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Life Cycle Economic and Environmental Impacts of CDW Recycled Aggregates in Roadway Construction and Rehabilitation

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Abstract: The use of recycled materials in roadway construction and rehabilitation can achieve significant benefits in saving natural resources, reducing energy, greenhouse gas emissions and costs. Construction and demolition waste (CDW) recycled aggregate as an alternative to natural one can enhance sustainability benefits in roadway infrastructure. The objective of this study was to quantitatively assess the life cycle economic and environmental benefits when alternative stabilized-CDW aggregates are used in pavement construction. Comparative analysis was conducted on a pavement project representative of typical construction practices in northern Italy so as to quantify such benefits. The proposed alternative sustainable construction strategies considered CDW aggregates stabilized with both cement and cement kiln dust (CKD) for the base layer of the roadway. The life cycle assessment results indicate that using CDW aggregate stabilized with CKD results in considerable cost savings and environmental benefits due to (i) lower energy consumption and emissions generation during material processing and (ii) reduction in landfill disposal. The benefits illustrated in this analysis should encourage the wider adoption of stabilized CDW aggregate in roadway construction and rehabilitation. In terms of transferability, the analysis approach suggested in this study can be used to assess the economic and environmental benefits of these and other recycled materials in roadway infrastructure elsewhere.

Keywords: construction and demolition waste; CDW aggregate; stabilization; life cycle assessment; roadway sustainability

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1. Introduction

The construction and rehabilitation of road pavements involve large amounts of natural resources such as raw materials, and energy [1–3]. However, when recycled materials are used in roadway construction potential environmental and economic benefits can be achieved [4–13]. A remarkable variety of studies have investigated several recycled materials to be used in road pavements: recycled aggregates (from different sources), clayey materials, industrial by-products (slags, pulverized fuel ash, etc.), plastic and rubber wastes [14–24]. Among these materials, aggregates recycled from the debris of construction and demolition waste (CDW) play a key role in the sustainability of road infrastructure [25–27]. CDW aggregate has been recognized as a valid alternative to natural aggregate (NA) for road pavement applications [28,29]. A great number of studies and practical applications recognize that recycled CDW materials can be employed in embankments and trenches of roadways as well as in the construction of subgrade layers [30–35]. However, when employed in base and subbase layers, CDW aggregates are usually stabilized to meet mechanical and durability requirements [36,37]. Several studies on engineering properties of CDW aggregates and their potential use in base and subbase have shown that they can be utilized in pavements structures of low to intermediate traffic volumes [36,38–40].

To reduce the ecological footprint deriving from the use of ordinary Portland cement (OPC), some studies recommended stabilizing CDW materials with alternative binders [41,42]. Alternative binders for stabilization purposes include blended cement with supplementary cementitious materials, industrial by-products, and clinker-free cementitious binders representing those deriving from the alkali activation of by-products and/or waste [43–47]. In this context, Bassani et al. concluded that CDW aggregate can be stabilized with cement kiln dust (CKD) as an alternative to OPC, reaching comparable results of unconfined compressive strength (UCS) and resilient modulus (RM) [38].

In addition to the proven feasibility of using CDW aggregate in substituting NA for road pavements, its implementation needs to recognize potential environmental benefits [43]. Some studies have demonstrated that recycling of CDW may: (i) reduce emissions of environmentally harmful substances, (ii) reduce the use of natural resources, and (iii) decrease the consumption of energy in comparison with the production of virgin NA [48–51]. Potential advantages from landfilling avoidance have been reported [32,52–54]. Economic savings deriving from the adequate management of CDW, more in general in the civil sector, were estimated as well [6,55–57].

LCA studies on CDW materials are mostly focused on the evaluation of environmental impacts of different recycling strategies in comparison to landfilling [58,59]. These studies are limited to the analysis of recycling processes from the demolition stage to the production of the recycled (end-of-waste) product (e.g., cradle-to-gate LCA approach). More work is effectively needed to extend the environmental impact assessment to real applications in which CDW material is included in substituting NA. Some LCA analyses have investigated the environmental benefits of using recycled CDW aggregate in concrete production [60–63]. Almost all the road pavement LCA-related studies consider the inclusion of recycled and/or alternative materials in substitution of traditional ones for asphalt and concrete layers of flexible and rigid pavements respectively [7,64–68]. Only a limited number of studies focused on the environmental assessment deriving from the use of CDW aggregate as granular material in base/subbase layers [53,69,70]. Thus, there is a need to extend the LCA analyses to alternative granular materials including stabilized-CDW aggregates with traditional and alternative binders. The previous studies on the LCA analysis using CDW materials focused on the economics and/or environmental impacts during the material production process [43,48,61–63,70,71]. Thus, there is a need to consider all stages in the roadway life-cycle performance phases (i.e., construction, maintenance, rehabilitation) in order to address all potential impacts and benefits of using CDW aggregates in the LCA analysis of roadway projects. This study addresses this need with the proposed novel methodology that quantifies the LCA environmental benefits and economic savings throughout the entire performance period of alternative sustainable strategies considering both construction and rehabilitation stages. This study addresses this need through the analysis of a pavement project representative of typical construction practices for average traffic volumes in Northern Italy. The life cycle economic and environmental benefits of using both natural-and CDW-stabilized aggregates as road base layer material were assessed. CDW aggregates stabilized with different binder types (i.e., cement and CKD) and contents were considered in the comparative analysis of alternative sustainable strategies. For each strategy, the pavement structure was designed to meet the structural requirements in the function of the materials used. The LCA analysis quantitatively assessed the economic and environmental impacts during the materials production, transportation, construction and rehabilitation phases.

2. Methodology and Evaluation Procedures

The proposed methodology for generating and assessing alternative sustainable strategies for roadway construction using recycled materials includes the steps of Figure 1. The methodology describes the general framework for generating and analyzing sustainable pavement and rehabilitation, which can be applied to any recycled materials or industry by-products. The proposed methodology considers LCCA and LCEA for all life cycle phases (e.g., materials processing, transportation, construction, maintenance and end life phases) throughout the performance period. The methodology also suggests that the strength parameters of each recycled material should be employed in determining rehabilitation strategies and predicting the service life of sustainable alternative designs so as to reduce the uncertainty associated with the long-term performance of these recycled materials.

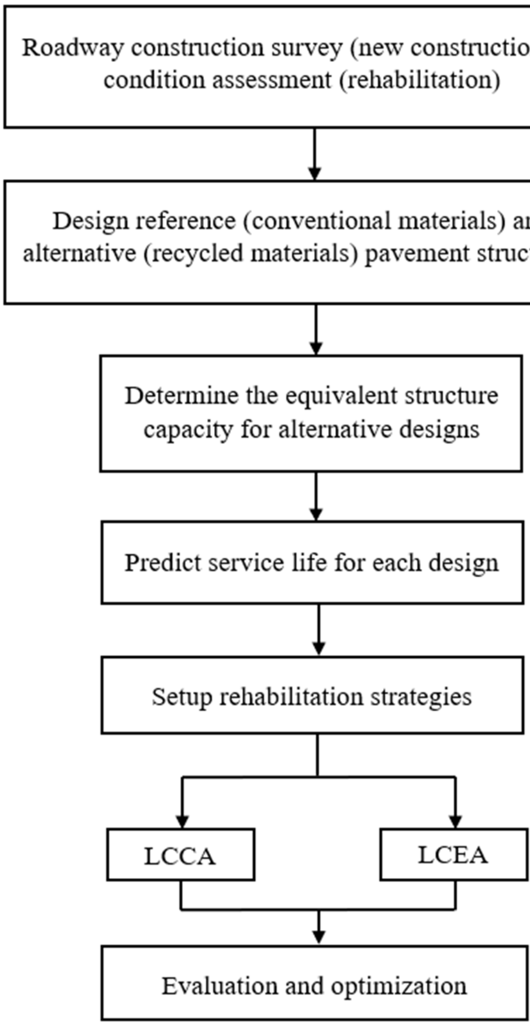


Figure 1. Methodology for generating and assessing alternative sustainable strategies for pavements. Note: LCCA = life cycle cost analysis, LCEA = life cycle environmental analysis.

The first step is pertinent to a survey of the existing conditions. If the project is related to a new pavement construction, then the survey will require information on current subgrade materials, traffic and environmental inputs, construction materials and design practices. For a rehabilitation project, condition assessment of the existing pavement is needed (e.g., layers, materials and thicknesses). This phase provides information for selecting the best materials and construction techniques and/or identifying what level of existing materials can be recycled along with the recycling method (e.g., cold in-place recycling, CIR, hot in-place recycling, HIR, full-depth reclamation, use of ex-situ recycling) [70].

The following step is related to the structural design of pavement considering both reference and alternative strategies. A reference design can be considered where 100% virgin materials are used. This will be used for comparative analysis in assessing the potential of more sustainable strategies in terms of cost and environmental impact. The pavement structural design of the potentially sustainable alternatives needs to be developed next considering the recycled materials of interest. To design such alternatives, the properties of materials for each case need to be assessed either in the lab and/or the field. Since recycled materials and industrial by-products have different engineering properties versus conventional raw materials, the equivalent layer thicknesses for the alternative strategies need to be determined. Furthermore, in order to identify appropriate rehabilitation strategies, the service life needs to be estimated depending on the initial design quality and the minimum acceptable condition, considering (i) material properties, (ii) layer characteristics, (iii) traffic load, and (iv) climatic conditions. In this study, the simplified approach of the 1993 AASHTO pavement design guide was employed for the structural design of the pavements with different materials, considering a minimum present serviceability index (PSI) of 2.5 as the lower acceptable condition [72]. Alternatively, the mechanical-empirical pavement design guide (MEPDG) can be used as well [73]. The use of alternative pavement design guides may result in slightly different equivalent thicknesses and service life for the alternative designs.

The life cycle economic and environmental impact analysis for both conventional and alternative sustainable designs is the next step (Figure 1). In this study, PaLATE was used in this study since it (i) includes data for a variety of recycled materials and industrial by-products, (ii) considers the environmental and economic impacts for the entire construction supply chain, and (iii) includes material production, construction and rehabilitation phases [74]. Reference values on energy consumption and emissions pertinent to the production of the recycled materials used in this study were obtained from the literature, construction industry, EPA (U.S. environmental protection agency inventory data), and values available within PaLATE [74]. Construction equipment air pollution emission factors are referenced within PaLATE to values obtained from the Organization for Economic Cooperation and Development (OECD) database [75]. The total environmental effects are computed as the product of emissions in the function of the quantity of material used and pertinent construction activity (e.g., material production, construction and transport distance) for the project. The environmental impact for transportation is computed as the product of unit truck emissions and the transport distance. The transportation distances identified in Table 1, represent actual typical distances for the region of this project. Thus, the impact of transportation distances is integrated into the environmental analysis. Moreover, PaLATE can be easily modified to consider new recycled materials in the different phases of the analysis.

Table 1. Design features of the paving construction project.

Design Considerations	Value
Width (two travel lanes)	7.32 m
Road length	1.6 km
Wearing course depth	100 mm
Asphalt content	4.5%
Performance period of analysis	40 years
Rehabilitation (50 mm mill and overlay)	every 10 years
Distance from plant to site	40 km
Distance from site to landfill	32 km

The last step of the analysis (Figure 1) is related to the comparative analysis of the sustainable alternatives by using either an overall ranking and/or rating, or specific attributes that represent the important target of sustainability objectives (e.g., target reductions in energy, water demand, emissions, costs, etc.) and their relative importance to the specific project location and region. In doing so, a sustainability rating system may be used. In this study, BE^{2}ST-in-Highways^{TM} was used since this rating tool is flexible enough to accommodate adjustments in targets of sustainability objectives (for example percent of the reduction in energy and associated sustainability score), as well as modifying the relative weights between sustainability objectives (i.e., the importance of reduction in energy versus water consumption, and so on) [76]. Thus, the LCA analysis can be used for developing such a rating for each sustainable alternative. This specific rating system provides the opportunity to present the sustainability scores in each category through an Amoeba graph, identifying visually which aspects of sustainability achieved the maximum score and which need to be further addressed. It is worth mentioning that such methodology could be potentially adapted into pavement management systems (PMS) for generating and assessing sustainable pavement designs.

3. Alternative Strategies

A pavement project representative of typical construction practices for average traffic volumes in Northern Italy was considered as a case study for the LCCA and LCEA analyses of this study. The project characteristics are presented in Table 1 and are for a two-lane pavement with a width of 7.32 meters and a length of 1.6 kilometers (equivalent to one mile). The analysis period considered was of 40 years with minor rehabilitation (i.e., overlay) every 10 years as estimated from the deterioration rate of the pavement structure. Reclaimed asphalt pavement (RAP) material is considered for an onsite process and reuse. Hot-mix asphalt (HMA), NA, CDW aggregate and cementitious materials were supposed to be delivered from a plant 40 km away from the construction site. The distance between the construction site and landfill was 32 km. These distances are representative of paving projects in the region of the construction project.

Figure 2 shows the different scenarios considered in this study. The reference strategy includes a conventional road pavement entirely made with virgin materials (design A), while the sustainable alternatives consider stabilized-CDW aggregates in lieu of NA for base layer formation (designs B, C, D, and E). The conventional design consisted of 100 mm hot mixed asphalt (HMA) over a 200 mm NA base treated with ordinary Portland cement (3%). All of the alternative design strategies maintained the 100 mm of HMA composed with new construction materials due to stringent requirements for the quality of the surface layer, with the exception of design C where a 20% RAP was permitted for comparative purposes with option B. The inclusion of such a low content of RAP did not produce changes in the HMA properties. For the base layer, alternative formulations of CDW aggregates were considered stabilized with different cementitious binders (e.g., CEM-II and CKD). The properties of such stabilized CDW materials are reported in Table 2, together with the different structural layer coefficients determined in relation to the properties of the materials. The equivalent thickness for the base layer for each case was determined in order to provide the same structural capacity (i.e., structural number SN, Equation (2)). The 7-day unconfined compressive strength was used for estimating the structural coefficient (i.e., a_1, a_2, a_3) of each material.

$$\begin{aligned}\log(W_{18}) &= Z_R \cdot S_0 + 0.36 \cdot \log(SN+1) - 0.20 \\ &+ \tfrac{\log[(\Delta PSI)/(4.2-1.5)]}{0.4+1094/(SN+1)^{5.19}} + 2.32 \cdot \log(M_R) - 8.07\end{aligned} \tag{1}$$

where,

W_{18} = accumulated 18-kip equivalent single axle load for the design period
Z_R = reliability factor
S_0 = standard deviation
ΔPSI = initial PSI–terminal PSI
M_R = subgrade resilient modulus
M_R = structural number:

$$SN = a_1 D_1 + a_2 D_2 \mathrm{m}_2 + a_3 D_3 \mathrm{m}_3, \tag{2}$$

where,

a_1, a_2, a_3 = structural layer coefficients for surface, base and subgrade layers
D_1, D_2, D_3 = thicknesses for surface, base and subgrade layers
m_2, m_3 = drainage coefficients for base and subgrade layers.

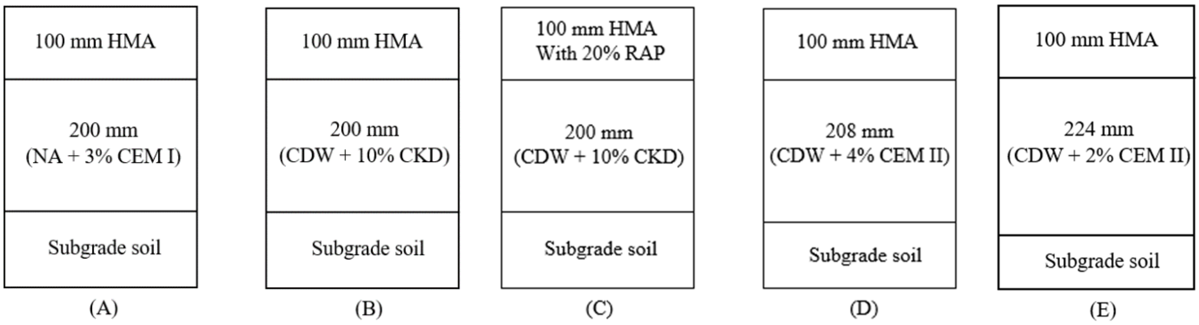


Figure 2. Schematic representation of alternative strategies and materials; (**A**) reference design, (**B**–**E**): alternative strategies Note: RAP = reclaimed asphalt pavement.

Table 2. Alternative Materials and Properties.

Design	Aggregate	Binder	Binder Content	Water Content	Compacted Density	7-Day UCS *
			(%)	(%)	(kg/m^3)	(MPa)
A	NA	CEM-I	3	6.5	2363	2.33
B and C	CDW	CKD	10	12.3	2138	2.32
D	CDW	CEM-II	4	11.7	2141	2.00
E	CDW	CEM-II	2	11.2	2152	1.59

DW = construction and demolition waste; CKD = cement kiln dust; CEM-I = ordinary Portland cement; CEM-II = cement type II; NA = natural aggregate. Note: * represents for Unconfined compressive strength.

The equivalent thicknesses for the base layer of each alternative design are presented in Figure 2. Comparatively, lower material strength corresponds to thicker base layer thickness, and vice versa.

4. Life Cycle Assessment

The life cycle assessment for both environmental and economic impact considered the entire supply chain (i.e., material production, construction, transportation, and maintenance activities) over the 40-year analysis period. Thus, material resources, energy use, water consumption, emissions, costs, and other pertinent parameters were included in the analysis. Costs of material, transportation and construction operations, labor, overhead, and profit were included in the LCCA. Material costs were collected from local contractors (Table 3), while typical construction, maintenance (i.e., mill and overlay) cost were used. Similarly, labor costs and overhead rates were based on typical construction projects in the region and reported in Appendix A (Table A1). Consumption and emission generation in the production and transportation of materials during initial constructions and maintenance were considered to estimate the environmental effects. The environmental impact (energy consumption, water consumption, CO_2, CO, PM_{10}, NOx, SO_2, and hazardous waste) due to CDW aggregate and CKD production were previously modeled using the software OpenLCA [77]. The total environmental impacts were calculated as the sum of materials production, transportation and construction equipment. The LCA sustainability analysis was conducted over an analysis period of 40 years with scheduled 50 mm overlay every ten years for both conventional and alternative designs. The time intervals were determined based on the estimated traffic level and deterioration rates using the rehabilitation design principles of the 1993 AASHTO design guide [72]. The CDW used in the alternative designs were tested for both short-and long-term performance assessment [38]. These materials show equal, or better, performance than conventional and alternative recycled materials. Thus, the long-term life of CDW materials is expected to match or exceed the performance of alternate materials, providing thus comparable or conservative values of performance life.

Table 3. Materials costs.

Material	Cost (USD/ton)
HMA	80.0
RAP	15.0
CDW aggregate (0–40 mm)	2.4
CDW aggregate (0–8 mm)	3.6
NA (for base)	12.0
CEM-I	92.4
CEM-II B-P	96.0
CKD	1.2

5. LCCA Results

The life cycle cost associated with each alternative is calculated and reported in terms of net present value (NPV) based on a discount rate of 4%. Figure 3 provides a comparison of the economic savings between the reference and the alternative strategies. Cost savings vary in relation to the type and percent of stabilizer used. Despite the relatively high percentage of CKD for stabilization of CDW aggregates in scenarios B and C, a higher level of cost saving is observed. Compared to the conventional case (scenario A), the use of CDW stabilized with 10% CKD (design B) in the base layer provides a cost reduction of up to 17%. This is related to the significantly lower price of CDW aggregates and CKD as compared to that of NA and ordinary cement respectively (Table 3). The use of RAP in the surface HMA (scenario C) led to additional savings with respect to references that are associated with the reduction in transportation and landfilling. Alternatives B and C have the same base layers (i.e., CDW aggregate with 10% CKD), however, alternative C presents a 5% lower cost, in relation to B, since 20% RAP is used in the surface HMA layer. The asphalt binder used in asphalt mixtures is the most expensive material in roadway projects. By using 20% RAP in HMA the new binder needed for HMA is reduced. For alternatives D and E, even though a higher amount of CDW aggregate and cement is needed to meet the structural requirements (i.e., thicker base layer according to the structural design) the associated costs were reduced by 11% and 13% respectively in relation to the reference strategy. Overall, the quantified cost savings for these strategies are attributed to the reduction of material costs. For alternative C additional cost savings are associated with the reduction in transportation and landfilling since 20% RAP was used in HMA.

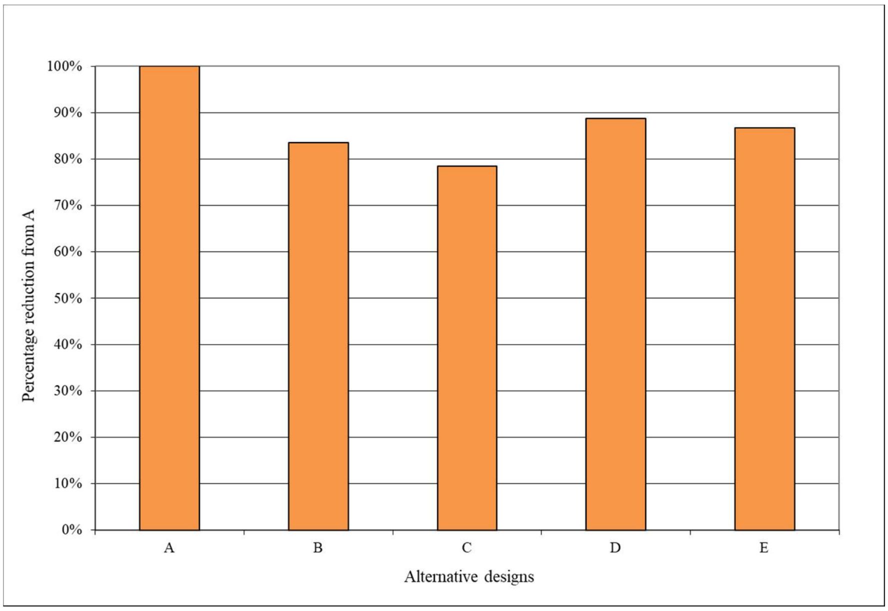


Figure 3. LCCA for alternative strategies. (**A**) reference design; (**B**–**E**): alternative strategies.

6. Life Cycle Environmental Impact Results

The environmental impacts were examined in relation to the resources and equipment used during all processing phases (i.e., production of materials, transportation and construction processes). Three major environmental impact components were reported including greenhouse gas emissions (CO_2), water consumption and energy consumption. Five pollutants that have a direct impact on human health, as identified by the Environmental Protection Agency, EPA, [78] were also considered and include (i) hazardous waste generation, (ii) SO_2, (iii) CO, (iv) PM_{10}, and (v) NOx. As shown in Figure 4, the life cycle CO_2 emissions for both conventional and alternative designs are dominated by materials production. The emission factors related to each material production are shown in Appendix A (Table A3). The processes (i.e., equipment for construction and maintenance) and transportation generated a similar amount of greenhouse gas emission for all strategies. This is because a similar level of activities and equipment are used during these construction operations. In terms of materials production, overall, the greenhouse gas emissions are reduced significantly by substituting NA with CDW aggregate in base layers formation. By comparing strategy D to the conventional option, the replacement of virgin aggregates with CDW aggregate decreases approximately 20% the CO_2 emission despite the 1% increase in cement. The main sources of CO_2 emissions during material production include heavy equipment operations and transportation. However, substantial environmental benefits are achieved by using CDW aggregate due to the reduction of virgin materials needed and landfill disposal. In the case of option E, an additional 15% reduction in CO_2 was observed by limiting the amount of cement from 4% (option D) to 2% (option E) despite the higher amount of CDW aggregates needed to address the increased base layer thickness. This reflects the high amount of CO_2 associated with cement production as compared to CDW aggregate production. In case of design B and C which employ 10% CKD to replace Portland cement, CO_2 emissions were reduced by 56% and 63%, respectively. Since CKD is a by-product of the cement manufacturing process, a significant reduction in CO_2 emissions is observed. In strategy C, CO_2 emissions from material production and transportation were further reduced due to the use of RAP (20%) in HMA.

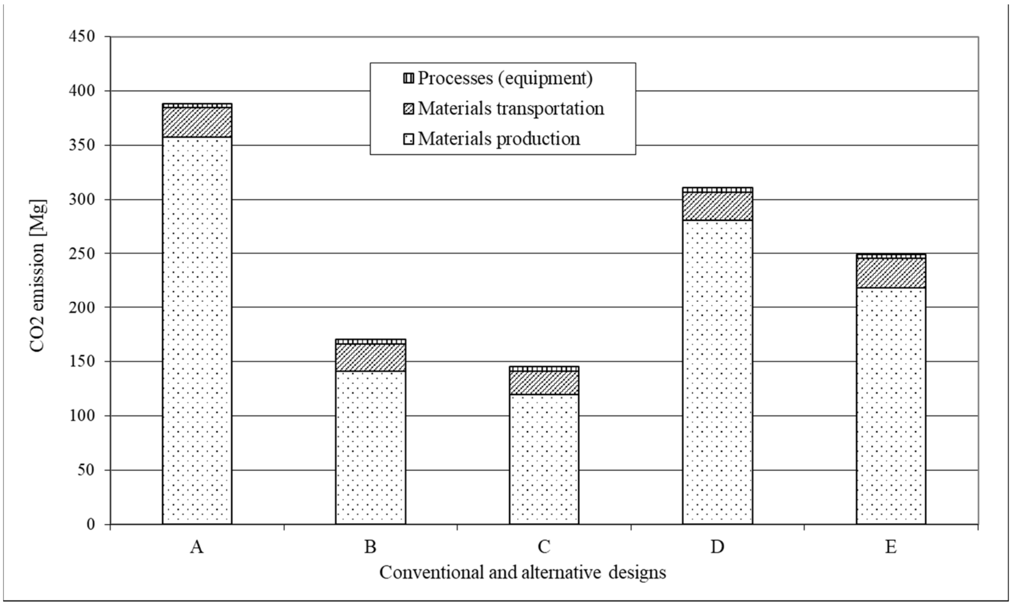


Figure 4. Life cycle greenhouse gas emissions (CO_2); (**A**) reference design, (**B**–**E**): alternative strategies.

Figure 5 presents the energy consumption results. The energy savings are analogous to the reductions in CO_2 emissions associated with material production. It can be observed that construction processes consumed the least amount of energy comparing to material production and transportation. A maximum energy saving (equivalent to

44%) was achieved by using 20% RAP in HMA and considering a base layer with CDW with 10% CKD (scenario C). The substantial energy savings from options B and C reflect the fact that cement production is an extremely high energy and emission intensive process. By comparing alternative D to the reference design, the energy consumption was reduced by 21% by substituting virgin aggregates with CDW ones. This indicates that the manufacturing of CDW aggregates is more energy efficient than that of NA.

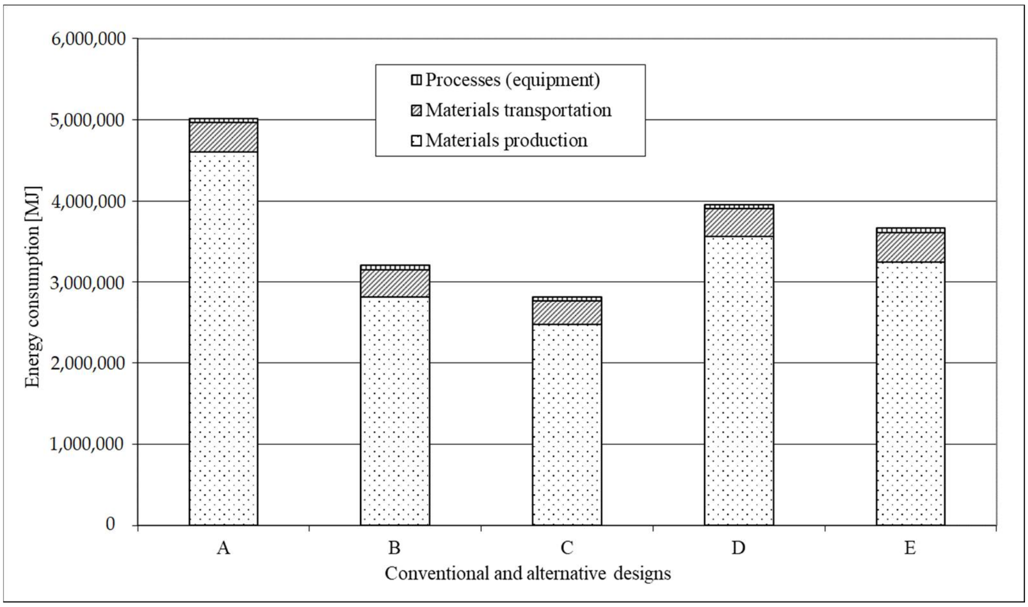


Figure 5. Life cycle energy consumption; (**A**) reference design, (**B**–**E**): alternative strategies.

The life cycle water consumption is shown in Figure 6. Material production, especially cement, requires a large amount of water. Since cementitious materials were used in the mixture, water needs to be added to develop the hydration process. The optimum water content for each mixture is shown in Table 2. The water consumption is mainly from material production and processes. As higher water contents are needed for stabilized CDW, the water consumption increases for the alternative strategies. However, the total water consumption was reduced by about 15% for strategy C since a lower amount of water is needed as compared to the reference case for material production of virgin aggregate and cement. In the case of option E, the total water consumption increased dramatically since a high water content is needed combined with the increased amount of material needed for the thicker base layer.

Table 4 summarizes the quantities for each environmental parameter considered in this study, while Figure 7 presents the comparison between the reference and the alternative sustainable strategies (the latter expressed as relative results with respect to the reference). Hazardous waste generation primarily comes from producing materials such as asphalt emulsion, bitumen and concrete additives, and disposal of these materials to landfill. Aggregate and cement production generates very little hazardous waste compared to these materials. This reflects that only around 6% hazardous waste reduction was observed in options B, D, and E. On the contrary, hazardous waste was further reduced by 17% when 20% RAP was used in HMA (strategy C). SO_2 emissions are analogous to hazardous waste generation associated with materials production. Additional pollutants (i.e., CO, PM_{10}, and NOx) were also quantified (Table 4). According to the results of Table 4, considerable environmental savings for all alternative strategies can be deduced. Design C outperformed other alternatives in terms of all environmental impacts, particularly in energy and water consumption, and CO_2 emissions.

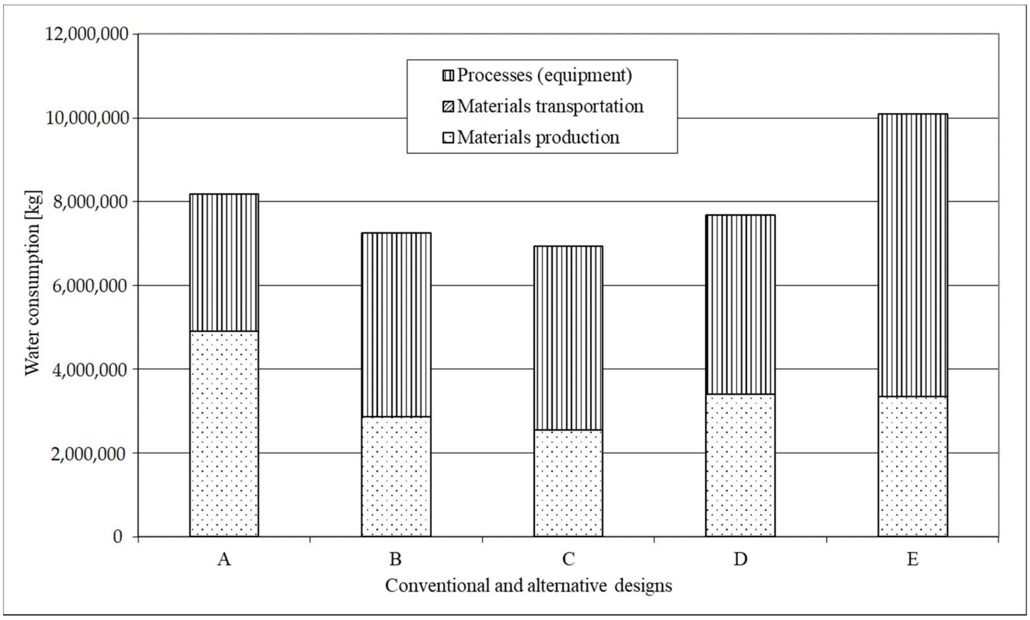


Figure 6. Life cycle water consumption; (**A**) reference design, (**B**–**E**): alternative strategies.

Table 4. Environmental impacts for alternative strategies.

Designs		Energy Consumption (MJ)	Water Consumption (kg)	Hazardous Waste (kg)	CO_2 (Mg)	CO (kg)	PM_{10} (kg)	NOx (kg)	SO_2 (kg)
Reference	A	5,018,259	818,330	35,514	388	804	1954	3040	52,288
Alternatives	B	3,207,405	725,435	33,287	170	466	1605	2483	49,012
	C	2,816,530	694,111	26,885	145	379	1416	2238	48,701
	D	3,956,628	767,996	33,664	311	575	1707	2761	49,109
	E	3,663,825	1,009,706	33,710	250	525	1773	2711	50,017

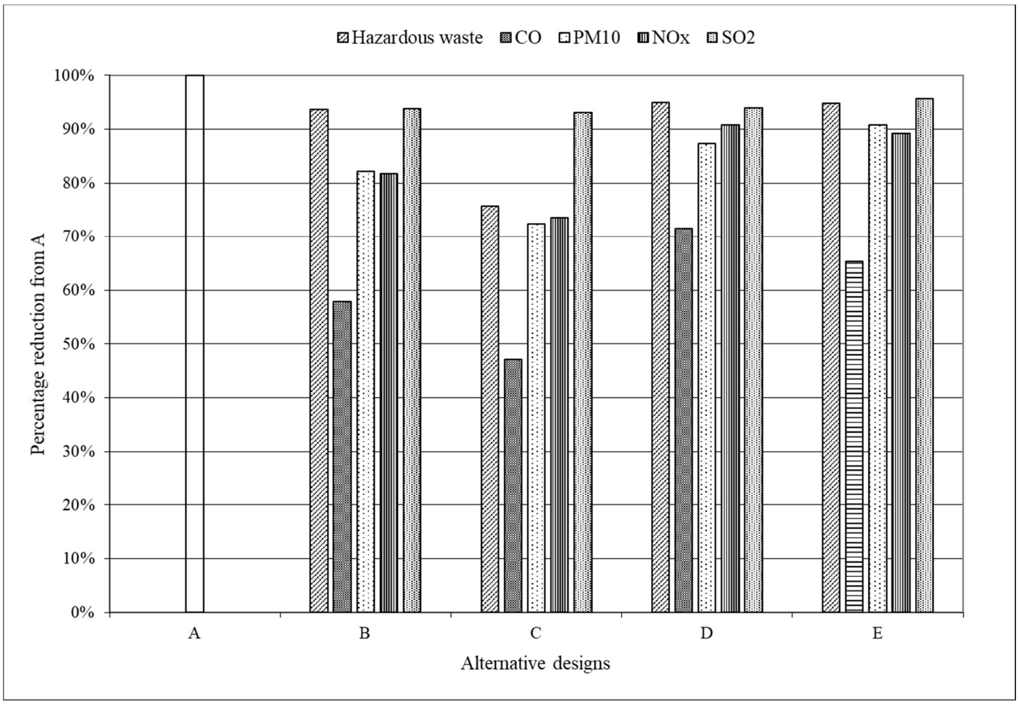


Figure 7. Environmental impacts of alternative strategies; (**A**) reference design, (**B**–**E**): alternative strategies.

7. Sustainability Criteria and Rating

An overall assessment of each alternative strategy in regard to sustainability was conducted using BE^{2}ST in-Highways [76]. This sustainability metrics tool evaluates each alternative strategy using a comparative assessments method and rating based on the LCA results. Eight criteria are used in this assessment and include (i) energy use, (ii) global warming potential (GWP), (iii) recycling content, (iv) water consumption, (v) life cycle carbon costs, (vi) social carbon costs (SCC), (vii) traffic noise, and (viii) hazardous waste. Each alternative strategy is compared in relation to the reference one (strategy A). The SCC represents the cost needed to eliminate or address issues caused by carbon emissions (i.e., USD/Mg of CO_2 emissions) and is associated with the cost of reducing global warming issues (e.g., GWP). Highway agencies often incorporate SCC for evaluating sustainable pavement construction and rehabilitation. As mentioned, in this study the alternative strategies were compared with the reference (i.e., conventional) option where new virgin materials were used for all processes and pavement construction stages. As mentioned earlier, weighting factors are assigned for each criterion to reflect their relative importance based on local conditions and policies for the construction projects. For instance, in some regions greenhouse emission or energy reduction may be more critical than cost savings, and so on. Therefore, higher weights are assigned to such critical parameters. The sum of weights should be equal to 100 (Figure 8). For this study, the sustainability criteria and targets, and the relative weights assigned to these parameters are as follows: 15% for energy consumption, global warming potential (i.e., CO_2 emission), recycling content and water consumption, 10% for hazardous waste and social carbon cost, and 5% for traffic noise. These parameters were selected to reflect current construction practice and policies with recycled materials for the specific region of the construction project. These parameters can be modified to reflect construction practices and policies elsewhere. Table 5 shows the sustainability target for each criterion. For instance, two points are rewarded if the energy consumption is reduced by more than 20%. While both targets and relative weights were selected for this region, such factors can be modified for roadway projects elsewhere.

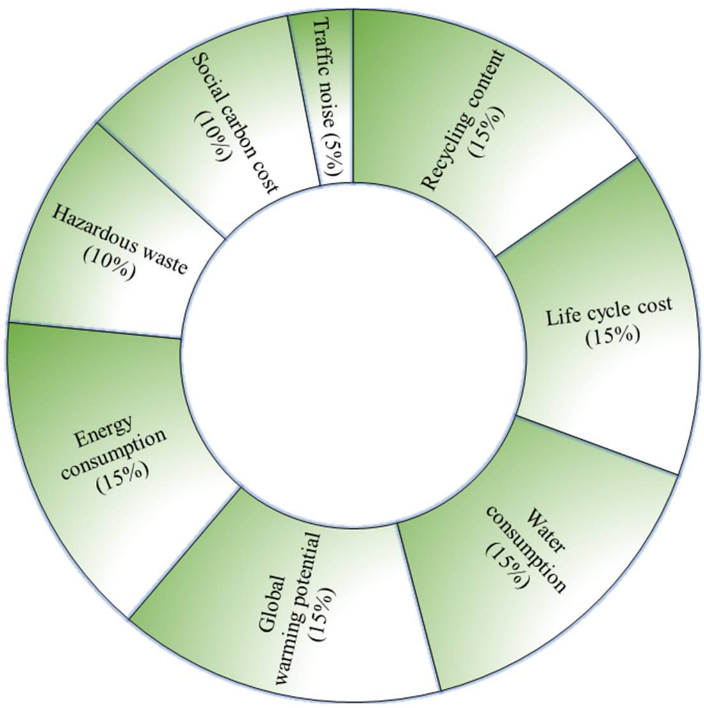


Figure 8. Relative weights for sustainability criteria.

Table 5. Criteria and sustainability targets.

Criteria	Unit	Target	
Energy consumption GWP Life cycle cost	MJ Mg USD	≥10% reduction ≥20% reduction	(1 pt) (2 pt)
Recycled content	%	≥10% recycling rate ≥20% recycling rate	(1 pt) (2 pt)
Water consumption Hazardous waste	kg	≥5% reduction ≥10% reduction	(1 pt) (2 pt)
Social carbon cost	USD	≥USD 12,344/km saving ≥USD 24,688/km saving	(1 pt) (2 pt)
Traffic noise	no unit	HMA SMA or OGFC	(1 pt) (2 pt)

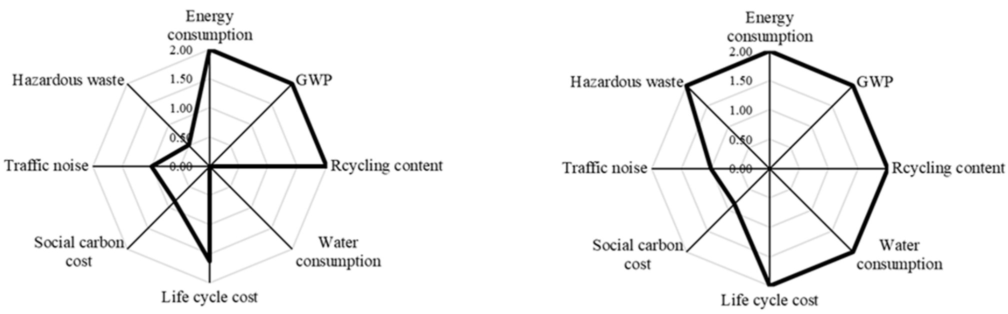
Note: SMA = stone mastic asphalt, OGFC = open graded friction course.

The sustainability assessments for each strategy, both in terms of reward points pertinent to each criterion and total rating score, are summarized in Table 6. A weighted point (i.e., production of obtained point and weighting factor) was computed for each criterion. The total score was then calculated by dividing the total weighted point (i.e., sum of the weighted points for each criterion) into the target (i.e., 2). Strategy C represents the most sustainable option among the four proposed alternatives, with a total score of 92%. The total score is achieved by a 21% reduction in life cycle cost, a 15% reduction in water consumption, a 44% reduction in energy, and 63% reduction in CO_2 emissions. The Amoeba graphs for strategies C (best) and E (worst) are shown in Figure 9 as an example. Alternative D achieved a total score of 67% which outperformed alternative E (i.e., total score of 47%) in terms of sustainability even though E used a higher amount of cement (i.e., 4%). This is because strategy E requires 20 mm more layer thickness than D due to the low material strength, and thus more CDW aggregates, and water are needed. The impact of each strategy on such criteria is evident and could be used in further improving each strategy. As it can be observed significant differences are observed between the two strategies in terms of water consumption, LCC, social carbon cost and hazardous waste. The use of cement stabilization for CDW aggregate is attributed to good part to such effects. Thus, the results could be eventually used to further modify such alternatives for better sustainability scores.

Table 6. Points obtained for each parameter and total rating score.

Strategy	Energy Consumption	GWP	Recycled Content	Water Consumption	Life Cycle Cost	Social Carbon Cost	Traffic Noise	Hazardous Waste	Total Weighted Points	Total Score
B	2.00	2.00	2.00	2.00	1.79	1.00	1.00	0.63	1.66	83%
C	2.00	2.00	2.00	2.00	2.00	0.85	1.00	2.00	1.83	92%
D	2.00	1.98	2.00	0.62	1.53	0.27	1.00	0.51	1.34	67%
E	2.00	2.00	2.00	0.00	1.63	0.48	1.00	0.51	0.94	47%

Note: A represents the reference strategy.



Strategy E Strategy C

Figure 9. Amoeba graphs for strategies C and E.

8. Conclusions

This study examined the life cycle cost savings and environmental benefits of using stabilized CDW recycled aggregates for base layers of roadway pavements. The proposed analysis approach for developing and accessing alternative sustainable strategies was presented in this process. The economic and environmental implications were quantified by comparing the results of the alternative recycled materials (i.e., CDW, CKD, and RAP) strategies with those of the reference case where new construction materials are used. In the analysis resources and equipment used during the production of materials, construction processes (i.e., equipment used for construction and rehabilitation), and transportation were considered. The alternative strategies were developed based on the laboratory-obtained strength parameters of different stabilized CDW recycled aggregates. The analysis indicated that the alternative strategy employing CDW aggregates stabilized with 10% CKD in the base layer combined with a 20% RAP in the HMA surface layer provided the best sustainable option. This resulted in significant reductions in life cycle cost, energy consumption, water consumption and greenhouse gas emissions. The results also showed that the replacement of Portland cement with CKD (i.e., alternatives B and D) stabilization of CDW aggregates further enhanced the environmental benefits. The LCCA indicated that cost savings were primarily attributed to the lower costs for CDW, and CKD compared to conventional materials, while the LCEA results indicated that the production of CDW and CKD requires less energy and generates lower emissions. The economic and environmental benefits quantified in this study could encourage the wider adoption of stabilized CDW aggregates in sustainable roadway construction. While the absolute values of the economic and environmental LCA are related to the inputs considered for this project, the relative benefits of using CDW in base and subbase layers are transferable, in scale, to any other projects where similar uses of these recycled materials are intended. Thus, the suggested approach for LCCA and LCEA can be adopted elsewhere for quantifying the sustainability benefits CDW and other alternative recycled materials on roadways.

In conclusion, this study provided a tangible method for assessing the sustainability and contribution of CDW materials on roadways that can be expanded to other recycled materials. While the specific values of the economic and environmental LCA are related to the inputs considered in this project, the relative benefits of using CDW are transferable to other construction projects where similar uses and materials are used. Thus, the suggested approach for LCCA and LCEA can be adopted elsewhere. Further research in this area should consider the potential adoption and implementation of sustainability criteria, and the proposed analysis in pavement management systems (PMS). This will permit the generation of optimal sustainable alternative construction and rehabilitation strategies at the project and network level.

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Appendix A

Table A1. Labor, processing cost and overhead rates (PaLATE).

Process	Cost
Mill and Overlay	USD 33/m^2/50 mm
Labor	USD 16,000/1.6 km
Equipment	USD 12,000/1.6 km
Overhead & profit	USD 11,000/1.6 km

Reference: PaLATE.

Table A2. Transportation emission factors (AP-42 Section 3.3. U.S. EPA).

Emission Factor, Grams/Tonne-km					
CO	CO_2	HC	NOx	SO_2	PM_{10}
0.25	140	0.32	3.00	0.18	0.17

Table A3. Environmental factors related to materials production (PaLATE and openLCA).

Materials	Energy MJ/ton	Water g/ton	Hazardous Waste g/ton	CO_2 g/ton	CO g/ton	PM_{10} g/ton	SO_2 g/ton
HMA	1968	96	3560	183,016	42.0	48.0	27.0
GAB	49	34,117	179	2718	6.6	2.0	9.2
Cement	4342	2,725,606	1636	879,729	661.9	189.4	783.9
CDW	−123	31,677	0	−5864	−25.2	−7.6	−13.8
CKD	19	12,632	0	4631	3.1	0.8	3.7

Note: The negative environmental effects representing the avoidance of landfill.

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