming from quarries and gravel pits were produced (European Aggregates Association, 2020).

CDW contains solid particles of concrete, asphalt, ceramics, and soils, all of which can be reused as road construction materials. CDW is transformed into recycled aggregate (RA) through cleaning, crushing and sieving operations (Kourmpanis et al., 2008; Marzouk and Azab, 2014; Zhao et al., 2010). Due to the large volume involved, the greatest amount of CDW-RA is currently employed as a filling material in earthworks (Arulrajah et al., 2013; Cardoso et al., 2016), and occasionally in unbound and stabilized layers of road pavements (Ossa et al., 2016; Tefa et al., 2021). In these applications, CDW-RA performs satisfactorily (Bassani and Tefa, 2018; Bennert et al., 2000; Leite et al., 2011; Tavira et al., 2018) and is also appreciated because it is cheaper than natural aggregates (Zhao et al., 2021).

Despite this evidence, there is significant scepticism among engineers and contractors regarding the use of CDW-RA due to the low quality of some recycled products and the conservative approach among users (Silva et al., 2019). Furthermore, several contractual clauses still require the exclusive use of materials of natural origin, hence ruling out the use of CDW-RA (Park and Tucker, 2017; Huang et al., 2018). In the current scenario, the economic benefits of a widespread use of CDW-RA in roadworks must be established beyond doubt, while also considering the significant environmental, sustainability-related issues.

### 1.1 Problem statement

Flexible and semi-rigid road pavements are layered systems. Hot mix asphalt (HMA) top layers require high quality aggregates but limited quantities of recycled materials. Conversely, the subbase and the subgrade can be made up with a predominant amount of RA as they are subjected to lower stress levels from vehicular traffic (Behiry, 2013). The mechanical properties of the subbase affect the structural response of the upper HMA layers in terms of design life and thickness (Christopher et al., 2006). Thicker HMA layers are necessary to compensate for a weaker subbase layer. Therefore, the environmental balance of the entire pavement structure may be compromised if the subbase contains low-quality RA.

A number of Life Cycle Assessment (LCA) studies have demonstrated the environmental benefits of converting CDW into RA rather than resorting to the use of primary aggregates (Di Maria et al., 2018; Knoeri et al., 2013; Marzouk and Azab, 2014; Jain et al., 2020; Simion et al., 2013). For instance, Ghanbari et al. (2018) compared the energy consumption and the level of $CO_2$ emissions for natural aggregate (NA) and RA production, concluding that CDW-RA is the best solution with 60 and 72% of energy saving and $CO_2$ emissions respectively. Other studies have demonstrated the environmental benefits of CDW recycling with respect to NA quarrying (Blengini and Garbarino, 2010; Blengini et al., 2012; Faleschini et al., 2016; Borghi et al., 2018). However, in these studies the LCA was limited to the production stage boundaries, i.e., the cradle-to-gate approach, without exploring the implications of using RA instead of NA in the construction and in the service life of a road pavement.

### 1.2 Study objective

This study integrates structural and LCA analyses so as to compare the environmental impacts of the use of NA and CDW-RA in the subbase layer of flexible and semi-rigid road pavements. Therefore, unbound granular materials (NA and CDW-RA), and cement-stabilized mixtures with both NA and CDW-RA were included in the comparative analysis. This study extends the "cradle-to-gate" approach, which typically characterizes LCA studies, to the specific application in which this secondary resource is employed. To meet this objective, the structural response of the entire pavement was assessed to determine the thickness of the upper HMA layers when different materials were employed for the subbase layer.

This integrated structural-LCA approach was supported by a laboratory investigation aimed at including the mechanical properties of the four subbase materials (i.e., unbound NA, cement-stabilized NA, unbound CDW-RA, and cement-stabilized CDW-RA) in the analysis. Four different pavement structures were considered while assuming the thickness of the HMA top layers to be dependent on the stiffness of the four subbase materials. Thus, the same subbase layer thickness and loading conditions were assumed for a standard 20-year service life. The LCA was set up by considering a functional unit of 1 $m^2$ of pavement including HMA layers, the subbase, and the subgrade.

Six different LCA scenarios were modelled and compared: two scenarios with unbound NA and CDW-RA, and four others with cement-stabilized materials with the two aggregate types (NA and CDW-RA) both of which were produced either in-plant or on-site before being laid on-site. The LCA included all the relevant operations required to build the road pavement: (i) the production and transport of raw and composite materials, (ii) the mixing in-plant or at the construction site of cement-stabilized materials, (iii) the construction of pavement layers with laying and compaction operations. Maintenance cycles and end-of-life scenarios were not included.

## 2. METHODS

### 2.1 Structural design and analysis

Table 1 lists the assumptions for (i) the structural behaviour of materials, (ii) the layer characteristics, and (iii) the pavement composition. The stress-strain response of each pavement structure was evaluated using KENPAVE pavement analysis software from Huang (2003). Three reference seasonal periods (Winter, Summer, and Spring/Autumn) were considered to account for the thermo-dependant behaviour of HMA layers. For each of these periods, the average temperature inside the pavement was estimated from the mean air temperature in the Turin area (North-West of Italy) according to the Witczak model (Witczak, 1972).

The HMA was considered a linear elastic isotropic material with a constant Poisson ratio of 0.35. The elastic modulus ($E_{HMA}$) was assumed equal to the norm of the complex modulus ($|E^*_{HMA}|$) and predicted according to the Hirsh model (Christensen Jr et al., 2003), which considers the shear complex modulus of the bitumen (G*) and the volumetric properties of the mixture (Table 2). G* at the specific temperature (depending on the seasonal period) and frequency (10 Hz) was retrieved from the master curve and the corresponding model parameters of a 50/70 pen grade virgin bitumen provided by Mazzoni et al. (2018). Base, binder, and wearing HMA layers were considered by bonding them together with a tack coat of bitumen emulsion, thus a full adhesion was assumed in the structural model. Similarly, the interface between the HMA base layer and stabilized subbase was deemed to be fully bonded in the analysis due to the presence of a prime coat.

Each subbase material was modelled as non-linear elastic isotropic. Unbound and cement-stabilized granular materials exhibit a stiffness that depends on the stress state (Lekarp et al., 2000). As a result, in the structural analysis the 0.30 m subbase layer was split into six 0.05 m sublayers, and the resilient modulus of each sublayer was iteratively calculated (Huang, 2003). The resilient response of the subbase layer was determined according to the k-θ model (Hicks and Monismith, 1971) using the regression coefficients $k_1$ and $k_2$, garnered from the laboratory tests performed on subbase materials (see Section 3). A Poisson ratio of 0.40 and 0.25 was assumed for unbound and cement-stabilized materials respectively. Details about the stress-strain response of the four investigated subbase materials listed in Table 1 are in Section 3. Finally, the subgrade was modelled as a semi-infinite elastic isotropic layer with a constant modulus of 50 MPa and a Poisson ratio of 0.45.

The pavement structure was designed to support $3 \cdot 10^6$ load applications of 80-kN equivalent single axle load (Huang, 2003), which can be regarded as a medium loading condition for a two-lane rural highway in Italy. The number of allowable load repetitions was estimated with the Asphalt Institute criteria for (i) fatigue cracking due to repeated horizontal tensile strain at the bottom of the HMA layers, and (ii) permanent deformation failure due to excessive repeated compressive vertical strain at the top of the subgrade (Asphalt Institute, 1982). The Miner’s law was used for the cumulative damage computation for failures caused by fatigue and permanent deformations in the HMA layers and on top of the subgrade layer respectively (Huang, 2003).

**Table 1 – Hypotheses for the structural analysis of pavements**

| Layer | Thickness | Materials | Structural behaviour |
|---|---|---|---|
| HMA layers | variable | HMA | elastic, isotropic |
| Subbase | 0.30 m | U-NA, U-CDW-RA, CS-NA, CS-CDW-RA | non-linear elastic, isotropic |
| Subgrade | semi-infinite | Soil | elastic, isotropic |

Notes: HMA = hot mix asphalt, U-NA = unbound natural aggregates, U-CDW-RA = unbound construction and demolition waste recycled aggregate, CS-NA = cement-stabilized natural aggregate, CS-CDW-RA = cement stabilized construction and demolition waste recycled

**Table 2 – Assumptions on volumetric properties of HMA layers**

| Layer | Volume in the asphalt mixture (%) | | |
|---|---|---|---|
| | Bitumen | Aggregate | Void content |
| Base | 10.5 | 83.4 | 6.1 |
| Binder | 11.7 | 83.0 | 5.3 |
| Wearing | 12.9 | 82.7 | 4.1 |

## 2.2 Life Cycle Assessment

The LCA was developed according to (i) ISO 14040 (International Organization for Standardization, 2006a), (ii) ISO 14044 (International Organization for Standardization, 2006b), and (iii) International Reference Life Cycle Data System (ILCD) Handbook (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2010). The life cycle impact assessment (LCIA) was evaluated as per the ILCD Midpoint+ (version 1.0.9) and the Cumulative Energy Demand (CED) methods, as recommended by the European Commission, with attention paid to the indicators of (i) acidification, (ii) climate change, (iii) photochemical ozone formation, (iv) total human toxicity, (v) total consumption of non-renewable resources, and (vi) total consumption of renewable resources. The choice was based on the relevance of these impact categories to the construction sector and/or on the higher level of readiness of the calculation method (European Commission - Joint Research Centre - Institute for Environment and Sustainability, 2012). The analysis was supported by openLCA 1.10.3 software and Ecoinvent 3.1 database.

## 2.3 Functional unit and scenarios

Fig. 1 shows the functional unit of 1 $m^2$ of pavement structure considered in the LCA. The pavement section includes the HMA layers divided between the surface layer (wearing and binder course), and the road base; the subbase layer is made up of unbound or cement-stabilized NA and CDW-RA and is laid over the subgrade.

Starting from the four pavement structures deriving from a combination of four different subbase materials (U-NA, U-CDW-RA, CS-NA, CS-CDW-RA), a total of six LCA scenarios were analysed by considering two common construction techniques for cement-stabilized subbase materials: (i) in-plant mixing with subsequent transport of the cement-stabilized material to the construction site, and (ii) on-site mixing and laying by means of a soil stabilizer machine.

The following codes were adopted to univocally identify the six structural and LCA scenarios: (i) **U-NA**, unbound NA; (ii) **CS-NA-p**, cement-stabilized NA mixed in-plant; (iii) **CS-NA-s**, cement-stabilized NA mixed on the construction site; (iv) **U-CDW-RA**, unbound CDW-RA; (v) **CS-CDW-RA-p**, cement-stabilized CDW-RA mixed in-plant; and (vi) **CS-CDW-RA-s**, cement-stabilized CDW-RA mixed on the construction site.

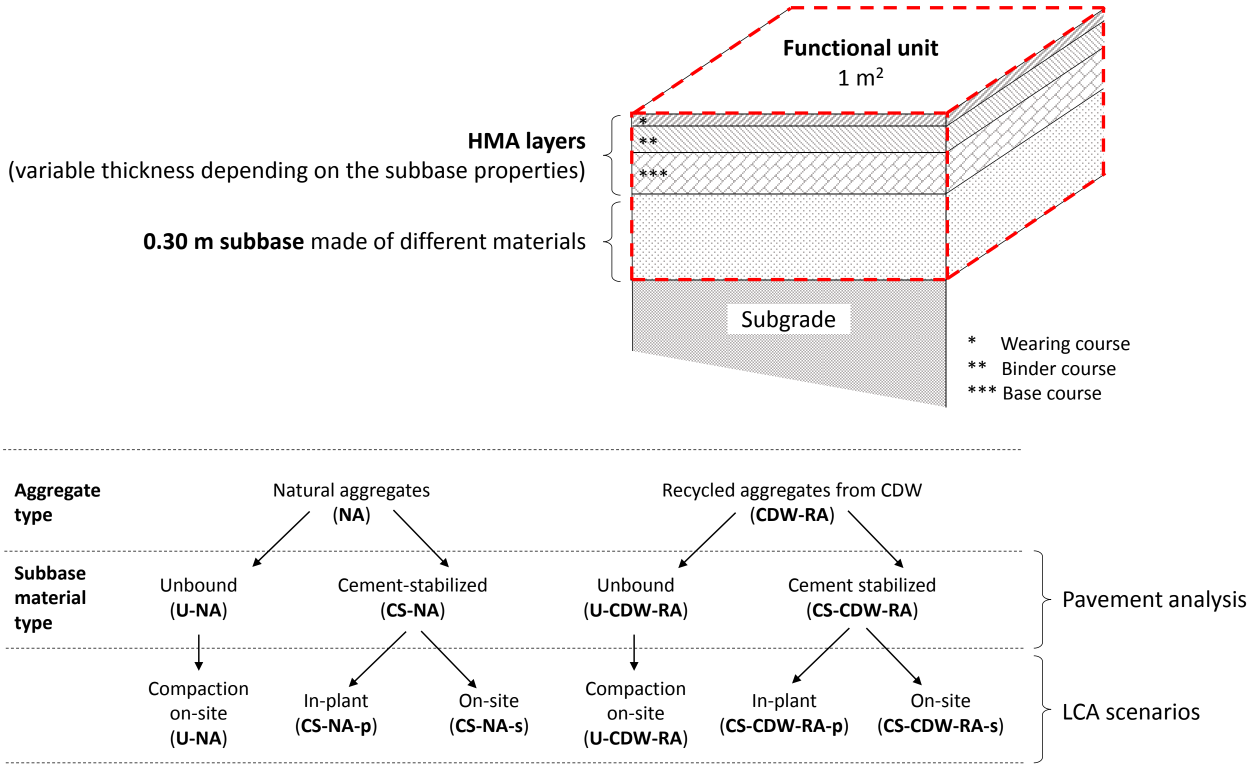



**Fig. 1 – Section of the four functional units considered in the structural and LCA analyses of the six scenarios**

## 2.4 System boundaries

The system boundaries included all relevant activities required for the six LCA scenarios, consistent with the adopted functional unit and considering the three sub-systems shown in Fig. 2. First, the production of primary (NA, cement, bitumen) or recycled (CDW-RA) materials was considered. Exploitation of non-renewable primary resources, quarrying operations with resource consumption, land use, emission levels, and the re-cultivation of the depleted quarry were included in the LCA model for the NA production (Blengini and Garbarino, 2010). In the case of CDW-RA, (i) the transport of waste from the construction/demolition site to the stationary recycling plant, (ii) treatment operations, and (iii) the avoidance of landfill operations for CDW were considered (Blengini and Garbarino, 2010). Moreover, a system expansion was introduced to consider the reduction in the production of primary steel due to the recovery of steel scraps in CDW (Borghi et al., 2018).

Primary/recycled materials were combined to evaluate the environmental impacts of the production of composite materials, i.e., cement-stabilized granular materials (CS-NA, CS-CDW-RA) and HMA, considering the levels of energy consumption for handling and mixing.

The construction of road pavement entailed: (i) transport, laying, humidification, and compaction of granular materials for the subbase formation, and (ii) paving and compaction for the HMA layer formation. Operations like cleaning, grubbing, and levelling of natural soil on which the embankment is built were not included in the system boundaries because they are identical in each scenario. Similarly, the preparation and the construction operations of the subgrade were not modelled in the LCA. Finally, maintenance and renovation phases were also excluded from the system boundaries.

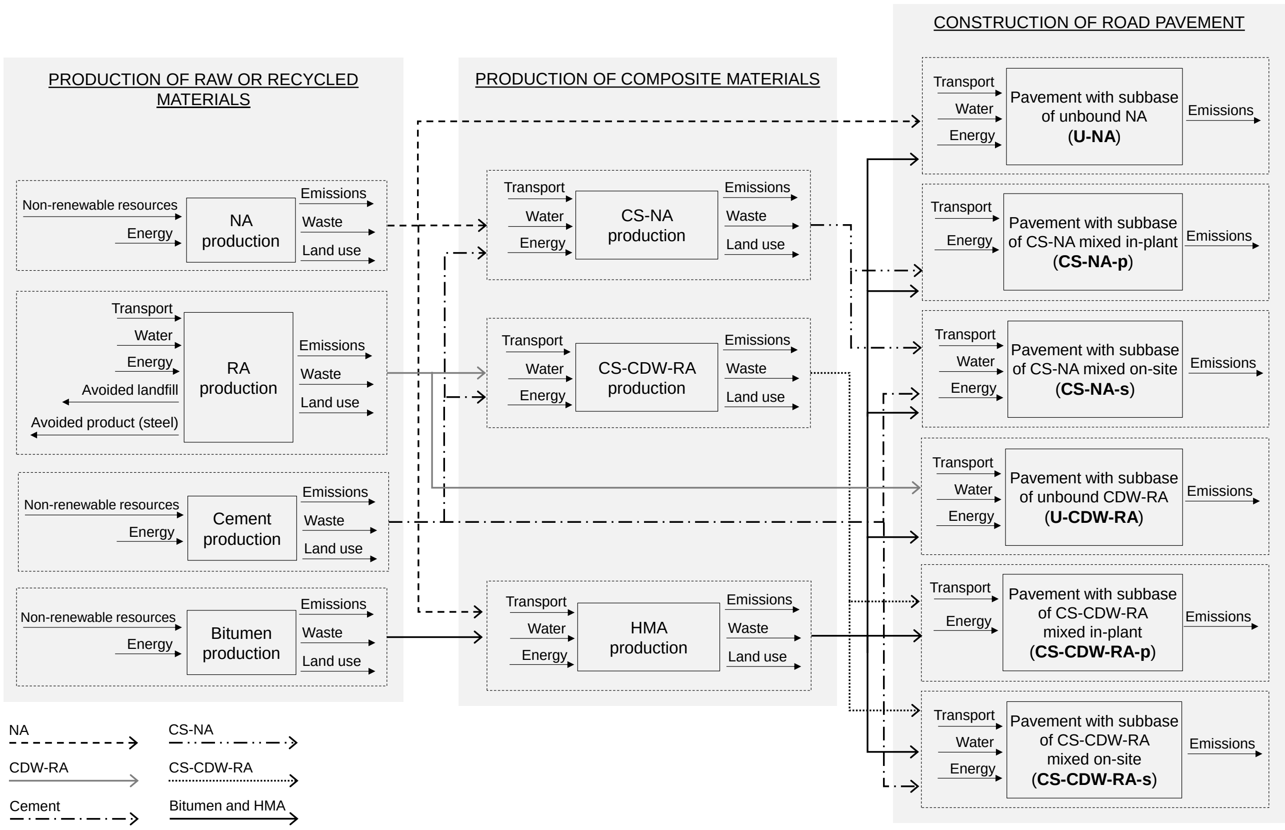



**Fig. 2 – Schematic representation of system boundaries in the investigated LCA scenarios**

## 3. LABORATORY TESTING OF THE STRUCTURAL PROPERTIES OF SUBBASE MATERIALS

A dedicated laboratory investigation aimed at characterizing the four unbound and stabilized materials was conducted. This stage was preparatory to obtaining the mechanical parameters of the subbase materials to be used as input data in the structural analysis.

Table 3 lists the mix-design proportions and the main properties of unbound (U-NA, U-CDW-RA) and cement-stabilized (CS-NA, CS-CDW-RA) subbase materials. To avoid any secondary effects on influencing factors, all materials had the same grading distribution in accordance with the Italian technical specifications (Ministero delle Infrastrutture e dei Trasporti, 2001). A Proctor study conforming to EN 13286-2 (European Committee for Standardization, 2010) was performed to estimate the optimum moisture content ($w_{opt}$). The two cement-stabilized materials included 3% in mass of a limestone Portland CEM-II/B-LL cement conforming to the EN 197-1 (European Committee for Standardization, 2011).

**Table 3 – Composition and properties of granular materials employed in the construction of the subbase layer**

| Material | $w_{opt}$ ([1]) (%) | Stabilizer | %s ([2]) | Curing (days) | Compacted dry density ($kg/m^3$) | k-θ model parameters and fitting evaluation | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | $k_1$ | $k_2$ | $R^2$ | Se/Sy ([4]) |
| U-NA | 6.5 | - | - | - | 2168 | 698 | 0.69 | 0.99 | 0.094 |
| CS-NA | 6.5 | CEM-II/B-LL ([3]) | 3.0 | 7 | 2172 | 3127 | 0.59 | 0.96 | 0.211 |
| U-CDW-RA | 8.5 | - | - | - | 1943 | 801 | 0.75 | 0.97 | 0.177 |
| CS-CDW-RA | 8.5 | CEM-II/B-LL ([3]) | 3.0 | 7 | 2069 | 2771 | 0.60 | 0.90 | 0.322 |

Notes: ([1]) optimal water content as mass percentage with respect to dry aggregates; ([2]) stabilizer content as mass percentage with respect to dry aggregates; ([3]) cement type II/B-LL according to EN 197 (European Committee for Standardization, 2011); ([4]) Se/Sy is the ratio between the standard error of estimate (Se) and the standard deviation (Sy) and expresses the goodness-of-fit as “excellent” for Se/Sy ≤ 0.35, “good” for 0.36 ≤ Se/Sy ≤ 0.55, “fair” for 0.56 ≤ Se/Sy ≤ 0.75, and “poor” for 0.76 ≤ Se/Sy ≤ 0.90 (Pellinen and Witczak, 2002).

Cylindrical specimens of 100 mm in diameter and 200 mm in height were compacted into four layers at the gyratory shear compactor (vertical pressure of 600 kPa, 100 gyrations for each of the four layers) and subjected to the repeated load triaxial tests for the resilient modulus (RM) measurement according to the AASHTO T-307 (American Association of State and Highway Transportation Officials, 2013). U-NA and U-CDW-RA specimens were tested immediately after compaction, while CS-NA and CS-CDW-RA specimens underwent mechanical tests after 7 days of curing at 90% of RH and at room temperature. All mixtures were replicated in three samples. Fig. 3 shows the average resilient modulus of the four subbase materials as a function of the first stress invariant (θ). RM test results were fitted according to the k-θ model (Hicks and Monismith, 1971) of eq. 1 for the estimation of regression coefficients $k_1$ and $k_2$ reported in Table 3.

$$\mathrm{RM} = k_1 \cdot p_a \cdot \left(\frac{\theta}{p_a}\right)^{k_2} \tag{1}$$

($p_a$ is the reference atmospheric pressure).

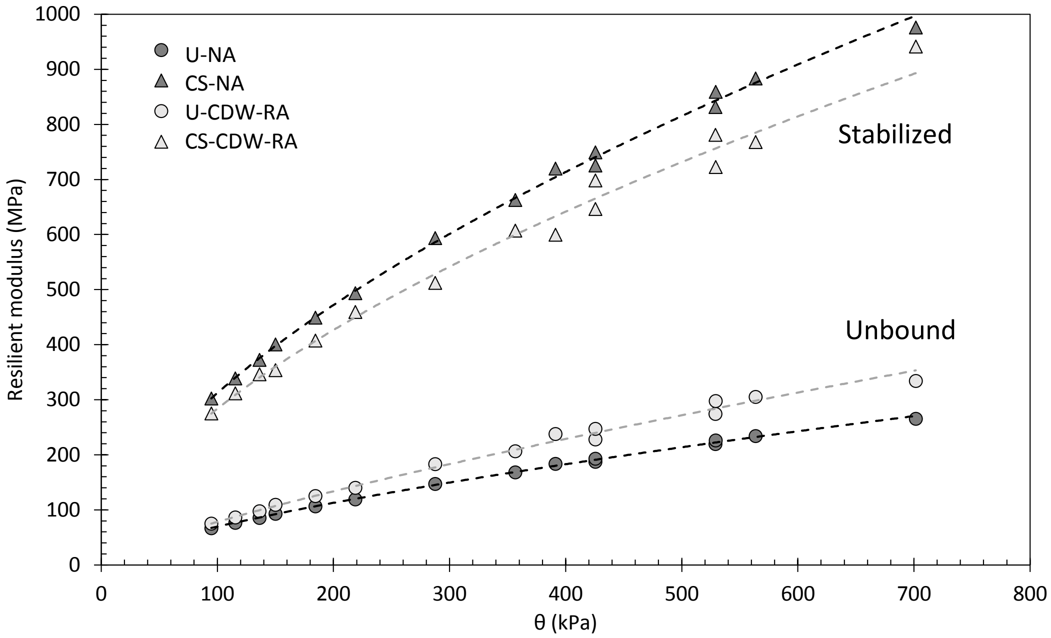



**Fig. 3 – Resilient modulus as a function of θ for (a) NA and (b) CDW-RA in both unbound and cement-stabilized conditions**

## 4. LIFE CYCLE INVENTORY

Life Cycle Inventory (LCI) data were collected from available literature specific to the Italian context. Interviews together with an analysis of energy consumption values were carried out to determine the LCI of the mixing plant to produce the cement-stabilized granular materials. The LCI data for the production of NA and CDW-RA were obtained from Blengini and Garbarino (2010). Eurobitume datasets of 2012 and 2020 (Eurobitume, 2012; Eurobitume, 2020) were used to model the production of bitumen emulsion and bitumen respectively. The LCA model of the pavement construction stage included the hourly production rates for roadwork machines and their respective fuel consumption rates (Celauro et al., 2017).

All materials were scheduled to be moved by road freight convoys from production facilities to mixing stations and/or the construction site. The travelled distances (Table 4) were selected based on the location of the aggregate quarrying/recycling plants and the binder (bitumen, bitumen emulsion, and cement) production plants in the North-West of Italy (Blengini and Garbarino, 2010).

**Table 4 – Assumptions on transport distances and truck type**

| Material | Route | Truck | Travelled distance |
|---|---|---|---|
| CDW (waste) | Demolition site → CDW recycling plant | 3.5-7.5 t (25% of mass)<br>7.5-16 t (25% of mass)<br>16-32 t (25% of mass)<br>>32 t (25% of mass) | 20 km |
| | Demolition site → Landfill | 3.5-7.5 t (25% of mass)<br>7.5-16 t (25% of mass)<br>16-32 t (25% of mass)<br>>32 t (25% of mass) | 25 km |
| CDW steel scrap | CDW recycling plant → Steel production plant | >32 t | 100 km |
| Cement | Production factory → Mixing plant for stabilized aggregates | 16-32 t | 50 km |
| | Production factory → Construction site | 16-32 t | 50 km |
| Bitumen | Production factory → Mixing plant for bituminous mixtures | 16-32 t (50% of mass)<br>>32 t (50% of mass) | 100 km |
| U-NA | Quarrying plant → Mixing plant for bituminous mixtures | >32 t | 30 km |
| | Quarrying plant → Construction site | >32 t | 20 km |
| U-CDW-RA | Recycling plant → Construction site | >32 t | 20 km |
| Water | Collecting plant → Construction site | 16-32 t | 10 km |
| CS-NA | Quarrying plant → Mixing plant | - | 0 km ([1]) |
| | Mixing plant → Construction site | >32 t | 20 km |
| CS-CDW-RA | Recycling plant → Mixing plant | - | 0 km ([1]) |
| | Mixing plant → Construction site | >32 t | 20 km |
| Bitumen emulsion | Production factory → Construction site | 7.5-16 t | 120 km |
| HMA | Mixing plant → Construction site | >32 t | 25 km |

Note: ([1]) mixing plants were considered to be located inside the quarrying site (for NA) or the recycling station (for CDW-RA) thus no transportation of NA or CDW-RA was accounted for in the LCA of production of in-plant cement-stabilized materials.

### 4.1 Production of raw materials

#### *4.1.1 NA*

The LCA model of NA quarrying was based on data reported by Blengini and Garbarino (2010), and was in reference to the Piedmont region. A quantity of 0.12 kg of gasoline, 3.0 kWh of electricity, and 0.06 kg of heavy fuel oil were the energy resources used to produce 1 ton of NA. The consumption of 1.39 m$^3$ of water, 0.044 kg of steel, 0.007 kg of rubber, and 0.002 kg of lubricating oil was included in the model as well. According to Blengini and Garbarino (2010), inventory data for the quarrying of NA also took into account factors relating to the quarrying plant construction and the recultivation of the site.

### *4.1.2 CDW-RA*

The CDW recycling process in stationary plants includes the transportation of waste from demolition/construction sites to the plant, and the operations to produce recycled aggregates (Blengini and Garbarino, 2010). The latter stage involves (i) cleaning operations of light materials (i.e., plastic, wood, and paper) and separation of steel residues, (ii) crushing and (iii) sieving (Coelho and Brito, 2013; Kourmpanis et al., 2008; Borghi et al., 2018).

The average distance from the demolition/construction site to the recycling plant was set equal to 20 km according to De Melo et al. (2011) and Rodríguez et al. (2015). A data inventory for the production of 1 ton of CDW-RA was taken from Blengini and Garbarino (2010), which assumed a consumption of 3.6 kWh of electricity, 0.56 kg of gasoline, 0.007 m$^3$ of water, 0.043 kg of steel, 0.019 kg of rubber, and 0.001 kg of lubricating oil. The LCI for RA production included flows and processes due to the installation of the stationary recycling plant. For the purposes of the analyses, an area of land extending to 25,000 m$^2$ was deemed to be occupied and transformed in use for 50 years and an annual production of 250,000 tons was considered for the recycling plant.

When CDW is recycled into RA, it is not disposed of into a landfill site, thus the avoidance of CDW landfill was included in the LCA according to Blengini and Garbarino (2010). Meanwhile, the reduction in the level of steel production needed due to the recovery of 0.13% in mass (Borghi et al., 2018) of steel scraps contained in CDW-RA was also introduced into the LCA analysis.

### *4.1.3 Binders*

The cement production was modelled using the Ecoinvent 3.1 database (Wernet et al., 2016), while the Eurobitume LCI was adopted for modelling the impacts due to the production of the bitumen (Eurobitume, 2020) and the bitumen emulsion (Eurobitume, 2012).

## 4.2 Production of composite materials

### *4.2.1 Cement-stabilized NA and RA (in-plant)*

Data for the in-plant production of cement-stabilized material were gathered from different sources. Average electricity consumption values for the mixing plant were calculated from technical datasheets available in the Italian market. The consumption of lubricating oil and steel and energy required for mixing aggregates and cement in a stationary plant were derived from Gschösser et al. (2012) and adjusted for the investigated materials (Table 5).

**Table 5 – Energy and material resources required for producing 1 ton of cement-stabilized material**

| | | CS-NA | CS-CDW-RA |
|---|---|---|---|
| Electricity | (kW) | 0.41 | 0.46 |
| Gasoline ([1]) | (MJ) | 13.8 | 15.2 |
| Lubricating oil | (kg) | 0.007 | 0.008 |
| Steel | (kg) | 0.014 | 0.015 |
| Mixing plant | (item) | $2.77 \cdot 10^{-7}$ | $3.07 \cdot 10^{-7}$ |
| NA | (kg) | 1505 | - |
| CDW-RA | (kg) | - | 1337 |
| Cement | (kg) | 45 | 40 |
| Water | ($m^3$) | 0.10 | 0.11 |

Note: ([1]) Gasoline burned in wheel loader.

The mixing plants were considered to be located inside the quarrying site for NA, and at the recycling station for CDW-RA, thus no occupation and transformation in land use was included in the inventory analysis of the infrastructure. The production of cement-stabilized materials also included the consumption of NA or CDW-RA, water, and cement. No transportation of aggregates was added, while the transport distance of cement from the production factory was set equal to 50 km (Table 4).

### *4.2.2 Hot mix asphalt (HMA)*

A data inventory for the production of 1 ton of HMA was derived from Gschösser et al. (2012) and included 11.1 MJ of gasoline burned by wheel loaders, 8.6 kWh of medium voltage electricity, 175.8 MJ of heat produced by natural gas and light fuel oil, 0.003 kg of lubricating oil and 0.009 $m^3$ of water. The impact due to the construction of a HMA plant was included in the inventory and quantified as $2.51 \cdot 10^{-7}$. The production of HMA also requires NA (Section 4.1.1) and bitumen in different proportions depending on the bitumen-bounded layer, i.e., the base, binder, and wearing courses.

## 4.3 LCA modelling of the six scenarios for road construction

The LCA model for the six scenarios relating to the functional unit included some common activities. Primary/recycled materials and composite mixtures were to be transported from the plant to the construction site in dump trucks for the distances reported in Table 4. The construction of HMA layers was modelled according to the LCI of values for the productivity and fuel consumption of equipment documented in Celauro et al. (2017). The impact of (i) the dump trucks for the transportation of HMA mixtures, (ii) the road pavers for laying the material, and (iii) the tandem vibratory rollers for compaction were accounted for in the LCA inventory of HMA layer formation. Each HMA layer (road base, binder and wearing courses) was modelled so as to include the impacts and the consumption rates of bituminous emulsion used to form tack and prime coats. The thickness of the HMA layers varied depending on the scenario, thus different quantities of HMA were included in the input data.

The subbase construction was split into two sublayers of 0.15 m height each. Fig. 4 illustrates all the activities and equipment considered in the LCA model for the subbase formation. The layers made from unbound granular materials (U-NA, U-CDW-RA) were laid, levelled, water corrected, and compacted. Cement-stabilized materials produced in plant (CS-NA-p, CS-CDW-RA-p) were considered simply laid and compacted on-site. For CS-NA-s and CS-CDW-RA-s scenarios (on-site mixing), (i) laying, (ii) spreading of cement, (iii) moistening and mixing through soil stabilizer machines (e.g., Pulvimixer), and (iv) compaction operations were all taken into account.

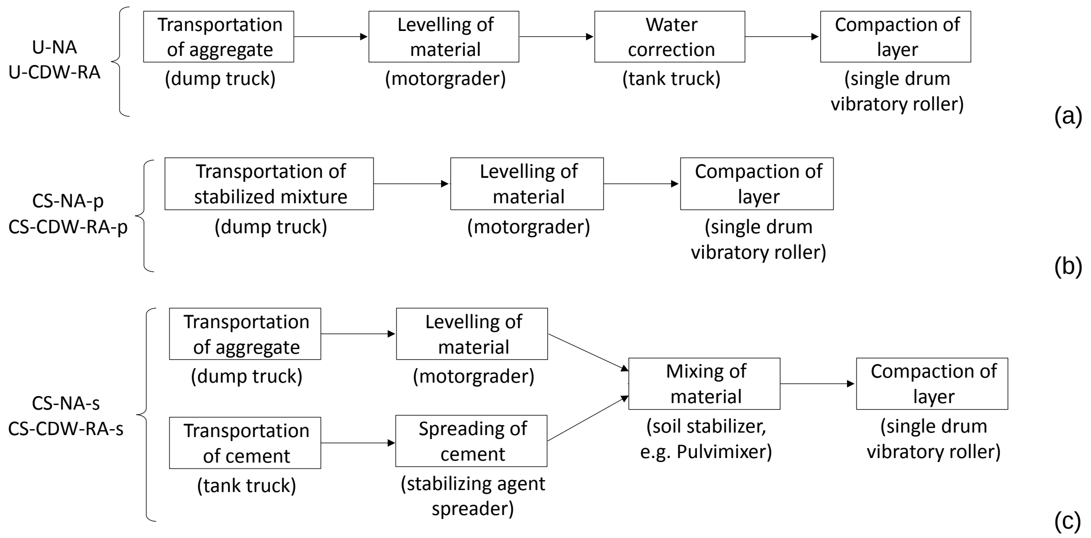



**Fig. 4 – Operations included in the LCA model for the construction of subbase layer depending on the scenario: (a) U-NA, U-CDW-RA, (b) CS-NA-p, CS-CDW-RA-p, and (c) CS-NA-s, CS-CDW-RA-s**

## 5. RESULTS AND DISCUSSION

### 5.1 Pavement structural analysis

Table 6 shows the results of the structural design of the road pavements for the four materials included in the subbase layer. Pavement structures with unbound materials (U-NA and U-CDW-RA scenarios) required a HMA layer to have a thickness of 0.28 m (0.16 m of base, 0.08 m of binder, and 0.04 m of wearing course) independently of the aggregate used (NA or CDW-RA).

The stabilization of both NA and CDW-RA with 3% (in mass) of cement entails an improvement in their stress-strain properties with respect to the unbound materials (Table 3 and Fig. 3). The structural analysis revealed that a stiffer subbase was able to reduce the horizontal tensile strain at the bottom of the HMA base layer (423.6 and 371.5 μm/m for the U-NA and CS-NA; 422.1 and 378.6 μm/m for the U-CDW-RA and CS-CDW-RA respectively). The vertical strain at the top of the subgrade remains almost constant regardless of the subbase material treatment (117.6 and 123.3 μm/m for the U-NA and CS-NA; 118.1 and 124.1 μm/m for the U-CDW-RA and CS-CDW-RA respectively). Therefore, a stiffer subbase made up of stabilized aggregates ensures a longer pavement service life than a subbase made of unbound aggregates. According to the assumption made in this study (i.e., HMA layer thickness adjusted to achieve a 20-year service life under design traffic), a reduction of 0.02 m in the upper HMA layer thickness for cement-stabilized subbases was assumed (Section 2.1). Table 6 shows the thickness (input for the structural analysis) and the critical strains resulting from the six scenarios.

Therefore, the total thickness of the HMA layer (i.e., 0.14, 0.08, and 0.04 m of base, binder, and wearing course respectively) of pavements with cement-stabilized subbase was set equal to 0.26 m independently of the origin of the aggregate (CS-NA or CS-CDW-RA). The structural analysis indicates that the use of CDW-RA in place of NA does not require thicker HMA layers due to the similar mechanical properties shown by NA and CDW-RA in both their non-stabilized and stabilized forms, as evidenced in Fig. 3.

Table 6 also summarizes the total cost (per m$^2$) for each scenario, derived from the unit cost of construction of each road layer as per the Regional Unit Cost list of the Piedmont Region, Italy (Regione Piemonte, 2021). The pavement structure with U-CDW-RA subbase has the lowest total construction costs (47.30 €/m$^2$) due to the significantly lower unit cost of recycled aggregates with respect to NA. Comparing U-NA and U-CDW-RA pavement solutions, the latter results in a cost saving of 9.5%. Despite the stabilization with cement of both types of aggregates leading to a thinner HMA base, the high construction unit costs of cement-stabilized subbase increase the total costs of CS-NA and CS-CDW-RA scenarios by 4.6 and 5.1% in comparison to pavements with unbound subbase layers (U-NA and U-CDW-RA).

**Table 6 – Thickness, structural response, and total costs (m$^2$) of pavement layers for the six LCA scenarios.**

| LCA scenarios | U-NA | U-CDW-RA | CS-NA-p<br>CS-NA-s | CS-CDW-RA-p<br>CS-CDW-RA-s |
|---|---|---|---|---|
| **Thickness (m)** | | | | |
| Subbase | 0.30 | 0.30 | 0.30 | 0.30 |
| HMA base | 0.16 | 0.16 | 0.14 | 0.14 |
| HMA binder | 0.08 | 0.08 | 0.08 | 0.08 |
| HMA wearing | 0.04 | 0.04 | 0.04 | 0.04 |
| **Structural response in strain for 20-year design life (μm/m)** | | | | |
| Horizontal strain at the bottom of HMA base | 423.6 | 422.1 | 416.9 | 425.6 |
| Vertical strain on top of the subgrade layer | 117.6 | 118.1 | 137.8 | 138.8 |
| **Unit costs (€/m$^3$) (*)** | | | | |
| Subbase | 28.88 | 12.16 | 46.85 | 30.13 |
| HMA base | 144.02 | | | |
| HMA binder | 162.76 | | | |
| HMA wearing | 189.62 | | | |
| **Total costs (€/m$^2$)** | 52.31 | 47.30 | 54.83 | 49.81 |

Notes: HMA = hot mix asphalt, (*) = Unit Costs list (Regione Piemonte, 2021).

## 5.2 LCIA of subbase materials production

Fig. 5 compares the main impacts arising from the production of 1 ton of different subbase materials albeit it only includes the LCA results to produce unbound (NA and CDW-RA) and cement-stabilized NA and CDW-RA materials mixed in-plant.

The LCA outcomes indicate that the production of CDW-RA has a lower environmental impact and resource consumption than the production of NA. All ILCD and CED indicators show negative values for the CDW-RA production, thus confirming the environmental benefits of this waste treatment. For instance, the acidification indicator (Fig. 5-a), which is mainly caused by air emissions of $NH_3$, $NO_2$, and $SO_X$ (Joint Research Centre and Institute for Environment and Sustainability, 2012), is equal to 0.019 Mole $H^+$ eq./ton for NA, while it results negative and equal to -0.036 Mole $H^+$ eq./ton in the case of CDW-RA. Analogously, when considering the consumption of non-renewable resources (Fig. 5-e), its value is equal to 44.3 and -119.6 MJ/t for NA and CDW-RA production respectively. The negative impact values for CDW-RA production are mainly ascribable to the environmental benefits stemming from the avoided CDW landfill (Blengini and Garbarino, 2010). This aspect can be appreciated in the climate change contribution analysis of Fig. 6-b, which expresses the percentage contributions of each factor to the overall climate change impact arising from the production of 1 ton of CDW-RA. The avoidance of CDW landfilling accounts for an environmental credit (i.e., a negative impact) of 229.4% when determining the impact of total climate change, thus compensating for the impacts (positive) of the operations conducted to convert the waste into a resource. In line with previous LCA studies on the management of CDW (Bovea and Powell, 2016; Chowdhury et al., 2010; Hossain et al., 2016), the transport of waste from the generation site to the recycling plant represents the greatest contribution (almost 79%) to the climate change impact figure. A significant contribution to the same indicator is also caused by the consumption of electricity and fossil fuels during the recycling operations. The beneficial impact due to the recovery of steel is limited because of the small percentage of steel scraps in CDW set equal to 0.13%.

As far as NA is concerned (Fig. 6-a), around two thirds of the climate change value (2.93 kg $CO_2$ eq./ton) due to its production is caused by the electricity consumption needed to quarry and treat the raw material.

The LCA results in Fig. 5 indicate that the addition of small quantities of cement to both NA and CDW-RA significantly increases the impacts. The acidification indicator increases around 3.5 and 2 times when passing from NA and CDW-RA to CS-NA and CS-CDW-RA respectively. When cement is added to stabilize the granular material, there is a marked increment in the climate change results, as well as the consumption of non-renewable (Fig. 5-e) and renewable (Fig. 5-f) resources. When considering the production of CS-CDW-RA, the addition of cement nullifies the environmental credits gained from CDW-RA production. Fig. 7 shows that the presence of cement in stabilized materials makes the greatest contribution to climate change (around 85.8% and 117.0% for CS-NA and CS-CDW-RA respectively), while the impact figures due to the aggregate production and mixing operations become relatively negligible.

Despite the use of limestone Portland cement significantly increasing all environmental indicators, the production of CS-CDW-RA has a lower environmental impact and resource consumption than the more common and traditional CS-NA because of the environmental credits associated with CDW-RA production. From an LCA point of view, the outcomes of this level of investigation strengthen the case for the use of CDW-RA in substitution of NA to produce cement-stabilized material to be employed in the subbase layers of road pavements.

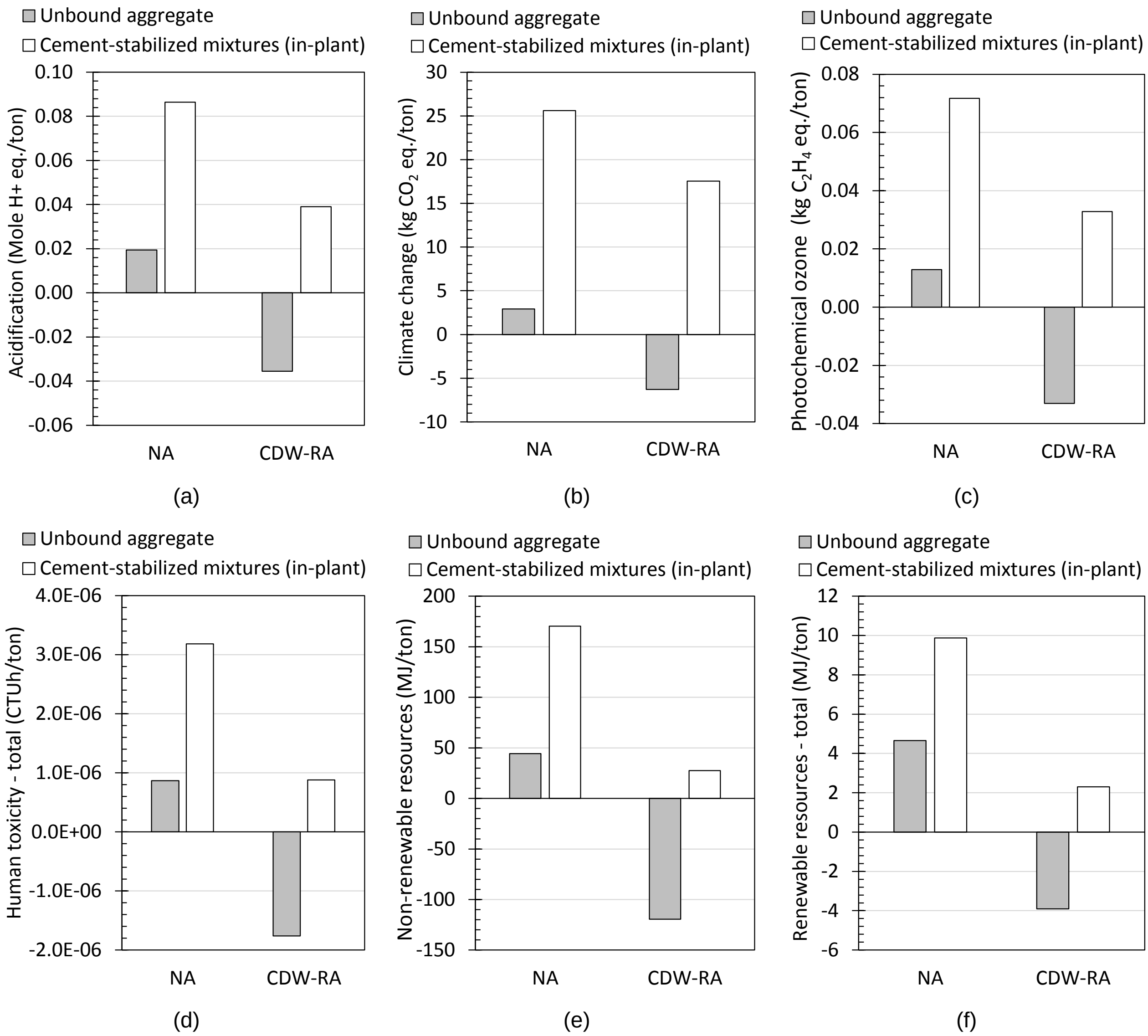
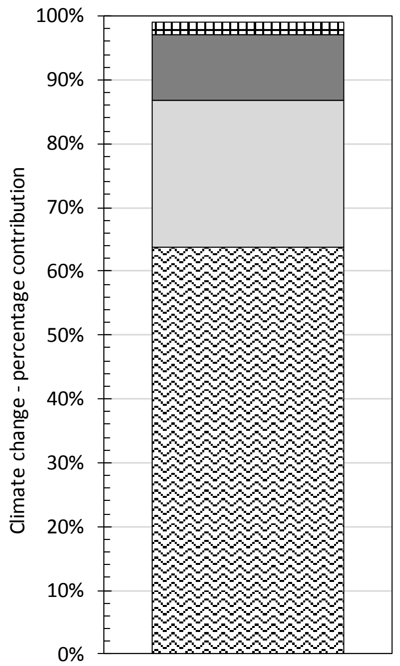
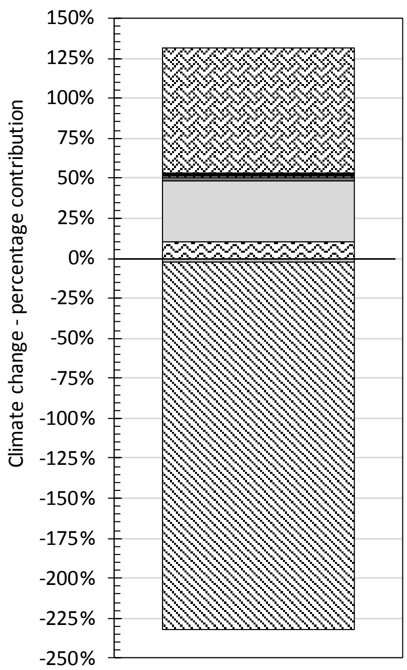



**Fig. 5 – Impacts associated with the production of 1 ton of NA (unbound and cement-stabilized) and CDW-RA (unbound and cement-stabilized), for subbase layer formation: (a) acidification, (b) climate change, (c) photochemical ozone formation, (d) total human toxicity, (e) total consumption of non-renewable resources, (f) total consumption of renewable resources**




| | Impact amount (kg $CO_2$ eq.) | % value [2] |
|---|---|---|
| Electricity | 1.87 | 63.7% |
| Diesel and oil | 0.68 | 23.2% |
| Infrastructure | 0.30 | 10.1% |
| Steel | 0.06 | 2.2% |
| Others [1] | 0.02 | 0.8% |
| **Total** | **2.93** | 100.0% |

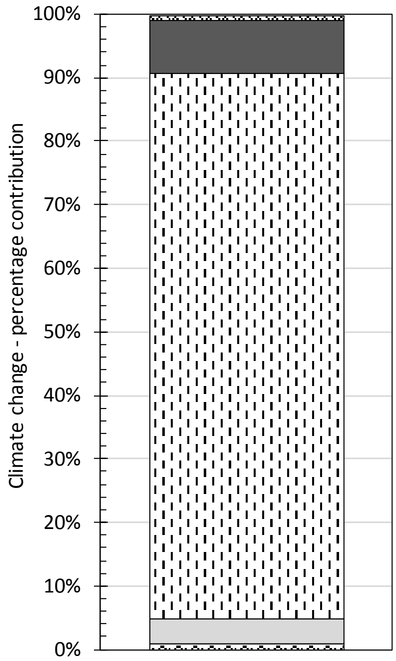
(a)




| | Impact amount (kg $CO_2$ eq.) | % value [2] |
|---|---|---|
| Electricity | 0.62 | 9.9% |
| Diesel and oil | 2.42 | 38.3% |
| Infrastructure | 0.14 | 2.2% |
| Steel | 0.09 | 1.4% |
| Transport | 4.98 | 78.9% |
| Rubber | 0.08 | 1.2% |
| Steel recovery | -0.16 | -2.5% |
| Landfill avoidance | -14.46 | -229.4% |
| Others [1] | 0.00 | 0.0% |
| **Total** | **-6.31** | -100.0% |

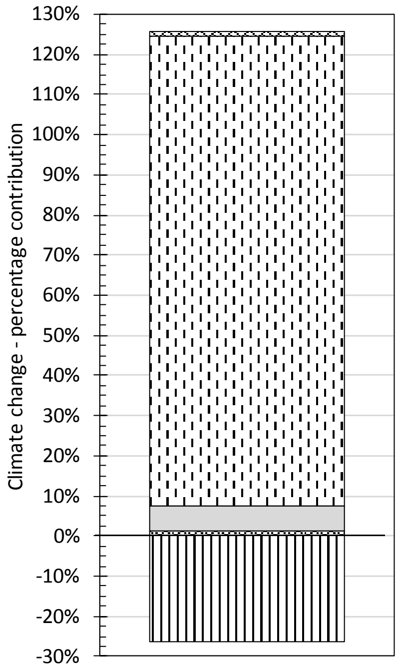
(b)

**Fig. 6 – Impact amounts and percentage contributions to climate change impact associated with the production of 1 ton of (a) U-NA and (b) U-CDW-RA. Notes: [1] "Others" include all factors with a percentage contribution lower than 1.0%. [2] The "%value" is the ratio between the impact amount and the total. In the case of negative total impact (U-CDW-RA), the sum of %value is -100%. For instance, considering that the impact of electricity on the production of 1 ton of U-NA is +1.87 kg $CO_2$ eq., its percentage contribution (% value) to the total climate change of +2.93 kg $CO_2$ eq. is 63.7% [= 100 · 1.87 / |2.93|]. In the case of production of 1 ton of U-CDW-RA, the electricity consumption generates +0.62 kg $CO_2$ eq., which is 9.9% [= 100 · 0.62 / |-6.31|] of the total (-6.31 kg $CO_2$ eq.) impact. The negative total impact of U-CDW-RA is due to the steel recovery and landfilling avoidance. The latter two factors permit the saving of 0.16 and 14.46 kg $CO_2$ eq. respectively, thus contributing as negative percentages to the total impact: steel recovery: -2.5% [= 100 · (-0.16) / |-6.31|], landfill avoidance -229.4% [= 100 · (-14.46) / |-6.31|].**




| | Impact amount (kg $CO_2$ eq.) | % value [(2)] |
|---|---|---|
| Electricity | 0.23 | 0.8% |
| Diesel and oil | 1.17 | 4.0% |
| Transport | 0.23 | 0.8% |
| NA | 2.42 | 8.3% |
| Cement | 24.90 | 85.8% |
| Others [(1)] | 0.09 | 0.3% |
| **Total** | **29.03** | 100.0% |

(a)




| | Impact amount (kg $CO_2$ eq.) | % value [(2)] |
|---|---|---|
| Electricity | 0.25 | 1.2% |
| Diesel and oil | 1.27 | 6.2% |
| Transport | 0.29 | 1.4% |
| CDW-RA | -5.45 | -26.3% |
| Cement | 24.22 | 117.0% |
| Others [(1)] | 0.11 | 0.5% |
| **Total** | **20.70** | 100.0% |

(b)

**Fig. 7 – Contributions to climate change impact associated with the production of 1 ton of (a) CS-NA and (b) CS-CDW-RA (in-plant). Notes: [(1)] "Others" include all factors with a percentage contribution lower than 1.0%. [(2)] The "%value" is the ratio between the impact amount and the total.**

## 5.3 LCIA for the road pavement construction

### *5.3.1 Road pavements with unbound subbase layers*

Fig. 8 shows the LCIA results for the subbase layer containing U-NA and U-CDW-RA. For each impact category, the results are expressed as a percentage of the maximum value obtained in that category.

The indicators are always lower in the case of pavement structures with CDW-RA than they are with NA. The U-CDW-RA-C scenario leads to an average reduction of 20-25% in almost all indicators (acidification, climate change, freshwater ecotoxicity, freshwater eutrophication, total human toxicity, ionizing radiation, marine eutrophication, ozone depletion, particulate matter, photochemical ozone formation, mineral resources depletion, terrestrial eutrophication, and total renewable resources). Both the U-NA and U-CDW-RA pavement structures have the same thickness, thus the environmental advantages deriving from the production of CDW-RA (discussed in Section 5.2) are entirely reflected in the construction of the pavement. The two scenarios show large differences in terms of land use: while the production of NA radically transforms the territory due to quarrying operations, the recycling of CDW and the storage of CDW-RA takes place in localized areas and large spaces of land are saved from being designated landfill sites for waste disposal.

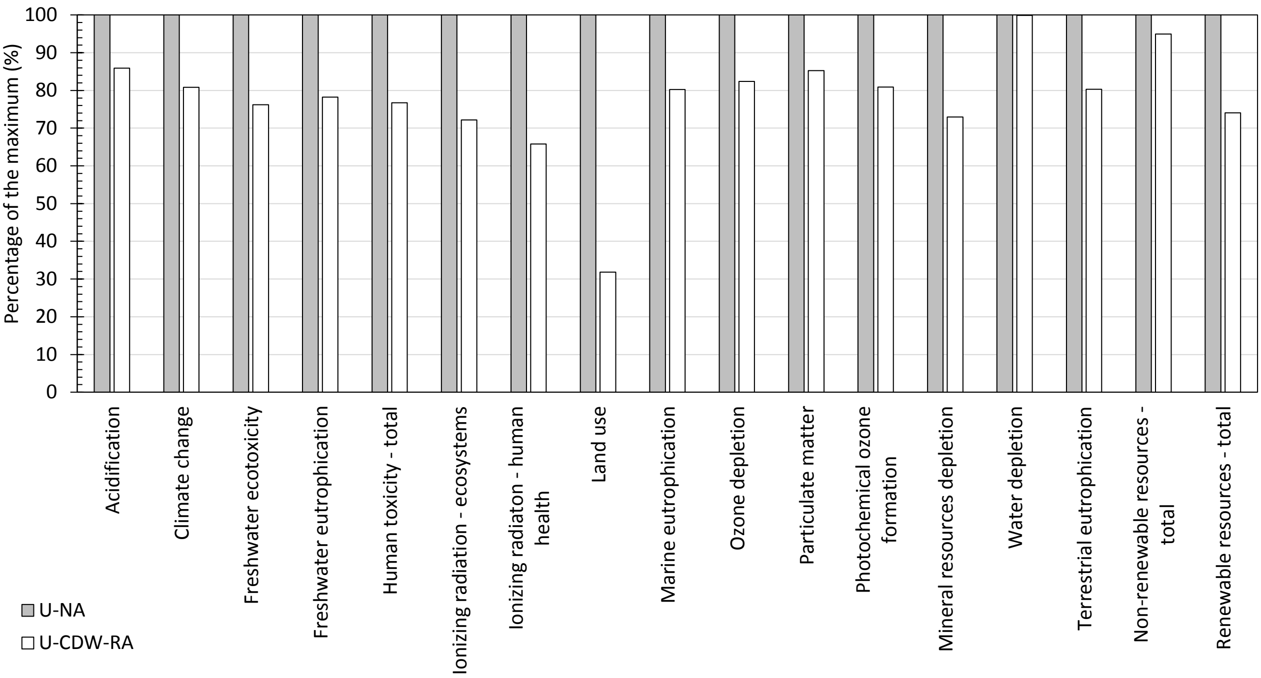



**Fig. 8 – Comparative ILCD 2011 (midpoint) and CED results for the construction of 1 m$^2$ of road pavement with subbase layer containing U-NA or U-CDW-RA.**

*5.3.2 Road pavements with cement-stabilized subbase layers*

Fig. 9 illustrates the LCA impacts depending on (i) the cement-stabilized materials employed in the subbase layer and (ii) the different construction techniques (in-plant production or on-site mixing). Once again, the results are shown as a percentage of the maximum value obtained in each impact category. The pavement structure with CS-NA in the subbase layer shows greater impacts than the one made from CS-CDW-RA. Both scenarios have HMA layers of equal thickness (see Section 5.1), therefore the environmental advantages of the CS-CDW-RA scenario derive entirely from the use of CDW-RA in lieu of NA. In line with pavement solutions with unbound subbases (U-NA and U-CDW-RA), the use of CDW-RA in cement-stabilized layers leads to an average reduction of 20-25% in all ILCD and CED impact indicators with respect to the CS-NA-p and CS-NA-s scenarios.

The stabilization technique (in-plant or on-site) has a marginal influence on the environmental impact calculation. When the material is mixed in a plant, the impact is slightly higher than when it is prepared on-site. The difference is attributable to the higher energy consumption (electricity and gasoline) of mixing plants. These LCA outcomes are valid under the hypothesis that cement-stabilized materials produced directly on-site have the same properties as those mixed in-plant. However, it is worth mentioning that a better control of mix proportion is usually obtained in-plant, where aggregates, stabilizing agent, and water are precisely dosed. The stabilization of materials on-site by means of soil stabilizers is less precise and characterized by less accurate dosage of constituent materials.

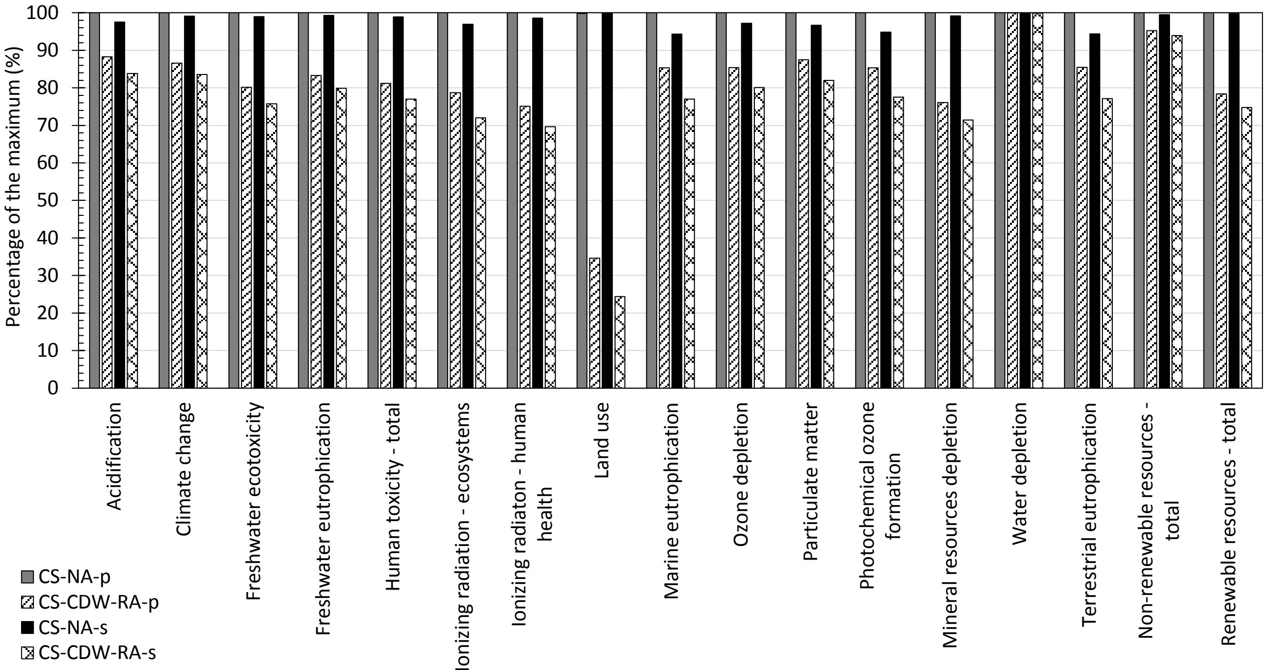



**Fig. 9 – Comparative ILCD 2011 (midpoint) and CED results for the construction of 1 $m^2$ of road pavement according to the different scenarios for cement-stabilized subbase materials.**

### *5.3.3 Comparison between scenarios*

Fig. 10 shows the best scenario of the six considered. Apart from the consumption of non-renewable resources impact category (Fig. 10-e), the impacts of pavements including cement-stabilized subbase layers are greater than those containing unbound aggregates.

The CS-NA-p and CS-NA-s scenarios have a greater influence on the values of the impact indicators. In these cases, the benefits deriving from the reduction of 0.02 m in the HMA road base layer with respect to the U-NA scenario do not offset the negative environmental impacts deriving from the use of cement. The same consideration holds when CS-CDW-RA-p and CS-CDW-RA-s scenarios are compared to the U-CDW-RA one. The benefits of a 0.02-m thinner HMA base layer do not compensate for the impact of cementitious products in the subbase layer. Conversely, despite U-CDW-RA implying a thicker HMA base layer, this scenario is the least impactful among those analysed here due to the significant advantages deriving from the production of CDW-RA without the use of cement.

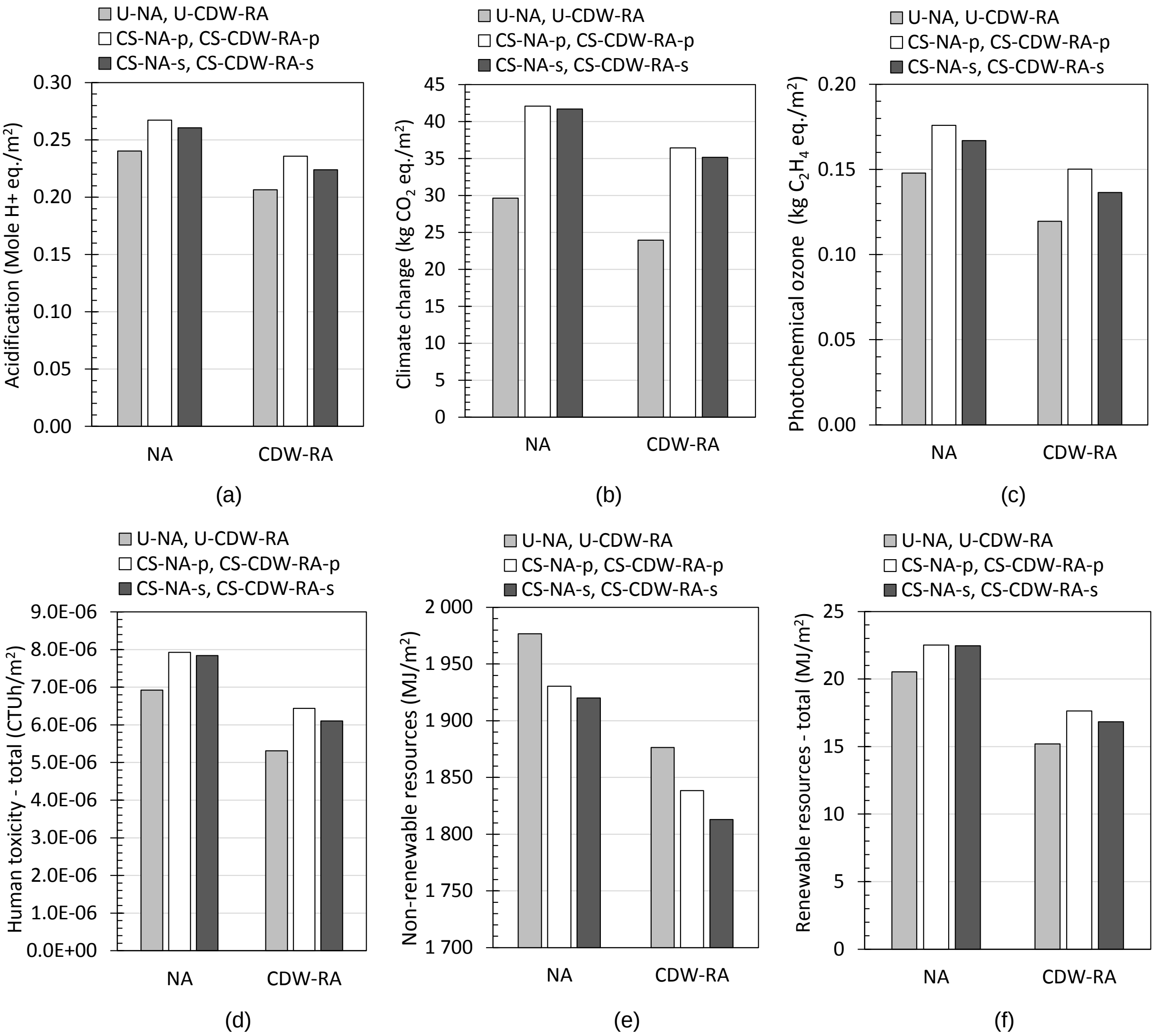
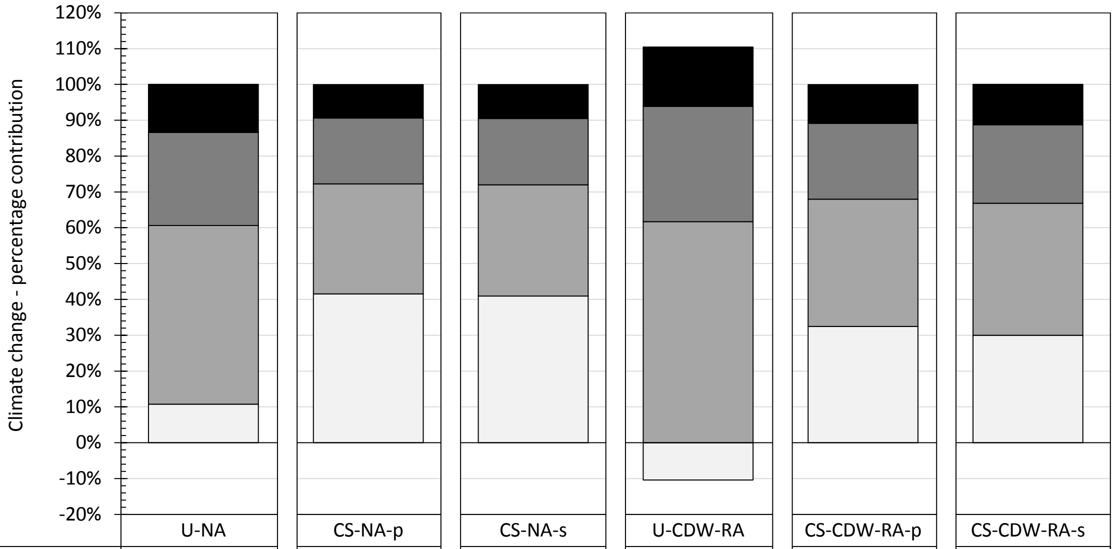



**Fig. 10 – Impacts associated with the construction of 1 m² of pavement with unbound and CS materials in the subbase (U-NA, U-CDW-RA, CS-NA and CS-CDW-RA) and different construction techniques (mixing in-plant or on-site for cement-stabilized mixtures): (a) acidification, (b) climate change, (c) photochemical ozone formation, (d) total human toxicity, (e) total consumption of non-renewable resources, (f) total consumption of renewable resources.**

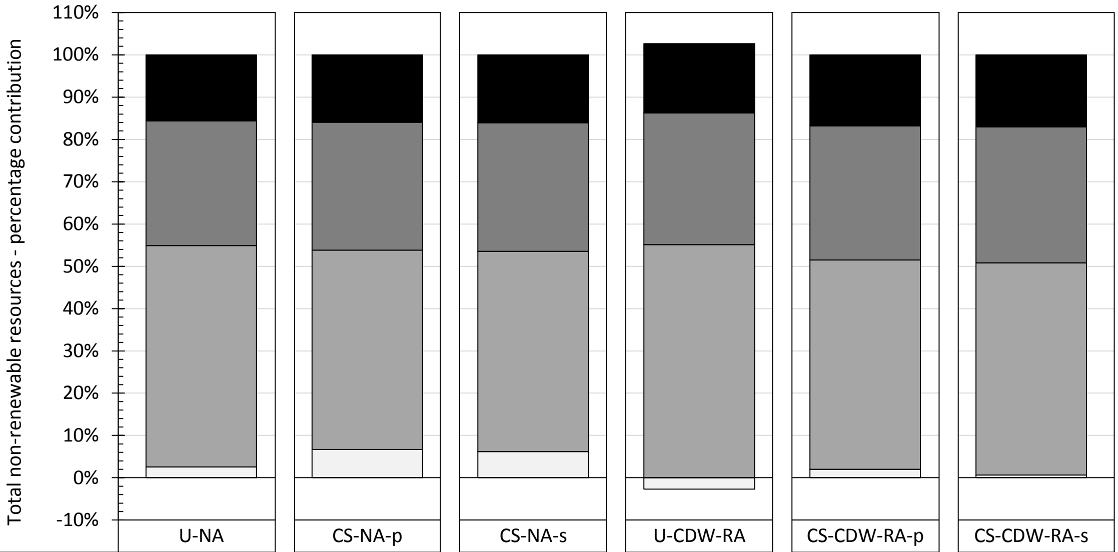
A comparison between the CS-CDW-RA-p and CS-CDW-RA-s scenarios and that of the U-NA-C is of interest. Acidification (Fig. 10-a), photochemical ozone formation (Fig. 10-c), total human toxicity (Fig. 10-d), and renewable resource consumption (Fig. 10-f) indicators suggest that road pavements with cement-stabilized CDW-RA subbase layers have a more favourable LCA than the reference U-NA scenario. These outcomes reveal that, for some impact indicators, the use of CS-CDW-RA in place of simply compacted NA leads to some environmental benefits due to the small but significant decrease in the thickness of the HMA road base. These advantages would be even more relevant if more sustainable stabilizing agents could guarantee a similar or even better structural behaviour. Alternative stabilizers to limestone Portland cement (e.g., more sustainable blended cements, supplementary cementitious products, alkali-activated binders, etc.) could improve the LCA results associated with the climate change indicator. In fact, the high environmental impact of the cement industry (Worrell et al., 2001; Schneider et al., 2011) results in significant increases in the emissions of equivalent $CO_2$ in scenarios with cement-stabilized subbases (Fig. 10-b). Fig. 11 emphasizes the contribution of each pavement layer to the climate change indicator. For U-NA and U-CDW-RA scenarios, the subbase layer accounts for around 10% of the climate change for the total pavement construction. For the sake of clarity, the contribution analysis of the U-CDW-RA scenario breaks through the value of 100% to compensate for the negative contribution of the subbase layer. As previously mentioned, the construction of the U-RA-CDW subbase garners environmental credits in terms of LCA thanks to its avoidance of CDW recycling. Despite the addition of very small quantities of cement, when the subbase layer is built with cement-stabilized NA (CS-NA-S-p and CS-NA-S-s scenarios) its contribution to climate change increases to 40% of the entire pavement construction. In the case of cement-stabilized RA, the contribution is lower (around 30%) since the 10% contribution from the avoided impact of CDW-RA production is included in the LCA balance as a credit.

The contribution analysis in Fig. 12 explains the results of Fig. 10-e related to the consumption of non-renewable resources. The high values relating to the construction of HMA layers are ascribable to the higher levels of energy consumed in the production processes of bitumen and HMA (Androjić and Alduk, 2016). According to this impact indicator, the subbase layer has a marginal contribution, from -2.7 to 6.7%, to the functional unit, while the major contribution, always greater than 93%, is due to the HMA layers formation. For this reason, 0.02 m more of HMA in the U-NA and U-CDW-RA scenarios leads to 2.4% and 2.1% of non-renewable resource consumption in comparison with CS-NA-p and CS-CDW-RA-p scenarios respectively. Vice versa, scenarios with thinner HMA layers (i.e., those with a cement-stabilized subbase layer), consume fewer non-renewable resources, notwithstanding the use of cement.




| | U-NA | CS-NA-p | CS-NA-s | U-CDW-RA | CS-CDW-RA-p | CS-CDW-RA-s |
|---|---|---|---|---|---|---|
| Total | 100.0% | 100.0% | 100.0% | 100.0% | 100.0% | 100.0% |
| ■ HMA wearing couse | 13.4% | 9.4% | 9.5% | 16.6% | 10.9% | 11.3% |
| ■ HMA binder couse | 26.0% | 18.3% | 18.5% | 32.2% | 21.1% | 21.9% |
| ■ HMA base couse | 49.9% | 30.8% | 31.1% | 61.7% | 35.5% | 36.8% |
| □ Subbase layer | 10.7% | 41.5% | 41.0% | -10.4% | 32.4% | 30.0% |

**Fig. 11 – Contributions to climate change impact associated with the construction of 1 m² of road pavement according to different scenarios**




| | U-NA | CS-NA-p | CS-NA-s | U-CDW-RA | CS-CDW-RA-p | CS-CDW-RA-s |
|---|---|---|---|---|---|---|
| Total | 100.0% | 100.0% | 100.0% | 100.0% | 100.0% | 100.0% |
| ■ HMA wearing couse | 15.6% | 16.0% | 16.1% | 16.4% | 16.8% | 17.0% |
| ■ HMA binder couse | 29.5% | 30.2% | 30.4% | 31.1% | 31.7% | 32.2% |
| ■ HMA base couse | 52.3% | 47.1% | 47.4% | 55.1% | 49.5% | 50.2% |
| □ Subbase layer | 2.5% | 6.7% | 6.2% | -2.7% | 2.0% | 0.6% |

**Fig. 12 – Contributions to consumption of non-renewable resources associated with the construction of 1 m² pavement according to different scenarios**

## 6. CONCLUSION

### 6.1 Key findings

This integrated structural-LCA study was aimed at evaluating and comparing six different scenarios depending on (i) the unbound and cement-stabilized material included in the subbase and (ii) the construction technique adopted. The key findings of the structural analysis are as follows:

- the same total HMA layer thickness (equal to 0.28 m) can be adopted by using 0.30 m of NA or CDW-RA in the subbase due to the comparable mechanical properties of the two alternative aggregates;
- similar conclusions are drawn when pavement structures with cement-stabilized NA and CDW-RA are compared to each other; therefore, primary and secondary aggregates of similar performance lead to comparable structural performance levels in a road pavement system;
- the addition of 3% of limestone Portland cement (CEM-II/B-LL) as a stabilizer to both granular materials reduces the thickness of bound HMA layers by 0.02 m.

The key findings of the LCA as they relate to the construction of the road pavement are as follows:

- the ILCD and CED impact indicators are all lower for the production of CDW-RA than they are for the production of NA from quarrying activities, mainly because of the environmental credits awarded for the avoidance of CDW landfilling;
- transport accounts for 79% of the climate change indicator for CDW-RA, so it is fundamental to limit the distance between the waste generation site and the recycling plant so as to preserve the environmental credit gained from its recycling;
- when considering the construction of the entire pavement, the environmental benefits of the CDW-RA production are preserved; the U-CDW-RA scenario exhibits climate change and renewable resources indicators which are 16% and 35% lower respectively than those for the U-NA one;
- the environmental impact and resource consumption due to the in-plant production of cement-stabilized granular material is attributable to the use of cement, the production of which is highly energy intensive;
- despite pavements with both cement-stabilized NA and CDW-RA subbases requiring 0.02 m less HMA in the road base layer, the environmental benefits of using lower quantities of HMA are lost due to the impact of cement;
- the on-site mixing of stabilized subbase materials provides some environmental benefit mainly due to energy savings in comparison to the in-plant mixing; considering the climate change factor, CS-NA-s and CS-CDW-RA-s had 1.0 and 3.6% lower values in comparison with CS-NA-p and CS-CDW-RA-p respectively; and 0.5 and 1.4% lower total non-renewable consumption

indicator values respectively for scenarios with NA and CDW-RA stabilized on-site with respect to those from the in-plant mixing;

- CS-CDW-RA-p and CS-CDW-RA-s scenarios revealed advantages with respect to the U-NA one for the majority of ILCD and CED impact indicators; however, to register positive results in terms of climate change, alternatives to CEM-II/B-LL must be considered;
- according to the ILCD impact category, the U-CDW-RA scenario is the most favourable because of the lowest impacts; the use of CDW-RA in lieu of NA and the avoidance of cementitious products counterbalance the necessity of a thicker HMA base layer;
- in contrast, since CDW-RA requires a thicker road base made with HMA, there is a greater consumption of non-renewable resources (according to the CED method); therefore, for this impact indicator both CS-CDW-RA-p and CS-CDW-RA-s scenarios are the most favourable.

### 6.2 Implications

In light of the results of this integrated and comparative structural-LCA analysis, the use of CDW-RA as an alternative to NA is more favourable in terms of environmental impact. This study supports the design decisions of engineers who tend to opt for the use of CDW-RA for road pavements. Moreover, the use of CDW-RA is also encouraged because of its lower costs. In both cases of unbound and cement-stabilized subbases, more than 9% of total costs can be saved by using CDW-RA in substitution of NA.

The impact of HMA layers is significant in terms of overall costs and energy consumption values, thus the use of recycled materials (i.e., reclaimed asphalt) and more sustainable production cycles (i.e., warm mixtures) should be advocated for with this category of material too. This study evidences the predominant environmental impact of cement in cement-stabilized materials (more than 85% of climate change). This outcome encourages new research to develop alternative binders to cement in order to reduce the environmental impacts of cement-stabilized road subbase layers.

### 6.3 Limitation and future needs

Both structural design and LCA modelling were based on several hypotheses and estimates that are valid for the Piedmont area (North-West of Italy) and should be reconsidered for different locations. Fluctuations in the availability of both natural and recycled materials may change the conclusions in terms of costs and environmental impacts. Furthermore, differences in the configuration and location of quarries in the territory may result in disparate transportation distances and, therefore, different costs and impacts. Similarly, different configurations of the recycling plants (i.e., mobile, semi-mobile, fixed), type of incoming waste, distribution of recycling stations throughout the territory all influence the LCA outcomes. Availability and fuel costs are also linked to the specific geographical area, as well as the production process for electricity (i.e., from renewable or non-renewable resources). All these factors combine to influence the costs of management, transport, and construction operations and have an impact on the environment.

Since this LCA study specifically aimed at evaluating the construction stage of road pavements with the same service life, maintenance and end-of-life scenarios were not included in the analysis. It should be noted that more accurate assumptions on the effects of material properties and construction processes deserve specific investigations. In terms of the structural design of road pavements, this study considered the specific environmental and traffic conditions for a medium-trafficked two-lane rural highway in Italy. The extension to different traffic conditions (i.e., more and less trafficked roads) will evaluate the advantages of employing recycled materials as well as stabilized products in subbase pavement layers.

On a final note, further research is necessary to evaluate the use of more sustainable stabilizers than cement because of its significant impact on ILCD and CED indicators in this investigation.

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