Environmental, Economic, and Social Implications of Highway Concrete Rehabilitation Alternatives

Kunhee Choi, A.M.ASCE[1]; Hyun Woo Lee, M.ASCE[2]; Zhuting Mao[3]; Sarel Lavy, A.M.ASCE[4]; and Boong Yeol Ryoo[5]

Abstract: Currently, there is no comprehensive benchmark of life-cycle assessment for the rigid pavement alternatives for highway rehabilitation. To fill this gap, the major objective of this study is to investigate the environmental, economic, and social impacts of the three most widely adopted rigid pavement choices through a life-cycle assessment approach with custom-built economic input-output life-cycle assessment (EIO-LCA) models. Quantity takeoffs were performed for each alternative assuming a 1-lane-km highway rehabilitation. Subsequently, the construction costs of each alternative were computed in order to determine the present values for a life span of 50 years, while at the same time accounting for a different life expectancy for each pavement rehabilitation strategy. The present values were then incorporated into a corresponding EIO-LCA model. The results clearly indicate that continuously reinforced concrete pavement (CRCP) is the most sustainable choice and much preferable to the other alternatives for minimizing negative environmental, economic and social impacts from the life-cycle perspective. This finding champions a wider adoption of CRCP for future sustainable transportation infrastructure development projects, as CRCP's relatively high initial construction cost can be recouped by long-term sustained benefits. The results and findings of this study can serve as a solid foundation for industry practitioners and decision-makers to make better-informed project decisions when choosing the most sustainable pavement alternatives from a life-cycle perspective. **DOI: 10.1061/(ASCE)CO.1943-7862.0001063.** *© 2015 American Society of Civil Engineers.*

Author keywords: Life-cycle assessment; Sustainable development; Pavement rehabilitation; Environmental assessment; Economic factors; Land use.

Introduction

The U.S. has nearly 6.5 million km (4 million mi) of highways (FHWA 2006b), and the U.S. roadway system transports over 9 trillion ton-km of passengers and freight every year (BTS 2010). However, a significant number of existing highways already exceed their original terminal service life since most existing concrete pavements were built during a construction boom between the 1950s and 1980s with 20 to 25 years' design life expectancy (Choi and Kwak 2012). Nationwide, trillions of dollars would be required to renew and improve aging, deteriorated infrastructure, including highways. For instance, the California Department of Transportation (Caltrans) estimates that 60% of the state's highway system needs to be rehabilitated or reconstructed at a project cost of $70 billion over the next 10 years (Choi et al. 2012). State transportation agencies (STAs) are therefore under increased pressure to rehabilitate aging concrete pavements to maintain their intended functionality (Choi et al. 2012). At the same time, because highway pavement construction activities represent significant environmental, economic and social impacts, the Federal Highway Administration (FHWA) encourages STAs to adopt low-maintenance and long-life concrete pavements lasting 40-plus years (AISI 2012). Therefore, selecting a sustainable concrete pavement alternative has become much more crucial for decision makers in STAs; consequently, a life-cycle assessment (LCA) is considered an effective means to help them make a better-informed selection among alternatives by accounting for the environmental and economic impacts of the choices (Eccleston 2008).

[1]Assistant Professor, Dept. of Construction Science, Texas A&M Univ., 3137 TAMU, Francis Hall 305, College Station, TX 77843-3137 (corresponding author). E-mail: kchoi@tamu.edu

[2]Assistant Professor, Dept. of Construction Management, Univ. of Washington, 120 Architecture Hall, Seattle, WA 98195. E-mail: hyunwlee@uw.edu

[3]Project Engineer, Balfour Beatty Construction, 10620 Treena St., San Diego, CA 92131. E-mail: zhutingmao@gmail.com

[4]Associate Professor, Dept. of Construction Science, Texas A&M Univ., 3137 TAMU, Francis Hall 208C, College Station, TX 77843-3137. E-mail: slavy@tamu.edu

[5]Associate Professor, Dept. of Construction Science, Texas A&M Univ., 3137 TAMU, Francis Hall 306, College Station, TX 77843-3137. E-mail: bryoo@tamu.edu

Note. This manuscript was submitted on December 19, 2014; approved on July 22, 2015; published online on September 30, 2015. Discussion period open until February 29, 2016; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Construction Engineering and Management***, © ASCE, ISSN 0733-9364.

Background

Life-Cycle Assessment (LCA)

A life cycle includes a product's raw-material extraction, processing and manufacturing, transportation and distribution, operation and use, and disposal (Weiland and Muench 2010). Fig. 1 illustrates the typical life cycle of pavement that begins with material extraction and production through construction and facility operation, maintenance and rehabilitation, and the end of life with either disposal or recycling. As these activities involve using equipment and transportation, an assessment must also incorporate resultant traffic delays and pollution.

An LCA typically has the following four steps (Guinee 2002):

1. Goal and scope definition: Determine the reference of inputs, standard of units, system boundaries, assumptions, and limitations.

J. Constr. Eng. Manage., 2016, 142(2): 04015079

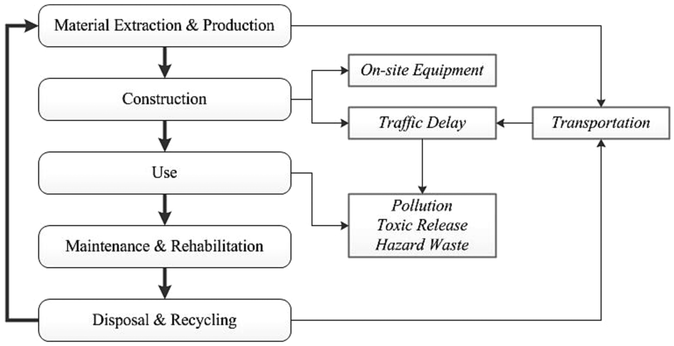


Fig. 1. Typical pavement life cycle

2. Life-cycle inventory analysis: Determine input flow (raw materials, energy, and activities in the direct and indirect supply chain) and output flow (releases to air, land, and water).
3. Life-cycle impact assessment: Evaluate potential impacts based on life-cycle inventory flows.
4. Interpretation: Draw a conclusion and recommendation based on the impact analysis.

However, the conventional process-based LCA has several crucial limitations as described in Table 1. First, due to time and monetary constraints, it may be challenging for researchers to properly apply the four-stage methodology described above. In addition, setting correct boundaries may be challenging (Hendrickson et al. 1998) due to direct and indirect interactions among heterogeneous sectors during the life cycle, which can lead to biased input parameters in the LCA. For instance, vehicles are made from steel, while steel needs vehicles for distribution. The production of cement requires steel for the associated manufacturing plants and equipment, and steel mills typically use cement and concrete for their initial construction. A traditional LCA usually ignores such circularity effects. The only possible way to realistically perform these tasks is to set inputs focused on only the most important processes or resources, which might lead to biased decision making.

Economic Input-Output Life-Cycle Assessment

In the 1930s, Wassily Leontief developed an economic input-output model and was awarded the Nobel Prize in 1973 for this achievement (Ochoa et al. 2002). Based on Leontief's general equilibrium model of economy, an economic input-output life-cycle assessment (EIO-LCA) represents a general interdependency model that quantifies the interrelationships among sectors of an economic system while identifying the direct and indirect economic inputs. It encompasses environmental impacts and energy analysis coupled with supply chain transactions by dividing production into sectors (Hendrickson et al. 1998). An EIO-LCA implies that total production from each sector can be calculated by knowing the final demands of each sector and the normalized input-output matrix of the sectors (Hendrickson et al. 2005).

In the mid-1990s, the Green Design Institute at Carnegie Mellon University designed EIO-LCA online software to estimate the resources and energy required for products as well as emissions resulting from products (CMU 2011). The output from this software provides the relative impacts of various products, services, and material use. The EIO-LCA models consist of national economic input-output models, including publicly available resource use and emissions data. By choosing only one sector category highlighting the monetary value of the products and effects to display, the user can obtain the analysis results immediately. These EIO-LCA models may be applied to different national economies, including those of the United States, Canada, Germany, Spain, and China (CMU 2011).

Table 1 is a comparison summary that distinguishes EIO-LCA from conventional process-based LCA. The conventional LCA uses an inventory analysis to obtain results for a specific product. During the data collection, units for each element can likely be different. LCA is also known to be susceptible to interactions and circularity issues. EIO-LCA captures the circularity effect and interactions among sectors of a chosen economic system because it provides a comprehensive analysis at the level of the U.S. economy (Hendrickson et al. 2005).

Previous Studies on Pavement Alternatives

Several studies to date have compared pavement alternatives using the EIO-LCA, including Horvath's early studies (Horvath 1997; Horvath and Hendrickson 1998a, b) that compared the environmental impact of asphalt pavements to that of reinforced concrete pavements. One study (Horvath 1997) concluded that asphalt is more environmentally friendly in manufacturing, while concrete has fewer environmental impacts during use. In a subsequent research study using a LCA inventory analysis, Horvath and Hendrickson (1998a) found that asphalt pavements are more

Table 1. Pros and Cons of EIO-LCA

Comparison	Conventional LCA	EIO-LCA
Methods	• Itemizes the input and output in each step of producing a product	• Quantifies interrelationships among sectors of an economic system
	• Provides an assessment of *specific processes* depending on data availability	• Provides an assessment of the *entire economy*
Pros	• The boundary includes all processes	• The boundary is the entire economy; no need to set the boundary by recognizing interrelationships among sectors
	• Detailed process-based results	• Resolves circularity effect issues
	• Allows comparisons between specific products	• Captures direct and indirect interactions among sectors in the entire economy
	• Can be advantageously used for an LCA of product use and end-of-life phases	• Provides comprehensive economy and sector-wide results
		• Faster and less costly
Cons	• Setting the analysis boundary is challenging	• Sectors may be too heterogeneous to correctly reflect a particular process
	• Cannot capture circularity effects	• Not suitable for process evaluations
	• Cannot be used to capture all the environmental consequences	• Must convert physical products into appropriate monetary values
	• Costly and time consuming	

Table 2. Summary of Pavement LCA Literature

Authors	LCA type	Pavement type	Summary of notable findings
Horvath (1997)	EIO-LCA	Asphalt versus reinforced concrete	Asphalt is more environmentally friendly in manufacturing, while concrete is more environmentally friendly during use
Horvath and Hendrickson (1998b)	EIO-LCA	Steel versus steel-reinforced concrete bridges	Steel-reinforced concrete bridges have more favorable environmental impacts than steel bridges, but steel might be a better option when considering recycling and reusing
Horvath and Hendrickson (1998a)	EIO-LCA	Asphalt versus reinforced concrete	Asphalt pavement requires higher energy inputs but lower ore and fertilizer inputs. It emits lower toxins and has a higher rate of recycling than reinforced concrete
Park et al. (2003)	Hybrid of conventional LCA and EIO-LCA	Asphalt	57% of total energy is consumed in the manufacturing stage of construction materials, followed by the maintenance and repair stage at 40%, and construction at 2%
Treloar et al. (2004)	Hybrid LCIA	8 types of asphalt and reinforced concrete	Full-depth asphalt indicates the largest amount of embodied energy
Zapata and Gambatese (2005)	Conventional LCA	Asphalt versus reinforced concrete	Asphalt uses less energy during the extraction, manufacturing, and transportation phases and can be recycled more than reinforced concrete
Cass and Mukherjee (2011)	Hybrid of conventional LCA and EIO-LCA	Concrete pavement rehabilitation	The production related to the construction phase accounts for over 90% the total CO_2 emissions. The impacts from the equipment use and transportation represent less than 10% of the total emissions through the construction phase
Kim et al. (2012)	Conventional LCA	Asphalt	The material extraction and transformation of asphalt account for 12% of the total energy consumption, while the manufacturing process accounts for 88.4%

sustainable because they have lower ore and fertilizer input requirements, lower toxic emissions, and a higher rate of recycling. Another study conducted by Horvath and Hendrickson (1998b) applied the LCA inventory analysis to steel and steel-reinforced concrete bridges. The study found that steel-reinforced concrete bridges are more environmentally preferable than steel bridges, but steel might be a better option when considering recycling and reuse at the end of life.

Several LCA studies used a conventional LCA approach (Zapata and Gambatese 2005; Kim et al. 2012). Zapata and Gambatese (2005) conducted a conventional process-based LCA study for comparing asphalt to Portland cement concrete (PCC). It showed that asphalt uses less energy during the extraction, manufacturing, and transportation phases and can be recycled better than concrete and steel. Table 2 is a synthesized summary of key literature related to the LCA. It is noteworthy that the previous studies' findings are contradictory on the choice of alternatives between asphalt and concrete. However, asphalt would become a better option when taking recycling into account. A thorough survey of existing literature indicates that although much research has occurred, very few studies have specifically investigated the environmental, economic, and social impacts of rigid pavement alternatives from the life-cycle perspective (Cass and Mukherjee 2011).

Research Objectives and Methods

Because the U.S. transportation infrastructure systems that were built between the 1950s and 1980s now exceed their original life expectancy, STAs are under increased pressure to rebuild these badly deteriorated transportation networks in a sustainably viable way. An LCA can effectively help agencies make a better-informed selection toward more sustainable transportation infrastructure development, as the LCA concurrently captures the alternatives' environmental, economic and social impacts throughout their life cycle (Eccleston 2008). However, a conventional process-based LCA for highway pavement alternatives poses a challenge to STAs because they struggle with increased overhead costs for data collection and analysis, all while being subject to a biased result due to the LCA's inherent limitations (Hendrickson et al. 1998; Treloar et al. 2004). Besides, most previous studies focused heavily on the comparison of asphalt pavements to concrete pavements (Horvath and Hendrickson 1998a; Berthiaume and Bouchard 1999; Roudebush 1999; Zapata and Gambatese 2005; Santero et al. 2011), and no systematic LCA research has been conducted with the specific goal of investigating environmental, economic, and social implications of highway rigid pavement rehabilitation alternatives.

In response to the challenge STAs face, while at the same time addressing the shortcomings of the conventional LCA, this study applies custom-built EIO-LCA models to the evaluation of three most widely used rigid pavement alternatives. The EIO-LCA models were devised to compensate for the weaknesses of the conventional process-based LCA model as noted in Table 1. The study analyzes the environmental, economic, and social implications of the pavement choices through a product's life cycle from raw material extraction and production through construction and operation/maintenance to the end of serviceable life. Three highway rigid pavement alternatives—jointed reinforced concrete pavement (JRCP), jointed plain concrete pavement (JPCP), and continuously reinforced concrete pavement (CRCP)—were compared and analyzed. This study also aims to develop a systematic procedure to conduct an EIO-LCA of highway rigid pavement alternatives to support STA decision-makers who consider multiple alternatives for pavement rehabilitation. Understanding the environmental, economic and social impacts of each alternative can assist STAs with selecting the most sustainable solutions, thus accounting for the implication their choices will have on future generations.

Inflation over time was taken into consideration by applying a 4% discount rate as suggested by Caltrans (2010). The main inputs to the EIO-LCA model for this study include ready-mix concrete and iron and steel mills manufacturing. This study is confined to the typical cross-section design of full-depth pavement rehabilitation because changes in pavement design have a significant impact on the pavement's terminal service life. To adjust the unit cost that mirrors the different service lives of the three alternatives, this study

J. Constr. Eng. Manage., 2016, 142(2): 04015079

captures the typically anticipated service durations of each alternative over a 50-year life span as follows:

- JRCP: 15 years (MoDOT 2004; Caltrans 2010);
- JPCP: 20 years (MoDOT 2004; Caltrans 2010); and
- CRCP: 30 years (MoDOT 2004; Caltrans 2010).

The life span is assumed to be 50 years based on recent STAs' movement toward the development of long-life concrete pavements that support a longer service life of 40 or more years (AISI 2012; FHWA 2007).

The following shows the detailed process of the EIO-LCA analysis as implemented in the study:

1. Determine the pavement cross section design of each alternative based on the guidelines of the AASHTO (1993);
2. Perform a quantity takeoff of each rigid pavement alternative under the assumption of a 1-lane-km (0.6-mi) segment of interstate highway rehabilitation;
3. Estimate the construction cost of each alternative using RS Means construction unit cost data;
4. Determine the present value of each alternative for a life span of 50 years given the different life expectancies of each alternative;
5. Develop three EIO-LCA models (one for each alternative) using the U.S. national purchaser price model from 2002;
6. Input the present values of each pavement alternative into a corresponding model;
7. Perform an environmental, economic, and social impact analysis for each alternative; and
8. Interpret the outputs of the models in terms of environmental, economic, and social impacts.

The *environmental* impacts of the selected pavement alternatives were analyzed in five categories: global warming potential, energy use, hazardous waste, toxic releases, and water withdrawals. The *economic* impact was captured by the economic transaction cost (i.e., year-of-expenditure dollars). The *social* impacts were examined in terms of transportation movement and land use. Details are further explained later in the interpretation section. The results and applicability of this study are limited to rigid pavements.

Rigid Pavement Alternatives for Rehabilitation

Most rigid pavements are made of PCC, and JRCP, JPCP, and CRCP are the three common types of rigid payments. This section provides a brief introduction to each pavement rehabilitation alternative.

JRCP requires both contraction joints and reinforcing steel (AASHTO 1993). A maximum of 15 m (50 ft) is allowed between joints (WSDOT 2011). Reinforcing bars or a thick wire mesh are required for holding cracks tightly together. Load is transferred by dowel bars placed transversely and reinforcing steel or wire mesh across cracks. Transverse joint distance ranges from 7.6 m (25 ft) to 15 m (50 ft) (WSDOT 2011). Fig. 2(a) illustrates a typical JRCP design. About nine U.S. states have JRCP design procedures (WSDOT 2011). JRCP can support an average life span of 15 years (MoDOT 2004). Due to its performance issues such as panel cracking and faulting, JRCP is not typically used in STAs.

JPCP is the most commonly used pavement alternative among the three types. JPCP has been used in 43 states across the nation with a well-established design procedure (WSDOT 2011). JPCP typically offers a design life expectancy of 20 to 25 years depending on design requirements and traffic volume (MoDOT 2004). JPCP requires both transverse and longitudinal contraction joints for crack control as shown in Fig. 2(b). The distance between two joints, mainly depending on slab thickness, usually ranges from 3.7 m (12 ft) to 6.1 m (20 ft) without reinforcing steel (WSDOT 2011). Dowel bars and tie bars transfer load transversely and longitudinally, respectively. If there is a crack in the middle of a slab, only aggregate interlock transfers load across the joint.

CRCP is known to support long-term performance and reduced maintenance, especially for high-volume pavements, because it requires no transverse joints (Caltrans 2011). CRCP is commonly used for the interstate systems of Illinois, Texas, and North Dakota (WSDOT 2011), with a life expectancy of 30 years and even up to 50 years (AISI 2012). As shown in Fig. 2(c), CRCP requires only continuous reinforcing steel, so only longitudinal joints are installed (CRSI 2012). Around 0.7% of the cross-sectional pavement is steel (AASHTO 1993); less steel may be applied in warmer climates. Cracks within 0.5 mm (0.02 in.) are allowed, and the continuous reinforcement can tightly hold the cracks together (AASHTO 1993). Loads are transferred from slab to slab by aggregate interlock, so no contraction joint is needed. CRCP is a prestressed concrete pavement, which can resist greater loads using smaller cross-section areas and longer spans. CRCP can be applied in both wet and dry conditions due to less water penetration.

Data Collection

This study investigated general but reliable guidebooks for designing pavement from publicly available resources, including the American Association of State Highway and Transportation Officials (AASHTO). The investigation is based on a life cycle of 50 years in terms of the analysis boundary and the RS Means unit cost data for cost estimation in terms of inputs to an EIO-LCA analysis.

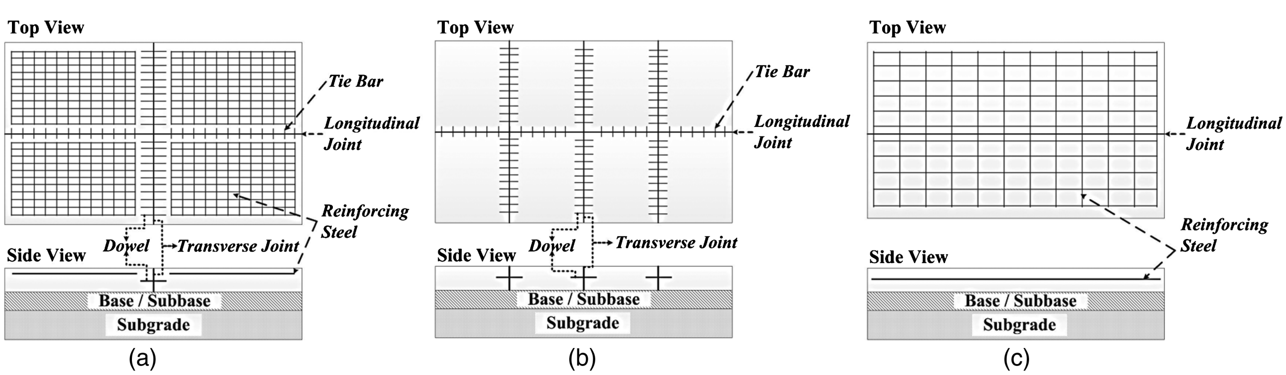


Fig. 2. Typical cross-section designs of three rigid pavement rehabilitation alternatives (adapted from WSDOT 2011): (a) JRCP; (b) JPCP; (c) CRCP

Typical Pavement Designs of Three Alternatives

In order to prevent a biased result, equivalent cross-section designs of typical JRCP, JPCP, and CRCP must be considered. A design for each pavement alternative was created such that each design would provide the same level of performance and function. The designs for each alternative are based on the *AASHTO Guide for Design of Pavement Structures 1993* (AASHTO 1993).

Suppose a typical major interstate highway is to be built in an urban area. It is 1 km (0.62 mi) long and 14.8 m (48.6 ft) wide [two lanes in each direction, with each lane 3.7 m (12.1 ft) wide]. Daily traffic is 1,900 single-unit trucks, 1,750 double-unit trucks, and 250 truck trains, with the annual traffic volume growth assumed to be 2%. Eighty percent of the loading occurs in the design lane. The pavement would be constructed on a cement-treated soil subbase. At the end of the service life, the serviceability index would decrease from 4.2 (the initial design serviceability index) to 1.5 (the terminal serviceability index). A reliability of 95% and a combined standard error of 0.4 are considered for the case study.

$$\log_{10}W_{10} = Z_R \times S_0 + 7.35 \times \log_{10}(D+1) - 0.06 + \frac{\log_{10}\left(\frac{\Delta PSI}{4.5-1.5}\right)}{1+\frac{1.624\times10^7}{(D+1)^{8.46}}} + (4.22-0.32p_t)\log_{10}\left\{\frac{S'_C \times C_d(D^{0.75}-1.132)}{215.63\times J\left[D^{0.75}-\frac{18.42}{(E_C/k)^{0.25}}\right]}\right\} \quad (1)$$

The AASHTO (1993) equation for rigid pavements [Eq. (1)] was applied to determine the slab thicknesses [D in Eq. (1)]. Eq. (1) supports an empirical design approach solely based on the field performance data that establish correlations between inputs and outputs of the equation (FHWA 2006a). By incorporating the values shown in Table 3 as the main parameters, and by rounding to the nearest 1.27 cm (0.5 in.), the pavement thickness for JRCP and JPCP was determined to be 29.21 cm (11.5 in.), and the thickness for CRCP was 27.94 cm (11 in.).

The next two sections describe the steps to perform the quantity takeoffs and cost estimation of each alternative for the 1-km-long and 14.8-m-wide highway rehabilitation project.

Quantity Takeoffs of Three Alternatives

JRCP requires reinforcing bars or wire mesh for its transverse joints and longitudinal joints. For a 29.21-cm-thick (11.5-in-thick) JRCP, the interval between transverse joints needs to be 12 m (40 ft). That subsequently requires No. 4 bars 45.72 cm (18 in.) long with an interval of 60.96 cm (24 in.) for dowels, and No. 4 bars 1.27 m (50 in.) long with an interval of 60.96 cm (24 in.) for tie bars. For the reinforcing bars, No. 4 bars at 60.96-cm (24-in.) intervals are used transversely, and No. 4 bars at 30.48-cm (12-in.) intervals are used longitudinally. The highway of 1-km-long (3,280-ft-long) and 14.8-m-wide (48-ft-wide) JRCP pavement would accordingly require 1,863 No. 4 bars 45.72 cm (18 in.) long, 4,920 No. 4 bars 91.44 cm (36 in.) long, and 74,464 ft of No. 4 reinforcing steel bars. As a result, the estimated total quantities of concrete and rebar for JRCP are 4,263 m^3 (5,576 yd^3) and 75,385 kg (166,195 lb), respectively.

JPCP only needs tie bars for transverse joints and dowels for longitudinal joints. For a 29.21-cm-thick (11.5-in.-thick) JPCP, the interval between transverse joints needs to be 4.57 m (15 ft). Subsequently, No. 9 bars 45.72 cm (18 in.) long with an interval of 30.48 cm (12 in.) are needed for dowels, while No. 6 bars 127 cm (50 in.) long with an interval of 91.44 cm (36 in.) are needed for tie bars. The given highway designed with JPCP pavement would accordingly require 10,464 No. 9 bars 45.72 cm (18 in.) long and 3,279 No. 6 bars 127 cm (50 in.) long. As a result, the estimated total quantities of concrete and rebar for JPCP are 4,268 m^3 (5,583 yd^3) and 33,515 kg (73,888 lb), respectively.

CRCP only requires reinforcing bars. A 27.94-cm-thick (11-in.-thick) CRCP would need No. 5 bars at 1.22-m (48-in.) intervals as transverse reinforcing steel and No. 6 bars at 60.96-cm (24-in.) intervals as longitudinal reinforcing steel. The given highway designed with CRCP pavement would accordingly require

Table 3. Pavement Design Parameters Used for Determining Thicknesses of Alternatives

Variables	Descriptions	Values	Notes
W_{18}	Predicted number of 80 kilo-Newtons (KN) equivalent single axle loads (ESALs)	54,326,933 ESALs	Total ESALs for 1,900 single-unit trucks per day, 1,750 double-unit trucks per day, and 250 truck trains per day
Z_R	Standard normal deviate	−1.645	95% confidence interval assumed
S_0	Combined standard error of the traffic prediction and performance prediction	0.4	Typical values of S_0 are 0.40–0.50 for flexible pavements and 0.35–0.40 for rigid pavements
p_0	Initial design serviceability index	4.2	p_0 ranges from 4.0 to 5.0 depending on quality and smoothness of projects. 5.0 is the highest score in the serviceability index, which represents a perfect pavement. The default p_0 is 4.2, the immediately-after-construction value
p_t	Terminal serviceability index	1.5	p_t ranges from 1.5 to 3.0 based on the usage of the roads. The default p_t is 1.5, the bottom line of the end-of-life value
ΔPSI	Difference between p_0 and p_t	2.7	The indicator of the pavement performance
S'_c	Modules of rupture of PCC	5.2 MPa (750 psi[a])	Assumed
C_d	Drainage coefficient	1.0	The default value per AASHTO (1993)
J	Load transfer coefficient	2.8 for JRCP and JPCP2.6 for CRCP	The average value per AASHTO (1993)
E_c	Elastic modulus of PCC	31,026 MPa (4,500,000 psi)	Assumed; where f'_c = PCC compressive strength
k	Modulus of subgrade reaction	67.5 MPa/m (250 psi)	k estimates the support of the layer underneath the surface layer. Typically, it ranges from about 50 psi (13.5 MPa/m) for the weak support, to over 1,000 psi (270 MPa/m) for the strong support

[a]Note that Eq. (1) requires its inputs to be based on the English units.

Table 4. Quantity Takeoffs and EIO-LCA Input Values

Quantity and input	Material	JRCP	JPCP	CRCP
Quantities	Concrete	4,263 m^3 (5,576 yd^3)	4,268 m^3 (5,583 yd^3)	4,071 m^3 (5,324 yd^3)
Steel	75,385 kg (166,195 lb)	33,515 kg (73,888 lb)	72,252 kg (159,289 lb)	
Input values[a]	Concrete	$1,441,502	$1,180,788	$884,965
Steel	$260,391	$94,710	$160,469	

[a]Input values reflect 2002 USD values based on a life cycle of 50 years.

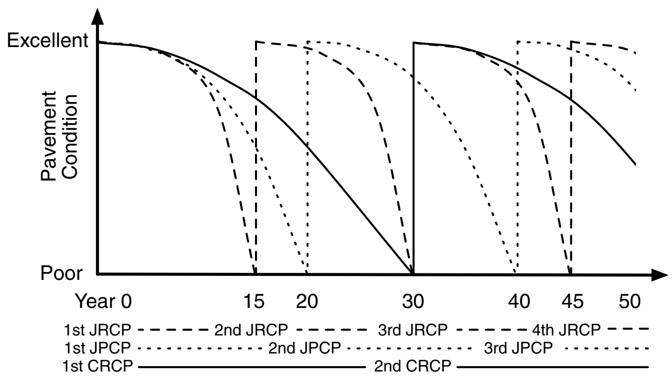


Fig. 3. Rehabilitation requirements of each alternative over a life cycle of 50 years

Table 5. Total Unit Cost Estimate (Data from RS Means 2002)

RS Means line number	RS Means description	Total unit costs in 2002 dollars
02750 100 0400	CONCRETE PAVEMENT including joints, finishing, and curing, 12 in. thick	$166.2/m^3$ ($115.5/$yd^3$)
03210 600 0600	REINFORCING IN PLACE, slab on grade, #3 to #7[a]	$1.7/kg ($1,400/t)

[a]Note that the same unit price was applied to the No. 9 bars in JPCP because it only represents a small quantity.

1,863 No. 4 bars 45.72 cm (18 in.) long, 4,920 No. 4 bars 91.44 cm (36 in.) long, and 74,464 ft of No. 4 reinforcing steel bars. As a result, the estimated total quantities of concrete and rebar for CRCP are 4,071 m^3 (5,324 yd^3) and 72,252 kg (159,289 lb), respectively.

Table 4 summarizes the concrete and steel quantities required for the three alternatives.

Cost Estimation for EIO-LCA

As stated previously, the researchers set the life cycle to 50 years in terms of the analysis boundary. Based on the literature review, the design life expectancies of JRCP, JPCP, and CRCP are set at 15, 20, and 30 years, respectively. As a result, JRCP would require three additional full-depth rehabilitations at years 15, 30, and 45, provided a life cycle of 50 years. On the other hand, JPCP and CRCP require only two and one additional rehabilitations, respectively, due to their enhanced durability (Fig. 3).

The study then employed 2002 heavy construction cost data from RS Means (2002) for the unit cost determination of the three alternatives. The 2002 cost data were deliberately selected to minimize the year discrepancy between the selected 2002 EIO-LCA model (presented in the following section) and the cost estimation. Table 5 summarizes the unit costs.

Adding a 10% waste factor to the cost estimation, the input values of Table 4 show the costs of each pavement alternative over the 50-year life cycle for the 1-km highway segment, after discounting to 2002 dollars at 4%. These costs serve as input values to the EIO-LCA analysis that is presented in the following section.

Data Analysis

The EIO-LCA analysis of the study was completed by using the EIO-LCA website (CMU 2011).

Model Selection

The EIO-LCA website currently offers 13 standard models for different years (1992, 1997, and 2002), which can be categorized in either "producer" or "purchaser" price models, depending on the analysis boundary. The boundary for producer price models includes the impact associated with all processes from resource extraction to product assembly (CMU 2011). The producer price models do not include all processes after the production site. Purchaser price models, however, include distribution of the product to the final consumer (CMU 2011). In terms of geography, six models out of the 13 are for the U.S. nationwide; three models are for two U.S. states (Pennsylvania and West Virginia) and the combination of both. The remaining four models support Germany, Spain, Canada, and China.

In terms of product types, the standard models can only be used for generic products such as pavement construction in this study. However, when different pavement types need to be investigated, a custom model must be used. A custom model can support a hypothetical product with a direct purchasing demand for multiple direct sectors (CMU 2011). Therefore, based on the premise of this study, three custom-built EIO-LCA models (one for each alternative) were created using the U.S. national purchaser price model in 2002 (the most recent data available). "Construction" and "other nonresidential structures" were then selected as the primary and subsectors for the analysis, respectively. These sectors include highway, street, and bridge construction, which are the main focus of this study. The life-cycle costs of the pavement alternatives were then entered into the models to determine the environmental, economic, and social implications of the three pavement alternatives.

Fig. 4 shows the inputs and outputs of the EIO-LCA model. The values in Table 4 were used as the inputs to Sector 327320 (ready-mix concrete) and Sector 331110 (iron and steel mills manufacturing) for the three models.

Interpretation of Environmental, Economic and Social Implications

As shown in Table 6, the environmental, economic, and social impacts of the selected pavement alternatives are analyzed in the following eight subcategories:

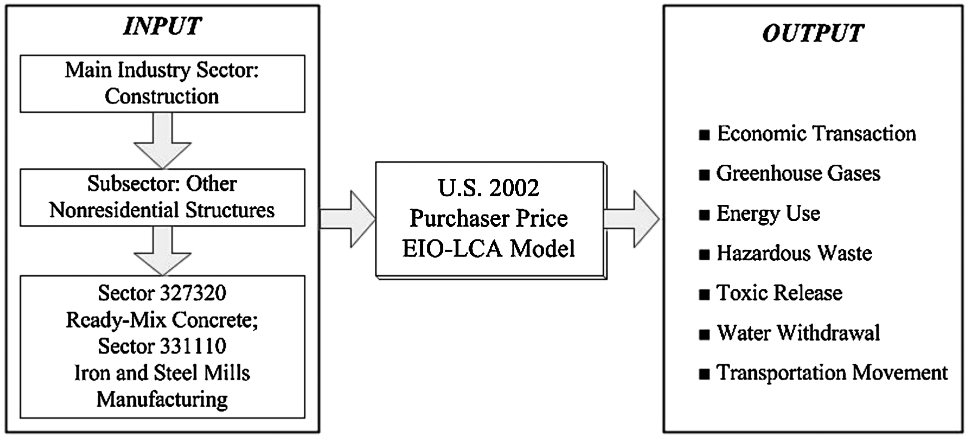


Fig. 4. Main framework of EIO-LCA model for this study

Economic Impact
- Economic transaction.

Social Impacts
- Transportation movement, and
- Land use.

Environmental Impacts
- Global warming potential and greenhouse gases emissions,
- Energy use,
- Hazardous waste,
- Toxic release, and
- Water withdrawal.

The results of the EIO-LCA analysis, comparing the environmental, economic, and social impacts of the three alternatives, are summarized in Table 6, and the associated interpretations are presented in the following sections.

Economic Transaction: From the perspective of economic activity, "year-of-expenditure dollars" represents the complete economic supply chain of purchases needed to make the product. Fig. 5, coupled with Fig. 6, clearly shows that over the life cycle of 50 years, CRCP has the least total and direct environmental, economic and social impact, followed by JPCP and JRCP. This result conveys the fact that CRCP requires the least amount of materials due to its durable and stable performance. CRCP can meet the equivalent design requirements (such as performance and functions) with 39% and 18% less economic cost to society than JRCP and JPCP, respectively. As depicted by Fig. 7, the top three sectors contributing most to the economic transaction cost for the three pavement alternatives are (1) other nonresidential structures, (2) ready-mix concrete manufacturing, and (3) retail trade.

Transportation Movement: The transportation movement category refers to movements in the eight types of transportation in ton-km, where 1 t-km refers to 1 t being transported for 1 km

Table 6. EIO-LCA Analysis Results for Three Rigid Pavement Rehabilitation Alternatives

Impact	Assessment	Unit	Type	Rigid pavement rehabilitation alternatives		
				JRCP	JPCP	CRCP
Economic impact	Year-of-expenditure dollars	\$1 million in 2002	Year-of-expenditure dollars	6.76	5.06	4.15
Social impact	Transportation movement	million t-km	Transportation movement	18.7	13.6	11.5
	Land use	Ha	Land use	153	114	94
Environmental impact	Global warming potential	tCO_2e	Global warming potential	4,840	3,530	2,970
	Greenhouse gases emissions	tCO_2e	CO_2 fossil	2,970	2,190	1,820
			CO_2 process	1,640	1,170	1,000
			CH_4	177	123	109
			N_2O	28.8	21.7	17.7
			HFC/PFCs	24.2	15.4	14.9
	Energy use	TJ	Total energy	49.8	35.5	30.6
			Coal	18.3	12.6	11.2
			Natural gases	10.6	7.32	6.53
			Petroleum-based fuel	13.8	10.5	8.51
			Biomass/waste fuel	2.27	1.77	1.39
			31% non–fossil fuel electricity	4.76	3.3	2.93
	Hazardous waste	Short ton	Hazardous waste	1,250,000	832,000	771,000
	Toxic releases	kg	Fugitive air	45.7	30.1	28.1
			Point air	340	254	209
			Surface water	108	51.3	66.4
			Underground water	44.6	33.6	27.4
			Land	535	349	329
			Off-site	564	238	348
	Water withdrawals	kgal	Water withdrawals	34,500	25,500	21,200

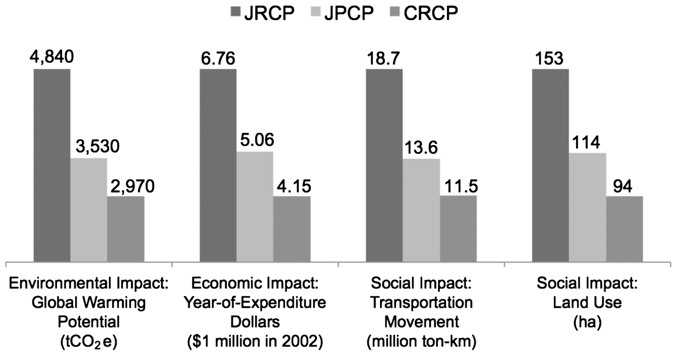


Fig. 5. Environmental, economic, and social impacts of three alternatives

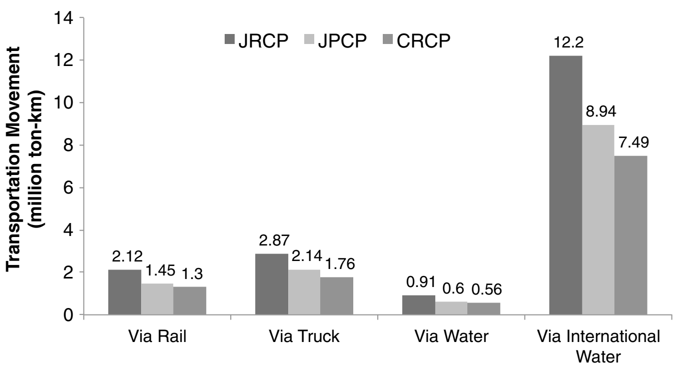


Fig. 6. Social impact of three alternatives: transportation movement options

in distance. The eight types include air, oil pipe, gas pipe, rail, truck, water, international air, and international water. Fig. 6 shows that transportation movement via international waters accounts for more than half of the total transportation movements. JRCP results in the most transportation movements, while CRCP requires the least (Fig. 5). The top three sectors contributing most to the transportation movement for the three pavement alternatives are (1) cement manufacturing, (2) iron and steel mills, and (3) ready-mix concrete manufacturing.

Land Use: Transportation improvement projects have long lasting impacts on adjoining communities, business enterprises, and regional land use planning. The land use analysis performed in this paper examines the social impact of the three pavement rehabilitation choices on land use. In this study, the results of the land use analysis were interpreted as spatial demand, taking no other controlling effects (e.g., soil quantity and land development activities) into account. Like transportation movement, the land use analysis clearly indicates that JRCP involves the largest land use, 62.8% more than CRCP does (see the social impact category in Table 6). In the land use category, the top three sectors contributing most are: (1) logging, (2) forest nurseries, and (3) all other crop farming.

Global Warming Potential and Greenhouse Gases: Global warming potential (GWP) measures a relative amount of heat that is captured in the atmosphere by different types of greenhouse gases. The unit of GWP is metric tons of carbon dioxide (CO2) equivalent emissions (tCO2e). GWP includes CO2 fossil, CO2 process, methane (CH4), nitrous dioxide (N_2O), and other high-GWP gases. In particular, the CO2 fossil and process gases represent the emissions of CO2 into the air from each sector's fossil fuel combustion and other sources. In the U.S., fossil fuels produce more than 90% of the greenhouse gas emissions due to heavy use of cars for transportation (U.S. EPA 2011).

For rigid pavements, the analysis shows that the cement manufacturing sector is the most responsible sector, producing more than 43% of the tCO2e of the total GWP, followed by the power generation and supply sector (Fig. 7). Fig. 5 shows that CRCP has 39% less GWP than JRCP and 16% less GWP than JPCP. The results also indicate that CO2 fossil gas is mainly from chemical reactions, coal mining, and solid waste in cement manufacturing.

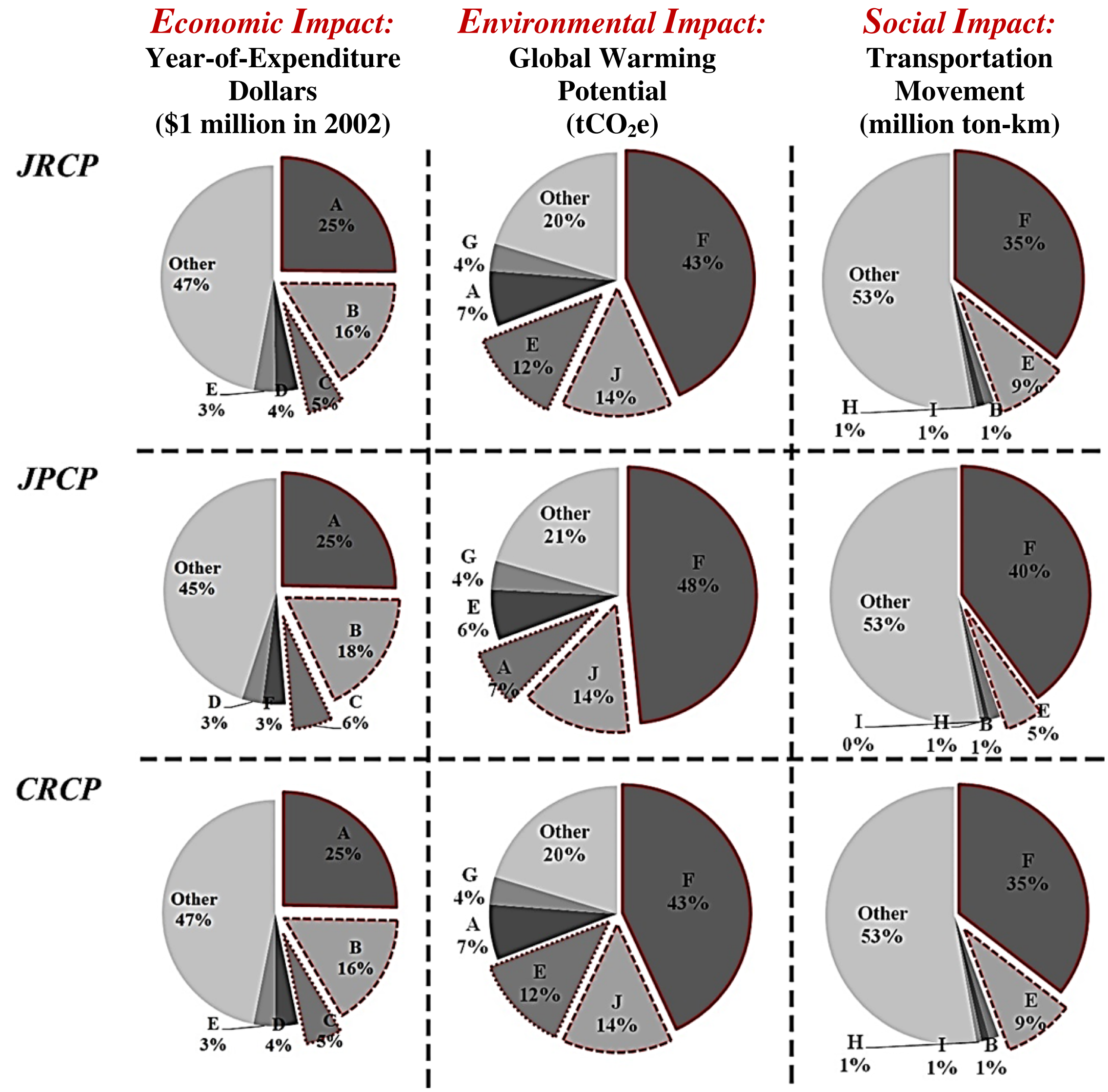
Energy Use: Total energy use is measured in terajoules (TJ), and calculated from all fuels and electricity including coal, natural gas, petroleum-based fuel, biomass/waste fuel, and 31% of non-fossil-fuel electricity (from nonfossil sources). In the energy category, cement manufacturing, power generation and supply, and ready-mix concrete manufacturing are the top three consumers. Table 6 summarizes the total and detailed energy consumption for the three rigid pavements. Overall, CRCP requires the least amount of energy; it consumes 39% less energy than JRCP and 14% less energy than JPCP. Among all the energy consumers, the amount of coal used indicates the largest difference.

Hazardous Waste: Hazardous waste is waste in any form or any stage of product that is potentially harmful to the health of human beings or the environment, as identified by the Resource Conservation and Recovery Act (RCRA) (U.S. EPA 2011). In the hazardous waste category, organic chemical manufacturing, iron and steel mills, and petroleum refineries are the top three sectors that contribute to RCRA hazardous waste. Table 6 shows that JRCP would yield the largest amount of RCRA hazardous waste among the three alternatives.

Toxic Release: The toxic release category in the EIO-LCA model summarizes toxic emissions by aggregating all toxic substances regardless of their relative impacts (CMU 2011). In terms of release sources, toxic releases include fugitive air releases, point air releases, surface water releases, underground water releases, land releases, and off-site releases. Fugitive air refers to the air released from unconfined air streams, such as equipment leaks, ventilation systems, and evaporative losses from surface impoundments and spills. Point air releases stem from confined air streams including stacks, vents, ducts, or pipes. In terms of discharging types, the water releases are categorized into surface water releases and underground water releases. Land releases refer to on-site waste buried in landfills and soil wastes. Off-site releases include all the transactions of chemical shipments off site with the purpose of disposal, recycling, and combustion for energy recovery or treatment (CMU 2011).

For rigid pavements, the top three sectors that contribute to toxic releases are organic chemical manufacturing, iron and steel mills, and petroleum refineries (Fig. 7). Fig. 7 shows that among all toxic releases, land, off-site, and point air toxic releases are five to ten times greater than the other toxic releases. While the toxic release category offers some detailed information, the EIO-LCA website warns that it is not a very robust way of summarizing the impact of toxins (CMU 2011).

Water Withdrawal: Measured in thousands of gallons (kgal), the water withdrawal category pertains to the process of diverting water from surface water or groundwater sources. Rigid pavements consume about 80% of water in power generation and supply; sand, gravel, clay, and refractory mining; and stone mining and quarrying. Table 6 shows that CRCP withdraws 39% and 17% less water than JRCP and JPCP, respectively.



Sectors

- **A: Other nonresidential structures**
- **B: Ready-mix concrete manufacturing**
- **C: Retail trade**
- **D: Wholesale trade**
- **E: Iron and steel mills**
- **F: Cement manufacturing**
- **G: Truck transportation**
- **H: Other basic organic chemical manufacturing**
- **I: Iron, steel pipe and tube manufacturing from purchased steel**
- **J: Power generation and supply**

Fig. 7. Top five contributing sectors in terms of economic, environmental and social impacts for 1 lane-km of highway rehabilitation work

Conclusions and Future Research

With the increased demand for a sustainable pavement method in highway rehabilitation projects, this study proposed the application of EIO-LCA to investigate the environmental, economic, and social impacts of three major rigid pavement alternatives, namely JRCP, JPCP, and CRCP. For each alternative, a pavement design was developed to meet the same level of performance and functions, based on AASHTO's empirical equation and design guidelines. Quantity takeoffs and construction cost estimation of each alternative were then performed based on 2002 dollars to prevent the year discrepancy with the selected 2002 EIO-LCA model. The study assumed a life cycle of 50 years as the analysis boundary, and the different numbers of rehabilitation requirements for each alternative were estimated accordingly. Three custom-built EIO-LCA models were developed based on the 2002 U.S. national purchaser price model, and the quantified present values of each alternative for a life span of 50 years were entered as inputs. Finally, the outputs of the models were interpreted for recommendations.

Although JPCP is the most commonly used pavement alternative in the United States among the three rigid pavement alternatives (WSDOT 2011), the study results clearly indicate that CRCP is much preferable to the other two alternatives for minimizing the negative environmental, economic and social impacts in all eight life-cycle assessments that were considered for a life cycle of 50 years. When the design requirements are equivalent in all three alternatives, CRCP requires fewer resources than JRCP or JPCP while providing more durability and longer performance. Therefore, CRCP could lead to significantly less recurring rehabilitation than the other two alternatives, thus lessening the maintenance cost over the life cycle. In general, CRCP requires a relatively high initial construction cost; yet, the LCA results of this study convey the fact that the initial cost can be recouped by long-term sustained benefits from the life-cycle perspective.

In conclusion, this study suggests that CRCP is the most sustainable choice among the three pavement alternatives, with the least amount of greenhouse emissions, energy consumption, RCRA hazardous waste, toxic releases, water withdrawals, transportation movements, and land use. Other noteworthy findings for rigid pavements are summarized as follows:

- Cement is a major consumer of raw materials as well as a major contributor to greenhouse gases and water and air pollution through the life cycle of rigid pavements.
- Cement manufacturing is also the top-contributing sector of environmental and social activity in rigid pavements. Overall, the sector accounts for more than 40% of the total GWP (tCO_2e) and more than 35% of total transportation movement (million ton-km). Within the cement manufacturing industry, the top energy consumers are from coal and petroleum-based fuels.
- The top two contributors to toxic releases are land and off-site releases; hence, proper management of storage, landfills, and soil waste could significantly reduce toxic releases.
- The most frequent means of movement is via international water for ready-mix concrete manufacturing. Thus, the use of local materials and manufacturing is recommended for consideration.
- CRCP involves the least land use, 62.8% less than JRCP.

The results and applicability of this study are limited to highway rehabilitation projects that consider a rigid concrete pavement due to its higher load bearing capability and longer durability compared to asphalt pavements. Therefore, the LCA analysis framework and results of this study should be of value to STAs when concrete pavement is considered for implementation. This study will assist STAs in making better-informed decisions, especially in the early project scoping stage, as this study clearly reveals that EIO-LCA can support their decision making by providing rapid and reliable advanced knowledge about environmental, economic, and social impacts. This study champions a wider adoption of CRCP for sustainable transportation infrastructure development. This study creates new knowledge in the assessment of highway rigid pavement choices from the life-cycle perspective. To the best of our knowledge, this is the first study of its kind to evaluate the three pillars (i.e., environmental, economic and social aspects) of LCA for highway rigid pavement alternatives, for the purpose of assisting STAs. It helps them make better informed decisions about green development and offers a guide for repeating the analysis procedures and techniques described in this study when they conduct similar LCA studies in the project scoping phase. This research will greatly benefit STAs by positively impacting their decisions about sustainable transportation infrastructure renewal projects.

Although CRCP appears to offer the most sustainable solution for long-term life-cycle impact on the environment, economy and society, we recommended that more factors be considered when choosing the most effective pavement alternative within given project constraints. For instance, life-cycle cost analysis that accounts for both the agency cost (i.e., total project cost plus road user cost) and future maintenance cost could be used in the decision-making process in conjunction with other factors with regards to annual average traffic volume, project type, size, and complexity. In addition, the results from this study were based on average data across the U.S., according to the EIO-LCA data resources. Given the differences in project circumstances, regional data could support EIO-LCA at more detailed levels of states and cities. Future LCA research is suggested for different types of cement concrete (e.g., fast-setting hydraulic cement concrete that requires 4-h curing time versus type III rapid strength concrete that requires 12-h curing time) that use alternative materials, such as fly ash and slag. Such research is expected to complement the study presented in this paper.

References

AASHTO. (1993). "AASHTO guide for design of pavement structures 1993." Washington, DC.

AISI (American Iron and Steel Institute). (2012). "Continuously reinforced concrete pavement: Roads for this generation and the next." ⟨http://www.steel.org/en/The%20New%20Steel/~/media/Files/SMDI/Construction/CRCP%20-%20Marketing%20-%20CRCP%20Brochure.ashx⟩ (Apr. 8, 2013).

Berthiaume, R., and Bouchard, C. (1999). "Energy analysis of the environmental impact of paving material manufacture." *Trans. Can. Soc. Mech. Eng.*, 23(1B), 187–196.

BTS (Bureau of Transportation Statistics). (2010). "National transportation statistics." Washington, DC.

Caltrans (California Department of Transportation). (2010). "Life-cycle cost analysis procedures manual." Sacramento, CA.

Caltrans (California Department of Transportation). (2011). "Highway design manual." ⟨http://www.dot.ca.gov/hq/oppd/hdm/hdmtoc.htm⟩ (Dec. 11, 2013).

Cass, D., and Mukherjee, A. (2011). "Calculation of greenhouse gas emissions for highway construction operations by using a hybrid life-cycle assessment approach: Case study for pavement operations." *J. Constr. Eng. Manage.*, 10.1061/(ASCE)CO.1943-7862.0000349, 1015–1025.

Choi, K., and Kwak, Y. (2012). "Decision-support model for incentives/disincentives time-cost tradeoff." *Int. J. Autom. Construct.*, 21(1), 219–228.

Choi, K., Kwak, Y. H., Pyeon, J., and Son, K. (2012). "Schedule effectiveness of alternative contracting strategies for transportation infrastructure improvement projects." *J. Constr. Eng. Manage.*, 10.1061/(ASCE)CO.1943-7862.0000431, 323–330.

CMU (Carnegie Mellon University). (2011). "EIO-LCA: Free, fast, easy life cycle assessment." ⟨http://www.eiolca.net⟩ (Dec. 2, 2011).

CRSI (Concrete Reinforcing Steel Institute). (2012). "Paving the prairie states: CRCP's success in north and south Dakota." ⟨http://www.conveyinc.com/things/crsi58.pdf⟩ (Apr. 10, 2012).

Eccleston, C. (2008). *NEPA and environmental planning: Tools, techniques, and approaches for practitioners*, CRC Press, Boca Raton, FL.

FHWA (Federal Highway Administration). (2006a). "Geotechnical aspects of pavements." ⟨http://www.fhwa.dot.gov/engineering/geotech/pubs/05037/05037.pdf⟩ (Mar. 10, 2013).

FHWA (Federal Highway Administration). (2006b). "Highway statistics 2005." Washington, DC.

FHWA (Federal Highway Administration). (2007). "Long-life concrete pavements: Best practices and directions from the states." ⟨http://www.fhwa.dot.gov/pavement/concrete/pubs/07030/07030.pdf⟩ (Jun. 25, 2013).

Guinee, J. (2002). "Handbook on life cycle assessment operational guide to the ISO standards." *Int. J. Life Cycle Assess.*, 7(5), 311–313.

Hendrickson, C., Horvath, A., Joshi, S., and Lave, L. (1998). "Economic input-output models for environmental life-cycle assessment." *Environ. Sci. Technol.*, 32(7), 184–191.

Hendrickson, C., Lave, L., and Matthews, H. (2005). *Environmental life cycle assessment of goods and services: An input-output approach*, Resources for the Future Press, London.

Horvath, A. (1997). "Estimation of environmental implications of construction materials and designs using life cycle assessment techniques."

Ph.D. dissertation, Dept. of Civil and Environmental Engineering, Carnegie Mellon Univ., Pittsburgh.

Horvath, A., and Hendrickson, C. (1998a). "Comparison of environmental implications of asphalt and steel-reinforced concrete pavements." *Transportation Research Record 1626*, Transportation Research Board, Washington, DC, 105–113.

Horvath, A., and Hendrickson, C. (1998b). "Steel versus steel-reinforced concrete bridges: Environmental assessment." *J. Infrastruct. Syst.*, 10.1061/(ASCE)1076-0342(1998)4:3(111), 111–117.

Kim, B., Lee, H., Park, H., and Kim, H. (2012). "Framework for estimating greenhouse gas emissions due to asphalt pavement construction." *J. Constr. Eng. Manage.*, 10.1061/(ASCE)CO.1943-7862.0000549, 1312–1321.

MoDOT. (2004). "Pavement design and type selection process." Jefferson City, MO.

Ochoa, L., Hendrickson, C., and Matthews, H. (2002). "Economic input-output life-cycle assessment of US residential buildings." *J. Infrastruct. Syst.*, 10.1061/(ASCE)1076-0342(2002)8:4(132), 132–138.

Park, K., Hwang, Y., Seo, S., and Seo, H. (2003). "Quantitative assessment of environmental impacts on life cycle of highways." *J. Constr. Eng. Manage.*, 10.1061/(ASCE)0733-9364(2003)129:1(25), 25–31.

Roudebush, W. (1999). *Environmental value engineering assessment of concrete and asphalt pavement*, Portland Cement Association, Skokie, IL.

RS Means. (2002). "Heavy civil construction cost data." Kingston, MA.

Santero, N. J., Masanet, E., and Horvath, A. (2011). "Life-cycle assessment of pavements. Part I: Critical review." *Resour. Conserv. Recycl.*, 55(9–10), 801–809.

Treloar, G., Love, P., and Crawford, R. (2004). "Hybrid life-cycle inventory for road construction and use." *J. Constr. Eng. Manage.*, 10.1061/(ASCE)0733-9364(2004)130:1(43), 43–49.

U.S. EPA. (2011). "Defining life cycle assessment." ⟨http://www.gdrc.org/uem/lca/lca-define.html⟩ (Nov. 24, 2012).

Weiland, C., and Muench, S. T. (2010). "Life-cycle assessment of reconstruction options for interstate highway pavement in Seattle, Washington." *Transportation Research Record 2170*, Transportation Research Board, Washington, DC, 18–27.

WSDOT (Washington State Department of Transportation). (2011). "WSDOT pavement guide." ⟨http://training.ce.washington.edu/wsdot/⟩ (Nov. 24, 2012).

Zapata, P., and Gambatese, J. (2005). "Energy consumption of asphalt and reinforced concrete pavement materials and construction." *J. Infrastruct. Syst.*, 10.1061/(ASCE)1076-0342(2005)11:1(9), 9–20.