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Systematic Assessment of Sustainability Strategies in Highway Projects through Parametric Analysis

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ABSTRACT: The use of recycled materials in highways has been the focus of many highway agencies around the world. In a "zero waste" environment of a circular economy, objective of the agencies and highway industry is to recycle as much as possible of the existing materials since they have a residual value. Furthermore the emphasis on Sustainability over recent years and the potential development of "green highways" identifies the need to develop systematic sustainability analysis methods that can quantify the contribution of each alternative strategy in reducing the use of natural materials, energy and water consumption, as well as greenhouse emissions. It was the objective of this study to propose a methodology for quantitative assessment of alternative strategies in terms of economic and environmental sustainability. To demonstrate the value of the approach a parametric study was developed considering the use of alterative recycled materials and variable recycling rates. The suggested approach provides the means of comparing the alternativestrategies and identifying which factors (i.e., materials processing, transportation, construction) contribute the most in sustainability assessment. The potential use of a sustainability rating systems is also explored in the search for the best (i.e., optimum) sustainable strategy. The methodology proposed here is transferable elsewhere where similar materials and construction technique are used.
KEYWORDS: Highway sustainability, life cycled analysis, environmental effects, recycled materials

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I. INTRODUCTION

The maintenance and rehabilitation of the highway network requires a significant amount of construction materials, energy and water consumption, as well as other resources, and contribute to a great degree to greenhouse gas (GHG)emissions and waste disposal to landfills.Alternative recycling and reclamation methods and technology have been developed over the years that provide the means for developing sustainable alternative strategies for highway pavements [1, 2, 3].Chesner et al. [4]identified as well alternative uses of wastes and by-products in pavement construction.The potential benefits in terms of economic and environmental impact have been reportedin past studies for specific applications and uses [5, 6]. However, none of the studies provided a systematic quantitative determination of the benefits when substituting conventional (virgin) materials with Recycled Asphalt Pavement (RAP), Recycled Concrete Aggregate (RCA), recycled Granular Aggregate Base (GAB) materials. Although Del et al. [7] quantified the environmental and economic benefits associated with the use of certain recycled materials in pavements, only a limited percentage of recycled materials used on-site was included in the analysis. For instance, the allowable percentage of RAP in hot mixed asphalt (HMA) may vary between 0-100% with an acceptable level of performance meeting pavement structural design criteria [8]. Thus, a more comprehensive analysis of life cycle cost analysis, LCCA, and environmental benefits of pavement recycling is necessary. Several methods have been proposed, and various sustainability metrics tools have been developed by researchers to assess roadway sustainability [9, 10, 11]. These methods indicate that a thorough condition assessment is required in order to identify proper recycled materials and rehabilitation techniques [12]. Based on the selected materials and rehabilitation strategies, a life cycle assessment can be conducted to quantify the economic and environmental benefits and identify the best sustainable strategy. This study builds on the recommendation to develop a systematic approach for assessing increasing rates of recycling materials in pavement construction when multiple sustainability alternatives need to be considered for the same project, or multiple projects [9]. The suggested methodology is presented next along with results from case studies.

II. SYSTEMATIC ASSESSMENT OF ALTERNATIVE SUSTAINABLE SOLUTIONS

Figure 1 presents the flow chart of the methodology for assessing and comparing alternative sustainable solutions for a specific project. Once the project site has been identified it is critical to assess the characteristics and current conditions for an existing pavement structure. This involves an assessment of the location (i.e., transportation distances between construction site, quarry, and materials production plant), pavement structural parameters (i.e., materials and layer thicknesses), traffic and environmental conditions. Current pavement condition (i.e., Pavement Condition Index, PCI, or similar measures) will identify (i) potential site specific issues that need to be addressed; and, (ii) the quality of the existing construction materials which will influence the level of possible recycling rates. Thus, depending on the condition of the existing pavement, (i)the proper recycling techniques and materials (i.e., RAP, recycled Granular Aggregate Base, GAB, other), and (ii)applicablerecycling rates (i.e., 10%, 20%, 30% or 50%) will be identified for generating the feasible alternative sustainable strategies. Based on such inputs the required structural layer thicknesses will be identified for each alternative strategy [8]. The life-cycle economic and environmental analysis for both the conventional design (i.e., no recycling) and the sustainable alternativesare then examined with a sustainability metrics tool, like PaLATE [10]. The alternative sustainable solutions are then compared in terms of life cycle (i) economic, LCCA, and environmental impact analysis, LCA, and, (ii) using a sustainability rating system, such as BE^2ST-in-Highways., to identify the most sustainable solution. Example results of the proposed methodology are presented next using a case study.

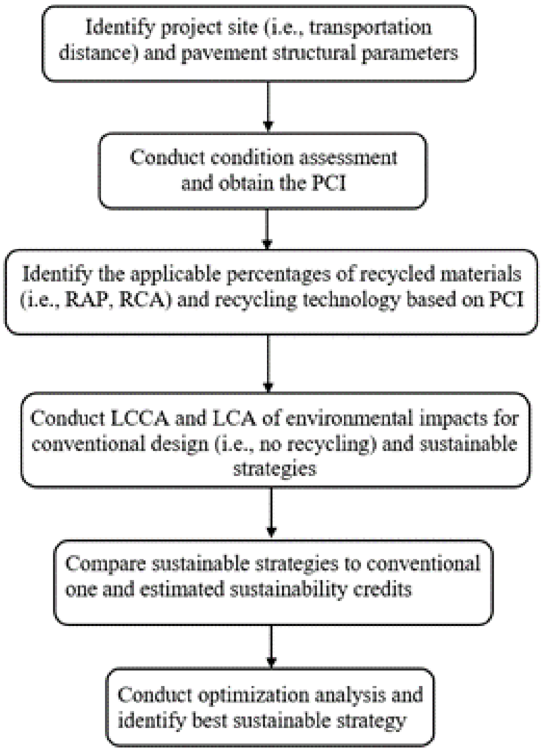

Figure 1:Assessment of Alternative Sustainable Strategies.

III. COMPARATIVE ANALYSIS OF ALTERNATIVE SUSTAINABLE STRATEGIES

A comparative life-cycle assessment (LCA) of alternative sustainable strategies was conducted in terms of environmental and economic effects for a specific case study. The analysis included conventional design using new construction materials and sustainable alternative designs considering RAP. For generating alternative sustainable strategies different percentages of RAP (e.g. from 0% to 100%) in the hot mixed asphalt (HMA) were considered. Also, the option of using recycled granular aggregate base (GAB) for the base layer was examined as well. The case study considered a two-lanehighway with 3.6 meters per lane. The performance period for the analysis was 40 years, and both life-cycle cost and environmental results were reported based on a unit length of 1.6km. For comparative purposes rehabilitation was considered for every 15 years after initial construction. Crack sealing was selected as the typical routine maintenance option and performed every 5 years.

The same pavement structural design (layers and thickness) was considered in the alternative designs. All design parameters for this case study are shown in Table 1.

Life cycle cost analysis (LCCA) in PaLATE involves all costs associated with the roadway construction throughout the entire period of analysis (40 years) including initial construction, routine maintenance and rehabilitation. The LCCA is based on cost of materials, construction process, labor, and transportation distances from construction site to plant and/or quarry. Economic indicators are used to spread the cost over the performance period through a certain discount rate. The cost data (i.e., cost of construction, material, transportation and equipment maintenance) used in this study were obtained from published construction cost data and default values reported in PaLATE [10, 13].

Table 1: Key Parameters for Case Study.

Parameter	Value (units)
Lane Width	7.2 (m)
Length	1.6 (m)
Surface Layer Depth	10 (cm)
Base Layer Depth	15 (cm)
Asphalt Mixture Binder Content	4 (%)
Analysis Period	40 (years)
Plant to Site Distance	40 (km)
Quarry to Plant Distance	24 (km)
Site to Landfill Distance	16 (km)

Three groups of sustainable strategies were analyzed in addition to the conventional one referred to as “reference” case where only virgin materials were used. The three groups of in-situ recycling strategies were setup as following for comparative parametric analysis (i.e., for assessing the contribution of each recycled material and percentage on the LCA results): Strategy 1-different percentages of RAP (0-100%) in HMA (surface layer), and virgin aggregate in GAB (base layer); Strategy 2- virgin HMA, and various percentages (0-100%) of recycled aggregate in GAB; Strategy3- various percentages of RAP (0-100%) in HMA, and recycled aggregate (0-100%) in GAB.This produced 15 alternative sustainable strategies to compare against the reference one where no recycled materials were used, and/or against each other. The economic results are reported in terms of net present value (NPV) based on a discount rate of 4%. The construction material cost for all sustainable strategies is shown in Figure 1 while the total LCCA cost (i.e., including materials production and transportation, as well as, processing/ construction equipment) in terms of NPV is shown in Figure 2. As expected a linear trend between the increasing percentage of recycled materials and reduction in material cost was observed. The higher reduction in material cost was observedfor Strategy 3 where recycled materials were used in both surface and base layers. The analysis indicated that a 15% savings of the total materials cost was achieved when 20% RAP was used in HMA and 20% recycled GAB in the base layer. As shown in Figure 3, overall the reduction of life cycle cost is higher when RAP is used in HMA (Strategy 1) comparable to the option of only recycling GAB (Strategy 2) since the cost of HMA materials is higher than that for the base layer. Thus recycling the surface layer leads to higher cost savings than recycling the base layer. The savings when both surface and base materials are recycled is clearly providing much better economic benefits, with a maximum total LCCA of 28.0% for 100% recycling rates, as shown in Figure 3.

Figures 4 to 6 provide the LCCA breakdown by initial construction, maintenance and material costs for the various alternative strategies. The total LCC reduction per 1.6 km roadway length was calculated to be $345,285 when the entire surface layer is recycled (100% RAP in HMA), Figure 4, while a $296,285 reduction in total LCC is observed when 100% of the GAB is recycled, Figure 5. The reduction of LCC is mainly attributed to the savingsfrom using recycled versus virgin materials, and the transportation cost savings associated with the in-situ recycling of these materials.The savings of material and transportation costs when both surface and base layers are in-situ recycled, Figure 6, provided a total LCC of $641,570 for 100% recycling rate.

The environmental impact analysis considers the contribution of (i) materials production and (ii) transportation, as well as (iii) processing/ construction equipment, during both the initial construction and maintenance activities. An example of the environmental LCA analysis for the reference design (i.e., no recycling materials used) and the 60% RAP in HMA & 60% recycled GAB strategy are presented in Table 2. It is shown that using 60% recycled materials in the surface and base layers result in a significant reduction in greenhouse gas emissions, energy consumption, water consumption and hazardous waste disposal. As can be seen from the analysis, there is a 29% reduction in global warming potential (CO_2) by recycling 60% of the paving materials on site. Most of the CO_2 emissions is from material production with on-site recycling requiring lower energy consumption and thus producing lower emissions [7]. Reductions in energy (17.7%) and water consumption (16.6%) were associated with the 60% recycled materials strategy. The energy pertinent to transportation was significantly reduced due to the on-site recycling and lower disposal of waste materials to the landfill. A significant reduction (57.1%) in PM_{10} emissions was also observedassociated with lower emissions pertinent to limited (i) loading and hauling operations of on-site recycling.

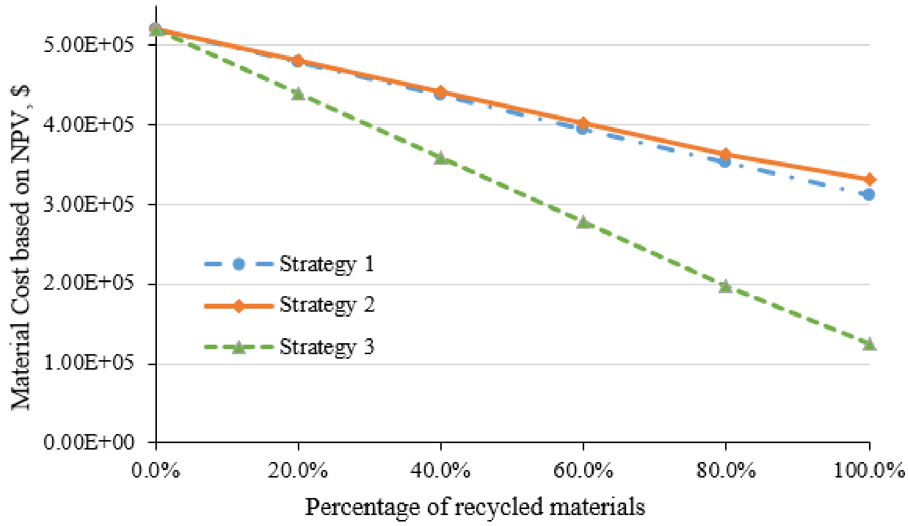

Figure2:LCA material cost for sustainable strategies.

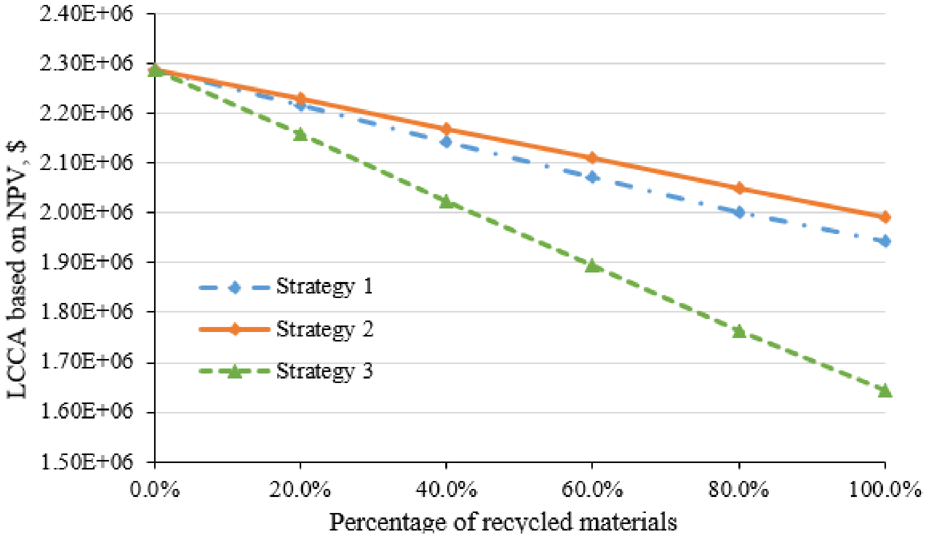

Figure 3:TotalLCCA for sustainable strategies.

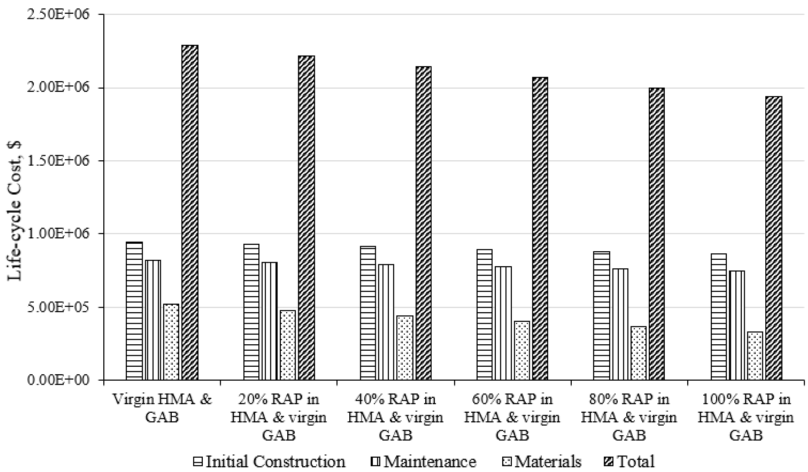

Figure4: LCCA breakdown by initial construction, maintenance and material for Strategy 1.

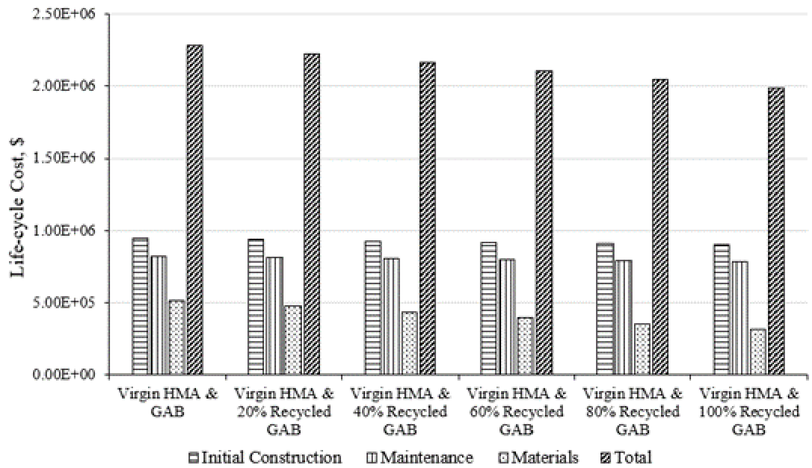

Figure5: LCCA breakdown by initial construction, maintenance and material for Strategy 2.

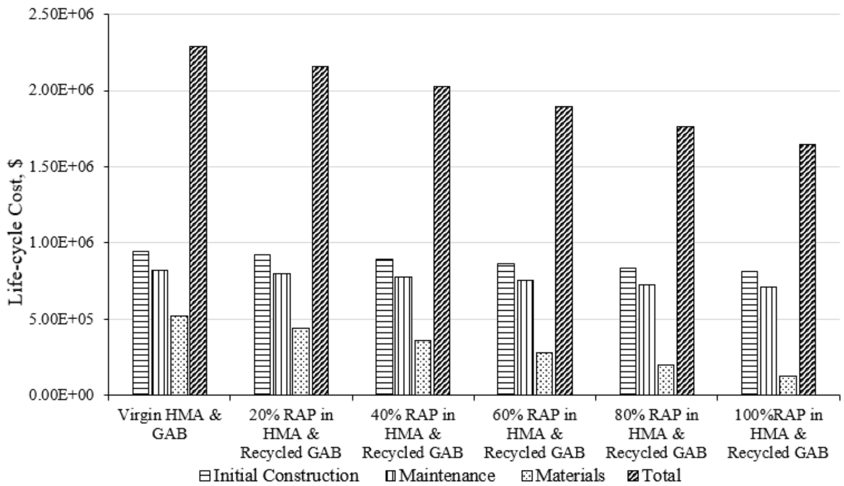

Figure 6: LCCA breakdown by initial construction, maintenance and material for Strategy 3.

Table 2:Environmental impact of conventional & 60% RAP in HMA with 60% recycled GAB.

	Conventional Materials			Sustainable Strategy			
Environmental Impact	Material Production	Transport	Processes (equipment)	Material Production	Transport	Processes (Equipment)	Change (%)
CO_2 (Mg)	268	27	4	195	10	7	-29.1%
Energy (MJ)	4,959,639	359,429	49,850	4,174,820	1,156	241,547	-17.7%
Water (kg)	1,152	54	5	980	21	9	-16.6%
Hazardous waste (kg)	39,230	2,306	172	38,792	894	161	-4.5%
PM_{10}(kg)	2,151	282	17	919	110	22	-57.1
SO_2(kg)	65,382	86	6	65,313	33	11	-0.18%
NO_x(kg)	1,642	1,432	84	1716	557	169	-22.6%

As in the example of Table 2, theenvironmentalimpact for all the sustainability alternatives were also examined in terms of the following components: material production andtransportation,andconstruction processes (equipment). The analysis for energy and water consumption and CO_2 emissions for the Strategy 3 alternatives are presented in Figures 7 to 9, respectively. As it can be observed the material production component dominates the energy and water consumption and CO_2 emissions in relation to the other two contributors (e.g. transportation and construction processes). Thus, overall the environmental benefits of using recycled materials are attributed to a reduction in material production. Reductions up to 37% in energy and 30% in waterconsumption, as well as 47% reduction in CO_2 emissions were observed for the 100% in-situ recycling. However, even though the increase in recycled materials rate in the surface and base layer implied a reduction in total energy and water consumption, as well as CO_2 emissions, the energy consumption for construction processes (equipment) increased. This is associated with the construction equipment used in in-situ recycling of materials processing requiring higher levels of energy for on-site processing.

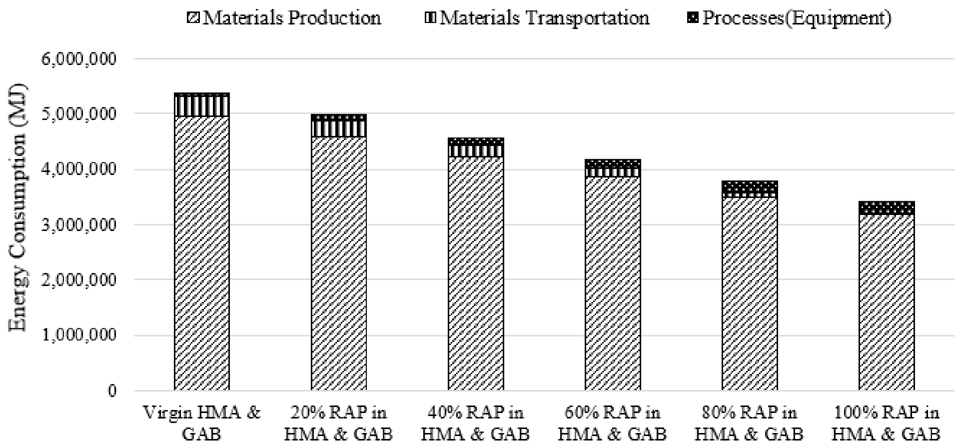

Figure 9: Life cycle energy consumption for Strategy 3 alternatives.

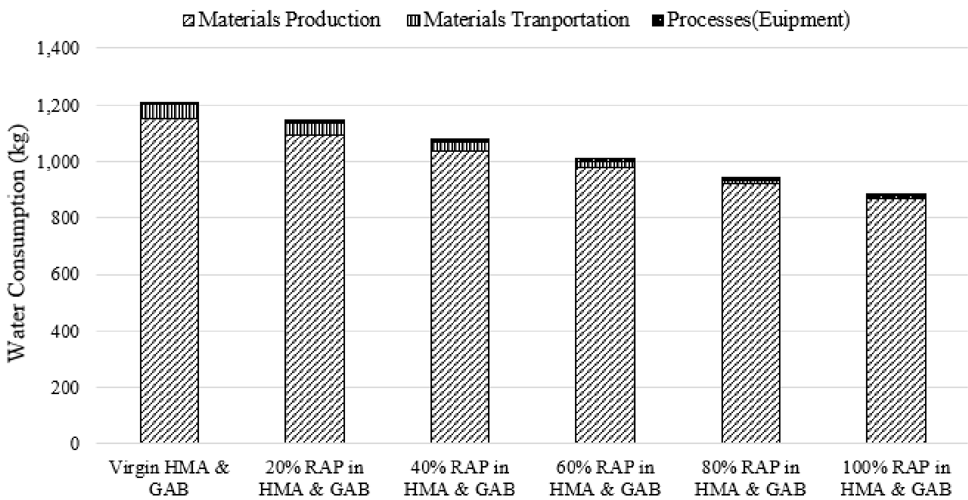

Figure 10: Life cycle water consumption for Strategy 3 alternatives.

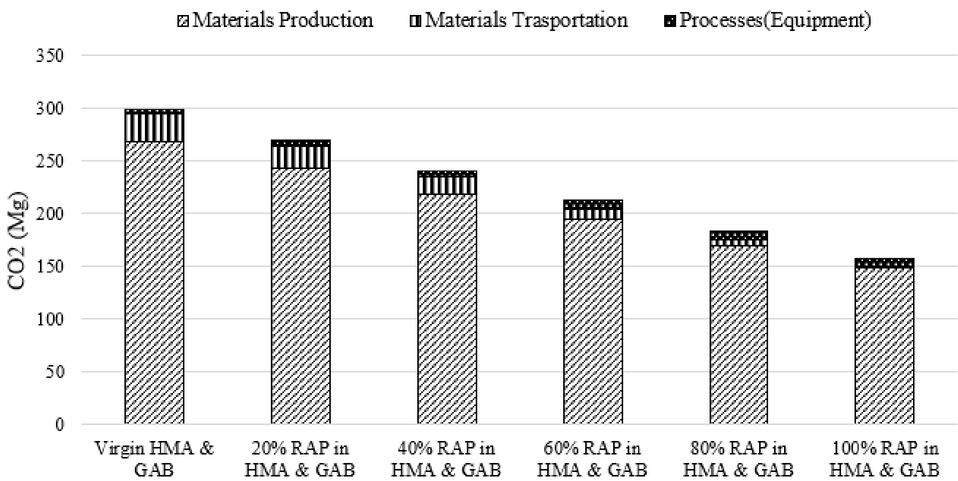

Figure 11: Life cycle CO2 emissions for Strategy 3 alternatives.

The LCA economic and environmental impact analysis can be coupled with a sustainability rating system, such as BE^2ST-in-Highways, in order to compare the alternatives and identify the most sustainable one for a specific project reflecting local sustainability policy strategies. Thus, this rating system was used in this analysis to showcase its potential use in identifying the best solution. An example of such an assessment is presented in Figure 10 where three different alternatives are compared. This rating system is used to quantitatively assess the environmental and economic sustainability of alternative designs compared to the conventional design (i.e., no recycling) through a comparison ofenergy consumption, greenhouse gas emissions, life-cycle cost, social carbon cost and other factors shown in Figure 10. It can also be used for comparing the potential improvement of one sustainable alternative to the next. The sustainability metric assigns “reward” points based on the level of reduction in cost and environmental impact. For example, two points are awarded if the life-cycle cost or environmental impact is reduced by 20%. This target can be identified by usersso as to reflect local practices and/or target policies in recycling, energy reduction, water reduction, emissions. Furthermore, relative weights maybe assigned to each one of these parameters to reflect the relative importance of each one (i.e., the importance of emissions versus cost versus energy, and so on). Such relative weights may reflect local reality and policies. In summary, such a rating system is flexible enough to be customized reflecting local practices and sustainability targets and thus could be used to identify the best (i.e., optimum solution once these user identified targets and weights have been defined). In the example of Figure 10, the effectiveness of the three alternative sustainable designs isimmediately evident by the shape of the AMOEBA graphs produced by BE^{2}ST-in-Highways. A more balanced graph represents a higher rating of sustainability. For example,whilethe 20% RAP in HMA and 20% recycled GAB provides good scores in recycling it does not provide a significant reduction in energy, hazardous waste reduction, social carbon cost, and so on, and thus gets a “failing” sustainability rating. For the case of the 60% RAP in HMA and 60% recycled GAB several of the target scores have been achievedproviding a more balanced result in terms of sustainabilitycontribution and eventually achieving a higher overall sustainability rating (i.e., “gold” rating). The 40% RAP in HMA and 40% recycled GAB met some of the sustanbility targets and thus achieved an overall “silver” rating. Thus, the LCA analysis combined with such a rating system could be usedin the comparative optimization analysis for identifying the best sustainablesolution for a specific project and reflecting the local reality and policies.

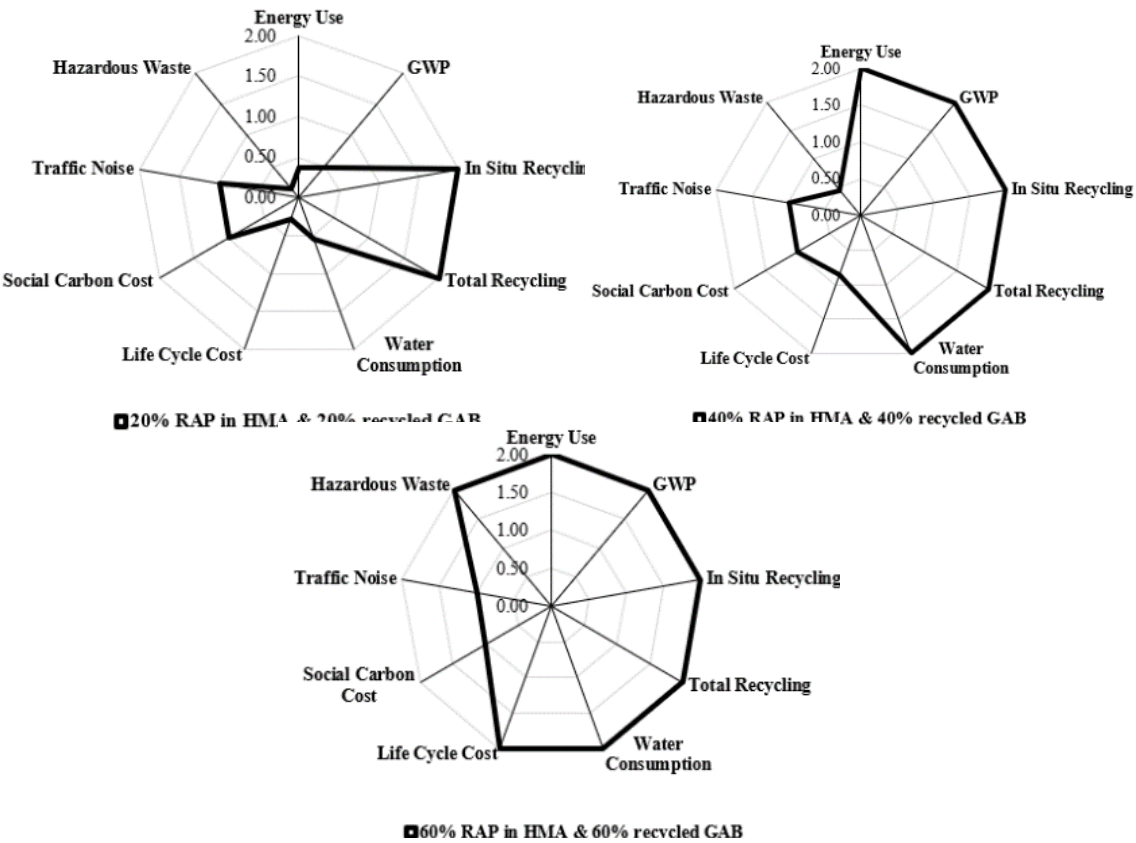

Figure 10: AMOEBA graphs for alternative sustainable alternatives

IV. CONCLUSION

The focus of sustainability on highway construction has generated the need for the development and adoption of sustainability analysis methods for assessing alternative rehabilitation strategies. This paper presents a methodology for highway sustainability analysis. The suggested approach considers economic and environmental LCA analysis for (i) comparing the alternative sustainability strategies, and, for (ii) identifying which factors (i.e., materials processing, transportation, construction) have the higher influence in sustainability assessment. To showcase the suggested methodology a parametric study was developed considering the use of alternative recycled materials and recycling rates. In terms of the specific conclusions pertinent to the case study included in the analysis, it was observed that an increase in the percentage of recycled materialreduce the life cycle cost. This was primarily associated with areduction in material costs. The magnitude of the cost savings varied depending on both the type and percentage of recycled material. The larger savings were observed for the strategies considering RAP in HMA surface layer as compared to those with recycled aggregate in GAB, and at comparable recycling rates. In terms of the environmental impact results, it was observedthat material production dominated the CO_2 emissions as well as energy and water consumption. Finally, the potential benefits of incorporating a sustainability rating system in the analysis was discussed for (i) identifying the best sustainable strategy for a specific project, and, (ii) the transferability of the approach to other regions with similar construction practices.

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