

Article

Life-Cycle Sustainability Assessment of Using Rock Dust as a Partial Replacement of Fine Aggregate and Cement in Concrete Pavements

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Abstract: The use of recycled materials and industrial by-products in pavement construction and rehabilitation can achieve substantial benefits in saving nature resources and reducing energy consumption as well as greenhouse gas (GHG) emissions. Alternative geological origin rock dust for the partial replacement of fine aggregate and/or cement in Portland cement concrete (PCC) pavements may provide positive environmental and economic benefits. The objective of this study was to quantitatively assess the life-cycle economic and environmental impacts when rock dust is used in PCC pavement roadway construction. Previous studies have primarily focused on the economics and/or environmental impacts during the material production process. Thus, a methodological framework considering all stages (such as material production, transportation, construction, maintenance, rehabilitation and end of life), involved in the life-cycle assessment of concrete pavements is proposed when using recycled materials/by-products. The life-cycle assessment (LCA) was conducted on a pavement project representative of typical construction practices in Poland to quantify such benefits. The alternative sustainable construction strategies considered partially replacing fine aggregate and/or cement with rock dust of basalt origin in PCC pavements. The LCA results indicate that using rock dust to replace 20% FA and 10% cement provided a reduction of 6.5% in cost, 10% in CO₂ emissions and 11% in energy consumption. This study also provides significant insights on the specific contribution of material production, construction processes and the transportation of materials to the overall environmental benefits and cost savings. The suggested approach for LCA analysis in pavement construction can be adopted elsewhere for quantifying the sustainability benefits of using alternative recycled materials in roadways.

Keywords: environmental impact; life-cycle assessment; PCC pavements; rock dust; sustainability



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1. Introduction

The global road network comprises several million kilometers, and such roadway system requires additional construction and extensive rehabilitation to meet the growing traffic demand and guarantee the safety of drivers [1–3]. Road construction and rehabilitation are responsible for the consumption of substantial natural resources and energy, as well as for greenhouse gas (GHG) emissions, and thus have a considerable environmental impact. Therefore, State Departments of Transportations (DOTs) have been supporting and promoting the use of recycled highway materials and by-products in an effort to preserve the natural environment, reduce waste and GHG emissions and provide a cost-effective material for construction. Over the last decade, there has been an increase in the use of recycled materials/by-products as alternative materials in pavement construction such as

recycled asphalt pavement (RAP), recycled concrete materials (RCMs), construction and demolition waste, fly ash, rock dust, glass and crumb rubber and others [4–10]. In recent years, the technical feasibility of using rock dust as a partial replacement for fine aggregate and/or cement in concrete has been extensively investigated. This stems from the fact that there is growing global concern about the depletion of sand deposits and the highly intensive energy consumption and CO₂ emissions associated with cement production [11]. Rock dust is a byproduct obtained from the production process of crushed stone aggregates. A large amount of waste material is produced in the form of rock dust during the quarrying and aggregate processing [12]. Thus, the use of rock dust as a partial replacement for sand and/or cement in concrete may have promising potential environmental and economic benefits in terms of reducing construction costs, energy consumption, GHG emissions and saving natural resources.

Rock dust has been found to produce concrete with equivalent or improved mechanical and durability properties when used as fine aggregate and/or cement [11–15]. The effect of rock dust on the mechanical properties of concrete significantly depends on the stone dust specific surface area and the percentage of replacement [13]. The use of rock powder as a partial replacement for fine aggregate generally leads to the improvement of mechanical properties and durability of cement composites [12,13]. Due to the fact that rock dust is an inert material, replacing cement with dust usually leads to the deterioration of the properties of cement composites. However, with a slight substitution of cement (i.e., in an amount of about 10–15%), a slight increase in strength and improvement in the durability of concretes and mortars is observed [12,13]. Beneficial rock dust interaction is attributed to the filler effect, which is the most important and dominant mechanism [16–18]. Very fine particles of rock powder fill the space between the cement and the aggregate particles which leads to the reduction in cement matrix porosity. A decrease in the large capillary pores and an increase in small pores content is observed at the same time. This results in the densification of the hardened cement paste microstructure and less permeable structure. As a result, cement composites with a rock dust additive feature higher strength and durability [13]. Thus, there is a potential to use rock dust as a partial replacement of fine aggregate or/and cement in Portland concrete cement (PCC) pavement construction.

While the mechanical performance of a concrete mix with rock dust can be met, the potential economic and environmental benefits associated with its implementation need to be assessed, especially in the context of PCC pavement construction which requires large quantities of concrete. Therefore, the objective of this study was to estimate the potential economic and environmental impacts related to the use of rock dust in rigid concrete pavements through life-cycle analysis (LCA). The analyses considered conducting a quantitative assessment of different sustainable PCC pavement designs with rock dust and identify the best sustainable alternative(s). The existing studies on the LCA of recycled materials and/or industrial by-products mainly focused on the economics and/or environmental impacts during the material production process [19–21]. Thus, there is a need to consider all stages in pavement life-cycle performance (i.e., roadway design, construction, maintenance, rehabilitation and end of life) in order to address all the potential impacts and benefits of using recycled materials and industrial by-products in the LCA of roadway projects. This study addresses this need by proposing a holistic methodology that quantifies the life-cycle environmental benefits and economic savings of using recycled materials/by-products in pavement construction and rehabilitation throughout the entire performance period of alternative sustainable strategies. To demonstrate the suggested approach and quantify the potential benefits, this study analyzed a roadway project representative of typical construction practices for average traffic volumes in Poland. The life-cycle economic assessment (LCCA) and life-cycle environmental analysis of using both conventional concrete and concrete with rock dust as a partial replacement of sand and/or cement in PCC pavements were conducted. The LCA considers all stages in the life cycle of pavements, including material production, construction, maintenance and rehabilitation, as well as the end-of-life phase (i.e., landfill or recycling). It is worth mentioning that while there are studies that

have looked at LCA of concrete with fly ash (FA) and granulated blast furnace slag (GBFS), there are no studies that have examined the life-cycle economic and environmental impacts of concrete with the addition of rock dust [12].

2. Materials and Methods

2.1. Characteristics of Rock Dust and Cement

Ordinary Portland cement, OPC, CEM I 42.5R was used in the concrete mixtures. The cement specific gravity is 3.13 while the specific surface determined by the Blaine method was 3500 cm²/g. The chemical and mineral composition of the OPC is presented in Table 1. The gravel of the group of fractions 2/16, and river sand of the group of fractions 0/2 were used as a coarse aggregate and a fine aggregate, respectively.

Table 1. Chemical composition of cement.

Chemical Composition [%]	
SiO ₂	19.33
Al ₂ O ₃	5.15
Fe ₂ O ₃	2.90
CaO	64.59
MgO	1.25
SO ₃	3.23
K ₂ O	0.47
Na ₂ O	0.21
Cl [−]	0.05

The chemical composition of the rock dust (basalt origin) used in this study is presented in Table 2. The rock dust particle diameters are in the range of 0.5–200 µm. The average particle size of rock dust is 20 µm in diameter. The specific surface area of rock dust determined by the Blaine method was 3500 cm²/g with a specific gravity of 2.99.

Table 2. Chemical composition of rock dust (basalt origin).

Chemical Composition [%]	
SiO ₂	42.61
Al ₂ O ₃	12.90
Fe ₂ O ₃	14.05
CaO	13.00
MgO	7.82
Na ₂ O	1.76
K ₂ O	1.15
P ₂ O ₅	1.80
SO ₃	0.07
MnO	0.25
Cl [−]	0.10

2.2. Concrete Mix Design

The mix proportioning for the concrete to be used when generating the feasible alternative strategies is presented in Table 3. These mixtures were developed during the experimental study for meeting the C30/37 class compressive strength value according to the European Standards EN 206 + A1:2016-12 [22].

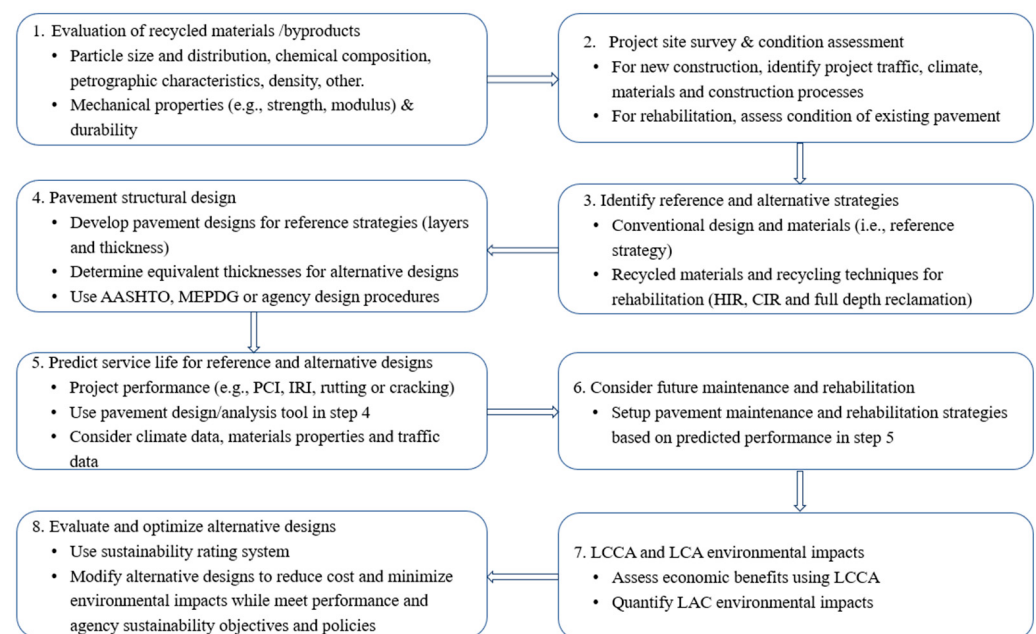
Table 3. Concrete mix proportioning.

Concrete	Cement (kg/m ³)	Water (kg/m ³)	Rock Dust (kg/m ³)	Fine Aggregate (kg/m ³)	Coarse Aggregate (kg/m ³)
A	350		0	533	
B	350		53.3	479.7	
C	350		106.6	426.4	
D	332.5	155	70.8	479.7	1400
E	315		88.3	479.7	
F	332.5		124.1	426.4	
G	315		141.6	426.4	

Six cube specimens of 150 mm × 150 mm × 150 mm were prepared for each concrete mix (i.e., the reference concrete and concretes with rock dust). All the specimens were cured in water at a temperature of 20 ± 2 °C. Compressive strength test was conducted at 28 days according to European Standards EN 12390-3:2019-07 [23].

2.3. Methodology for Evaluating Alternative Sustainable Strategies

The proposed methodology for assessing the life-cycle environmental and economic impacts with the use of recycled materials/by-products in pavement construction and rehabilitation includes the steps seen in Figure 1. The methodology describes the general framework for generating and analyzing sustainable pavement and rehabilitation strategies, which can be applied to any recycled materials or industry by-products.

**Figure 1.** Methodological framework for generating and evaluating alternative sustainable strategies.

The primary objective of encouraging the use of recycled materials in the construction of highways is to reduce economic costs and minimize environmental impacts without comprising the performance. Thus, the mechanical properties, such as compressive strength and elastic modulus, as well the durability of concrete with recycled materials need to be examined. In this study, the compressive strength results of concrete with rock dust were obtained from laboratory experimentation results, which indicated improved strength when rock dust is used as a partial sand and/or cement replacement. Once the engineering properties requirements are evaluated, the next step is to conduct a site-specific survey or condition assessment: for a new roadway construction project, the survey will require

information on project traffic and climate inputs, construction materials and processes; while for a rehabilitation project, condition assessment of the existing roadway needs to be performed. This step 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 or use of ex situ recycling [24].

The objective of step 3 is to identify the reference conventional and the alternative sustainable strategies. The reference strategy considers conventional (virgin) materials throughout the life cycle of the pavement structure, while alternative strategies use recycled materials or recycling techniques. The reference strategy is used for comparative analysis (step 7) in assessing and comparing against, and in between them, the alternative sustainable strategies in terms of cost and environmental impacts. The next step is related to pavement structural design for both reference and alternative strategies. The pavement structures (layers and thicknesses) are firstly determined. Since the concrete mix with recycled materials may have different mechanical properties compared to virgin materials, the equivalent layer thicknesses for the alternative strategies need to be determined using pavement analysis tools such as the 1993 AASHTO pavement design guide [25], the mechanical-empirical pavement design guide (MEPDG) [26] or local agency design procedures. 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 performance condition, considering (i) material properties, (ii) layer characteristics, (iii) traffic load, and (iv) climatic conditions [6]. In this study, the 1993 AASHTO pavement design guide was employed for the structural design and performance prediction of the pavements with different materials, considering a minimum present serviceability index (PSI) of 2.5 as the lower acceptable condition [27].

The following step is to conduct the life-cycle economic and environmental assessment. LCA models can be used as a sustainability tool given the flexibility of the methodology in providing a holistic analysis of the environmental and economic impacts of different recycled materials and processes on pavement construction [28]. While any LCA tool available may be used, in this study the Pavement Life-Cycle Assessment Tool for Environmental and Economic Analysis (PaLATE) was used to evaluate the economic and environmental impacts of construction materials and processes for the specific roadway project [29]. PaLATE is a project-level LCA tool that considers all life-cycle phases of pavements (e.g., materials processing, transportation, construction, maintenance and end of life). Three categories of data are used in PaLATE: environmental-related data (e.g., emission factors, energy and water consumption associated with material production, equipment and processes), cost data (materials and processes) and design-related data (e.g., layers, thicknesses, transport distances, etc.). Figure 2 presents the data used in each stage of the life-cycle analysis (materials production, transportation, initial construction and maintenance and end-of-life phases). The input data and calculations within this LCA tool are easily updated to reflect current emission models, local costs and site conditions. Thus, in this study, updated emission parameters were used following the Environmental Protection Agency (EPA) input–output model, USEEIO [30,31]. The design parameters represent typical roadway construction practices for average traffic volumes in Poland. The material costs, labor costs and overhead rates were collected from local contractors, while typical construction, maintenance and transportation costs were based on typical construction projects in the region. PaLATE outputs relate to the life-cycle inventory (cost, energy, water consumption, emissions, etc.) as shown in Figure 2. Such LCA analysis provides an understanding of where environmental impacts are created in the life cycle of pavements, as well as how and to what extent various sustainability strategies do in fact reduce those environmental impacts, and identifies potential unintended consequences that can result in increased environmental impacts. Once the LCA analysis is completed, a sustainability rating system should be used to evaluate each alternative in terms of its effectiveness to meet sustainability targets [32].

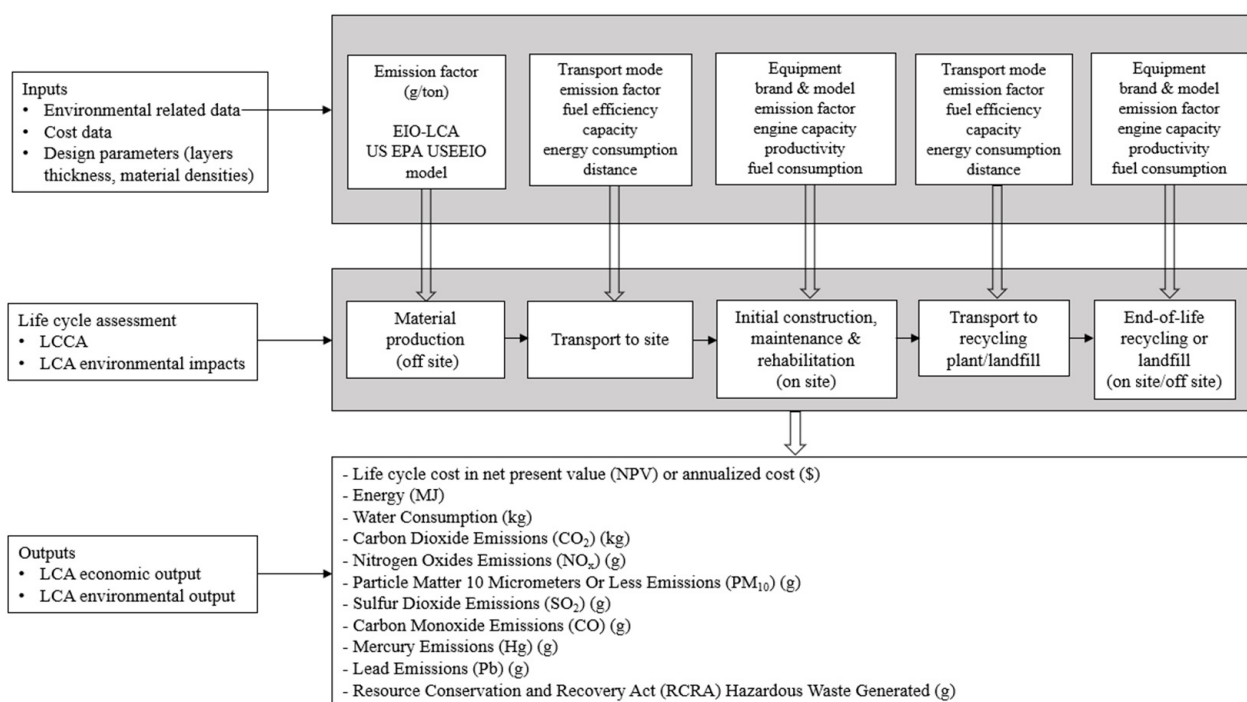


Figure 2. Inputs–outputs of the LCCA and LCA environmental impact analysis.

Thus, the proposed methodology for generating and analyzing feasible sustainable alternatives when rock dust is used in concrete for pavement structures was customized and reflects the approach adopted for this specific study. Figure 3 presents the specifics for each step while details are presented in the subsequent sections referred herein. Step 1 involved assessing the properties of rock dust, the results of which are presented in Section 2.1, and developing concrete mix compositions meeting the target strength, as seen in Section 2.2 and Table 4. The next step, Step 2, involved identifying the project site characteristics. As mentioned earlier, the identified project is representative of typical rural road construction in Poland. Section 2.4 presents such details. Step 3 involved the identification of feasible alternative strategies to be assessed along with the reference design where no rock dust is used in concrete. The details are presented in Section 2.3 and Table 4. Step 4 involved the pavement structural design analysis for each alternative strategy. This requires identifying the site and project-specific design inputs, as seen in Section 2.4 and Table 5, and the use of material properties (Section 2.4, Table 4) into the AASHTO design equation for identifying the layer thickness for each sustainable design alternative, as seen in Table 4. Step 5 involved predicting the performance for the design alternates in regard to the LCA time period. The deterioration rate for each design strategy was estimated from the design equations as identified in Section 2.4. Such input was then used in Step 6 for identifying the rehabilitation timing and overlay thickness, as indicated in Section 2.4. Step 7 involves the sustainability assessment of the alternative strategies in regard to LCCA, as seen in Section 3.1, and LCA environmental impacts, as seen in Section 3.2. The input and outputs of such analysis were presented in Figure 2, along with the specific cost and environmental inputs which presented later in Sections 3.1 and 3.2. The final step, Step 8, includes a sustainability rating assessment for each alternative, as seen in Section 4, so as to identify areas for further improvement of the existing and possible development of new strategies.

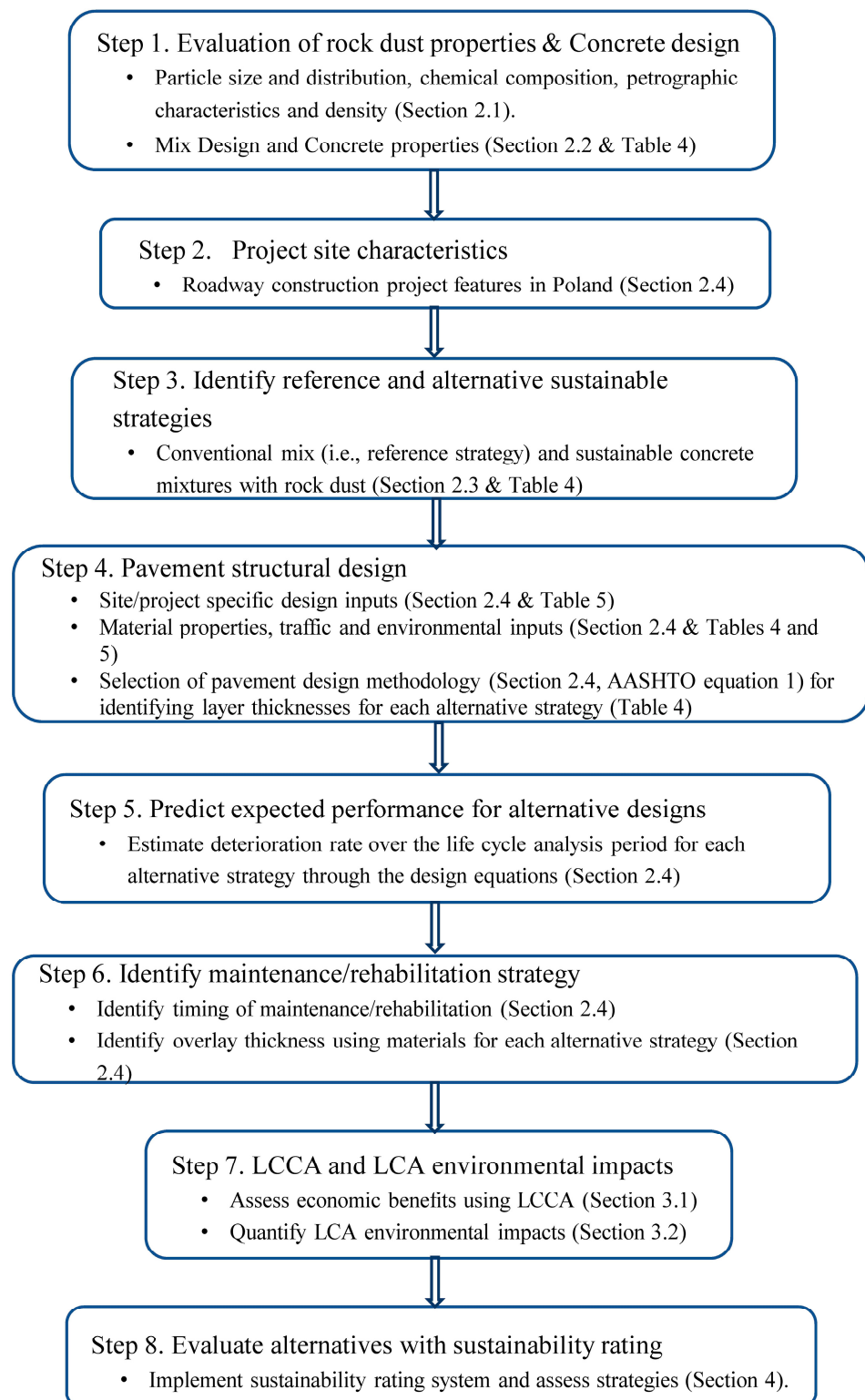


Figure 3. Tailoring proposed methodology for the development and assessment of alternative strategies for the case of rock dust in concrete for pavements.

2.4. Feasible Sustainable Strategies with Rock Dust Addition in Concrete

This study quantified the potential economic and environmental impacts related to the use of rock dust in rigid concrete pavements through the proposed methodology. For this purpose, a typical rural pavement section in Poland consisting of a 1.6 km (1 mi) length with two lanes, each lane 3.65 m (12 ft) wide, a distance of 40 km for the transport of

materials to and from the plant to the project site and 32 km for the transport of waste materials to landfill/recycling plants. Embankment and shoulders were not considered in this case.

The alternative sustainable strategies included different alternative PCC pavement designs with rock dust in concrete. Table 4 shows the various sustainable strategies considered in this study in relation to the concrete strength and stiffness properties when rock dust is added as a fine aggregate and/or cement replacement. As mentioned earlier, concrete strength values for each mixture were obtained from the concrete properties' experimental study, while the corresponding modulus was estimated using Equation (3). The concrete slab and base layer thicknesses were obtained from the pavement design structural analysis. The reference strategy is a conventional PCC pavement entirely made with new materials (design A), while the sustainable alternatives consider the partial replacement of sand and/or cement by rock dust in the concrete layer (designs B, C, D, E, F and G). The conventional design with new raw materials consisted of 203 mm (8 ft) PCC slab over a 150 mm (6 ft) granular base to meet the traffic and climatic conditions of the project. The feasible sustainable alternatives considered a maximum of 20% sand and 10% cement replacement with rock dust since larger amounts result in significant concrete strength reduction [12]. Since the impact of various contents of rock dust in concrete strength was kept to comparable levels, the concrete slab thickness did not change significantly according to the structural analysis. Thus, the 150 mm of granular base layer was also used for the alternative design strategies, as seen in Table 4. The analysis period considered was of 40 years with minor rehabilitation (i.e., overlay of 75 mm) at the 20th year as estimated from the deterioration rate of the pavement structure and as identified by the AASHTO design equation.

Table 4. Conventional and alternative sustainable strategies.

Strategies	Reference	Sustainable Alternatives					
	A	B	C	D	E	F	G
Concrete mixture	Conventional concrete	10% rock dust in FA	20% rock dust in FA	10% rock dust in FA + 5% in cement	10% rock dust in FA + 10% in cement	20% rock dust in FA + 5% in cement	20% rock dust in FA + 10% in cement
Strength [MPa]	43.5	46.5	48	45	43	46	44
E [GPa]	34	35	35	34.5	34	35	34
Concrete slab thickness (mm)	203	195	190	200	201	200	205
Granular base (mm)	150	150	150	150	150	150	150

The design parameters used for the conventional and alternative strategies are shown in Table 5. The equivalent single axle load ESAL was equal to 7000 kg (15,500 lb) and an annual average daily traffic flow (AADT) of 5000 was considered with 4% trucks. The equivalent thickness for the PCC slab for each alternative was determined for the same performance period using the AASHTO 1993 rigid pavement design guide [25]. The concrete modulus of rupture and elastic modulus were obtained from the laboratory experimentation, as seen from Table 4, and Equations (2) and (3).

$$\log_{10}(W_{18}) = Z_R S_o + 7.35 \log_{10}(D + 1) - 0.06 + \frac{\log_{10} \left[\frac{\Delta PSI}{4.5 - 1.5} \right]}{1 + \frac{1.64 \times 10^7}{(D+1)^{8.46}}} + (4.22 - 0.32 p_t) \log_{10} \left[\frac{S'_c C_d (D^{0.75} - 1.132)}{215.63 J \left[D^{0.75} - \frac{18.42}{(E_c/k)^{0.25}} \right]} \right] \quad (1)$$

W_{18} = design traffic (18-kip ESALs)

Z_R = standard normal deviate

S_o = combined standard error for reliability

D = thickness of concrete pavement slab

ΔPSI = initial and difference between terminal serviceability indices

p_t = terminal serviceability value

S'_c = modulus of rupture for Portland cement concrete

J = load transfer coefficient

C_d = drainage coefficient

E_c = modulus of elasticity for Portland cement concrete

k = modulus of subgrade reaction

Concrete properties based on compressive strength

$$S'_c = 6.7\sqrt{f'_c} \quad (2)$$

$$E_c = 57,000\sqrt{f'_c} \quad (3)$$

Table 5. Pavement Design Input Parameters for the Roadway Site.

Rigid Pavement Parameters	Values
Standard normal deviate, Z_R	−1.645
Overall standard deviation, S_o	0.3
Modulus of rupture, S'_c	As per Equation (2)
Difference between initial and terminal serviceability indices, ΔPSI	2.0
Terminal serviceability value, p_t	2.5
Elastic modulus, E_c	As per Table 1
Modulus of subgrade reaction, k	5.5 kg/cm ³
Load transfer coefficient, J	2.8
Drainage coefficient, C_d	1.0

3. Results and Discussions

3.1. LCCA Results

The life-cycle assessment for both environmental and economic impacts considered all life-cycle stages (i.e., material production, construction, transportation and maintenance/rehabilitation activities) over the 40-year analysis period. The LCCA disaggregates calculations over materials, transportation, landfill tipping fee, labor, process and equipment (including PCC demolition and paving) and overhead rates. Since recycling concrete pavement has been a common practice in recent years, this study considered that the existing PCC pavement was demolished and transported to a recycling plant instead of the landfill. Thus, there was no landfill tipping fee. The material costs were collected from local contractors (Table 6), while transportation, labor and equipment costs were based on typical construction projects in the region. The overhead rate was equal to 7% of the total cost, representing construction practice in the region. Since rock dust is a waste material from aggregate production, there was no production cost for this material.

Table 6. Cost of materials in the region.

Materials	Cost (USD/ton)
Sand	6
Aggregates	26
Cement	115
Concrete additives	1918

The life-cycle cost associated with each alternative was calculated and reported in terms of net present value (NPV, Equation (4)) based on a discount rate of 4%, representative of the discount rate of transport infrastructure investment in the US and the EU [33,34].

As identified in the first two rows of Figure 2, all pertinent costs accounted for in LCCA include expenditures related to material production (such as labor, equipment, overhead),

cost pertinent to material transportation to site, cost associated with initial construction and future maintenance and rehabilitation activities, costs pertinent to material transport from and to the plant and/or to the landfill and end-of-life recycling or landfill disposal. Equipment performance, energy cost, labor and overhead are all accounted for in each of these construction stages.

Figure 4 provides a comparison of the economic savings between the reference and the alternative strategies. Compared to the conventional case (strategy A), 10% sand replacement by rock dust (alternative B) provides a life-cycle cost reduction of 1.6%. This is mainly contributed to the cost savings in materials (i.e., fine aggregate). Furthermore, the concrete mix with a lower rock dust content provides relatively slightly higher compressive strength than the conventional strategy with new raw materials. Thus, the PCC thickness is reduced without compromising performance, which also leads to cost savings. Alternative C and D have similar life-cycle cost reductions, equivalent to 3.3%. Despite the relatively small quantity of cement used in PCC in relation to sand, 5% cement replacement with rock dust produces the same economic benefits as the 20% sand replacement. This is related to the significantly higher prices of cement as compared to sand (Table 6). Alternative strategy E has a slightly higher cost reduction (i.e., 5.2%) than option F (i.e., 5.0%) also attributed to the higher cement replacement (i.e., 10%) with rock dust. As can be observed, sustainable strategy G provided the highest overall life-cycle cost reduction of 6.8%. It should be noted that the construction and rehabilitation of 1 km of roadway may cost millions of dollars, and thus, a 6.8% reduction in cost could contribute to significant economic benefits for the entire project.

$$NPV = \frac{R_t}{(1+i)^t} \quad (4)$$

where

NPV = net present value

R_t = net cash flow at time t

i = discount rate

t = time of cash flow

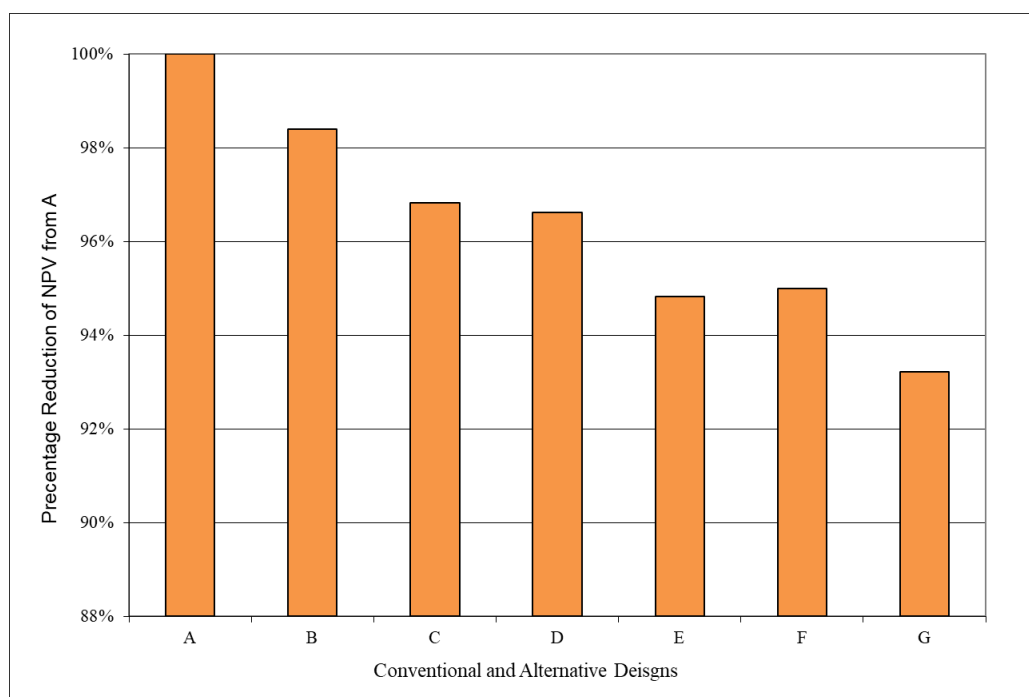


Figure 4. Comparison of life-cycle costs for alternative strategies.

Figure 5 shows the NPV life-cycle cost broken down by materials and processes for alternative F, which is included here as an example in order to provide some insights on which components have the higher impact on the total LCCA. While the actual cost breakdown for each alternative sustainable strategy is different, the relative impact of these components on the total cost are comparable, yet not the same.

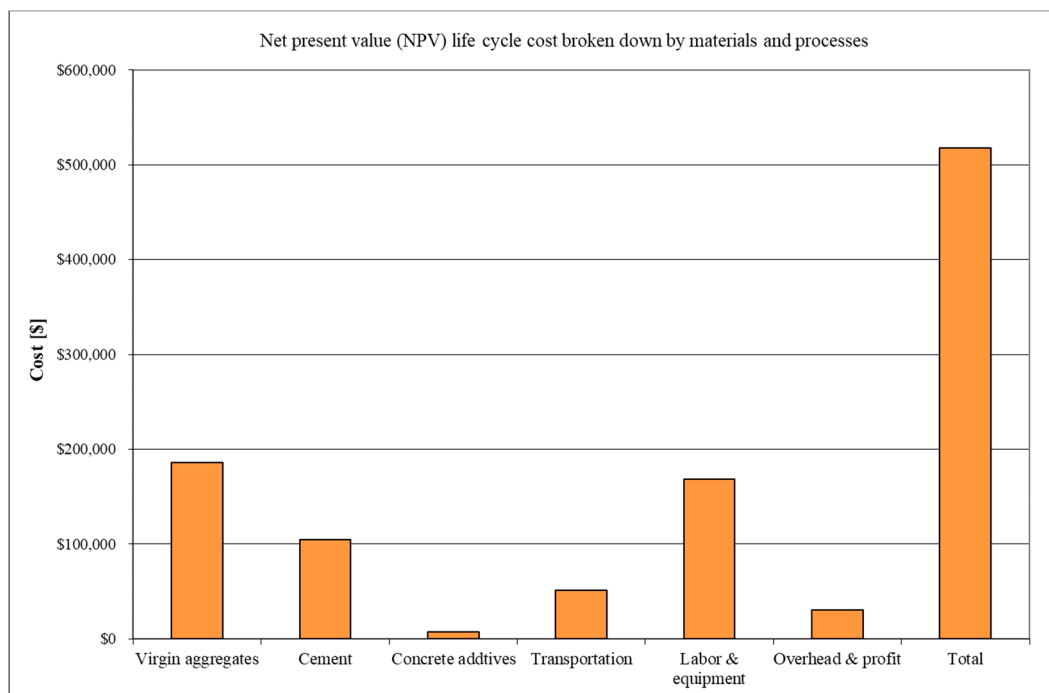


Figure 5. NPV life-cycle cost broken down by materials and processes for sustainable strategy F.

As can be seen from this Figure, the total project cost per two-lane km was calculated to be USD 518,533 in which 57% was associated to the cost of materials and 32% to labor, equipment and processes. Such cost is equivalent to USD 38.5 per square meter of installed PCC pavement (for a 200 mm thick slab), USD 14.5 per square meter of in-place granular base (150 mm thick layer) in regard to the initial instruction and USD 10.8 per square meter of PCC overlay (75 mm thickness) for maintenance. These costs reflect the typical construction projects in the region. While this reflects the construction and cost data in the region of the project site, as mentioned earlier the cost data in PaLATE can be easily revised to reflect the practices for a project at any specific region of interest. It is also expected that since changes in material and processes unit costs proportionally affect the alternative strategies, the relative economic benefits from their comparison will still be valid in regard to the findings presented herein.

3.2. Life-Cycle Environmental Impacts

The environmental impacts were examined in relation to the resources and equipment used during all processing phases (i.e., production of materials, transportation, construction and maintenance/rehabilitation). Three major environmental impact components include greenhouse gas emissions (CO₂), water consumption and energy consumption. Five pollutants that have a direct impact on human health, as identified by the Environmental Protection Agency (EPA), are also included: (i) hazardous waste generation, (ii) SO₂, (iii) CO, (iv) PM₁₀ and (v) NO_x. The emission factors related to each material production are shown in Table 7. As mentioned earlier, these factors were obtained from the updated EPA emissions data (EPA 2022). Since rock dust is a byproduct/waste material that has already been processed, and since the emissions are accounted for during the aggregate production, no environmental loads were considered in this case so as to not double count

such effects. The environmental impacts associated with transportation and processes (e.g., PCC paving, installing base and demolition of existing pavement) were obtained using the available equipment and data in PaLATE.

Table 7. Emission factors of materials production (after EPA 2022).

Materials and Processes	Energy [g/ton]	Water Consumption [g/ton]	CO ₂ [g/ton] GWP	NO _x [g/ton]	PM10 [g/ton]	SO ₂ [g/ton]	CO [g/ton]	Hg [g/ton]	Pb [g/ton]	RCRA Hazardous Waste Generated [g/ton]
Aggregates	309	43	21,884	44	189	21	29	0	0	359
Cement	5168	2561	362,695	4362	817	4324	1550	0	0.4	2240
Concrete additives	23,784	22,190	1,423,609	5796	2084	4285	7299	0.1	3	354,745
Concrete mixing	536	932	37,099	551	172	484	337	0	0	169

Resource Conservation and Recovery Act (RCRA).

As shown in Figure 6, the life-cycle CO₂ emissions for both conventional and alternative designs are dominated by materials production. 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. Comparing strategy D to the conventional option, the replacement of sand with rock dust produces a CO₂ decrease of approximately 3%. The main sources of CO₂ emissions during material production include heavy equipment operations and transportation. In the case of strategy D, an additional 4% reduction in CO₂ was observed by replacing 5% of cement by rock dust. This reflects the high amount of CO₂ associated with cement production as compared to sand production. In the case of designs E and F, a similar reduction (i.e., 7.5%) in CO₂ emissions was observed. Alternative G produced approximately a 10% reduction (100 Mg) in CO₂ emission.

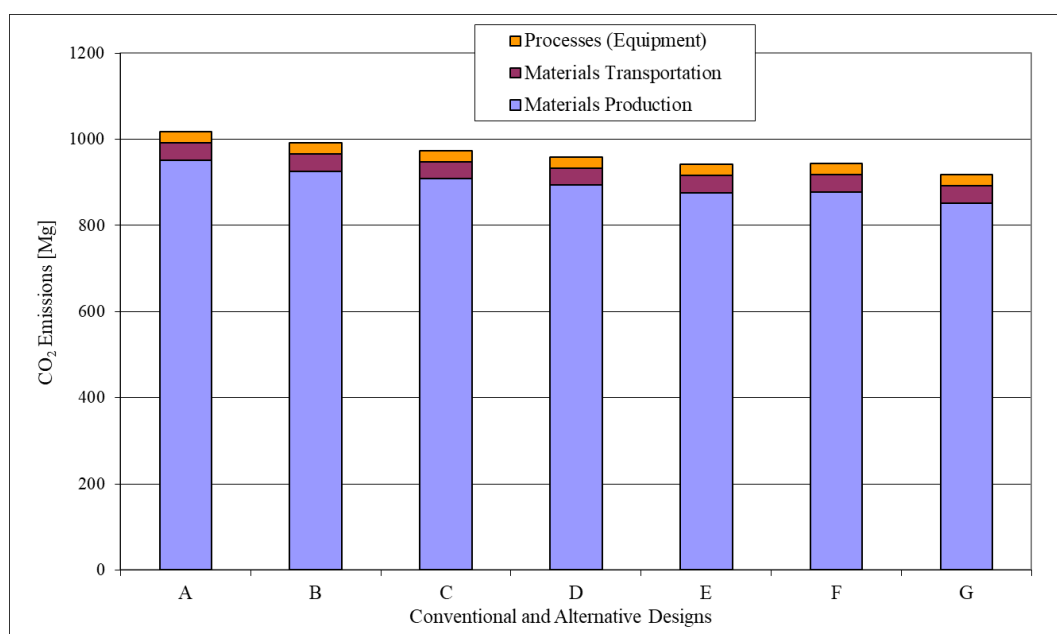


Figure 6. Life-cycle greenhouse gas emissions (CO₂) for alternative strategies.

Figure 7 presents the life-cycle energy consumption for each alternative. The energy consumptions are analogous to the reduction in CO₂ emissions associated with material production. It can be observed that the construction and maintenance processes consumed the least amount of energy compared to materials production and transportation. A maximum of 11% (1,488,033 MJ) reduction in energy consumption was achieved by replacing 20% of sand and 10% of cement with rock dust (alternative G). This reflects the fact that cement and aggregate productions are high-energy and emission-intensive processes. The

life-cycle water consumption results are presented in Figure 8. Since water consumption is primarily affected by the production of the concrete mix, no significant changes were observed between the sustainable strategies.

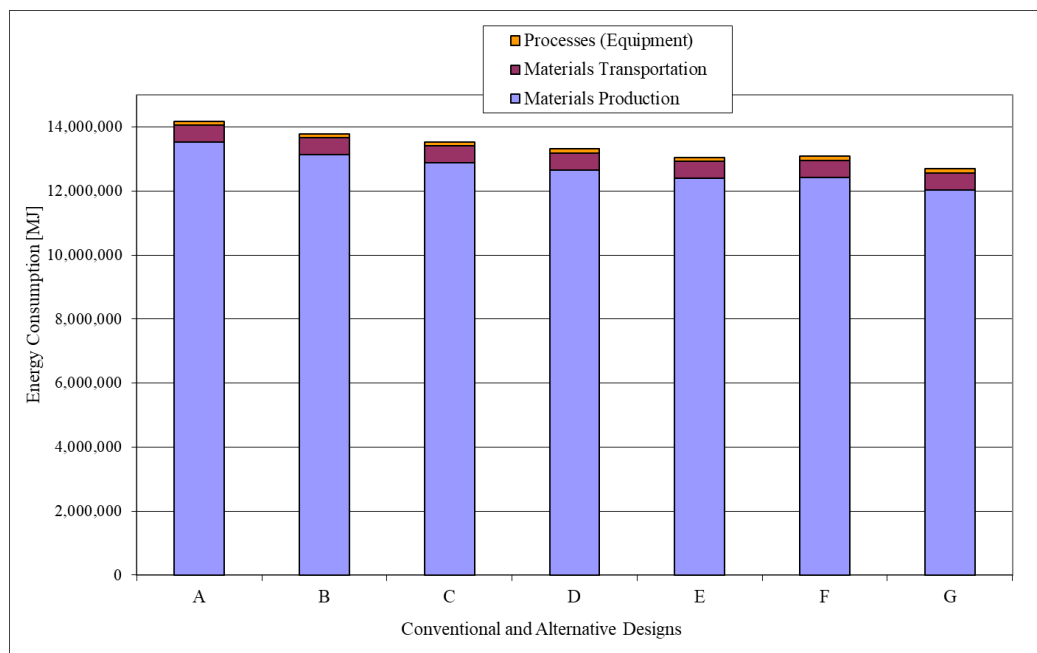


Figure 7. Life-cycle energy consumption; reference design (A), alternative strategies (B–G).

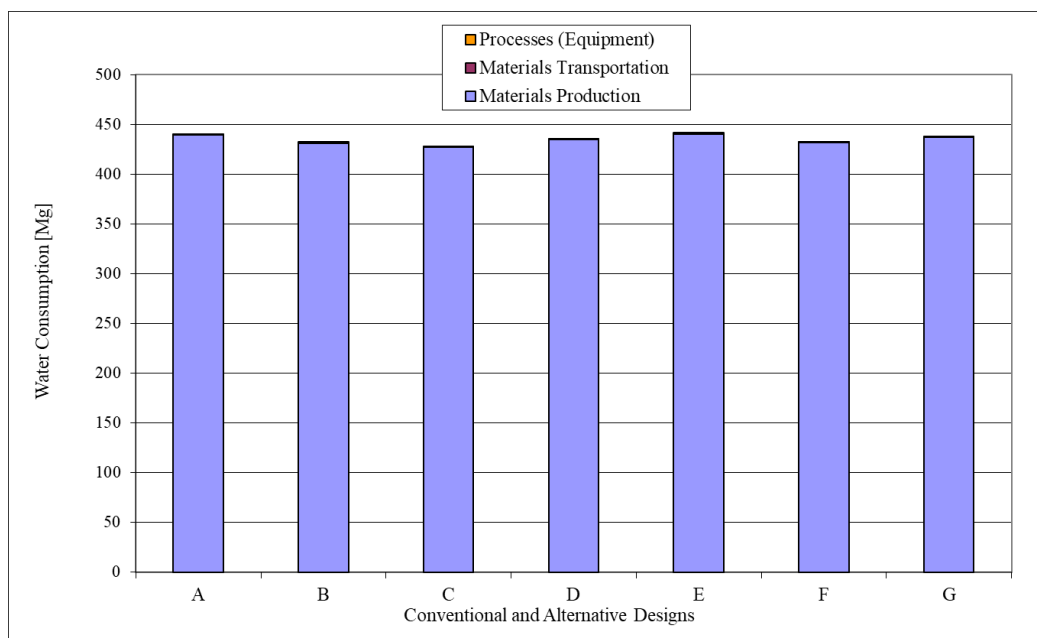


Figure 8. Life-cycle water consumption; reference design (A), alternative strategies (B–G).

Table 8 summarizes the environmental impacts broken down by materials production, transportation and processes for strategy F as an example. It can be observed that these environmental parameters are dominated by materials production, especially by cement, aggregate and concrete mix production. This reveals where the environmental impacts are generated in the life-cycle analysis, as well as how and to what extent various sustainability strategies do in fact reduce them. Table 9 provides further details on the comparative

assessment of the environmental impacts for each strategy. Overall, the environmental impacts decrease with an increase in the percentage of rock dust in concrete. The energy consumption and CO₂, SO₂, CO, Hg and Pb emissions are dominated by materials production, while transportation significantly contributes to NO_x (approximately 17.2% associated with transportation), PM₁₀ (about 9.2% from transportation) and hazardous waste generation (15.4% from transportation).

Table 8. Environmental impacts broken down by material production, materials and transportation for strategy F.

Phases		Energy [MJ]	Water Consumption [kg]	CO ₂ GWP [Mg]	NO _x [kg]	PM ₁₀ [kg]	SO ₂ [kg]	CO [kg]	Hg [g]	Pb [g]	RCRA Hazardous Waste Generated [kg]
Material production	Aggregates	2,692,434	368,398	200,386	458,881	1,625,638	189,268	246,631	0	56	3416
	Cement	5,299,818	2,626,233	371,960	4,473,129	837,777	4,434,189	1,589,180	5	433	2298
	Additives	128,777	120,145	7708	31,383	11,286	23,201	39,522	0	18	1921
	Concrete mixing	4,310,516	1,362,680	298,275	4,431,384	1,383,974	3,887,396	2,706,768	9	471	7493
Transportation	Concrete from plant to site	246,521	41,972	18,430	981,871	191,393	58,912	81,823	0	8	1776
	Waste materials from site to landfill/recycling plant	280,395	47,739	20,962	1,116,787	217,795	67,007	93,066	0	9	2020
Processes	Base construction	16,796	1633	1261	27,248	4295	1802	5872	0	1	121
	PCC paving	24,865	2418	1866	38,473	13,790	2544	8290	0	1	179

Table 9. Environmental impacts for alternative sustainable strategies.

Strategy	NO _x [kg]	PM ₁₀ [kg]	SO ₂ [kg]	CO [kg]	Hg [g]	Pb [g]	RCRA Hazardous Waste Generated [kg]
A	12,368	4540	9271	5106	15	1096	24,879
B	12,124	4421	9079	4982	15	1063	23,150
C	11,996	4340	8980	4907	15	1041	21,665
D	11,801	4369	8748	4846	14	1017	21,197
E	11,671	4361	8598	4782	14	989	19,364
F	11,703	4298	8674	4785	14	998	19,761
G	11,462	4267	8417	4681	14	959	17,854

4. Sustainability Rating

A sustainability rating system, in this case BE2ST in-Highways, can be used to assess each alternative strategy [3]. The selected sustainability rating system evaluates each alternative strategy using a comparative assessments and rating method based on the LCA results. Seven criteria are used in this assessment and include: (i) energy consumption, (ii) global warming potential (GWP), (iii) recycling, (iv) water consumption, (v) life-cycle carbon costs, (vi) social carbon costs (SCCs) and (vii) hazardous waste. Each alternative strategy is compared in relation to the reference one (strategy A). SCCs represent the costs needed to eliminate or address issues caused by carbon emissions (i.e., USD/Mg of CO₂ emissions) and are associated with the cost of reducing global warming issues (e.g., GWP). Highway agencies often incorporate SCCs for evaluating sustainable pavement construction and rehabilitation. As mentioned earlier, in this study the alternative strategies were compared with the reference (i.e., conventional) option in which new raw materials are used for all processes and pavement construction stages.

For each alternative, a normalized score was calculated based on the percentage reduction in emissions, cost, consumption or percentage of recycled materials (rock dust) used. If the percentage reduction equals to or is larger than 10%, a score of 1 is assigned.

Such method of calculating scores can be modified to encourage more sustainable solutions (e.g., 20% reduction corresponding to a score of 1). A comparison of alternatives is shown in Figure 9. The score (i.e., 0–1) for each alternative strategy was calculated based on the percentage reduction in each sustainability criterion of Figure 9. A higher score represents a higher reduction for that economic environmental impact parameter. It can be observed from Figure 9 that alternative G outperformed other strategies in all sustainability criteria, except for water consumption. The impact of each strategy on such criteria is evident and could be used in further improving each specific strategy. As it can be observed as more sand and/or cement is replaced by rock dust, a higher reduction in energy consumption, hazardous waste, GWP, life-cycle cost and social carbon cost can be achieved. However, the alternative strategies do not have a significant impact on water consumption. Thus, the results could be eventually used to further modify such alternatives for better sustainable scores.

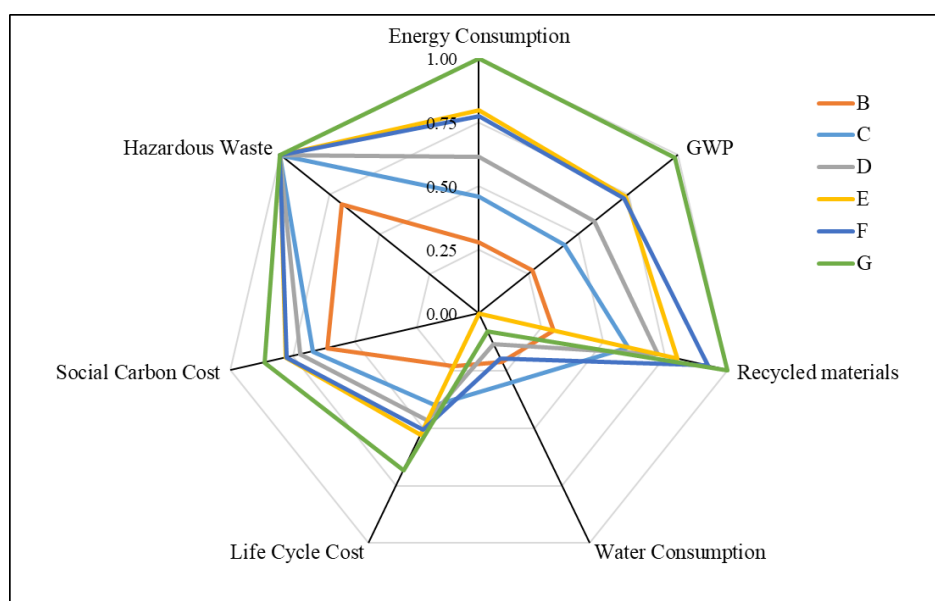


Figure 9. Sustainability rating for each alternative.

5. Summary and Conclusions

This study examined the life-cycle economic savings and environmental benefits of using rock dust for the partial replacement of fine aggregate and/or cement in concrete for roadway pavement construction. The proposed methodological approach for developing and accessing alternative sustainable strategies was presented in this process. The life-cycle economic and environmental impacts were quantified by comparing the results of sustainable alternative strategies (i.e., with rock dust use in concrete) with the reference design where new raw construction materials are used. In the proposed holistic analysis approach, the LCCA and LCA environmental analysis considered all stages in the life cycle of pavements, rather than just the material production that past studies have focused on. Thus, the suggested methodology includes analyses and inputs pertinent to material production, construction, maintenance and rehabilitation and end of life (landfill or recycling). The feasible alternative strategies were developed based on the laboratory experimentation results on using rock dust in concrete and providing acceptable strength properties. The analysis indicated that the alternative strategy with 20% fine aggregate and 10% cement replacement with rock dust provided the best sustainable option. This sustainable alternative provided a reduction in life-cycle cost, energy consumption, greenhouse gas emissions, hazardous waste and other environmental parameters. The LCA analysis indicated that cost savings and environmental benefits were primarily attributed to materials production. The economic savings and environmental benefits quantified in this study may encourage

the wider adoption of rock dust for sustainable PCC roadway construction. While the reported values of LCA analysis are related to the specific inputs considered for this project, the relative comparison between such alternative strategies is expected to be maintained, since changes in unit costs and environmental parameters proportionally affect the various materials and construction phases in each option. The methodology and analysis presented in this study can be adopted elsewhere for quantifying the sustainability benefits of rock dust or other recycled materials in roadway construction. Furthermore, such analysis could be integrated into the pavement management systems (PMSs) that agencies currently use for identifying optimal allocation of resources in maintaining their highway network.

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