Eco-Street: Quantifying Energy Efficiency of Roads over Their Lifespan

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Abstract

The objective of this paper was to investigate the practicality and benefits of applying theoretically proposed environmental competency measures to the construction of roads, with LEED standards for building construction as the initial framework for analysis. A short coming of credit based systems for environmental evaluation is that they have the potential to reward activities of minimal positive environmental impact activities equally with activities that have a greater impact on the environment. A rating system that certifies projects on achieving a certain level of energy conservation in measureable units of consumed energy (Eco-Streets) is developed herein.

To validate the rating system developed, three road design options of varied environmental impact are evaluated with the Eco-Streets rating system. For comparative purposes, the road cases are also evaluated under Green Roads; a credit-based system developed by the University of Washington for environmental rating of roadways.

The results of Eco-Street and Green Roads agree other with respect to overall environmental benefit. The conventional road structure was the least desirable option environmentally, followed by remove and replace using recycled materials, with the best results for in-place recycling and full depth reclamation design option. However, there was a significant difference in total energy consumption calculated for the design options under Eco-Street with respect to the transportation of materials, there is a significant difference. Under Green Roads all options are rated equally. Since transportation of materials consumes a large portion of the energy consumed during construction, it is believed that points attributed to transportation of materials under Green Roads are insufficient.

1. Introduction

1.1. Background

Since the publication of the Brundtland Report in 1987 there has been an unprecedented interest in examining the sustainable dimension of societal development [1]. The global concern with transportation infrastructure and the environment has been with emissions from vehicles associated with different modes of transport. There has been minimal focus on the environmental impacts related to the materials or processes of building road networks.

In Canada, such trends are evident from relative amount of greenhouse gases emitted from different construction sectors. In 2006, the transportation sector accounted for 26.3% of the total emissions, while all construction activities amounted to only 4.6% [2]. However, recent research reveals that the perception of reclamation and recycling of road materials suffer from a rather narrowed vision by focusing primarily on the leaching behaviour of the recycled content [3]. As quantified energy savings from the use of recycled road materials has so far been largely unexplored, the potential environmental benefits associated with alternate road construction processes could be significantly more than what is apparent from its share of greenhouse gas emissions.

Currently, several building standards are available that offer credits to buildings based on a number of environmentally and equitably relevant criteria such as amount of recycled material used in construction and distance to public transport access. Amongst these, Leadership in Energy and Environmental Design (LEED), Building Research Establishment Environmental Assessment Method (BREEAM), Green Star, Haute Qualité Environnementale (HQE) are the primary ones.

The LEED framework is the most commonly applied of these building standards in North America and offers credits to buildings that demonstrate superior environmental profile that are broken down to several categories. Several states have institutionalised a reward system for LEED standard buildings by providing tax benefits for raw materials used in a certified building and other reward strategies [4]. However, there are few of such standards that can be applied to roads.

Green Roads is an environmental rating system for roadways conceived at the University of Washington in 2006 [5]. Arguably the most rigorous amongst the road construction standards, the Green Roads Rating System derives the basic categories of energy reduction mechanism over a life cycle performance basis, much like the LEED system. However, the lack of an explicitly physical basis of awarding credits in Green Roads raises questions over the correlation of an apparently good practice measure to the importance it is endowed with by way of its rating.

The preceding discussions imply that exploring road construction process related energy is a valid and valued domain of research, indentifying energy consumed at different stages of construction is the first step towards strategizing effective and efficient road construction practices. This research concerns credits attributed to different stages of road construction by the Green Roads framework and a comparison to a system based on quantifiable energy consumption.

1.2. Review of environmental impacts of road transportation

Road construction consumes energy like all other types of construction through materials production, preparation, transport, placement, and maintenance. While most of these factors have a direct impact on the environment, some of the indirect consumption occurs through increased energy needed by a vehicle on a rough road surface. This indicates that along with increased maintenance costs, an inferior pavement management system can lead to higher energy consumption over a road's lifecycle. However, consideration of service life, one the most important factors influencing energy requirements of a road, has traditionally been neglected [6].

Insufficient consideration of environmental impacts of road construction material and process can be traced to the tenets of highway engineering traditions where performance of the road has been of primary concern [7]. Such trends meant that technical and economic issues were determinants of type of road to build, with energy commitments of the different alternatives having limited or no importance whatsoever [8]. The lack of importance credited to environmental impact of different construction materials and processes has been attributed specifically to a narrow vision that encompasses only the chemical impacts on the environment from the construction material [3]. For Canada, this is of immense concern given the significant amount of energy consumption and greenhouse gas emission that the construction sector is responsible for.

A key factor in ensuring superior environmental management standards above and beyond legal requirements in construction operations is support from higher administration of the organisations undertaking such measures [9]. Canada has been somewhat ambiguous towards policies for superior environmental management standards. While on one hand Transport Canada has been developing Sustainable Development Strategies for nearly a decade now, its vision of sustainable transport makes explicit consideration of only air pollutants or pollution [10, 11].

While the top down governmental approach to implementing environmental stewardship in Canada might have been somewhat ambiguous, bottom up approaches led by entrepreneurs have explored inclusion of voluntary environmental performance measures into building designs. The leading standard containing criteria for low net energy consuming buildings in North America is LEED. The LEED analysis framework contains a total of sixty nine points in six categories and a building can be graded in one among four classes with a superior environmental profile endowing more points and hence a better classification.

As for road construction, there has been only one available standard so far and is still under development and refinement [12]. Green Roads offers a total of six categories with a maximum of fifty two points that can be scored by a stretch of road. Neither LEED nor Green Roads is able to attribute the allocation of points based on a quantifiable and tangible parameter, but instead depends on consensual knowledge of a vast group of wide ranging professionals. However, LEED has been successful in creating a pro-environmental mindset amongst customers, and entrepreneurs and has been able to attract government recognition and support across North America [14].

1.3. Study Objective

The objective of this study is to develop and validate Eco-Street; an environmental rating system that is based on measureable energy units for use in rating the environmental impact of alternate construction processes for roads.

1.4. Study Scope and Methodology

The developed rating system focuses on the environmental impact of road construction activities. The focus is on measureable energy consumption of materials processing and the related construction activities. The research project behind this presentation has been carried out in four phases described as follows:

Phase one is a literature review. The literature review explores what previous developments have been undertaken with regard to the environmental impact of construction activities.

A rating system is developed based on the quantifiable energy consumption involved in the construction of roads in phase two. The rating system accounts for all typical stages of road construction including the major energy consuming materials and processes.

Phase three develops three design options to represent three options of varied environmental impact for the re-construction of a typical urban road within the City of Saskatoon. These design options are subject to environmental evaluation under the Eco-Street rating system. The design options are also evaluated under the Green Roads rating systems for comparative purposes.

In phase four the results of the environmental evaluation of the case studies are used for comparison of the rating systems. The environmental impact of the case studies as determined under the Green Roads and Eco-Street rating systems will be compared to analyze the merits and shortcomings of each of the rating systems.

2. Existing Environmental Rating Systems

2.1. LEED

In 1994, the US Natural Resources Defence Council initiated the development of LEED. The Report of the 'Brundtland Commission, Our Common Future' would have much to lend to the core LEED principle of energy conservation. However, Yudelson and Fedrizzi [15] point out that two more events influenced the creation of the United States Green Building Council (USGBC), an organisation which later completed the development of LEED: the 20^{th} US anniversary of the Earth Day in 1990 and the United Nations Conference on Environment and Development in 1992. Apart from the overall aim to reduce energy consumption by building stock, the USGBC (2009) further enumerates the benefits of LEED certified construction that aims to reduce infrastructure life cycle expenses as well as promote sustainability and social responsibility.

LEED Version 2.2 offers a total of 69 points that can be scored by a building project. These points are arranged in the following 6 categories:

- Sustainable sites (14 points);
- Water efficiency (5 points);
- Energy and atmosphere (17 points);
- Materials and resources (13 points);
- Indoor environmental quality (15 points); and
- Innovation and design process (5 points).

The process for claiming the credits for LEED certification commences with the developer or owner contacting USGBC and supplying the necessary documentation. A third party evaluator then reviews the application and determines which of the following three rating class may be awarded: Certified (26 to 32 points), Silver (33 to 38 points), Gold (39 to 51 points), Platinum (52 to 69 points).

The original focus of LEED was commercial buildings. However, with the publication of the latest version, in 2009 [4], LEED has entered existing buildings, commercial interiors, schools, and core and shell renovations. Four categories of buildings are used: offices, retail and service establishments, institutional buildings (e.g., libraries, schools, museums and religious institutions), hotels and residential buildings of four or more habitable stories. In Canada, a rating system for neighbourhood development has also been proposed [16].

2.1.1 Critique of LEED

USGBC has accomplished much in creating awareness for sustainability in building construction as evidenced by the rapidly increasing number of projects that have been 'LEED certified' since the inception of the standard. As well, the LEED standard has gone beyond just the building envelope and addressed some of the other resource sensitive aspects such as water efficiency, and site location.

When considering applying LEED to roads, a significant drawback of LEED lies in its allocation and definition of credits. The USGBC relied on consensual knowledge alone to develop the LEED standard, rather than available scientific research [17]. Bland pointed out that the standard has an implicit imperative to minimise cost rather than environmental impact [18]. It is perhaps without any surprise that in the absence of sound scientific baseline and operational principles, the LEED standard does not meet most of the measures of a successful standard development process as given by the American National Standards Institute.

In conclusion, LEED has been able to establish a much needed common measuring standard in North America. The European BREAM had failed to adapt to North American building standards [19]. However, to develop future standards to measure and recognise the ecology of infrastructure assets the drawbacks of LEED should be taken into consideration.

2.2. Green Roads

Green Roads is an environmental rating system for roadways modeled after LEED. Conceived at University of Washington in 2006, the Green Roads initiative provides a quantitative means to assess the sustainability and environmental stewardship of roads, and a tool for decision-makers that allows them to make informed design and construction decisions regarding sustainability and environmental stewardship of a road [5]. Green Roads is unique in a sense that it is the only known sustainability rating system for roads funded by both the US State Pavement Technology Center (a consortium of the state transport authorities) as well as the TransNow (a Washington based US DOT Region 10 University Transportation Center committed to fund innovative research in transportation).

Some of the other related tools to integrate sustainability in transportation are the Green Highway Program and the Sustainable Sites Initiative. The first relies on integrated planning, regulatory flexibility, and market-based rewards as qualitative guiding concepts to bring about sustainability in highway planning, design, and operation [20, 21]. Given by American Society of Landscape Architects, the Sustainable Sites Initiative provides a framework to quantitatively evaluate performance of landscapes and land management including transportation projects [22]. Neither framework provides the full functionality of Green Roads.

Green Roads offers 62 points that can be scored by a new road construction or rehabilitation project. These points are arranged in 6 categories as summarized in Table 1. Green Roads does not offer different classes of certification like LEED but requires a minimum number of credits be scored for certification. As well for some categories (e.g., storm water management), the regulations of the state of Washington is mandated as basic requirement towards certification.

2.2.1 Critique of Green Roads

It is challenging to come up with a comprehensive critique of Green Roads due to the limited use of the system. From a theoretical standpoint, the intention to extend an environmental rating system to transportation should be commended first and foremost. As well, the coverage of different aspects appears to be comprehensive.

Arguably, the greatest disadvantage of Green Roads is similar to the LEED system, an inherent lack of scientific basis to allocation of credits to construction activities and provisions. As the Green Roads standard is still in development, it may be useful if further development avoids the pitfalls of LEED, by establishing a scientific basis for allocation of credits and conforming to the measures of national or international standards development guideline.

3. Proposed Eco-Street Rating System

3.1. Quantification of Energy Consumption

As previously discussed, a rating system for infrastructure that centers on quantifiable energy consumption across alternate road construction methods may be a more practical and meaningful system than LEED or Green Roads when applied to road rehabilitation. In order to provide a quantifiable energy consumption system, a model needs to be developed to output the energy consumption of the processes for infrastructure development.

This study employed an approach to estimate the diesel fuel consumption for processes across alternate road construction processes. Although there are other sources of energy consumption in the road construction process, this study only considered fuel consumption of major equipment as this was assumed to be the major influence in energy consumption as related to road rehabilitation. Each road project requires alternative processes influencing different equipment and operation hours.

To apply the proposed Eco-Street rating system to a specific road construction case, equipment are identified for an analysis to estimate the productivity. The productivity and construction requirements can be used to estimate the equipment hours of operations. Documented equipment specifications will be used to estimate the fuel consumption for the construction task. Each process and type of equipment will have a variation of the same analysis, but all foreseeable road construction processes can be estimated in this manner. Summing the fuel consumptions by process produced an estimate of diesel fuel required for the entire project. One last step will be required to convert the fuel consumption to energy unit of KJ using a documented conversion process. Table 2 contains the aspects of the construction process that were identified in the Eco-Street rating system as aspects that would have significant energy consumption associated with each activity. Therefore the energy consumption of the parameters described below was quantified with respect to investigating the environmental impact of a road construction project.

3.2. Qualitative Environmental Criteria

The proposed Eco-Street rating system has been designed on the basis of energy consumption at every stage of the construction of a road. However, not all environmental impacts can be quantified in terms of a physical parameter, such as energy. This dilemma is not unique to the physical based nature of Eco-Street, as LEED has also been criticised for failing to recognise the difficult to measure aspect of human dimensions in construction [23].

The challenge of considering environmental impacts that are intangible or have incongruent units with the rest of the documented impact categories is a commonly encountered challenge in the cost-benefit analysis of Environmental Impact Assessment (EIA). In such cases, two main techniques are used to consider such impacts: direct and indirect [24, 25, 26]. The direct approach includes contingent valuation method (willingness of parties with vested interest to pay for a certain feature, or prevent an undesirable feature), and contingent ranking method (parties are asked to rank their preferences for a choice of predetermined features). In the indirect approach market value of a certain enhancement or deterioration of an environmental feature is measured. When applied to transportation, an example could be the increase in the land price due to the construction of a new access road which can be determined by stakeholders' opinion of the land price they would offer (direct approach), or by comparing the development with a similar project to arrive at a likely land price(indirect approach).

In order to conform to measures of Standards Council of Canada, the standard development process will be required to involve a balanced committee of stakeholders and be subjected to public scrutiny [27]. These measures will provide opportunities to seek effective ways to incorporate qualitative environmental criteria in the standards. Though the methods used in EIA are prospective, they pose two major challenges if applied to a rating system:

- Economic evaluation of natural assets are most often complex if not controversial; and

- Unlike the project specific nature of EIAs, Eco-Street shall have utility across more than one transportation project implying that the credits offered for a qualitative environmental criterion will not have the privilege to be based on environmental costs and benefits specific to one project

In the current stage of development of Eco-Street there is no provision for qualitative environmental criteria. However, the importance of such criteria is acknowledged and shall be appropriately addressed with further refinement and maturity of the system.

4. Pilot Case Study

To evaluate the proposed Eco-Street rating system, design options for a case study were selected and subjected to evaluation. The pilot case study is intended to represent three design options for the rehabilitation for a theoretical section of road 1000 meters in length and 10 meters in width that consists of an existing structure of 150mm of hot mix asphalt concrete (HMAC) on 450mm of granular base as summarized in Table 3. The design options explored were intended to produce an equivalent life expectancy while using different products including virgin granular, offsite recycled asphaltic concrete materials and in-place recycled materials.

As illustrated in Figure 1, Design Option #1 involved a full-depth remove and replace of the existing structure with 450mm of virgin granular base with 150mm of HMAC. Design Option #2 involved removal of the existing structure to a depth of 575mm, replacing with 500mm of crushed recycled asphaltic concrete and overlaying with 75mm of HMAC. Design Option #3 involved the in-place recycling of the structure and cement strengthening of the recycled aggregate to a depth of 250mm with a 75mm surfacing HMAC.

4.1. Design Option Materials Comparison

To demonstrate the mechanistic properties of the chosen materials for the three design options, this research conducted triaxial frequency sweep characterization the structural design materials for comparative purposes. Figure 2 illustrates the mechanistic material characterization results obtained from the triaxial frequency sweep characterization applied across stress state and load frequency representative of typical Saskatchewan field state conditions.

As illustrated in Figure 2, the recycled HMAC was found to have a higher dynamic modulus than the granular base. The cement strengthened granular base was found to have a dynamic modulus that was significantly higher than both the virgin granular base and the recycled HMAC. The HMAC exhibited the highest phase angle overall with the recycled HMAC exhibiting the second highest phase angle. These phase angles are the results of effects of the bitumen in the HMAC and recycled AC. the recycled HMAC was found to have a similar Poisson’s ratio to the granular base. The cement strengthened granular base was found to have a Poisson’s ratio that was significantly lower than both the granular base and the recycled HMAC

The granular materials were tested for moisture susceptibility by subjecting samples to bottom moisture and measuring the moisture intake of the samples. As seen in Figure 3, the moisture intake of the recycled HMAC was significantly lower than the other materials. The recycled base with cement also exhibited reduced moisture susceptibility in comparison to the granular base and recycled *in situ* base.

5. Implementation of the Eco-Street Rating System

5.1. Application of Proposed Eco-Street Rating System to the Case Studies

The method as previously described as the proposed Eco-Street rating system was followed for each piece of construction equipment used in the case studies. For simplification and consistency, all equipment analyzed are manufactured by Caterpillar. All equations, tables, and operating estimates are from Caterpillar equipment specification documents [28].

Table 4 summarizes the results of the energy consumption analysis of the three design options. Items that related to the off-site production of materials for the design options were out of scope for due to lack of available information for the calculation of energy consumption. As seen in Table 4, the energy consumption for the accounted for aspects of construction was:

- 762,010 MJ for Design Option #1 (conventional remove and replace),
- 85,845 MJ for Design Option #2 (remove and replace using stockpiled recycled asphalt concrete with thin asphalt overlay), and
- 343,027 MJ for Design Option #3 (in place recycling and strengthening of materials with thin asphalt overlay).

5.2. Application of Green Roads Rating System to the Case Study

For the application of Green Roads rating to the case study, it was found that several of the parameters were not applicable to the case of a structural re-construction of a road, as they are the result of the existing alignment of the road. The case study investigated only detailed certain aspects of the construction process which are limited to the category of material and resources within the context of the Green Road rating system. The material and resources category consists of twelve credits out of a possible 62 for the entire Green Road system. Only four of the criteria within the material and resources category are applicable to the design options for this report resulting in a possible nine Green Road credits for the case study. Table 5 outlines the Material and Resource category for Green Roads and the achieved credits for each design option. Table 6 describes the reasoning for each of the design options to achieve their total credits. Each of the design option achieved a different level of Green Road accreditation. Design option #3 has the highest level of accreditation with nine credits followed by six and two credit for design options #2 and #1 respectively.

6. Discussion

6.1. Comparison Final Results of Alternate Rating Systems

As seen in Figure 4 and Figure 5, the results of Eco-Street and Green Roads appear to be in agreement with each other with respect to overall environmental benefit. The conventional structure (Design Option #1) proved to be the least desirable option environmentally under both rating systems, followed by remove and replace using recycled materials (Design Option #2) with the best results for in-place recycling and strengthening (Design Option #3).

As illustrated in Figure 6 and Figure 7, the total energy consumption under Eco-Street for transportation on materials, there is a significant difference between the given design options, but under Green Roads there each design option obtains two points for regionally provided materials, which is the only place in the Green Roads rating system that any credit is awarded for a reduction in haul distance. Furthermore, when looking at the energy consumption of transportation of materials in comparison to all other accounted factors under Eco-Street, transportation of materials is the highest contributing factor while in Green Roads it is not given a comparable amount of weighting.

7. Conclusion of Results

This research shows that there is potential for use of the proposed Eco-Street method of rating roads for construction energy conservation. Doubts regarding the validity of the weighting of points under the Green Roads rating system were also presented.

The overall rating given to the case study design options under Eco-Street and Green Roads was similar, with the conventional remove and replace options given the lowest rating and in-place recycling and strengthening receiving the best rating. However, for the total energy consumption calculated under Eco-Street for transportation of materials, there is a significant difference between the given design options. Under Green Roads all options are rated equally. Given the significant quantity of energy consumed for the transportation of materials, this suggests that the allotment of points under Green Roads to the transportation of materials may be insufficient.

Though the Eco-Street environmental rating system is still in development, it can be seen from the case study that Eco-Street can pinpoint where significant energy consumption is occurring. This serves as a tool for determining where adjustments can be made on a given construction project to make a greater impact in terms of reduction of energy consumption. Additional research that is required to fully develop the system includes:

- Data regarding the energy consumption of the processing of materials,
- Development of the soft environmental criteria,
- Life cycle analysis of road structures and the influence of maintenance, and
- User costs and in-service energy consumption,
- Certification of roadways that meet a significant level of energy conservation.

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28. Cat Performance Handbook #39

Tables:

Table 1 Green Roads Rating System Parameters

Category and total points	Subcategory and points	Strategy to reduce environmental impact
Construction Activity (13)	Quality Process Management – 2 On-site Recycling & Trash Collection – 1 Track Water Use – 1 Reduce Fossil Fuel Use – 1 to2 Reduce Equipment Emissions – 1 to 2 Reduce Paving Emissions - 1 Environmental/ Safety Training – 1 Performance-Based Warranty – 3	Encourage best practices in safety and reduction of emissions
Materials and Resources (12)	Enhance LCA – 2 Native Soil rehabilitation – 1 Pavement Reuse – 2 Recycled Content – 1 to 4 Regionally Provided Material – 1 to 2 Energy Efficiency – 1	Reduce the need for material extraction, use, and transportation.
Pavement technologies(11)	Long Life Pavement – 3 Pavement Performance Monitoring – 1 Warm Mix Asphalt – 2 Cool Pavement – 1 Permeable Pavement – 1 Quiet Pavement – 3	Encourage best practices in quality pavement and operational lifetime
Exemplary Performance (7)	Exemplary Performance – 1 to 6 Professional Accountability - 1	Encourage innovative practices to meet the goals of environmental stewardship
Project Requirements (11)	NEPA Compliance - Requisite Pavement Preservation Plan - Requisite Environmental Maintenance Plan - Requisite LID Technique for Storm water - Requisite Educational Outreach - Requisite Construction Quality Control - Requisite C&D Waste Management Plan - Requisite Life Cycle Cost Analysis - Requisite Life Cycle Inventory Tool - Requisite Storm water Pollution Prevention Plan - Requisite Noise Mitigation Plan - Requisite	Establish a minimum requirement of practices that should be incorporated in every construction project in the interest of sustainability
Environment & Water (10)	Environmental Management System – 1 to 2 Storm water Management Plus – 2 Native Landscaping – 1 Ecological Connectivity – 1 Reduce Light Pollution – 1 Life Cycle Cost Analysis of BMPs – 1 Habitat for Watershed Creation – 2	Encourage best practices in water management and the surrounding environment
Access& Equity (9)	Safety Audit - 1 Intelligent Transportation Systems - 2 Promote Art and Culture – 1 Scenic Views - 1 Pedestrian Access – 1 Bicycle Access – 1 Americans with Disabilities Access – 1 Transit Access - 1	Promote accessible and efficient mean of sustainable transportation

Table 2 Eco-Street Energy Consumption

Demolition of Existing Structure	
	Break up and removal of original structure
	HMAC & base removal
	Subgrade removal
	Haul to landfill
Subgrade preparation	
	Production of subgrade strengthening additives
	Haul distance from additive source to site
	Mixing of subgrade additive
	Shaping and compaction of subgrade
Base	
Virgin Granular materials	
	Aggregate production (removal from pit and crushing)
	Haul from aggregate source to site
Stockpiled Recycled Granular Materials	
	Recycled materials production (crushing)
	Haul from recycled materials stockpile to site
In-Place Recycled Granular Materials	
	Milling* (May be captured category in demolition above)
	Moving of recycled granular to remove subgrade from below
Modifications to in-place Granular Materials	
	Production of base strengthening additives
	Haul distance from additive source to site
	Mixing of base & cement and/or emulsion
Shaping and Compaction	
HMAC Surfacing:	
Asphalt Cement	
	Asphalt cement production energy
	Haul from asphalt cement source to HMAC plant
Asphalt Aggregate	
	Aggregate production (removal from pit and crushing)
	Haul from HMAC aggregate stockpile to HMAC plant
HMAC	
	HMAC production energy (plant mixing)
	Haul distance to HMAC plant from site
	Placement and compaction

Table 3 Parameters of Case Study Existing Road

		Existing Road
Structural Composition:		
	HMAC thickness	150 mm
	Base thickness	450 mm
Dimensions:		
	Length of section for rehabilitation	1000 m
	Width of road	10.0 m
Location:		
	Distance to quality aggregate source	20 km
	Distance to recycled material stockpiles	15 km
	Distance to HMAC plant	10 km
	Distance from asphalt oil source to HMAC plant	700 km
	Distance from aggregate stockpile to HMAC plant	15 km
	Distance to cement plant	1000 km
	Distance to landfill	20 km

Table 4 Results of Eco-Street Energy Consumption Analysis of Case Study

	Energy Consumption (MJ)		
	Option #1: Conventional Remove and Replace	**Option #2: Remove and Replace using Recycled Materials**	**Option #3: In-Place Recycling and Strengthening**
Demolition of Existing Structure			
Breaking up and removal of original structure	17,031	16,321	17,618
Haul to landfill	228,567	219,044	28,571
Subgrade preparation			
Production of strengthening additives	Out of Scope	Out of Scope	Out of Scope
Haul distance from additive source to site	--	--	--
Mixing of subgrade additives	--	--	--
Shaping and compaction	--	--	--
Base			
Granular Materials			
Aggregate production (removal and crushing)	Out of Scope	Out of Scope	Out of Scope
Haul distance from aggregate source to site	228,567	--	--
Stockpiled Recycled Granular Materials			
Recycled materials production (crushing)	Out of Scope	Out of Scope	Out of Scope
Haul from recycled materials stockpile to site	--	190,473	--
In-Place Recycled Granular Materials			
Milling* (captured in demolition, above)	--	--	--
Moving granular to remove subgrade	--	--	--
Modifications to In-place Granular Materials			
Production of strengthening additives	Out of Scope	Out of Scope	Out of Scope
Haul from additive source to site	--	--	126,982
Mixing of base and additives	--	--	9,848
Shaping	11,383	13,281	13,281
Compaction	12,745	14,869	14,869
HMAC Surfacing:			
Asphalt Cement			
Asphalt cement production energy	Out of Scope	Out of Scope	Out of Scope
Haul asphalt cement to HMAC plant	133,331	66,665	66,665
Asphalt Aggregate			
Aggregate production (removal and crushing)	Out of Scope	Out of Scope	Out of Scope
Haul from aggregate stockpile to HMAC plant	51,999	26,000	26,000
HMAC			
HMAC production energy (plant mixing)	Out of Scope	Out of Scope	Out of Scope
Haul from HMAC plant to site	38,095	19,047	19,047
Placement	29,660	14,830	14,830
Compaction	10,633	5,316	5,316
TOTAL ENERGY CONSUMPTION (MJ)	**762,010**	**585,845**	**343,027**

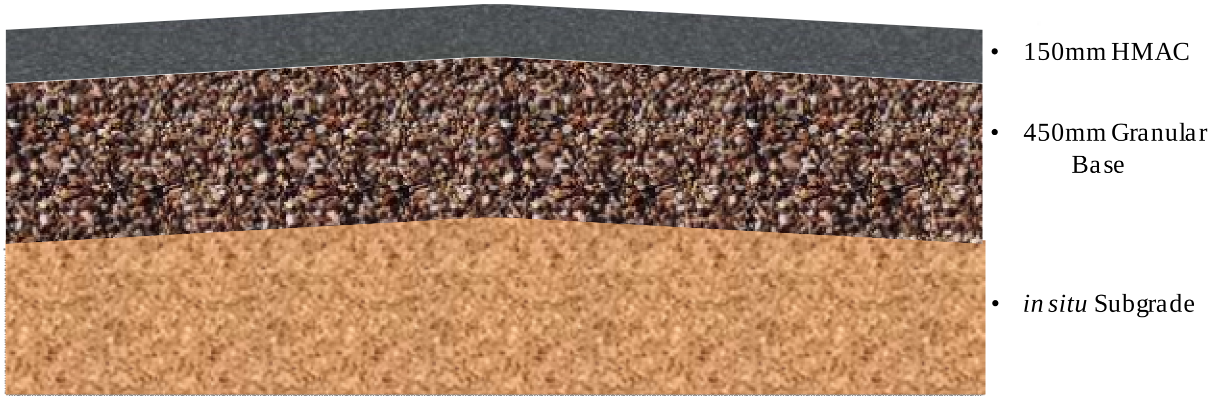
Table 5 Results of Green Roads Analysis of Case Study

Category and Total Points	Subcategory and Points	Option #1: Conventional Remove and Replace	Option #2: Remove and Replace using Recycled Materials	Option #3: In-Place Recycling and Strengthening
Materials and Resources (12)	Enhance LCA – 2	N/A	N/A	N/A
	Native Soil Rehabilitation – 1	--	--	1
	Pavement Reuse – 2	--	--	2
	Recycled Content – 1 to 4	--	4	4
	Regionally Provided Material - 1 to 2	2	2	2
	Energy Efficient Lighting - 1	N/A	N/A	N/A
Total Materials and Resources Points:		2	6	9

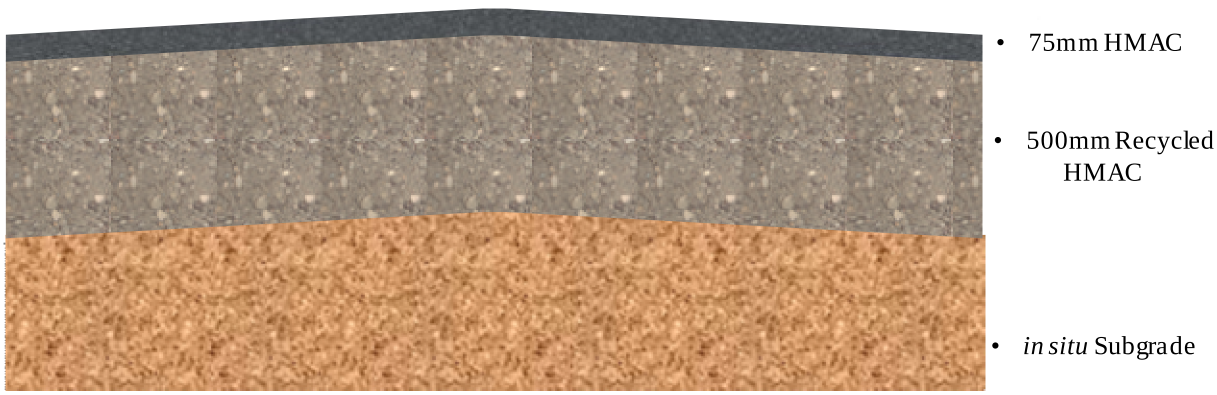
Table 6 Justification of Green Roads Rating of Case Study

Subcategory and Points	Option #1: Conventional Remove and Replace	Option #2: Remove and Replace using Recycled Materials	Option #3: In-Place Recycling and Strengthening
Enhance LCA – 2	N/A	N/A	N/A
Native Soil rehabilitation – 1	Import Fill	Import Fill	Import Fill
Pavement Reuse – 2	No Reuse	No Reuse	Reuses pavement in base layer
Recycled Content – 1 to 4	No Recycled Content	87% Recycled (4 pts = 50% min)	87% Recycled (4 pts = 50% min)
Regionally Provided Material - 1 to 2	Less than 50 miles/ton travel	Less than 50 miles/ton travel	Less than 50 miles/ton travel
Energy Efficient Lighting - 1	N/A	N/A	N/A

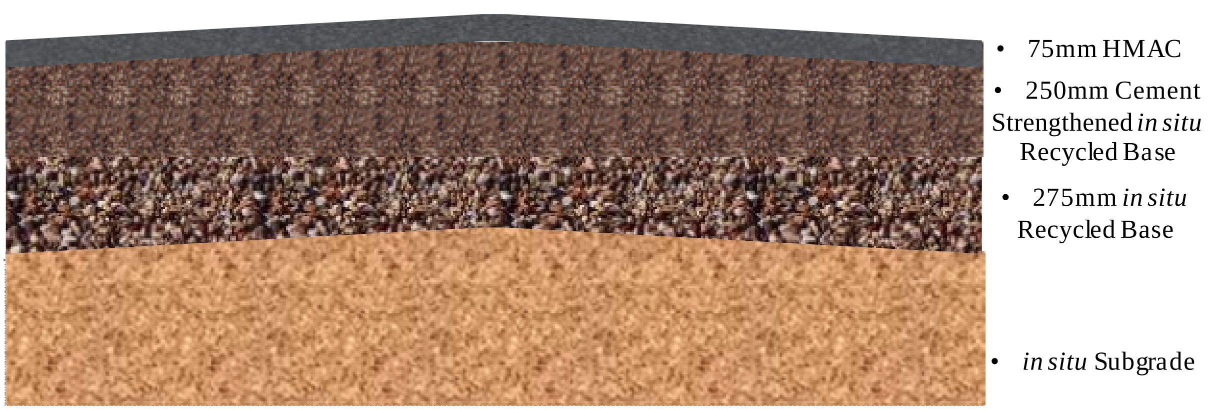
Figures:



a) Design Option #1: Conventional Remove and Replace

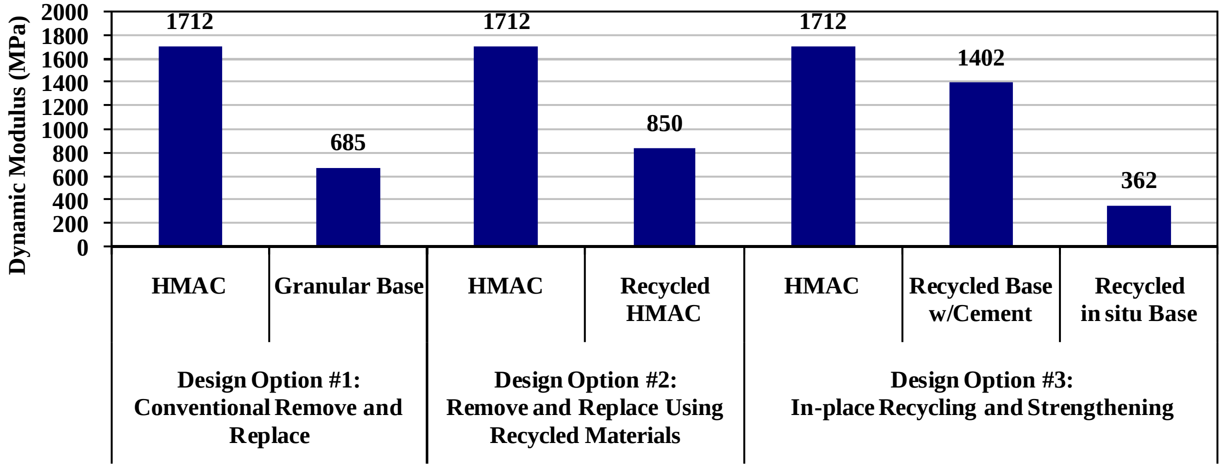


b) Design Option #2: Remove and Replace using Recycled Materials

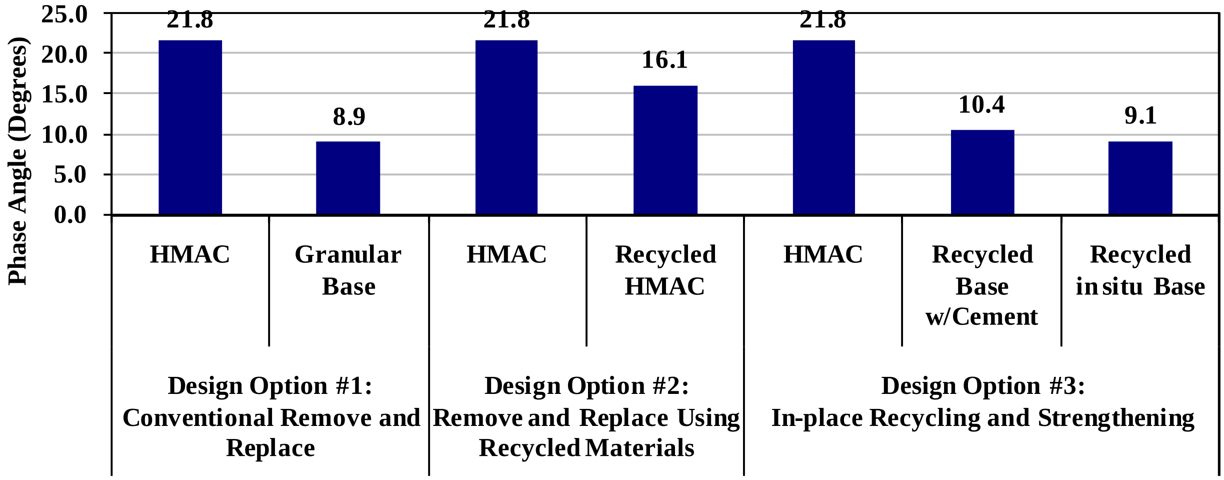


c) Design Option #3: In-place Recycling and Strengthening

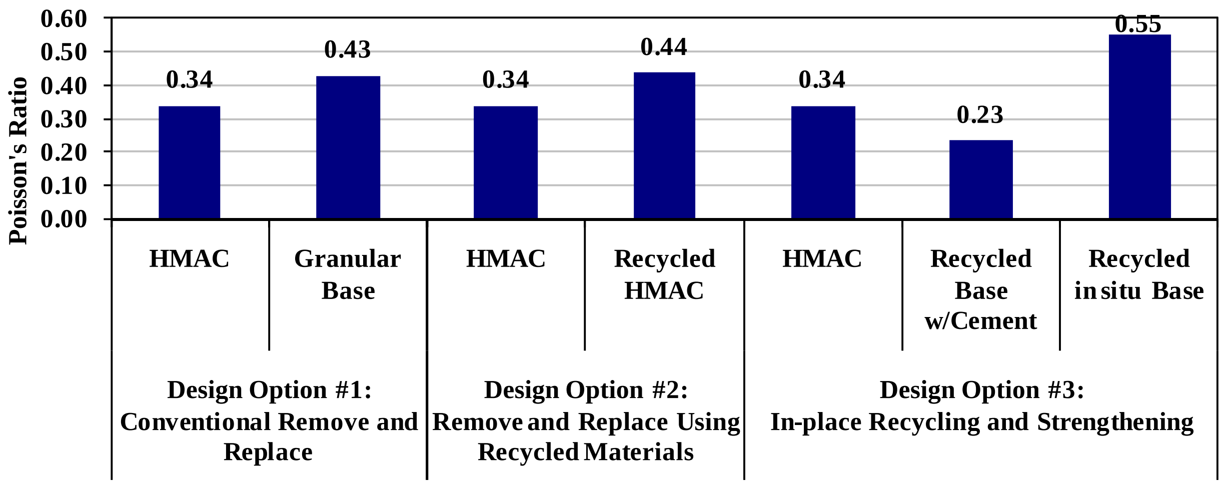
Figure 1 Layer thicknesses for Design Options



a) Mean Dynamic Modulus



b) Mean Phase Angle



c) Mean Poisson's Ratio

Figure 2 Mechanistic Material Properties across Design Options

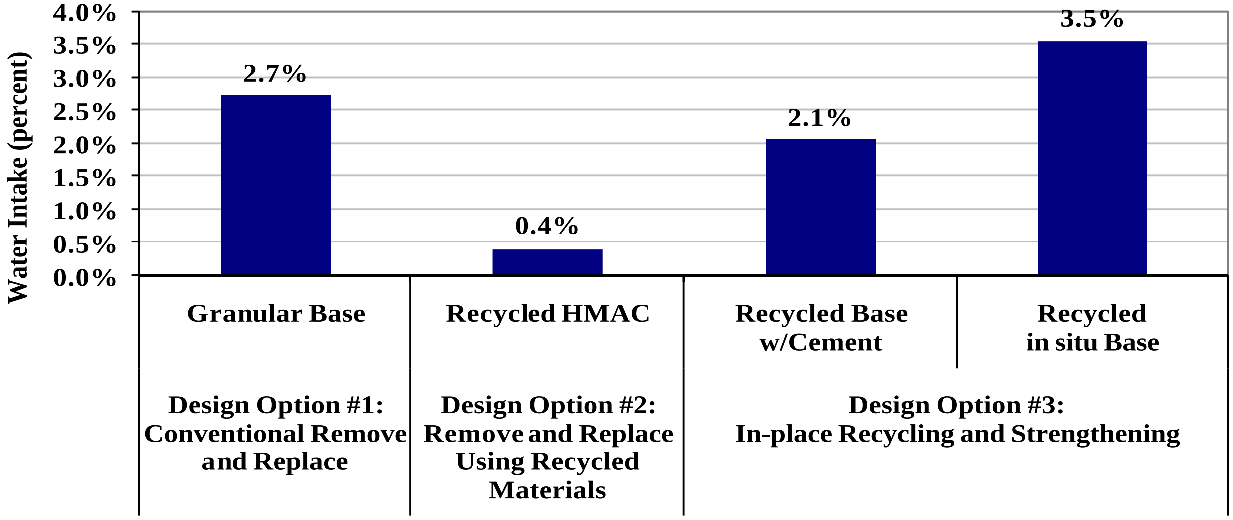


Figure 3 Climatic Moisture Intake across Design Options

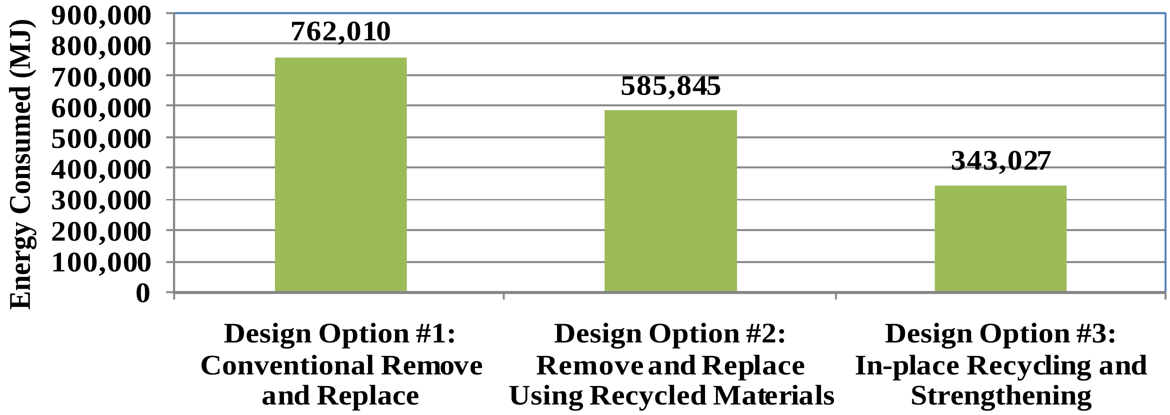


Figure 4 Results of Eco-Street Rating of Design Options

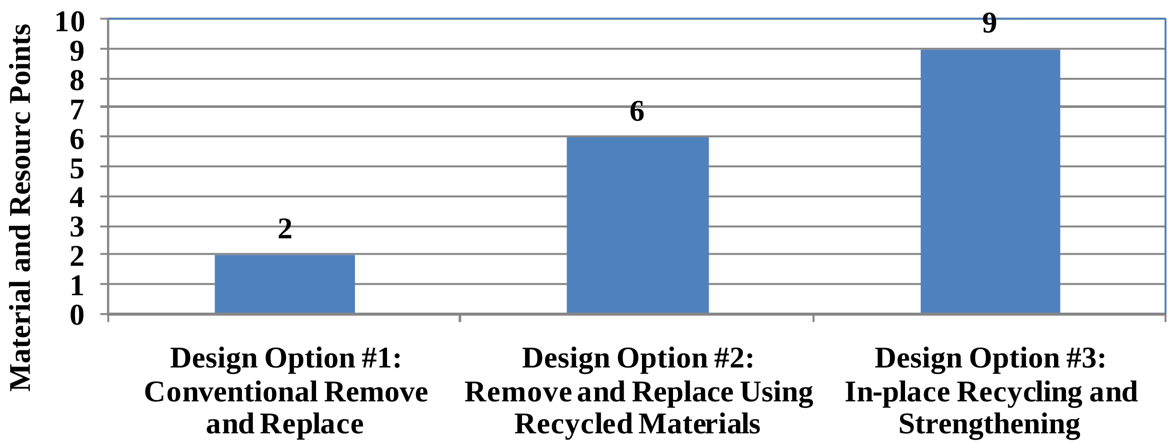


Figure 5 Results of Green Roads Rating of Design Options

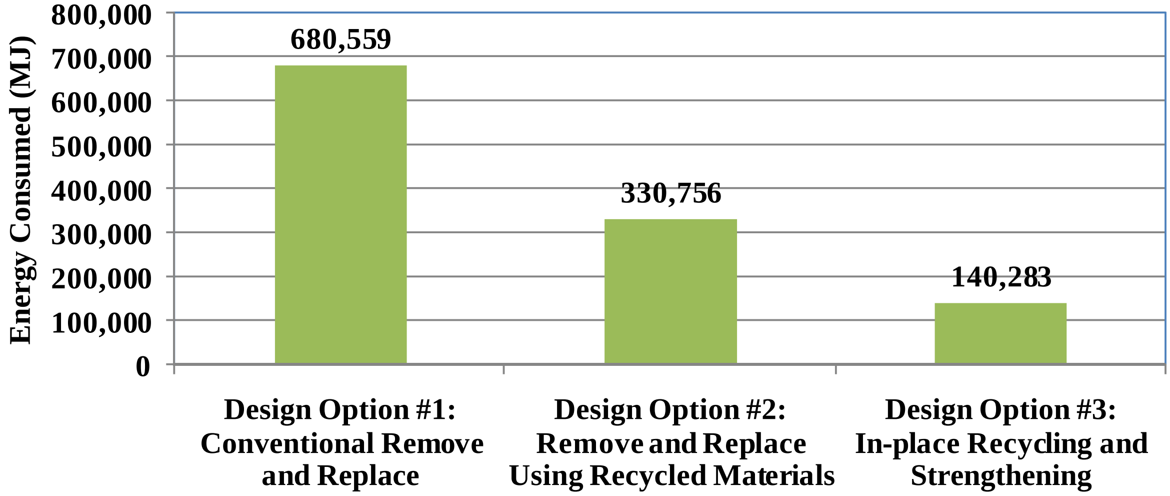


Figure 6 Results of Eco-Street Rating of Transportation of Materials for Design Options

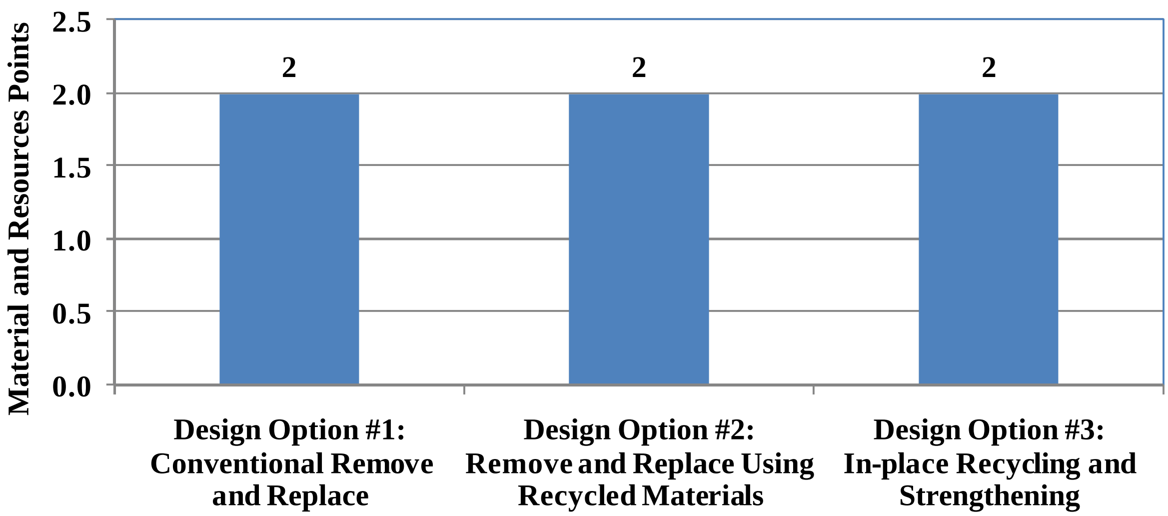


Figure 7 Results of Green Roads Rating of Transportation of Materials for Design Options