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Holistic Approach for Generating and Assessing Sustainable Rehabilitation Strategies in Roadway Construction

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ABSTRACT:*Construction and rehabilitation of infrastructure consume large amounts of natural resources, such as raw materials, energy and water, produce significant waste and consequently generate greenhouse gas emissions. While past studies focused on the sustainability assessment of specific aspects of recycled materials and infrastructure components, this study addressed the need of providing a holistic approach in generating and analyzing feasible roadway rehabilitation strategies that are sustainable. The proposed methodology considers all the phases of generating such rehabilitation alternatives, from the planning phase to condition assessment, structural design, life cycle economic and environmental impact analysis, and the criteria for selecting the best solution. Specific steps of the analysis used in the methodology are presented herein with example results from two case studies, a two-layer and a three-layer roadway system. Because of the ability of the proposed approach to provide tangible and quantifiable analysis, it can be directly implementable within the Pavement Management Systems, PMS, that highway agencies are required to have in order to properly manage their highway infrastructure. Thus, the adoption of the proposed methodology and analysis has a direct impact on embracing sustainability in infrastructure projects. The methodology and findings are transferable to other regions where similar approaches to roadway construction are used.*

KEYWORDS:*Sustainability, roadway construction, life-cycle analysis, environmental implications, recycling materials.*

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I. INTRODUCTION

With the aging infrastructure, limited resources, and the recognition of the "salvage value" of recycledand industrial byproducts within the "circular economy" there is a strong need to identify and develop analysis methods for identifying the best and most effectiveroadway rehabilitation strategies in regards to sustainability [1].While past studies focused on the sustainability assessment of specific aspects of recycled materials and infrastructure components [2, 3, 4], there is a need for a holistic approach to generate and analyze feasible roadway rehabilitation strategies that are sustainable and minimize the use of natural resources. Such approach should consider all the phases of generating rehabilitation alternatives, from the planning stage to condition assessment, structural design, life cycle economic and environmental impact analysis, and, incorporating the criteria for selecting the best solution.Construction and rehabilitation of highways consume large amounts of energy, produce wastes and generate greenhouse gas emissions, among other. Energy and greenhouse gas emissions have been receiving more attention in recent years. Nowadays, phrases like "Green Construction," "Environmental Impact," "Global Warming," "Greenhouse Gases," among many other, are becoming more common and are a reflection of the need to systematically address such analysis with a holistic approach to projects' sustainability.A good practice to build a sustainable highway is to reuse and incorporate as much of the existing materials on the road. However, potential implications in terms of costs and environmental impact from the reprocessing of these materials need to be assessed for identifying the best sustainable practice for each specific project.

Over the years highway agencies have been experiencing the use of recycled materials on roadways [5]. The most common materials include recycled asphalt pavement (RAP), recycled concrete aggregate (RCA), recycled granular base, GAB, as well as other. However, their focus has been primarily on addressing the mechanical properties and performance when alternative types and percentages of recycled materials are used.Pavement systems are considered to be serviceable until their actual condition reached a minimum threshold beyond which safety and structural performance is compromised [6, 7, 8].This study focused on the need of providing a holistic approach to generate and analyze feasible roadway rehabilitation strategies. While the methodology is briefly described herein specific steps of the analysis are presented with example results of two case studies, a two-layer and a three-layer roadway system.

II. STEPS FOR GENERATING AND ANALYZING ALTERNATIVE SUSTAINABLE REHABILITATION STATEGIES

The proposed methodology considers the various steps in generating and analyzing alternative rehabilitationstrategies in regards to sustainability, Figure 1.Once the project site is identified, thenext step is to assess the current conditions of the existing roadway. This assessment is particularly critical since it will identify the quality of the existing materials and roadway providing valuable input into: (i) to what level existing materials can be recycled, and, (ii) potential structural issues and constraints that need to be considered and addressed in the rehabilitation strategies. Among the common condition surveys currently used by highway agencies is the distress survey (i.e., pavement defects). Such survey involvesdistressidentification and measuring severity and density of these defects on the roadway. These data are then used torate the roadway condition throught the calculation of the pavement condition index, PCI, [7].

As mentioned previously the current condition will identify, among other, the possible type and percentage rate of recycled materials that can be reused, the recycling methods to be used, such as hot-in place recycling (HIR), or plant based recycling, and, potential constraints in regards to the use of permeable versus impermeable materials for enhanced sustainability benefits. The possibility of using permeable surfaces also depends on the expected traffic level andsite specific pavement design considerations. The next step in the analysis, Figure 1, is to identify alternative rehabilitation strategies, like those presented in the case studies next, and examine whether these are structurallyfeasible. To this regard a pavement design methodology should be used, like the 1993 AASHTO pavement design [9], or, the Mechanistic Empirical Pavement Design, MEPDG [10]. Based on these analyses structurally feasible rehabilitation strategies are identified for inclusion into the next step of the analysis for life cycle cost and environmental impact assessment.

The life-cycle cost analysis (LCCA) can be performed either in terms of net present worth value, NPV, or the uniform annual cost approach [11]. It involves considering for each strategy all possible costs that will occur during the performance period, and including construction, maintenance and future repairs [6]. Similarly, the life-cycle environmental impact analysis should consider all environmental loads (i.e., energy and water consumption, emissions, hazardous waste disposal) associated with such operations. Several tools are currently available for conducting such analysis, like PaLATE and BE^2ST-in-Highways[2, 3]. Thesewere used in the comparative analysis of the case studies presented herein. The economic and environmental impact results from each strategy can be then compared to the “reference strategy” representing the use of conventional “virgin” materials. Such assessment will provide a relative comparison of all feasible sustainable strategies between them and in relation to the “reference” one [12, 13]. A rating system can be then used, like the one presented in the case studies analysis, for obtaining a relative score of sustainabilityfor each strategy and thus select the one with the higher score to implement.

III. EXAMPLE ANALYSIS WITH CASE STUDIES

Objective of the case studies was to demonstrate how the proposed methodology is able to quantify the economics benefits and environmental implications as the recycling material content increases, and, at the same time present case studies where increasing the amount of recycling is not always providing monotonically increasing benefits. Two types of roadway projects were considered in the analysis, Table 1. The first case, Roadway 1, represents a typical medium level traffic road built with two pavement layers, a surface hot mix asphalt, HMA, and a granular base, GAB. The second case, Roadway 2, represents a higher-level traffic road requiring higher bearing capacity support and thus built with three pavement layers, a surface hot mix asphalt, HMA, an intermediate asphalt treated base, ATB, on top of the granular base, GAB. The structural characteristics of these two roadway projects are presented in Table 1 along with the current condition ratings in Present Condition Index, PCI. The life-cycle cost and environmental results were analyzed based on a 1.6 kilometers roadway length with an analysis period of 40 years. A roadway reconstruction every 20 years was considered after the initial construction.

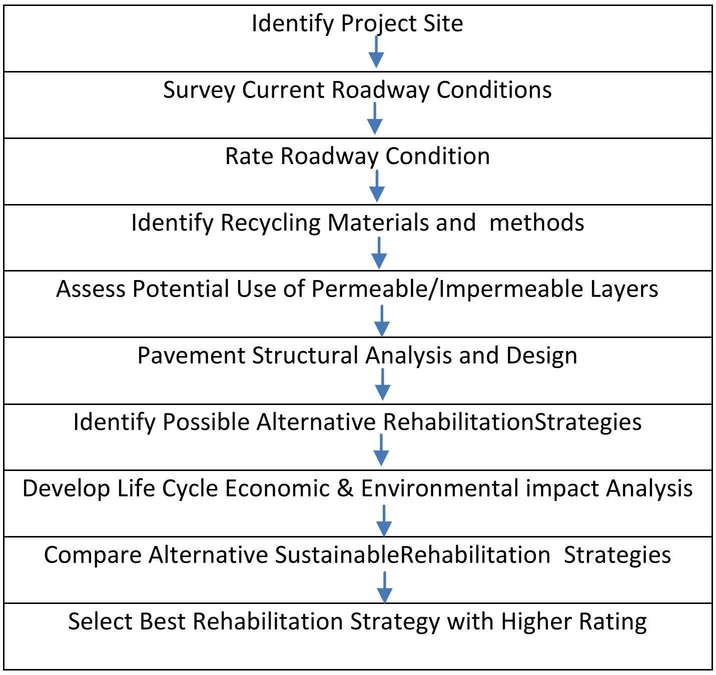

Figure 1: Analysis Steps for Generating and Analyzing Alternative Sustainable Rehabilitation Strategies

Table 1:Pavement Structural Parameters for Roadways

Roadway	Lane Width (m)	HMA Layer (cm)	ATB Layer (cm)	GAB Layer (cm)	PCI
1 (two layer system)	7.3	10.1	N/A	20.3	70-80 (satisfactory)
2 (three layer system)	7.3	12.7	15.2	20.3	60-70 (fair)

Alternative rehabilitation strategies were considered for each case based on the current PCI condition rating for each pavement structure, Tables 2 and 3. These alternatives were compared to the “reference strategy” (i.e., control) for each case representing rehabilitation where only conventional virgin (i.e., new) construction materials were used.For the two-layerroadway case, Table 2,two groups of alternative sustainable rehabilitation strategies were considered. Alternative strategy 1 aims to evaluate the economic and environmental implications when substitutingportion of the HMA and GAB layers with RAP.Alternative strategy 2 considers the implications when both RAP and recycled GAB are recycled in the two pavement layers at different percentages.As it can be observed from Table 2, the RAP percentage in HMA for both strategies ranged from 10% to 50% by volume. For the GAB layer in alternative strategy 1 virgin aggregate and RAP were used at different percentages. Alternative strategy 2 considered using no new raw materials but only RAP and recycled GAB at various percentage levels. This produced in each case five different cases in relation to the percentage of recycled material used in each scenario.The life cycle economic analysis results are presented in Figure 2. The use of recycled materials has provided a reduction in cost for both strategies and alternatives in relation to the reference strategy where only new raw materials are used. These cost savings ranged from 24% to 40% depending on the case. For strategy 2 the savings increase with increasing the amount of RAP in HMA and recycled GAB in the base layer. For strategy 1 the savings decreased when a lower percentage of RAP in the GAB layer since new raw material had to be used for the remaining portion of the layer.

For the three layer roadway case, Table 3, six alternative sustainable rehabilitation strategies were considered by generating combinations of varying: the percentage of RAP in the HMA layer; and, the recycled percentage of asphalt treated base, ATB, and RAP in the ATB and GAB layers. The life cycle economic analysis results are presented in Figure 3. In the three-layer roadway case the use of recycled materials has provided a reduction in cost for all the alternative strategies in relation to the reference strategy where only new raw materials are used. The largest cost reductions were observed when no new materials were used in the ATB and GAB layers (strategies 5 and 6).

Similarly to the economic analysis, the life cycle environmental impact analysis for all the alternatives of the two-layer and three-layer roadway systems were examined. The results for the three-layer roadway system are presented herein as an example, Figure 4. The results are presented in relation to the “control” case, in percentage, where new materials are used in all three layers. Overall, the alternative rehabilitation strategies have lower energy and water consumption in relation to the control case, as well as emissions. Strategy 6 provided the best environmental results in relation to the remaining strategies. While the combined effects of

RAP, recycled GAB and ATB percentage in each alternative strategy affect such parameters there is a need to combine economic and environmental impact in order to identify which is the best sustainable strategy.

Table 2: Alternative Rehabilitation Strategies for the Two-Layer Roadway System

		Reference Strategy	Alternative Strategy 1					Alternative Strategy 2				
			1	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
HMA layer	Virgin HMA (%)	100	90	80	70	60	50	90	80	70	60	50
	RAP (%)	0	10	20	30	40	50	10	20	30	40	50
GAB layer	Virgin GAB (%)	100	55	60	65	70	75	0	0	0	0	0
	RAP (%)	0	45	40	35	30	25	45	40	35	30	25
	Recycled GAB (%)	0	0	0	0	0	0	55	60	65	70	75

Table 3: Alternative Rehabilitation Strategies for the Three-Layer Roadway System

		Reference Strategy	Alternative Strategies					
			1	**2**	**3**	**4**	**5**	**6**
HMA layer	Virgin HMA (%)	100	80	50	80	50	80	50
	RAP (%)	0	20	50	20	50	20	50
ATB layer	Virgin ATB (%)	100	33	58	0	0	0	0
	RAP (%)	0	67	42	67	42	67	42
	Recycled ATB (%)	0	0	0	33	58	33	58
GAB layer	Virgin GAB (%)	100	100	100	85	70	0	0
	Recycled ATB (%)	0	0	0	15	30	15	30
	Recycled GAB (%)	0	0	0	0	0	85	70

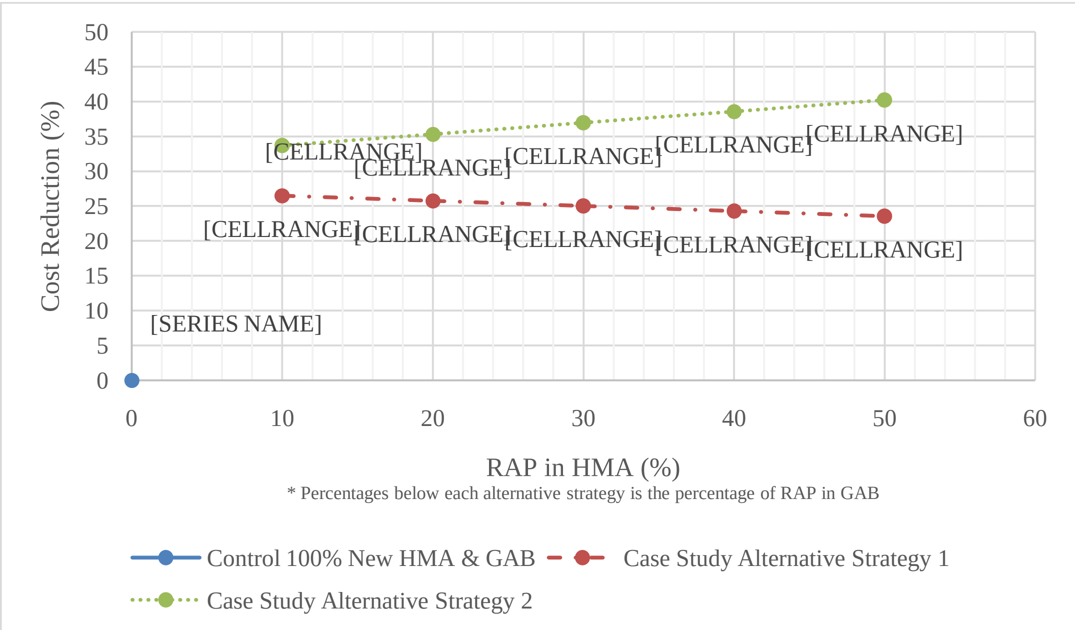

Figure 2: Economic Comparison of Alternative Strategies for the Two-Layer Roadway System

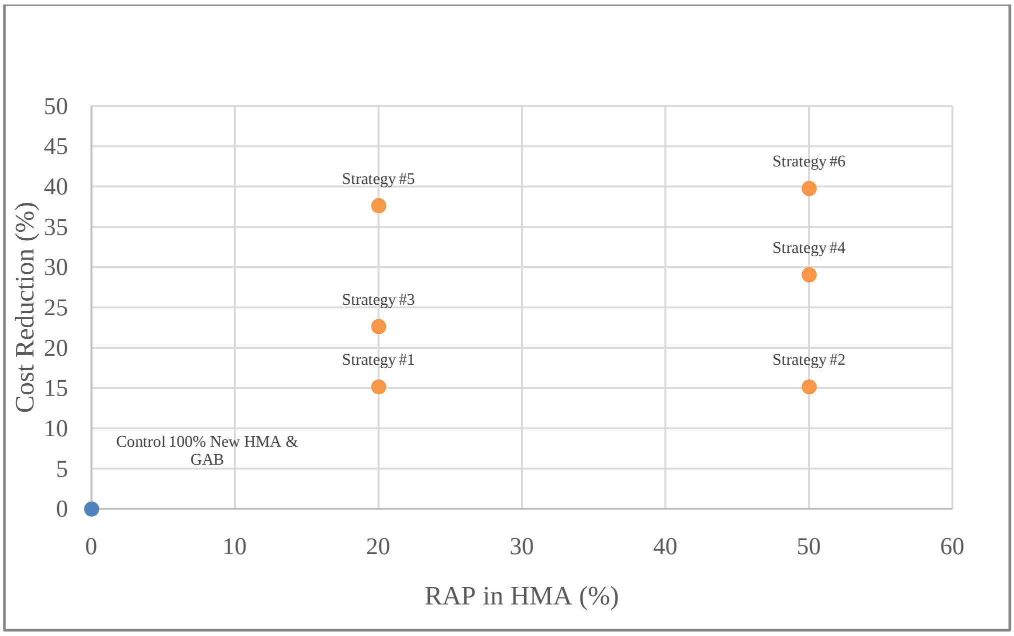

Figure 3: Economic Comparison of Alternative Strategies for the Three-Layer Roadway System

In order to achieve so a rating system can be used to weight in relative scale the importance of life cycle cost and environmental parameters in regards to sustainability. For the case of BE^{2}ST-in-Highways [7] the parameters include those in Table 4. These may include among other energy use, global warming, in-situ recycling, water consumption, life cycle and social carbon costs, and hazardous waste. The relative weights ranging from 0 to 100% can be adjusted to reflect the importance of each one in regards to the local policies and conditions that the roadway is to be built or rehabilitated. An example of values for these relative weightis presented in Table 4. For example, for a specific country, county, city or agency, some parameters are more important than others (i.e. water consumption may be not that critical in sustainability assessment in a place where water is in abundance, while energy could be because of limited supply). Furthermore, the award points in regards to sustainability assessment consider the desired target values that a strategy should achieve, Table 5. These values should be set based on local recycling target values representing the policies of the specific country, county, city or agency. For example an agency already implementing a higher level of recycling could adjust these at higher levels in order to award sustainability points, while a county just starting on sustainability and recycling without prior history and experience or recycling practices may start at a lower level representing achievable targets in their region.

Finally, the product of award points and relative weights for each of these parameters provides the overall sustainability rating. According to the BE^{2}ST-in-Highways rating system the awarded levels are: “Gold” for score from 100 to 90%, “Silver” for score from 90 to 75%, and “Bronze” 75 to 50%. Scores with less than 50% are not considered as “green” sustainable solutions. As an example, in this analysisthe highest rating for the three-layer roadway system alternatives was rehabilitation Strategy 2, Table 6.This provided an overall sustainability score of 79.67% equivalent to a silver rating. As mentioned in the steps of the proposed methodology, such iterative analysis could consider additional rehabilitation strategies in order to achieve the best solution with eventually a higher sustainability score.

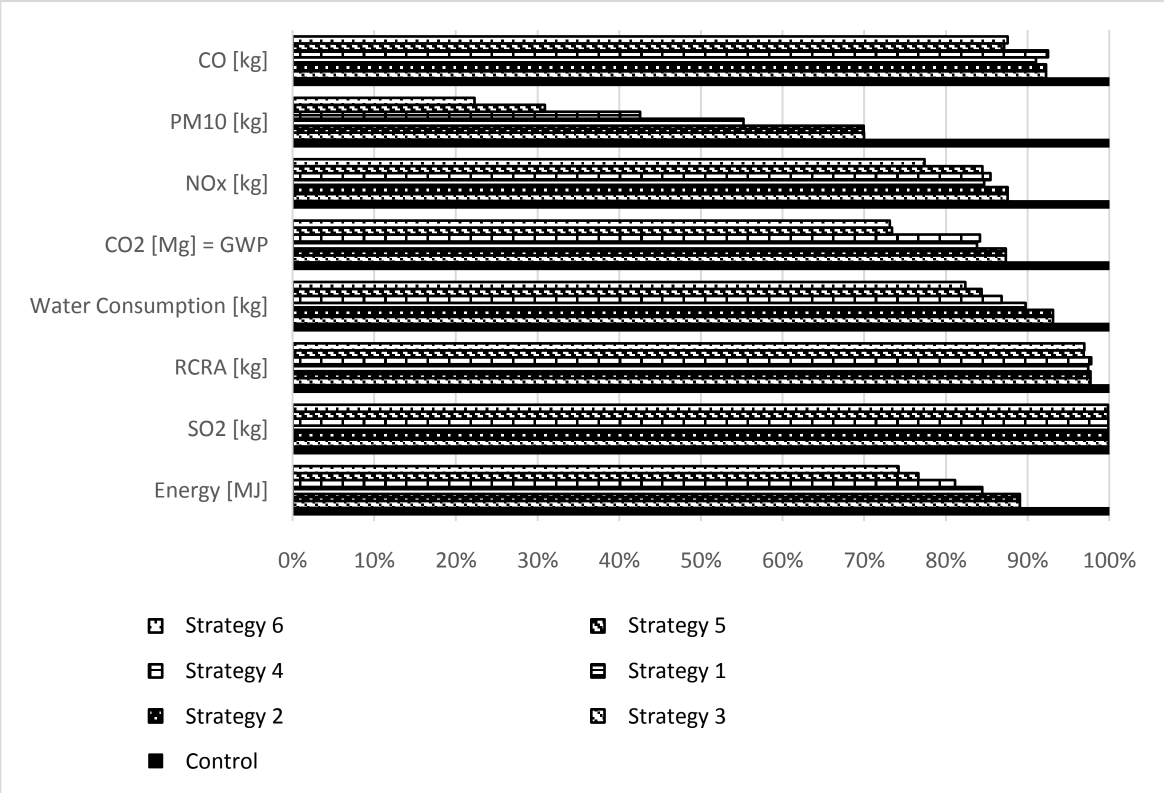

Figure 4: Life-Cycle Environment Analysis for Three-Layer Roadway System

Table 4:Example Sustainability Rating Parameters and Relative Weights

Parameters	**Weight Factors (%)**
Energy	15
Global Warming	15
In-situ Recycling	15
Water Consumption	15
Life Cycle Cost, LCC	15
Social Carbon Cost, SCC	10
Hazardous Waste	15
Total	**100**

Table 5:Target Sustainability Value and Award Points

Parameter	**Units**	**Target Values (Award points)**
Energy Use	MJ	>= 10% Reduction (1 pt)
		>= 20% Reduction (2 pt)
GWP	Mg	>= 10% Reduction (1 pt)
		>= 20% Reduction (2 pt)
In Situ Recycling	m^3	< 25% Recycling Rate (1 pt)
		>= 25% Recycling Rate (2 pt)
Water Consumption	Kg	>= 5% Reduction (1 pt)
		>= 10% Reduction (2 pt)
Life Cycle Cost	$	>= 10% Reduction (1 pt)
		>= 20% Reduction (2 pt)
Social Carbon Cost	$	>= $19,750/mi Saving (1 pt)
		>= $39,500/mi Saving (2 pt)
Hazardous Waste	kg	>= 5% Reduction (1 pt)
		>= 10% Reduction (2 pt)

Table 6: Results for Strategy 2 of Three-Layer Roadway system

Criteria	Reference Strategy	Alternative Strategy #2	Normalized Score (award points)
Energy Use (MJ)	10,342,136	6,795,907	2
GWP (Mg)	573	346	2
In-Situ Recycling (m^3)	0.00	1,529	2
Water Consumption	2,290	1,773	2
Life Cycle Cost ($)	2,552,620	1,526,756	2
Social Carbon Cost ($)	$27,446.65	$16,573.37	0.28
Hazardous Waste (kg)	78,161	74,726	0.31

IV. CONCLUSION

The current focus of the engineering community towards sustainability generates the need for developing analysis methods that can be integrated into the current construction process that highway agencies are dealing with for maintaining and rehabilitating their highway network. This paper presented an overview of a proposed methodology for addressing the development of feasiblesustainablerehabilitation strategies for roadway construction. The proposed methodology considers a holistic approach for generating alternative sustainable rehabilitation strategies and identifying the best one for implementation.Specific steps of the analysis were presented through typical case studies of roadway construction in order to showcase primarily the analysis pertinent to the sustainability assessment. This paper also provided some of the insides on the comparative analysis and the criteria used in assessing such sustainable rehabilitation alternatives. The ability of adjustingassessment and rating criteria for sustainabilityto local policies and achievable recycling levels was also discussed in terms of custom tailoring: (i) the recycling target values and correspondingsustainability reward points; and, (ii) the relative weights used in producing the overall sustainability rating score, in regards tothe importance of each economic and environmental impact parameter in the specific region.It is expected that the adoption of the proposed methodology and analysis will have a direct impact on embracing sustainability in infrastructure projects. The methodology and findings are transferable to other regions where similar approaches to roadway construction are used

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