A Methodology for Sustainable Mechanistic-Empirical Pavement Design

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ABSTRACT: Roads cause significant impacts on the environment, such as contributing to emissions responsible for climate change. For this reason, pavement design methodology should integrate environmental as well as economical impacts. The objective of this study was to incorporate environmental impacts as part of the Mechanistic-Empirical (ME) pavement design procedure using Environmental Product Declarations (EPDs). This was accomplished through integration of environmental and economic impacts into the current ME pavement design framework. To facilitate the use of EPDs, a windows-based tool with a graphical user interface, was developed. The simple interface tool enables the user to filter and query the environmental impacts based on criteria such as compressive strength, product name, and product mix number. The final selection criteria can be adjusted by the user, based on feedback from the stakeholders. Two design case studies are presented to demonstrate the use of the developed tool.

INTRODUCTION

The Mechanistic-Empirical Pavement Design Method (MEPDG), referred to as Pavement ME, has been implemented by a number of state agencies as a tool for pavement design and performance prediction. This approach calculates pavement responses such as stresses, strains, and pavement deflections under different climatic conditions. The procedure then accumulates pavement damage over the design period and relates calculated damage over time to pavement distresses and smoothness, based on performance models (What Is Mechanistic-Empirical Design 2012).

The MEPDG does not incorporate the environmental impacts into the design framework. Design analyses performed do not quantify the environmental impacts of pavements such as Global Warming Potential (GWP), Ozone Depletion Potential (ODP), Acidification Potential (AP), Eutrophication Potential (EP), and Photochemical Ozone Creation Potentials (POCP). If the MEPDG does not address current global trends by targeting environmentally-responsible design, it will be of little value in the long-term. Therefore, an incorporation of environmental impacts into the overall design, as well as in the transportation stage, is becoming of primary importance. One of the tools to quantify environmental impact is Life-Cycle Assessment (LCA). However, it is time-consuming and requires extensive amount of data (Inyim et al. 2016).

Another method to quantify environmental impacts is Environmental Product Declaration (EPD), which represents an internationally standardized method (ISO 14025 standard - ISO, 2006c). EPDs are documents, which communicate information about the environmental performance of a product based on LCA. EPDs also provide quantifiable environmental data, based on pre-determined parameters (ISO 2006c). A recent literature review showed that the use and disclosure of environmental information through EPDs is gaining acceptance (Fazil et al. 2016). The intended audience for those EPDs includes consumers and professional buyers involved in the decision-making process (Fazil et al. 2016). However, it should be noted that while LCA may be used to quantify the environmental impact in any stage of the lifecycle of the product (e.g., cradle to grave), EPDs only cover a cradle to gate analysis.

OBJECTIVE AND SCOPE

The objective of this study was to integrate environmental and economic design criteria as part of the mechanistic empirical Pavement ME design framework. The developed framework was used to evaluate two case studies in Texas. The first case study was SH-121 consisting of a Continuously-Reinforced Concrete Pavement (CRCP) design. It compared conventional vs. internally cured concrete. The second case study was on Interstate I-45 consisting of a Jointed-Plain Concrete Pavement (JPCP) design. It also compared conventional vs. internally cured concrete (ICC). The environmental impact considered the following phases: raw materials extraction, transportation to the manufacturing location, and manufacturing, which was obtained from EPDs. The transportation impact from the manufacturing to construction phase was evaluated using LCA. The final design selection was evaluated using a weighted average criterion considering both economic and environmental criteria.

BACKGROUND

Tools for Evaluating Environmental Impact

Life-Cycle Assessment (LCA)

LCA presents a method that can be used to evaluate the net environmental impacts of products and services across a set of environmental matrix inclusive of all interactions with human and natural systems (Fazil et al. 2016). It consists of four main steps (Strazza et al. 2016):

a. Goal and scope definition: Defines the goal for conducting a life-cycle assessment for a given product.
b. Inventory analysis: Documents the resulting emissions, materials, and energy used in the atmosphere, land, and water.
c. Impact analysis: The effects of resource use and emissions are grouped and quantified into a number of impact categories, which can be weighted for importance.
d. Interpretation: The results are interpreted for evaluation towards reducing the environmental impacts of a product.

Many studies have used LCA to quantify the environmental impacts of pavement (Santero et al. 2010). However, these studies used different functional units, different data sources, and evaluated different environmental impact categories. This renders those LCA studies incomparable. Therefore, a more consistent and comparable approach is needed to evaluate the environmental impacts.

Environmental Product Declarations

An emerging method for quantifying the environmental impacts of a product employs Environmental Product Declarations. EPDs are defined as independently verified and registered documents that communicate transparent and comparable information regarding the life-cycle assessment of a product (What Is Mechanistic-Empirical Design 2012). EPDs are the summary of the data collected in LCA. These are verified by a third party to guarantee transparency based on ISO

14025. However, the phases in EPDs only cover cradle to gate analysis: raw materials acquisition, manufacturing, and transportation from the manufacturing place to the use phase. Hence, the use phase is not included in the analysis. The environmental impacts covered include (a) Global Warming Potential (GWP), (b) Ozone Depletion Potential (ODP), (c) Acidification Potential (AP), (d) Eutrophication Potential (EP), and (e) Photochemical Ozone Creation Potential (POCP).

Product Category Rule

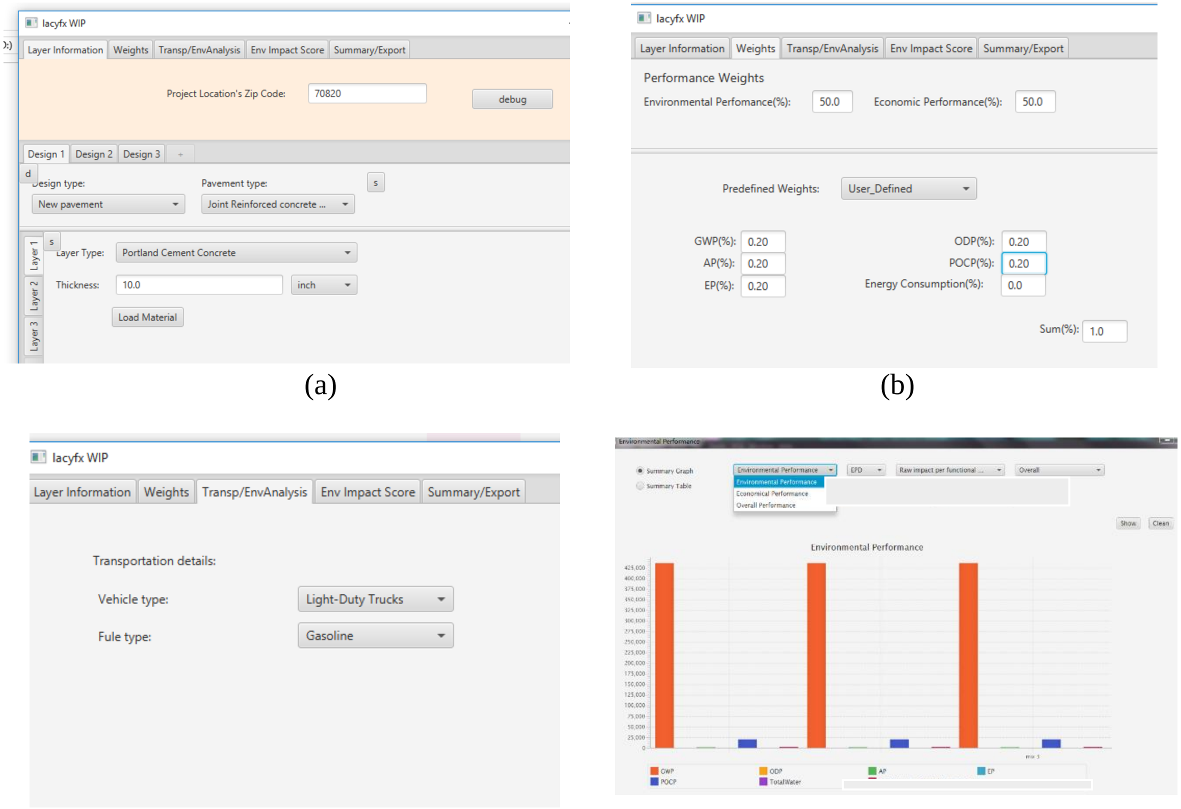
Product Category Rules (PCRs) are defined in ISO 14025 as a set of specific rules, requirements, and guidelines for developing EPDs for one or more products that can fulfill equivalent functions. PCRs determine what and how information should be gathered for an environmental product declaration. This is important for facilitating the comparison of EPDs. The product category rule considered in this study focused on concrete products and thereby enables the development of EPDs related to this product from cradle to gate. The considered PCR outlines both mandatory and optional impact categories that may be included. The PCR was developed for use in North America and in Canada, as well as other countries according to the following standards: ASTM C94, ASTM C90, and CSA A231.1/A23.2, UNSPSC code 30111500. In the considered product category rule, the transportation phase to construction site is optional. However, the following factors in the transportation phase were considered: (a) fuel and truck type, (b) average miles per gallon (or liters per kilometers) of gasoline or diesel, (c) total annual distance traveled for each type of truck, and (d) the impact from the truck backhaul (return trip of the truck to the plant) (ISO 2006).

RESEARCH METHODOLOGY

Environmental impacts, associated with a specific product, were queried from EPDs, and were then integrated into the overall design framework of Pavement ME. The developed algorithms analyze the results from the output file as follows: (a) The results are analyzed to assess whether the design passed or failed technical criteria; (b) If the design is technically acceptable, the user selects the number of material alternatives to be evaluated. Selection can be based on strength requirements such as the required compressive strength for concrete materials and transportation radius. Once the required compressive strength value is selected, the available products are displayed along with their respective environmental impacts. Based on the user’s selection, the tool provides the products that match the required compressive strength along with the associated environmental impacts (GWP, AP, EP, ODP, and POCP). After selecting feasible products, the transportation distance from the manufacturer location to the project location is calculated and the environmental impacts are evaluated. The environmental impacts from EPD are then added to the environmental impacts of transportation to get the total environmental impacts. Values are then normalized and summed to get one final score for the environmental impact.

The design alternatives are then evaluated for cost analysis. The cost analysis uses the net present value method for evaluating different design alternatives. This includes factors such as initial cost, maintenance and rehabilitation costs, and salvage value. Finally, depending on stakeholder decision criteria, each component is assigned a weight for environmental and cost performances. For example, weights can follow the weights recommended by Building for Environmental and Economic Sustainability (BEES), which were assigned by the EPA Science Advisory Board. The final design selection is based on a weighted average value between these two factors, considering that these products have already satisfied the technical design criteria. The default weight value is 0.5 for both the economic and environmental impacts.

This process was incorporated on a windows-based design tool for ease of use. As illustrated in Figure 1, the software allows the analysis of multiple designs and layers. The design layer thickness is inputed as well as the project zip code. As shown in Figure 1(b), weights for environmental impacts are inputed as well as the weights for economic and environmental criteria. As shown in Figure 1(c), the vehicle type as well as the type of fuel used is selected to evaluate the environmental impacts of transportation. Furthermore, the material cost is inputed and is discounted to the net present value. A final report is displayed showing the results of the environmental and economic impacts, Figure 1(d).



Project Location's Zip Code: 70820

Design type: New pavement

Pavement type: Joint Reinforced concrete ...

Layer Type: Portland Cement Concrete

Thickness: 10.0 inch

Environmental Perfomance(%): 50.0

Economic Performance(%): 50.0

Predefined Weights: User_Defined

GWP(%): 0.20

AP(%): 0.20

EP(%): 0.20

ODP(%): 0.20

POCP(%): 0.20

Energy Consumption(%): 0.0

Sum(%): 1.0

Vehicle type: Light-Duty Trucks

Fule type: Gasoline

(a) (b)

(c) (d)

Figure 1 Layout of the Developed Computer Tool

Calculating the Environmental Impacts of Transportation

The environmental impact of the transportation phase is an important factor, which may affect the results of the analysis. The proposed framework adopted the following equation to estimate the emissions associated with the transportation phase (Heather and Lester 2016):

$$E_{\text{of substance}} = 2\times\,(\text{VKT} \times \text{FC} \times \text{substance content} \times \text{Factor}) \qquad (1)$$

where $E_{\text{of substance}}$ is the emissions of the required substance in grams; VKT is the vehicle kilometers traveled (input by the user); and FC is the fuel consumption (L/100 km) (Heather and Lester 2016). FC can be assumed 12.8 for light trucks (Heather and Lester 2016). It is noted that the emission calculated by Equation (1) is multiplied by a factor of 2 to account for the backhaul distance, as per the PCR requirements. Substance content represents the grams of the material per liter of fuel recommended by EPA and other agencies (Wilde et al. 1999) as follows: For carbon emissions (global warming potential): 2,421 grams-carbon / gallon for gasoline (Carbon Dioxide Emissions Resulting from Gasoline and Diesel 2005); and for sulfur emissions (acidification potential): 30 ppm for gasoline. The Factor in Equation (1) accounts for converting the molecular mass of carbon to carbon dioxide to account for global warming potential and to convert the molecular mass of sulfur to sulfur dioxide for acidification potential. The conversion factors used were (44/12) for global warming potential and (64/32) for acidification potential.

Evaluating Life Cycle Cost Analysis

Life-cycle cost of the different design alternatives are evaluated based on the net present worth method (life cycle cost analysis in pavement designs 1998). This method considers the initial cost, rehabilitation cost, and salvage value.

DEMONSTRATION OF THE DEVELOPED TOOL IN CASE STUDIES

Case Study #1:

Project Description

The selected project was located in SH 121 west of I-75 and east of the Dallas North Tollway. (Rao and Darter 2003) falling in The Dallas-Fort Worth weather station. The pavement is expected to serve moderate traffic volume with an average annual daily traffic (AADT) of 23,400 with a linear traffic growth of 4%.

Design Inputs

The design analysis period was assumed to be 30 years with a CRCP, Initial International Roughness Index (IRI) limit of 63 and a terminal IRI of 160 with a reliability level of 90%. The terminal thresholds for transverse cracking, longitudinal cracking, and corner cracking represented 10% of the slabs cracked (Rao and Darter 2003).

Initial and Alternative Designs

The original vs. the alternative trial designs are illustrated in Figure 2. The alternative design has thinner concrete thickness, consisting of internally cured concrete (ICC), leading to lower environmental impacts and lower cost.

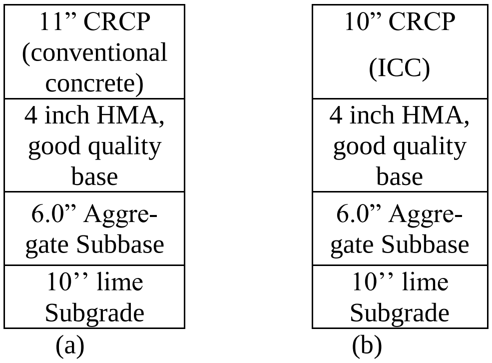


Figure 2: (a) initial design vs. (b) alternative design

Concrete Products Description

The concrete mix designs that were used in this analysis were 5,500 psi for ICC and 6,000 psi for conventional concrete. The 5,200 psi was extrapolated to 5,500 psi, to match the value in EPD’s, and the 6,000 psi was used as listed.

Technical Analysis

Designs were re-analyzed to optimize the design thicknesses. This was performed by decreasing the thickness of the CRCP design by increments of ½ inch. The optimization process led to thicknesses of 10 in. for ICC at a 97% reliability. The performances of both designs were identical. In fact, when the performance of those designs was plotted on the same chart, the predictions coincided for a period of 30 years (Rao and Darter 2003).

Environmental Performance

The environmental impacts for the mix design alternatives are presented in Figure 3, based on the EPDs and the developed tool; the environmental impacts for the five categories (i.e., GWP, ODP, AP, EP, POCP) are presented. As shown in Figure 3, the ICC alternative was more environmentally-friendly in terms of GWP and POCP, while all the other impacts were negligible.

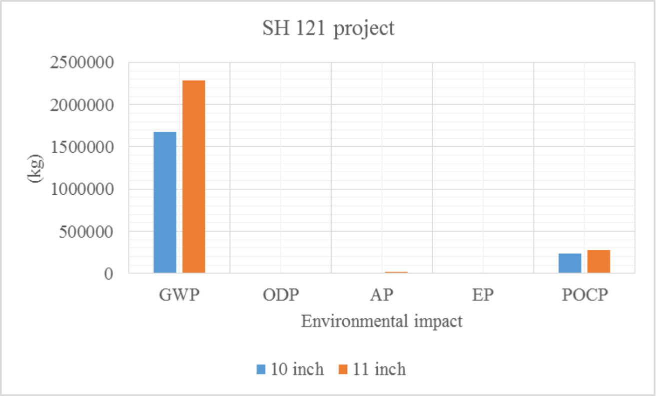


Figure 3: Environmental impact for conventional vs. ICC alternative

Environmental Impacts of Transportation

The environmental impacts of the transportation phase are illustrated in Table 1, indicating that the ICC alternative contributed less emissions compared to the conventional one, since it was transported from a shorter distance.

Table 1 Environmental Impact of transportation

Project	Thickness (inch)	Distance (km)	Global Warming Potential (kg)	Acidification Potential (kg)
SH121	10	5	3.001	0.0768
	11	6	3.60	0.09216

Economic Impact Analysis

Values were calculated per directional mile length of a roadway consisting of two lanes and a shouldee. The analysis period was selected to incorporate at least one rehabilitation activity (LCCA 1998). Therefore, the analysis period was selected at 60 years. Materials unit cost was obtained from Dallas-Fort Worth area. Results are presented in Table 2 for the conventional vs. the optimized designs. As shown in Table 2, the initial cost was lower for the ICC.

Table 2 LCCA Comparison for SH 121 Project. Conventional concrete and ICC alternative.

Alternative (1)- Conventional Concrete		**Alternative 2 - ICC**	
Description (year)	Total NPV ($)	Description (year)	Total NPV ($)
Initial cost	3,727,390	Initial cost	3,281,530
Full-depth repair (15)	4108	Full-depth repair (15)	4,108
Diamond Grind Existing Surface (25)	59,626	Diamond Grind Existing Surface (25)	59,626
Full-depth pavement repairs (25)	382	Full-depth pavement repairs (25)	459
Full-depth pavement repair (42)	1,156	Full-depth pavement repairs (40)	245
Full-depth pavement repairs (50)	18,066	Full-depth pavement repairs (60)	4,685
Place asphalt tack coat (9 sy/gal)	961	Place asphalt tack coat (9 sy/gal) (60)	715
2.0-in HMAC binder	36,690	2.0-in HMAC binder (60)	27,301
2.0-in HMAC surface	36,690	2.0-in HMAC surface (60)	27,301
Salvage value	-57,754	Salvage value	-75,002
Total (NPV)	3,827,315	Total (NPV)	3,330,968

*Note the analysis is performed for the top layers only, since all the other layers are similar. Design costs, overheads, etc.. are assumed zero

Final Design Selection

As illustrated in Table 3, the final design criteria were selected based on a weighted average between the economic and the environmental impacts, resulting in a total score of 0.46 for the ICC design and 0.54 for the conventional design. These results indicate lower environmental impacts and lower costs for the ICC design.

Table 3 Summary of Environmental and Economic analysis

Project	Design #	Thickness (in.)	Env. impact	weight	Sum (Env.)	Env. Impact (0.5)	Ec. impact	Ec. impact (0.5)	Total Weight
SH121	1	10	GWP	0.2	0.44	0.22	0.48	0.24	0.46
			ODP	0.2					
			AP	0.2					
			EP	0.2					
			POCP	0.2					
	2	11	GWP	0.2	0.56	0.28	0.52	0.26	0.54
			ODP	0.2					
			AP	0.2					
			EP	0.2					
			POCP	0.2					

Env. = environmental; Ec. = Economic

Case Study #2:

Project Description

The selected project is located on I-45 east of the UP Intermodal Terminal falling in the Dallas-Fort Worth weather station. It is a connector that connects Dallas and Houston. This highway has a two-way Annual Average Daily Truck Traffic (AADTT) of 7,200 trucks.

Design Inputs

The design analysis period was assumed to be 30 years with a Joint-Plain Concrete Pavement (JPCP), initial International Roughness Index (IRI) limit of 63 and a terminal IRI of 160 with a reliability level of 90%. The terminal thresholds for transverse cracking, longitudinal cracking, and corner cracking represented 10% of the slabs cracked (Rao and Darter 2003).

Alternative Designs

The original and alternative designs are illustrated in Figure 4. Both designs are the same, except that the original design had a concrete thickness of 11.5 in. and the alternative design consist of internally cured concrete of 10.5 in.

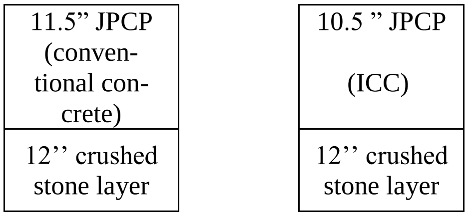


Figure 4 Design and design alternative- I-45 project

Concrete Product Description

The concrete mix designs that were used in this analysis for ICC were 5,120 psi, extrapolated to 5500 psi to match the product database, and 6,000 psi for conventional concrete.

Technical Analysis

The performances of both designs were identical over the entire analysis period, when plotted on the same chart, at a reliability level of 97% (Rao and Darter 2003).

Environmental performance

As illustrated in Figure 5, both alternatives had similar environmental impact, except for GWP and POCP, where the conventional concrete alternative had a higher impact due to greater thickness.

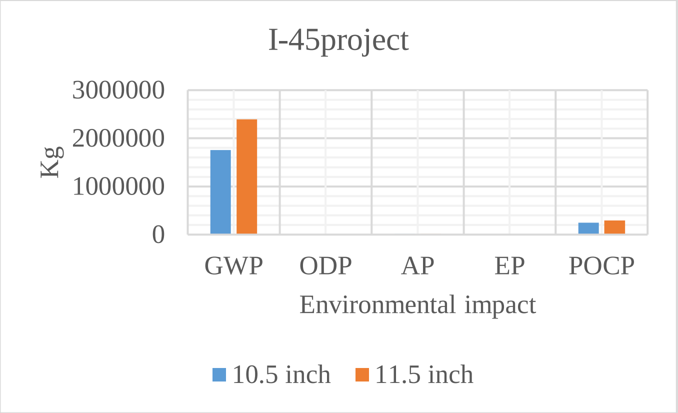


Figure 5 Environmental impact for different alternatives - I-45 project

Environmental Impact of Transportation

The environmental impact of transportation is illustrated in Table 4. The conventional concrete resulted in more emissions, since it was transported for longer distances.

Table 4 Transportation Environmental Impact Data for Different Alternatives

Project	Thickness (in.)	Distance (km)	Global Warming Potential (kg)	Acidification Potential (kg)
I-45	10.5	10	6.00	0.1536
	11.5	12	7.24	0.18432

Economic Impact Analysis

The cost-analysis was performed for a 60-year analysis period. The use of ICC resulted in a thickness reduction leading to cost savings. However, in the long-term, the maintenance and rehabilitation costs were higher by 6.7%. However, the overall net present value decreased by 1.2%. Results are illustrated in Table 5. The maintenance and rehabilitation cost varied. The Control CRCP will have maintenance in years 15, 25, 42 and a rehabilitation at year 50. The ICC will have maintenance at years 15, 25, 40 and a rehabilitation at year 60, offsetting the salvage value.

Final Design Selection

Detailed environmental and economic results are illustrated in Table 6. The final weighted average criteria was 0.47 for the ICC design vs. 0.53 for the initial design indicating lower emissions and costs for the ICC design.

Table 5 LCCA comparison for I-45 optimized design alternatives with conventional concrete and ICC. The analysis period is 60 years.

Alternative (1)- Conventional concrete		**Alternative 2 - ICC**	
Description (year)	Total NPV ($)	Description (year)	Total NVP ($)
Initial cost	3,896,816	Initial cost	3,445,606
Full-depth pavement repairs (15)	2,862	Full-depth pavement repairs (15)	2,862
Full-depth pavement repairs (25)	4,259	Full-depth pavement repairs (25)	4,259
Diamond Grind Existing JPCP (40)	38,271	Diamond Grind Existing JPCP (40)	38,271
Full-depth pavement repairs (40)	64,241	Full-depth pavement repairs (40)	72,442
Full-depth pavement repairs (50)	5,085	Full-depth pavement repairs (50)	5,085
Full-depth pavement repairs (60)	2,838	Full-depth pavement repairs (60)	5,676
Place asphalt tack coat (60)	715	Place asphalt tack coat (60)	715
2.0-in HMAC binder (60)	27,301	2.0-in HMAC binder (60)	27,301
2.0-in HMAC surface (60)	27,301	2.0-in HMAC surface (60)	27,301
Total (NPV)	4,069,689		3,629,518

*Note the analysis is performed for the top layers only, since all the other layers are similar. Design cost is assumed zero

Table 6 Summary of Environmental and Economic analyses

Project	Design #	Thickness (inch)	Env. impact	weight	Sum (Env.)	Env. Im-pact (0.5)	Ec. im-pact	Ec. impact (0.5)	Total Weight
I-45	1	10.5	GWP	0.2	0.45	0.23	0.49	0.24	0.47
			ODP	0.2					
			AP	0.2					
			EP	0.2					
			POCP	0.2					
	2	11.5	GWP	0.2	0.55	0.27	0.51	0.26	0.53
			ODP	0.2					
			AP	0.2					
			EP	0.2					
			POCP	0.2					

Env. = environmental; Ec. = Economic

CONCLUSIONS AND RECOMMENDATION

This paper developed a tool incorporating the environmental and economical impacts into the Mechanistic- Emperical Pavement Design (MEPDG). The environmental impact was included by incorporating Environmental Product Declarations (EPDs) to evaluate the environmental impacts from cradle to gate. This method evaluates the environmental impact in a comparable way, thereby solving the limitations of LCA. The use of the developed tool enabled the evaluation of alternative materials in terms of performance, environmental impacts, and economical impacts. Alternative materials such as internally cured concrete, based on this analysis, proved to have a better performance when compared to conventional concrete. This is due to its lower thickness and saving in intial cost as well as its better performance saving maintenance and rehabiltiation costs on the long term.

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