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Laboratory, field and environmental characterisation of construction and demolition waste stabilised with pozzolanic cement

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Abstract

Construction and demolition waste aggregates (CDWA) are increasingly used in subbase pavement layers, especially when stabilised with cement to meet strength and stiffness requirements. While cement significantly improves the mechanical properties of CDWA, it also has a relevant environmental impact that offsets the benefits of using them. This field and laboratory investigation, coupled with a life-cycle assessment, evaluates the use of a pozzolanic cement (CEM-IV/B) as an alternative to the conventional Portland-limestone cement (CEM-II/B) for CDWA stabilisation. Two sections of an experimental road, each measuring 40 m in length, were built with a 30 cm cement-stabilised CDWA subbase, with each section using a different cement type. Lightweight deflectometer field tests were performed 3 days after construction. Samples cured for 7 and 28 days were also tested in the laboratory to measure their compressive strength and resilient modulus values. Field measurements showed statistically equivalent surface moduli between the two cement-stabilised materials. The laboratory test results confirmed that the two mixtures had comparable strength and stiffness values. Life cycle analysis revealed that using CEM-IV/B instead of CEM-II/B for CDWA stabilisation resulted in a 16% reduction in its climate change impact. The two cements demonstrated their ability to stabilise CDWA with equivalent bearing capacity in both short- and long-term laboratory and field tests. In light of current European green public procurement policy, preference should be given to CEM-IV/B as a stabiliser for CDWA.

Keywords: pozzolanic cement; construction and demolition waste; road subbase; cement-stabilized aggregate; lightweight deflectometer

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1. Introduction

The significant growth in construction activities (buildings and infrastructure) is resulting in a substantial increase in the production of inert waste. This expanding volume of waste poses significant environmental and economic challenges since its disposal contributes to pollution and resource depletion, and conflicts with the circular economy principles promoted by European policies (European Commission, 2020). Against this backdrop, construction and demolition waste aggregates (CDWA) derived from the recycling of mixed waste materials such as concrete, ceramics, asphalt, natural rock, and excavated soil are increasingly being used in road construction, particularly in embankments and in subgrade layers, and occasionally in subbases (Ossa et al., 2016; Zhang et al., 2020). This tendency is consistent with the principles of green public procurement policy, as evidenced by the adoption of Italy's Minimum Environmental Criteria for roadworks (Garbarino et al., 2016), in which it is stipulated that at least 50% of the content of unbound and stabilised subbase layers must consist of recycled materials (*Ministero dell'Ambiente e della Sicurezza Energetica*, 2024).

Portland cement has traditionally been employed as a stabilizer agent for granular materials to ensure that the minimum technical requirements for pavement subbases are met (Li and Hu, 2020). While this is effective in enhancing strength and stiffness values, its use undermines the environmental benefits of CDWA and could prevent compliance with sustainability-oriented procurement criteria (Tefa et al., 2022; Purkayastha et al., 2025). Several technical specifications, including those currently in use in Italy, recommend using class 32.5 Portland cement for stabilising soil and aggregates. However, this practice of defaulting to Portland cement, means that due consideration is not given to alternative binders that could better align with the mechanical requirements of road layers and the need to reduce their environmental impact. In this regard, pozzolanic cements (e.g., type IV) represent a particularly promising innovation for stabilisation purposes. Their slower hydration kinetics, progressive strength development and lower clinker content make them a valid alternative to ordinary Portland cements (Antiohos and Tsimas, 2004; Navarrete et al., 2023). Moreover, the availability of by-products containing pozzolana (i.e., waste clay, fly ash), which are generally used in the production of type IV cement, is leading to the rapid increase in use of these alternative cementitious products.

This study utilises a multi-perspective methodology involving (i) the construction and testing of two experimental road sections, (ii) laboratory testing and (iii) a life cycle assessment (LCA), to investigate the effectiveness of a pozzolanic cement (classified as CEM-IV/B) to stabilise CDWA, with the results achieved being compared to those for a standard Portland-limestone cement (CEM-II/B) which is typically used to stabilize granular materials. The research was conducted as a regional case study in northern Italy, where the level of CDWA production is substantial and both types of cement are available on the market.

2. Materials and methods

2.1. Materials

A 0-40 mm size fraction of CDWA was used. The particle size distribution, determined according to EN 933-1 (European Committee for Standardization, 2012), is shown in Fig. 1-a. The composition analysis of the CDWA sample indicated a high content of concrete particles (24.4%) and natural aggregates (52.5%), with lower amounts of ceramics (13.3%), bituminous materials (9.3%), and impurities (0.5%) such as plastic, rubber, metal, and wood. Two types of cement were used to stabilise the aggregate (Table 1): (i) a CEM-II/B, conventional Portland-limestone cement containing 65-79% clinker and 21-35% limestone in accordance with EN 197-1 (European Committee for Standardization, 2011) was used as the reference material and; (ii) a low-clinker pozzolanic cement (CEM-IV/B), was investigated as the alternative. The latter consisted of 45-64% clinker and 36-55% of pozzolanic material mainly fly ash and waste clay derived from the production of lightweight aggregates (Tefa et al., 2025b).

Consistent with previous studies, the cement-stabilised (CS) mixtures were prepared at a mixing plant near the construction site with the cement content ratio being 3% of the dry weight of the aggregates (Tefa et al., 2025a). The water content for each mixture was determined using the modified Proctor compaction test (European Committee for Standardization, 2010). Fig. 1-b illustrates Proctor compaction curves, while compaction parameters and mixture designations are given in Table 1.

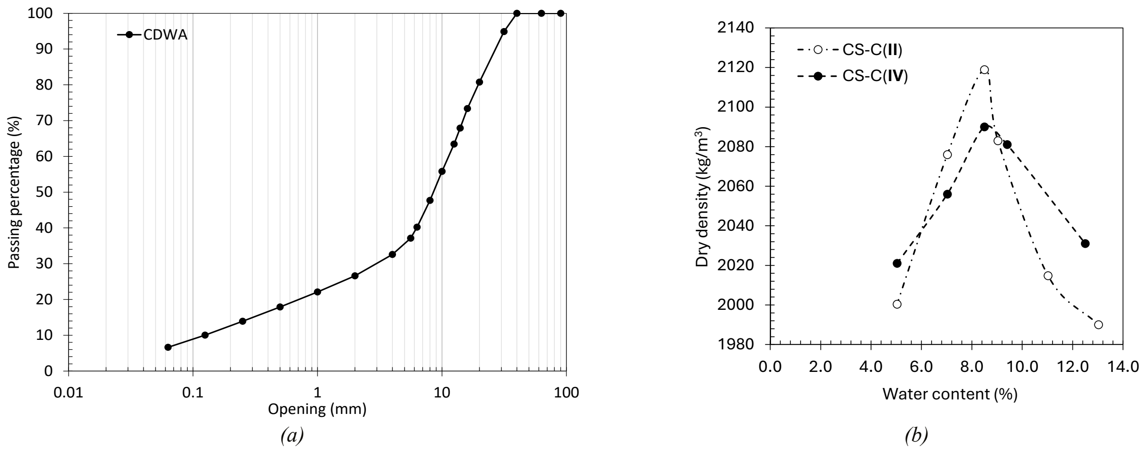

Fig. 1. (a) CDWA particle size distribution curve; (b) Proctor curves of CS materials.

Table 1. Cement properties and CS mixture characteristics (including Proctor compaction parameters: w_{opt} = optimum moisture content, $\gamma_{d,max}$ = maximum dry density).

Cement properties					CS mixture characteristics			
Cement type	Compressive strength @28 d (MPa)	Blaine (cm^2/g)	Setting time (min)	Density (kg/m^3)	Aggregate	Mixture designation	w_{opt} (%)	$\gamma_{d,max}$ (kg/m^3)
CEM-II/B	> 32.5, < 52.5	4490	> 75	2930	CDWA	CS-C(II)	8.5	2119
CEM-IV/B	> 32.5, < 52.5	5051	> 75	2860	CDWA	CS-C(IV)	8.5	2090

2.2. Experimental road construction and testing

The pavement of the two experimental road sections, each measuring 40 m long by 8 m wide (Fig. 2-a), was composed of a 30 cm-thick subbase including the two CS mixtures, both laid over a 40 cm-thick subgrade made of unbound CDWA (Fig. 2-b). The CS mixtures were prepared in a discontinuous mixing plant where CDWA, cement, and water were accurately dosed and mixed for at least three minutes before being laid and compacted with vibrating rollers. The testing focused on the subbase layer following three days of curing during which time the traffic was restricted to prevent any surface damage. Once the subbase testing campaign was completed, a 10 cm-thick hot-mix asphalt (HMA) surface layer was laid, after which no further tests were conducted on the finished pavement.

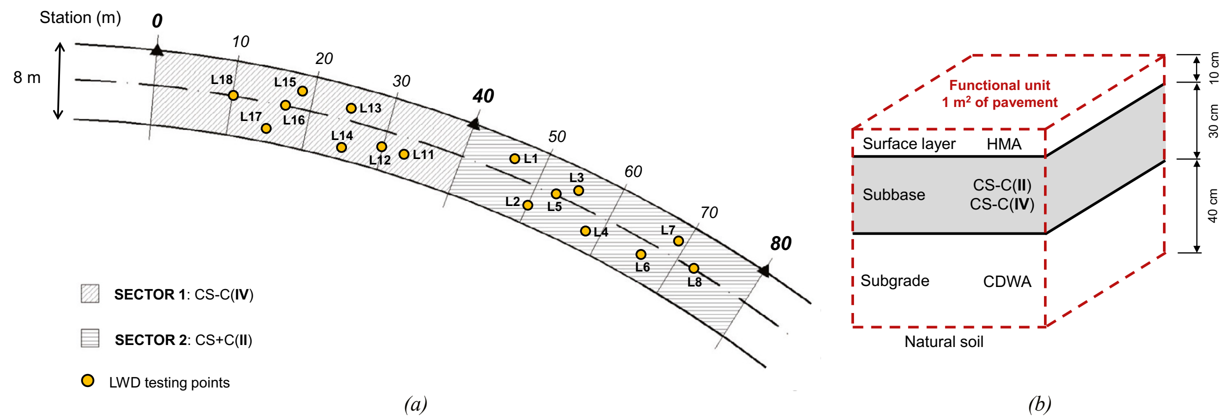

Fig. 2. (a) locations of testing points on the two sections of the experimental road; (b) pavement cross-section with the indication of the functional unit for the LCA analysis.

The bearing capacity of the two subbases were assessed with light weight deflectometer (LWD) tests (*Dynatest 3032*) in accordance with ASTM E2583 (American Society for Testing and Materials, 2007). The testing campaign was performed using a 200 mm diameter loading plate, a constant falling mass of 20 kg, and a drop height of 58 mm to generate a plate pressure of (340 ± 5) kPa. Each test consisted of nine drops with the first three considered seating drops and excluded from the analysis. The surface modulus (E_{LWD}) was calculated using Boussinesq's elastic theory, assuming a stress distribution factor of 2 and a Poisson's ratio of 0.25 (Ullidtz, 1998). Each subbase section was evaluated at eight different locations which were randomly selected excluding margins from all edges (Fig. 2-a).

2.3. Laboratory tests

During field construction, cylindrical specimens with a diameter of 100 mm and a height of 200 mm were prepared for laboratory testing. Before compaction the loose CS material was sieved to a maximum particle size of 20 mm and compacted into eight layers (25 blows/layer) to achieve the required specimen height. A constant modified Proctor energy of 2.6 MJ/m³ was applied throughout the process. After compaction, the specimens were wrapped in a plastic bag to prevent moisture evaporation and transported to the laboratory. There, they were cured at a temperature of 25°C and a relative humidity value > 90% for 7 and 28 days. Three replicate specimens were produced for each mixture and curing period. The mechanical properties were evaluated in terms of (i) resilient modulus (RM) using repeated load triaxial tests in accordance with the AASHTO T307 protocol for base/subbase materials (American Association of State and Highway Transportation Officials, 2013) and (ii) unconfined compressive strength (UCS) tests using a compressive machine at a constant displacement rate of 0.50 mm/min.

2.4. Environmental assessment

Environmental performance was assessed by means of an LCA analysis. LCA outcomes compare the impacts associated with the construction of 1 m^2 of experimental road pavement with the subbase layer made up of CS-C(II) or CS-C(IV) mixtures (Fig. 2-b). Primary data on CDWA and cements were collected directly from manufacturing and production plants located in the Northwest of Italy in 2023 (Tefa et al., 2022; Tefa et al., 2025b). The transportation distances depended on the geographical location of the mixing plants and cement factories in the north-west of Italy. CS mixtures and HMA were assumed to be transported by road freight convoy for 20 km from the mixing plant to the construction site. To produce the CS mixture, it was assumed that the cement plant was located 50 km from the mixing facility for both cement types. As the mixing plant was assumed to be located within the aggregate production plant, a transportation distance of zero was attributed to CDWA in the LCA for the production of the CS mixture. HMA production was modelled according to available literature (Santos et al., 2018; Ma et al., 2019). Additional inventory data were obtained from *Ecoinvent 3.11* database (Wernet et al., 2016). Environmental impacts were calculated using the *Environmental Footprint 3.1* method (European Commission, 2021).

3. Results and discussion

3.1. Bearing capacity through LWD test

Fig. 3 illustrates the average E_{LWD} values for eight locations across each of the two testing sections. The reference subbase with CS-C(II) shows a wide range in E_{LWD} from 600 to 1400 MPa, while the subbase containing CS-C(IV) exhibits a lower variation in average E_{LWD}, with values in the range 800-1200 MPa. Recoded data suggests that CEM-IV/B results in a more uniform mixture than CEM-II/B. The CS-C(IV) subbase achieved elastic properties equivalent to that of the CS-C(II) subbase with 950 ± 286 MPa for the former and 962 ± 191 MPa for the latter. The independent samples *t*-test confirmed that the difference between these two values is not statistically significant (t_{14} = -0.10, *p*-value = .92). The heterogeneity of CDWA results in significant variability in the surface modulus E_{LWD} (Teijón-López-Zuazo et al., 2020). Although the CS materials were carefully blended in a mixing plant, CDWA components like ceramics have different water absorption capacities, which likely affects the hydration process culminating in the variability of E_{LWD} values. Furthermore, LWD equipment is relatively sensitive to the local characteristics of the layer (Hossain and Apeagyei, 2010), particularly when working with materials like as CDWA (Tefa and Bassani, 2023). This contributes to the observed spatial variability in both subbase sections.

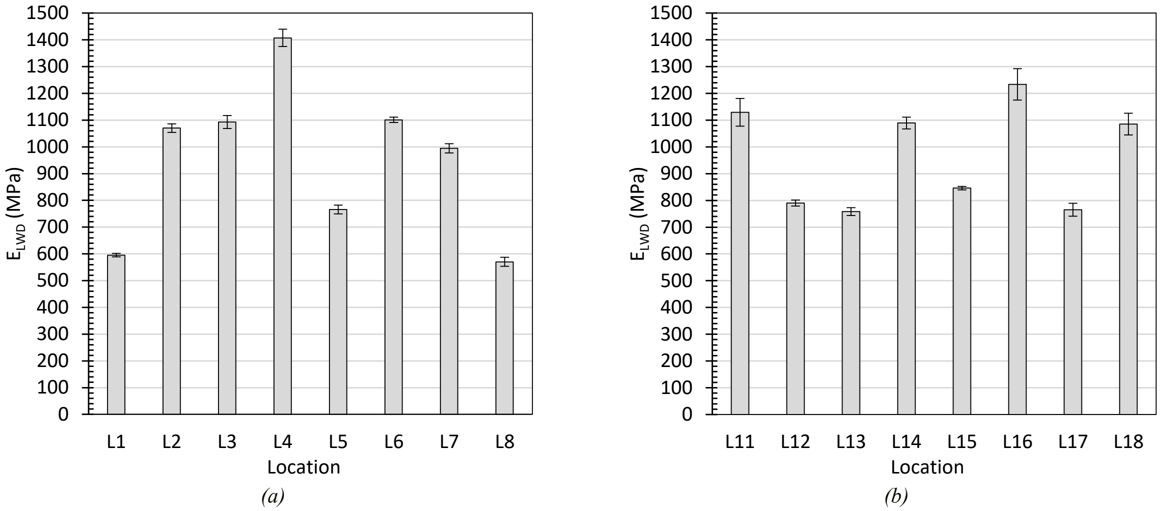

Fig. 3. Lightweight deflectometer tests results for experimental road sections with (a) CS-C(II) and CS-C(IV) materials; error bars indicate one standard deviation.

3.2. Laboratory tests

Fig. 4 illustrates the evolution of RM as a function of the first stress invariant I_1 for both CS mixtures after 7 and 28 days. Each data point represents the modelled RM data obtained from an application of the M-EPDG equation (American Association of State Highway and Transportation Officials, 2015) to the experimental results of the three replicates. After 7 days of curing, the CS-C(IV) mixture exhibited a higher RM than CS-C(II) across the entire I_1 range investigated. After 28 days, the behaviour of the two CS mixtures was broadly comparable. Specifically, CS-C(II) material exhibited slightly higher average RM values at lower I_1, while CS-C(IV) displayed slightly higher RM values at higher I_1. The RM values recorded are consistent with those reported in literature for similar materials (Mohammadinia et al., 2014; Corradini et al., 2021) and are also in line with those obtained with the stabilised granular mixture of natural origin that is traditionally used to form road pavement subbase layers (Huang, 2003).

Table 2 shows that CS-C(II) exhibits a higher UCS at 7 days of curing with an average value of 2.20 MPa in contrast to a lower value of 1.86 MPa for CS-C(IV).

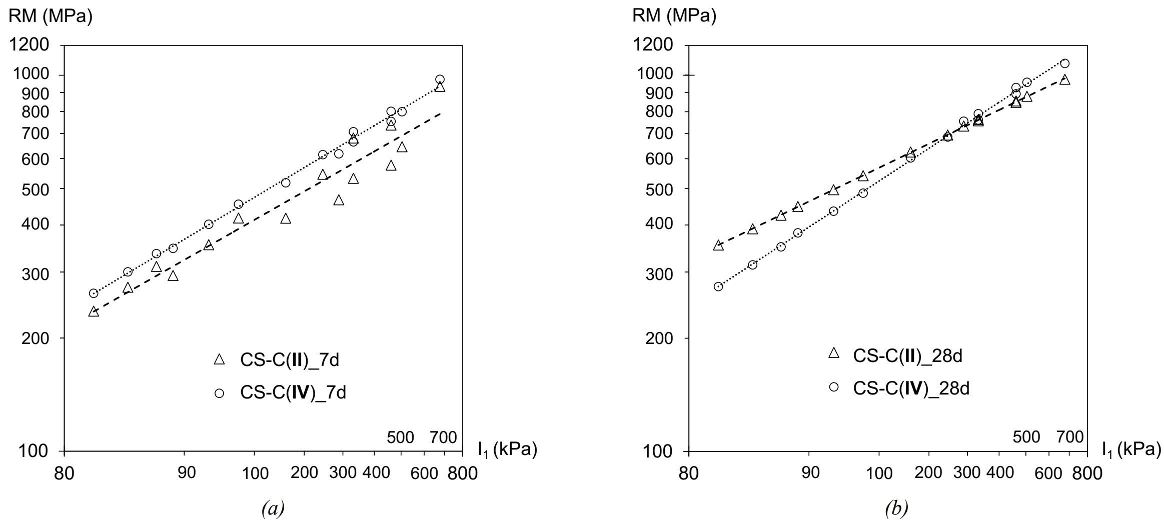

Fig. 4. Resilient modulus test results for CS-C(II) and CS-C(IV) mixtures after (a) 7 and (b) 28 days of curing.

Table 2. UCS results (average and standard deviation) for the two CS mixtures after 7 and 28 days of curing.

Material	UCS (MPa)			
	7 days		28 days	
	Average	Std. dev.	Average	Std. dev.
CS-C(II)	2.20	0.18	3.16	0.26
CS-C(IV)	1.86	0.16	3.18	0.26

It is worth noting that both CS mixtures satisfied the minimum UCS of 1.7 MPa (250 psi) at 7 days of curing for stabilised subbase layers as per the AASHTO's guide for the design of pavement structures (National Cooperative Highway Research Program, 2004). The lower clinker content of CEM-IV/B compared to CEM-II/B impacts negatively (albeit slightly) on the 7-day UCS value (pairwise comparison *t*-test, $t_5 = 2.58$, *p*-value = .05), while there are no significant differences between the two CS mixtures after 28 days ($t_5 = -1{,}10$, *p*-value = .92).

3.3. Life-cycle assessment

The environmental impacts associated with the construction of 1 m^2 of the experimental road pavement with different subbase materials (see cross-section in Fig. 2-b) are presented in Fig. 5. The environmental indicators are expressed both in absolute values and as a percentage of the maximum value for each category. The pavement with a CS-C(IV) subbase guarantees a reduced environmental impact across all indicators when compared to the pavements with a CS-C(II) subbase. This is due to the use of CEM-IV/B, which has a lower clinker content (45-64%) than CEM-II/B (65-79%) consistent with literature (Salas et al., 2016). Considering the construction of 1 m^2 of pavement structure, the use of CS-C(IV) subbase results in an average 16% saving across all environmental impact values, with a considerable reduction in acidification (22%), climate change (17%), eutrophication of freshwater (58%), carcinogenic (24%) and not-carcinogenic human toxicity (24%), and material consumption (15%) impact indicators. The advantage is greater still when only the production of the CS material is considered in the LCA. A comparison of the environmental impacts associated solely with the production of CS materials indicates even more relevant reductions in acidification (58%), climate change (36%), eutrophication of freshwater (78%), ecotoxicity of freshwater (29%), non-renewable energy resources (42%), carcinogenic (42%) and not-carcinogenic human toxicity (42%), land use (34%), material consumption (26%), particulate matter formation (20%), and photochemical oxidant formation (38%) impact indicators for the CS-C(IV) material compared to those for the CS-C(IV) one.

Impact category	Unit	Pavement CS-C(II)	Pavement CS-C(IV)
Acidification	mol H^+ eq.	0.20	0.15
Climate change	kg CO_2 eq.	43.5	36.0
Ecotoxicity: freshwater	CTUe	55.2	49.8
Energy resources: non-renewable	MJ	970.3	902.7
Eutrophication: freshwater	kg P eq.	0.008	0.003
Eutrophication: marine	kg N eq.	0.050	0.041
Eutrophication: terrestrial	mol N eq.	0.551	0.457
Human toxicity: carcinogenic	CTUh	$7.41 \cdot 10^{-9}$	$5.63 \cdot 10^{-9}$
Human toxicity: non-carcinogenic	CTUh	$2.77 \cdot 10^{-7}$	$2.13 \cdot 10^{-7}$
Land use	dimensionless	288.7	270.3
Material resources: metals/minerals	kg Sb eq.	$1.06 \cdot 10^{-4}$	$8.97 \cdot 10^{-5}$
Ozone depletion	kg CFC-11 eq.	$7.31 \cdot 10^{-7}$	$7.25 \cdot 10^{-7}$
Particulate matter formation	disease incidence	$2.38 \cdot 10^{-6}$	$2.27 \cdot 10^{-6}$
Photochemical oxidant formation: human health	kg NMVOC eq.	0.187	0.164
Water use	m^3 eq. deprived	8.97	8.86

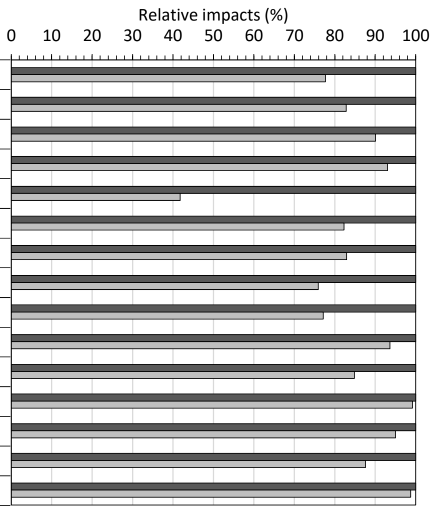

Fig. 5. Absolute and relative environmental impact values associated with the construction of 1 m^2 of testing pavement with CS-C(**II**) and CS-C(**IV**) subbase layers.

The contribution analysis for the climate change indicator in Fig. 6 highlights that the 30 cm-thick subbase has the highest environmental impact during the construction of the experimental pavement. This is mainly due to the use of cementitious products in the CS mixture. In fact, 80.3% and 68.9% of the climate change indicator in the production of CS-C(II) and CS-C(IV), respectively, is attributed to the use of CEM-II/B and CEM-IV/B, while a smaller proportion is attributed to the CDWA. Notably, using a more sustainable cement (CEM IV/B) decreases the contribution share of the subbase to the environmental impact of the entire pavement structure, with the 10 cm-thick HMA layer having the greatest environmental impact (Fig. 6-b). The high impact of HMA material is mainly due to the elevated mixing temperatures required and the use of energy-intensive raw materials, particularly bitumen (Huang et al., 2009). In both pavement scenarios, the subgrade containing CDWA makes only a marginal contribution to climate change.

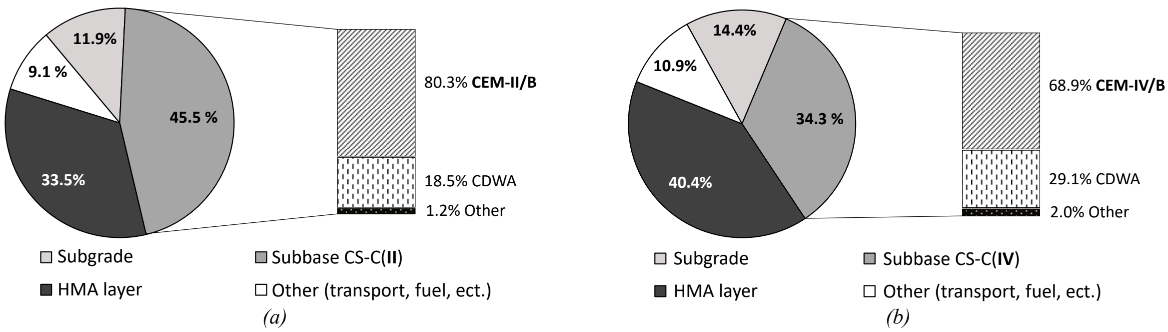

Fig. 6. Contribution analysis for the climate change indicator of testing pavement with (a) CS-C(**II**) and (b) CS-C(**IV**) subbase.

4. Conclusion

Unlike most existing literature, which often focuses on mechanical behaviour at the laboratory scale, this study provides an integrated assessment of cement-stabilised materials that, in addition to a comparison of laboratory and field test results, includes an evaluation of their environmental impacts.

Field measurements conducted three days after construction using a lightweight deflectometer apparatus indicated statistically equivalent surface moduli for both stabilised subbases. Although the cement-stabilised mixtures were blended under controlled conditions, the heterogeneous nature of the CDWA, made up of ceramics with different water absorption capacities, influenced the hydration process locally and resulted in a relatively high spatial variability in bearing capacity.

Laboratory testing confirmed that the two mixtures had comparable resilient modulus and unconfined compressive strength values after 28 days, with the only difference being that the CS-C(IV) mixture had a slightly lower 7-day UCS. Nevertheless, both mixtures met the minimum strength requirements for subbase applications at early development stages, demonstrating that performance criteria can be met even when using a cement with reduced clinker content (CEM-IV/B).

From an environmental perspective, the LCA analysis revealed that the lower clinker content of CEM-IV/B has a lower environmental impact across all investigated impact categories. On average, the use of a CS-C(IV) subbase rather than a CS-C(II) one reduced the overall environmental impact of the entire pavement construction by around 16%. Focusing solely on the production of the cement-stabilised mixture, the climate change indicator showed that the CS-C(IV) was 36% lower than CS-C(II).

These results demonstrate that CEM-IV/B can replace CEM-II/B as a stabiliser for CDWA in road subbase layers. Using it provides significant environmental benefits, particularly in terms of reduced greenhouse gas emissions and resource consumption. This supports the principles of the circular economy and the objectives of European green public procurement policies. Given the growing emphasis on sustainable construction practices, replacing conventional Portland cements with pozzolanic cements with lower levels of clinker is a pragmatic way to minimise the environmental impact of road infrastructure.

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