View metadata, citation and similar papers at core.ac.uk
brought to you by CORE
provided by Texas A&M Repository

ENVIRONMENTAL, ECONOMIC, AND SOCIAL IMPACTS OF CONCRETE PAVEMENT MATERIAL CHOICES: A LIFE-CYCLE ASSESSMENT APPROACH

A Thesis

by

HYUNSOUNG PARK

Submitted to the Office of Graduate and Professional Studies of
Texas A & M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Chair of Committee,	Kunhee Choi
Committee Members,	Jose L. Fernandez-Solis
	Weiling He
Head of Department,	Joe Horlen

December 2014

Major Subject: Construction Management

Copyright 2014 Hyunsoung Park

ABSTRACT

Most of the transportation systems in the United States were constructed during construction booming periods between the 1950's and 1980's with the maximum 20-year serviceable life. For this reason, most of the built transportation infrastructure systems in the U.S. already exceeded their intended design life. However, these highways are still in service, and therefore, immediate reconstructions or rehabilitations are needed for public safety and economical health of nation.

To assist State Transportation Agencies (STAs) in rendering better-informed decisions for the concrete pavement material choices, the major research objective is to analyze the environmental, economic, and social impacts of the four concrete pavement alternatives from the perspective of life-cycle assessment.

This research analyzes the three different types of concrete alternatives such as Portland Cement Concrete (PCC), Fast Setting Hydraulic Cement Concrete (FSHCC) and Rapid Strength Concrete (RSC) with as well as without type III Portland cement by using the economic input-output life-cycle assessment (EIO-LCA). The quantity of each concrete was calculated based on a 1-lane kilometer of highway rehabilitation with the continuously reinforced concrete pavement rehabilitation strategy. The unit price of each concrete was converted from 2013 to 2002 because

EIO-LCA used the 2002 data base. The results of this study revealed that PCC is the most sustainable highway alternative. The results champion the adoption of the PCC for sustainable pavement rehabilitation projects. Therefore, for the decision making in highway rehabilitation projects, STAs can choose the most sustainable pavement alternatives for their better decision-making.

DEDICATION

To my GOD

Jesus

To my Family

Eonbae Park
Geumjin Oh
Miyoung Park
Sunyoung Park
Jinyoung Park

ACKNOWLEDGEMENTS

I would like to thank you my committee chair, Dr. Kunhee Choi, and my committee members, Dr. Jose L. Fernandez Solis and Dr. Wiling He, and Dr. Changseon Shon, a researcher, Texas Transportation Institute (TTI), for their guidance and support throughout the course of this research.

Thanks also to the department faculty and staff and my friends and colleagues; Jimyong Kim, Sangguk Yum, Junseo Bae, Kyeongrok Ryu, Jaeheum Yeon, Sukjoon Oh, Nelson Han, Leeseok Chae, and Mingun Sim for making my time at Texas A&M University a great experience.

NOMENCLATURE

AASHTO	American Association of State Highway and Transportation Officials
AISI	American Iron and Steel Institute
ARRA Act	American Recovery and Reinvestment Act
Caltrans	California Department of Transportation
CPI	Consumer Price Index
CMU	Carnegie Mellon University
CRCP	Continuous Reinforced Concrete Pavement
DOTs	Department of Transportations
EIO-LCA	Economic Input-Output Life Cycle Assessment
EO	Executive Order
ESLs	Equivalent Single Axel Loads
FHWA	Federal Highway Administration
FSHCC	Fast Setting Hydraulic Cement Concrete
GWP	Global Worming Potential
IRF	International Road Federation
JRCP	Jointed Reinforced Concrete Pavement
JPCP	Jointed Plain Concrete Pavement
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory

LTPP	Long-Term Pavement Performance
OPC	Ordinary Portland Cement
PCC	Portland Cement Concrete
RSC	Rapid Strength Concrete
STAs	State Transportation Agencies
TTI	Texas A&M Transportation Institute
TxDOT	Texas Department of Transportation
WSDOT	Washington State Department of Transportation

TABLE OF CONTENTS

Page

Page

LIST OF FIGURES

Page

LIST OF TABLES

Page

1 INTRODUCTION

Environmental issues have been gaining significant attention from general public. People have paid more attention to the consumptions of products and services that have serious impact on the environment. Due to the increased attention to the environment, the protection of the environment and reduction of consumption that negatively affects the environment have become a growing concern (WCED 1987). Furthermore, infrastructure industry regards environment as considerable issue.

The Obama Administration declared the Executive Order (EO) in October 2009 to improve environment, energy, and economic performance. Particularly, the Administration would invest approximately 80 billion dollars for the infrastructure recovery. The EO asked federal agencies to restrain environmental pollution and maintain sustainability (Eccleston and March 2011). Therefore, many State Transportation Agencies (STAs) in United States have adopted sustainability concerns in their vision statements. For example, one of Texas Department of Transportation's (TxDOT) vision statements is providing safe, durable, cost-effective, environmentally sensitive, and aesthetically appealing transportation systems working in collaboration. Likewise, the National Academy of Engineering mentioned that one of the big challenges in the 21st century is the restoration of infrastructure (IRF 2010).

The highways take the largest portion of the national transportation system and are the major public source for daily commuting. With the increases of populations and demands of public commuters, highways have been actively and continually constructed or rehabilitated. There are about 4 million miles of highways in the United States (FHWA 2006). To maintain existing pavement on the highways, nearly 400 billion dollars are estimated (IRF 2010). Most of the current transportation systems in the United States were constructed between 1950s and 1980s. The average service lifetime of a highway is 20 to 25 years (Choi and Kwak 2012). However, these highways are still in service (Uhlmeyer and Russell 2013) even though their expected service lives went over the limits. As a result, 60 percent of highways currently need reconstruction or rehabilitation for safety and economical maintenance (Choi et al 2012). An enhanced transportation infrastructure system would bolster social and economic development. Therefore, using long-life and low-maintenance concrete pavement is recommended by the Federal Highway Administration (FHWA) (AISI 2012).

Highway projects have only been taking into account the economic factors until now; the environmental issues in the highway projects were not considered as a key concern. Also, even though highway construction uses diverse materials, no study had been conducted in the past to assess the concrete materials causing environmental problems. Sustainable construction has risen as a significant issue in construction industry. Pavement material is a major substance which can pollute a large portion of nature such as lands, air, and water. Thus, studies focused on the sustainable concrete materials are necessary for devising the most environmentally friendly concrete pavement.

2 RESEARCH SCOPE AND SGNIFICANCE

2.1 Problem Statement

The major annual budget of STAs was contributed to maintain the existing highways since the FHWA constructed the greater part of highways between the 1950's and 1980's with a service life span of approximately 20 years (Choi and Kwak 2012). In fact, many highways have passed their service life time. Nevertheless, for economic reasons, the outdated highways, which need to be reconstructed or rehabilitated, are still in service for public transportation.

In a highway project, concrete pavement is the essential part because of its longer service life span compared to others. Also, each year, about 21 to 31 billion tons of concrete are used around the world (Sathiyakumari 2010). FHWA mentioned that nearly 76 percent of the transportation infrastructure in the United States consumes concrete for pavements (FHWA 1998). Many studies have focused on the comparison between asphalts and concrete (Horvath and Hendrickson 1998a; Berthiaume and Boucjard 1999; Roudebush 1999; Zapata and Gabatese 2005). However, no research for concrete pavement alternatives, which focuses on the materials, has been conducted yet. Therefore, to provide critical recommendations for concrete pavement rehabilitation projects, the four types of concrete pavement alternatives (PCC, FSHCC and RSC with and without type III Portland cement) have been compared using Economic In-put Out-put Life Cycle Assessment (EIO-LCA). In addition, the old highway pavements call for a massive pavement rehabilitation project. Therefore, this study will assist the STAs in their decision making on selecting cost effective and sustainable concrete pavement.

2.2 Research Objectives

Sixty percent of the U.S. highways have already outrun their service life. Thus, these outdated highways must be rehabilitated with sustainable alternatives as well as sustainable material. Previous studies focused on the comparison between asphalt and concrete pavements, and none of them handled concrete pavement issues in terms of the materials used. To fill the gap of the studies, this research focuses on concrete materials, where four concrete pavement alternatives, PCC, FSHCC, and two types of RSC, which are rehabilitation methods, were analyzed and compared.

The main purpose of this study is to assess the economic, environmental, and social impacts of four concrete pavement alternatives, PCC, FSHCC, RSC with type III Portland cement, and RSC without type III Portland cement with respect to EIO-LCA. Since these four concrete pavements are common rehabilitation alternatives, this study selected these four types of concrete as comparison alternatives. Furthermore, another objective is to suggest a practical solution for STAs or state

Department of Transportations (DOTs) making a critical decision for highways rehabilitation project during the project planning phase.

To achieve the desired objectives, the following tasks were performed:

Task 1: Comprehend the backgrounds of LCA and EIO-LCA via literature review.

Task 2: Verify types of concrete pavement for highway rehabilitation.

Task 3: Analyze components depending on the types of concrete.

Task 4: Quantify each concrete alternative based on the 1 lane kilometer of CRCP.

Task 5: Estimate the cost of each type of concrete.

Task 6: Perform LCA according to each type of concrete by using EIO-LCA model produced by Green Design Institute at Carnegie Mellon University.

Task 7: Interpret the EIO-LCA outputs analyzing economic, environmental, and social impacts.

2.3 Research Assumptions and Limitations

Several assumptions are needed to conduct the EIO-LCA models (CMU 2014). First, the price of most concrete materials is the same in the United States. Second, consumer Price Index (CPI) can convert the current material price to that of the designated year. Third, materials such as chemicals and admixture less than 1 percent in concrete are not considered as materials that have environmental impacts. Fourth, there are nearly 500 sectors that deal with almost all products, services, and sectors of the US economy in EIO- LCA model. Fifth, typical life expectancy of CRCP is 30 years (Caltrans 2007).

With these several assumptions, this research got several limitations due to the limited dependable data. First, this research is limited to only four types of concrete pavements: PCC, FSHCC, RSC (with Type III Portland cement), and RSC (without Type III Portland cement). Second, EIO-LCA model applies a single nation's economy. Third, the database of EIO-LCA model did not consider inflation since the data is obtained from public resources and surveys. Fourth, the US 2002 producer price model offered by the EIO-LCA online tool was used. Fifth, only ready-mix concrete was used as the most crucial sector for the input value because dependable data are limited. Sixth, this research only considers the main components of concrete and analyzes eight major categories of impacts: economic, greenhouse gas emission, energy use, hazardous waste, toxic releases, water withdrawals, land use, and transportation movements.

2.4 Significance of the Research

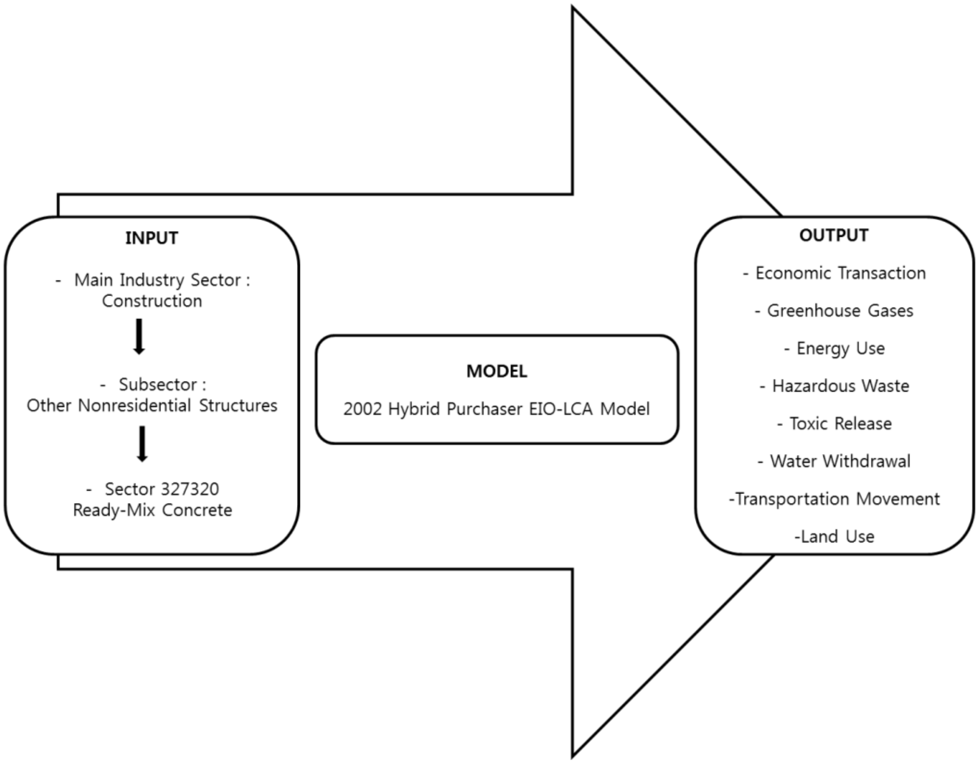
This research will provide recommendations to STAs for better-informed decision making for reconstruction or rehabilitation projects that use concrete pavement alternatives. Having analyzed four different types of design mixes of concrete, this study will assist in analyzing the concrete pavement alternatives focusing on the economic, environmental, and social impacts.

2.5 Research Methodologies

The EIO-LCA is the major source leading this study, which is also available at the website of the Green Design Institute in Carnegie Mellon University (www.eiolca.net). On the website, 13 different standard models are offered and grouped into two categories: producer price model and purchaser price model. In addition to the producer price model, it contains all process impacts while the purchaser price model has the all process impacts by significantly less chances. Moreover, the purchaser price model involves in the product’s distribution. In terms of product types, there are two types of models. First, a custom model supports multiple direct sectors for purchase, whereas a hybrid model offers the opportunity of regulating the purchase demand in all the economic sectors (CMUGDI 2014).

This study evaluates the three concrete pavement alternatives by utilizing the hybrid custom model which enhances assessing the accurate impact of concrete and provides the U.S. market price of all items. One lane-kilometer of pavement is defined as a unit area product of 1 kilometer length and 3.7 meter width. In the hybrid custom model, construction option was chosen for a broad sector group and other non-residential structure was selected for a detailed sector. The model evaluated the concrete and its supply chain in each type of the concretes to estimate the demanded components and energy claimed for manufacturing of products. Figure 1 below indicates the EIO-LCA model framework used in this study.

Figure 1. Main framework of EIO-LCA model for this study



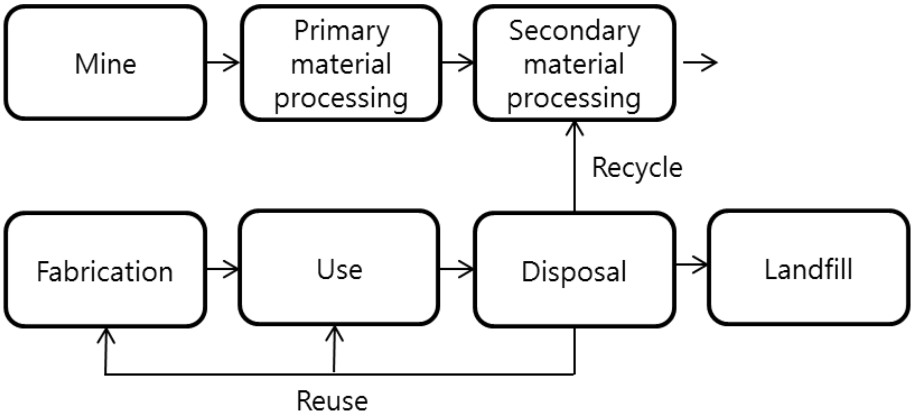
3 LITERATURE REVIEW

The main purpose of this literature review is to identify the concepts of LCA and EIO-LCA. The literature review also explores concrete pavement materials used in case of rehabilitation and key findings from previous studies.

3.1 Backgrounds of Life Cycle Assessment (LCA)

LCA is a "cradle-to-grave" approach for evaluating environmental aspects and potential impacts (ISO 1997). Cradle-to-grave means that LCA evaluates all stage of a product's life and enables the estimation of the cumulative environmental impacts; it provides a more accurate picture of the true environmental trade-offs in product by converting all the impacts into measurable quantities (Weiland and Muench 2010).

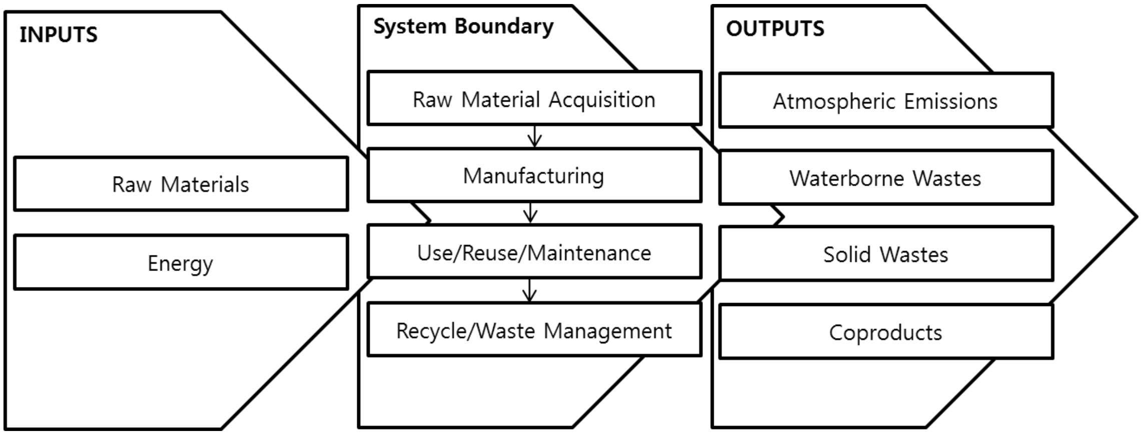
Figure 2. Generic Supply Chain life Cycle Model



LCA begins from raw material acquisition, followed by production and use, and it ends at the point when all materials are disposed (Park et al 2003). Figure 2 briefly explains the components of a life cycle.

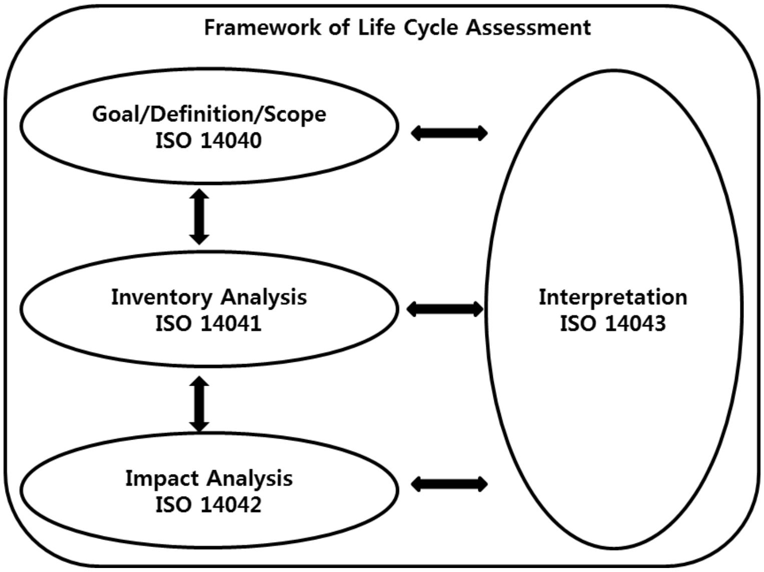
The LCA can be divided into three interrelated components such as inventory, impact, and improvement along with an integrative procedure. The process analysis LCA was developed by the Society of Environmental Toxicology and Chemistry (SETAC), and the U.S. Environmental Protection Agency (EPA) established the life cycle circle in 1993 as shown in Figure 3. It shows the conceptual life-cycle stages to make materials and energy balances for all the process involved (SAIC 2006).

Figure 3. Life Cycle Stages (SAIC 2006)



LCA requires energy and material balances for all the steps of the life cycle. (Hendrickson et al 2006). In the 1960's, standards were needed to overcome uncertainties. Methodologies and standards for LCA were developed by the EPA and International Standards Organization (ISO) 14000 series (SAIC 2006; Weiland and Muench 2010). LCA is the most helpful way to evaluate the environmental impacts throughout their lifespan of the product or service (Park et al 2003; SAIC 2006). ISO and EPA set up a framework of LCA as seen in Figure 4.

Figure 4. Framework of Life Cycle Assessment (SAIC 2006)



The purpose of each framework step is (SAIC 2006; Weiland and Muench 2010):

1. Goal/Definition/Scope:

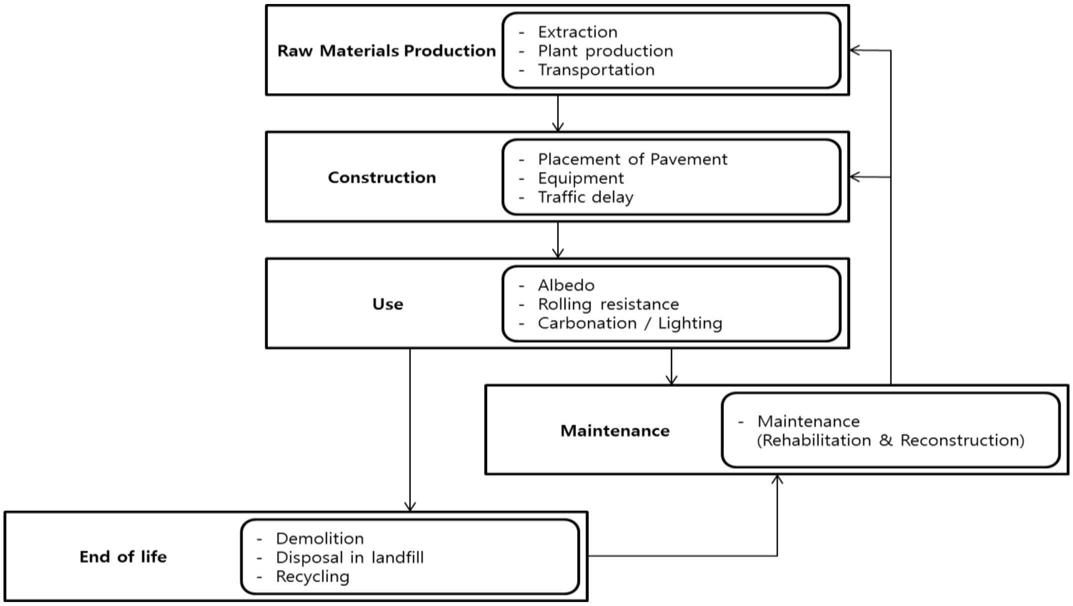
   - Describe and define a service, process, and product to perform LCA.
   - Identify environmental effects and determine scope borderlines and set up relationship.
2. Life-cycle Inventory analysis
   - Identify and quantify energy, water, material usage and its release into the environment.
3. Life-cycle Impact analysis
   - Evaluate the environment and potential impacts with the inventory analysis.
4. Interpretation
   - Assess the results of the inventory analysis in order to provide information for critical decision making.

3.2 LCA for Concrete Pavement

The University of California at Berkeley studied the pavement LCA (Gopalakrishnan 2011). LCA techniques play a role in evaluating the environmental and potential impacts during the entire highway construction process by designer and clients. The evaluating procedures are composed of 3 steps. First, identifying and collecting an inventory related to energy, and materials inputs and release; second, clarifying the potential impacts with the inventory; third, providing decision-makers with the analysis of the environmental impacts for perceptive decision making. Therefore, STAs enable better-informed decision making with LCA (Horvath 1997; Treloar et al. 2004).

For LCA of highway projects, there are five stages of pavement life, i.e., raw material extraction and production; construction; use; maintenance and rehabilitation; and demolition and recycling (Gopalakrishnan 2011; Santero et al. 2011). On the other hand, LCA has unique items such as albedo, rolling resistances, traffic delays, etc. These items can be included or excluded depending on research scope or objectives. If some of the items are included in research scope, they should be considered not to produce biased results (Santero et al. 2011).

Figure 5. Pavement Life Cycle (Santero et al. 2011)



3.3 Concept of Economic Input-Output Life Cycle Assessment (EIOLCA)

In the 1930's, Harvard University economist Wassily Leontief developed input-output models of the United States economy. Leontief's model performed the diverse inputs demanded to provide a unit of output in each economic sector. Leontief could trace all the direct and indirect inputs to make outputs in every sector by creating entire sectors. The results made a comprehensive model of the U.S. economy. For this accomplishment, Leontief received the Nobel Prize in economics in 1973 (CMUGDI 2014; Ochoa et al. 2002).

Researchers of Green Design Institute at Carnegie Mellon University (CMU) assumed the environmental life cycle assessment as an effective tool in designing products, processes, and policies. The purpose of EIO-LCA was to build a sustainable economy and to assess cost effective ways to decrease pollution (Hendrickson et al 2006). The input-output model makes partition of a whole economy into distinct sectors. The model can be depicted as a large table with 480 rows and 480 columns as shown in Table 1. Each row and column stands for a section of the economy. The tables represent entire sales from one sector to another or the amount of purchases from one sector to produce a dollar of output for the sector. EIO-LCA considers a more comprehensive view of the sections producing all products and services in the economy. The advantage of the EIO-LCA is that it does not need to make any boundary. Therefore it deals with the whole economy, involving almost all the energy and material inputs (Hendrickson et al 2006).

The EIO-LCA software (CMUGDI 2014) can be found on the website, www.eiolca.net. Based on Leontief's method, the Green Design Institute has produced a comprehensive EIO-LCA online service, beginning the 1990's. The online service has been used as an elemental tool for analysis of services and products of infrastructure for the past 15 years (CMUGDI 2014). Output values yielded are eight parts including economic activity, greenhouse gases, energy use, hazard waste, toxic releases, water withdrawals, transportation movements, and land use.

Table 1. EIO-LCA Sector Model (Hendrickson et al. 1998)

Output from sectors	Input from sectors				O Intermediate output	Y Final demand	X Total output
	1	2	…	n			
1	X_{11}	X_{12}	…	X_{1n}	O_1	Y_1	X_1
2	X_{21}	X_{22}	…	X_{2n}	O_2	Y_2	X_1
…..	…	…	…	…	…	…	…
n	X_{n1}	X_{n2}	…	X_{nn}	O_n	Y_n	X_1
I Intermediate input	I_1	I_2	…	I_n			
V Value added	V_1	V_2	…	V_n		GDP	
X Total input	X_{11}	X_{11}	…	X_{11}			

Where:

$X_{ij:}$ amount that sector j purchased from sector i

$Y_{i:}$ final demand for output from sector i

$X_{i:}$ total output from sector i

$X_{i:} = Y_i + \sum_j Xij$

If $A_{ij} = \frac{Xij}{Xj}$

Then

$X_i = Y_i + \sum_j Xij \cdot X_j$

In vector notation, it can be represented like

$X = Y + AX$

$Y = (I - A)X$

$X = (I - A)^{-1} Y$

3.4 Comparison of Two Primary Types of Life Cycle Assessment Models

Two major types of LCA approaches are process-based LCA (P-LCA) and economic input-output LCA (EIO-LCA). These two methods are generally used to assess environmental impacts in a quantitative approach (Kucukvar and Tatari 2011). Both models have advantages and disadvantages. The two types of LCA could make fairly different results. The traditional process-based LCA has some critical defects. Satisfying the entire demand is unlikely in process-based LCA because of a large amount of financial data and time needed, and the difficulty of collecting additional data (Hendrickson et al 2006). Making accurate boundaries poses another challenge. Due to the life cycle, direct and indirect interactions can make ambiguous input parameters in the LCA (Hendrickson et al 1998). Typically, a conventional LCA neglects this circularity problem, and confirming the data is difficult. Almost all the data are outdated and are incapable of considering a reliable impact (Hendrickson et al 1998). In the traditional LCA, an inventory analysis is utilized to make results. In addition, LCA is known to be vulnerable to interplays and circularity problems.

However, the EIO-LCA takes the circularity problems and interactions because it is programmed for a whole economy-wide comprehensive analysis (Hendrickson et al 2006). The EIO-LCA does not need to make clear boundaries. It is also useful and beneficial because it is cheap, yields results quickly, and it includes the all economy. The table 2 compared the strengths and weaknesses of the two types of LCA models. Recently, in the two types of LCA approaches, to minimize the ambiguity and the lack of data, a hybrid LCA has appeared. In part, the hybrid EIO-LCA is able to overcome the defects of the EIO-LCA model by using national input-output tables which clarifies the data collection processes (Treloar et al. 2004).

Table 2. Comparison Table of Two Main Types of LCA (CMUGDI 2014)

	Process-Based LCA model	**EIO-LCA**
Advantages	- Attempts to include all processes relating the product - Results are detailed, process-specific analysis - Allows for specific product comparison - Identifies areas for process improvements, weak point analysis - Provides for future product development assessments	- All direct and indirect environmental and economic effects included - Evaluated result economy-wide and comprehensive perspectives - Allows to compare at system level - Provides information of all products in the economy - Fast and cheap - No need to make boundaries - Uses publicly available data and reproducible results - Provides for future product development assessments
Disadvantages	- Setting system boundaries is complex and problematic - Tend to be costly and time consuming - Difficulty in applying to new process design - Use of proprietary data - Uncertainties in data	- Difficulties in process evaluation - Some product assessment combined aggregate data - Difficulty in relating dollar values to physical units - Difficulty in applying in open economic system - Uncertainty of data - Environmental and economic data probably reflect past practices

3.5 Rigid Pavement for Rehabilitation

Water, aggregate, and cement are essential components in concrete, but ad-mixtures and substitute materials have been used to achieve advanced concrete performances depending on the types of structures, performance, function, and required capacity. To meet environmental standards, concrete manufacturers are required to recycle materials as a substitute for cement in concrete alternatives, which are fly ash and slag cement (Marceau et al. 2007). As a critical constituent, concrete ad-mixtures enhance concrete performances even in small amounts. Typically, concrete ad-mixtures can be nested under four types depending on their main purposes such as plasticizer, accelerating, water controlling, and air-entraining. These ad-mixtures commonly take less than 1% of concrete, and therefore, in aspect of LCA, ad-mixtures nearly have no environmental impacts for concrete (Marceau et al. 2007).

In the U.S., many highway agencies have standardized concrete strength for rigid pavements. Concrete pavement needs to achieve its compressive strength, 3,000 psi (20.7 MPa), within 28 days (Lane 1998; Lange and Roesler 2006; Nemati et al. 2003). The compressive strength setup depends on work, location, and weather conditions (Lane 1998).

Concrete pavements are usually made with Portland Cement Concrete (PCC). PCC has three main types of pavements: Jointed Rein forced Concrete Pavement (JRCP), Jointed Plain Concrete Pavement (JPCP), and Continuously Reinforced concrete Pavement (CRCP). Among the three types of pavements, CRCP is frequently used in Illinois, Texas, and North Dakota, because CRCP is the most sustainable alternatives (WSDOT 2011). Thus, in this study, only the CRCP was considered as the concrete pavement type. In the U.S., CRCP has been utilized for a long time (AISI 2012). CRCP has a long service life, requires a small amount of maintenance, and has dependable and secure performances. Also, CRCP is suitable for highway pavements that have high traffic volumes (Caltrans 2011). According to the Long-Term Pavement Performance program (LTPP), CRCP can keep their initial surface condition, most convenient to road users (AISI 2012). This is because CRCP has no connection joints and cracks. It maintains gentle surfaces, which leads to higher vehicle fuel efficiency. Road maintenance is costly and expends much time. This also requires large amounts of traffic control, site workers, and materials are required. However, CRCP necessitates less of them than does JRCP or JCPC. In other words, CRCP does not cause traffic delays and interruptions as much during the rehabilitation process. Advantages of CRCP have been highly valued in several states. CRCP is accepted by Illinois, Texas, Oklahoma, Oregon, South Dakota, and Virginia, whereas other states considered CRCP as an experimental type.

3.6 Strategies for Rigid Pavement Rehabilitation

In Concrete pavement rehabilitation project, there are four main types of concrete pavements: PCC, FSCHCC, RSC with types III Portland cement, and without type III Portland cement.

PCC is the common type of concrete for road globally. Some types of PCC are applicable to the typical Ordinary Portland Cement (OPC) whose color is gray in most cases, but sometimes a white PCC is feasible. PCC is a notably important construction material used in infrastructure projects worldwide. This is because concrete can be used in a variety of purposes, but the most importantly, the ingredients of PCC are very economical and adaptable (Mindess et al. 1981)

RSC is a special concrete and often used with type III cement. An RSC enables enough strength to open the traffic within 12 hours after a replacement pavement. In the past decades, RSC has been broadly used for rehabilitation of freeways, interstate roads, and airfields. RSC has the two most critical achievement characteristics which can rehabilitate the old PCC pavements; they are the less time needed in the process, and the corollary, the reduction of the road-closure time (Long-life 2007). The two types of main cement brands are CTS Rapid-Set Cement and Ultimax Cement DOT. Slump of RSC has a range of 4 to 9 inches. Since the RSC has the least curing time, public can use highways within 12 hours, which is a considerable advantage to traffic, public safety, and construction schedules. Curing time is affected by the mix ratio and used materials. RSC can reach a minimum strength of 400 psi in 12 hours of curing or less (Sugar et al. 2001).

FSHCC is able to achieve the adequate strength of 400 psi (2.8 MPa) in 4 to 8 hours and 600 psi (4.2MPa) within 28 days to open the lane back to the public after placement. Most of concrete pavement rehabilitation projects with FSHCC are processed overnight. In most cases, it takes around 7 hours with partial lane closure. Thus, FSHCC allows the public to reuse the lane within 4 to 8 hours of replacement. This is the critical reason for using FSHCC in nighttime closures. To reduce the lane closure time in concrete pavement rehabilitation, FSHCC is recommended, although FSHCC is more expensive than PCC and RSC because its material costs are higher than others (Lee et al 2002). The contractor, Coffman Specialties Inc., designed the FSHCC; and Caltrans accepted the FSHCC design mix. The FSHCC consists of one coarse and fine aggregate, two cement types such as PCC and Ultimax, water, air entraining agent, and liquid or solid retarder.

3.7 Noticeable Findings from Previous Studies

Many studies show comparisons of pavement alternatives using the EIO-LCA (Horvath 1997; Horvath and Hendrickson 1998a and 1998b). Horvath (1997) handled the study comparing soft pavement with rigid pavement. This study presented that asphalt is more sustainable when manufactured, but concrete is more environmentally friendly when it is built onsite (Horvath 1997). In a following research, Horvath and Hendrickson found that asphalts were more environmentally friendly by using LCA. Because asphalts do not have much ore and fertilizer, noxious emissions, and have a superior recycling performance, asphalt is more reasonable to use (Horvath and Hendrickson 1998a). However, in the two studies mentioned above, it is significant that they used unidentified data and ignored the decisive cause that can affect the environment.

Another study conducted by Horvath and Hendrickson used the LCA inventory analysis for steel and steel-reinforced concrete bridges (Horvath and Hendrickson 1998a). The outcome from this research is that steel-reinforced concrete bridges are environmentally friendlier. In the case of recycling and reuse, on the other hand, steel is probably the better choice at the end of the designed service life. However, this result can be biased because the data used are lacking.

Some LCA Studies used the conventional LCA approach making comparisons between asphalt and PCC (Zapata and Gambatese 2005; Muga et al. 2009; Kim et al. 2012). These studies noticed that asphalt uses small amounts of energy when they are in extraction, manufacturing, and transportation stage; and it is easy to recycle with asphalt than concrete. According to the Muga et al (2009), CRCP was more expensive than JPCP when they were in construction; however, for 35 years, JPCP required more maintenance fees and emitted more toxics materials than did CRCP (Muga et al. 2009).

4 DATA COLLECTION

4.1 Data for Life Cycle Inventory

Life Cycle Inventory (LCI) analysis has to be finished before beginning the analysis. Data for manufacturing the designed product and chain relating constituents have to be included in the LCI process. In this study, the LCI data comes with the EIO-LCA database. However, the range of input data has to be designed to analyze EIO-LCA. Table 3, Table 4, and Table 5 shows the utilized data. This research assesses environmental, economic, and social impacts by using EIO-LCA based on materials of each concrete.

Table 3. Components of Portland Cement Concrete (Marceau et al. 2007)

Concrete Mix Description	**Portland Cement Concrete**	**Unit**
Cement	112 (189)	Kg/m^3 (lb/yd^3)
Fly ash	0	Kg/m^3 (lb/yd^3)
Slag Cement	112 (189)	Kg/m^3 (lb/yd^3)
Coarse aggregate	1,127 (1900)	Kg/m^3 (lb/yd^3)
Fine aggregate	831 (1401)	Kg/m^3 (lb/yd^3)

Table 4. FSHCC Mix Design (Lee et al. 2002)

Concrete Mix Description	**Fast Setting Hydraulic Cement Concrete**	**Unit**
Cement	390 (657)	Kg/m^3 (lb/yd^3)
Fly ash	0	Kg/m^3 (lb/yd^3)
Slag Cement	0	Kg/m^3 (lb/yd^3)
Coarse aggregate	900 (362)	Kg/m^3 (lb/yd^3)
Fine aggregate	215 (1517)	Kg/m^3 (lb/yd^3)

Table 5. Rapid Strength Concrete Mix Design (FHWA 2001)

Concrete Mix Description	**Rapid Strength Concrete**		**Unit**
	W/O Type III	**W/ Type III**	
Cement	448 (755)	442 (745)	Kg/m^3 (lb/yd^3)
Fly ash	0	48 (81)	Kg/m^3 (lb/yd^3)
Slag Cement	0	0	Kg/m^3 (lb/yd^3)
Coarse aggregate	1,070 (1803)	778 (1311)	Kg/m^3 (lb/yd^3)
Fine aggregate	613 (1034)	776 (1308)	Kg/m^3 (lb/yd^3)

4.2 Common Pavement Design

There are three comparable alternatives for rigid pavement, including jointed reinforced concrete pavement (JRCP), jointed plain concrete pavement (JPCP), and continuously reinforced concrete pavement (CRCP). Among the three types of pavement design, CRCP is the most sustainable alternative and typically used for rigid pavement in Texas, Illinois, North Dakota, Oklahoma, Oregon, South Dakota, and Virginia (WSDOT 2011). So in this study to compare the three types of concrete in the same condition, CRCP was considered as a typical pavement type.

The pavement was designed based on the American Association of State Highway and Transportation Officials (AASHTO) Guide for Design of Pavement Structures 1993, (AASHTO 1993). It is 3,280 feet (~1 kilometer) long, 12 feet (~3.7 meters) wide, and 11 inches (~27.94 centimeters) thick for the highway rehabilitation project. Based on this condition, the four types of concrete alternatives, including PCC, FSHCC and the two types of RSC, had the same quantity. The average daily traffic is about 3,900 types of trucks, and the traffic volume grows by 2 percent annually. In the design lane, 80 percent loading occurs. At the end of the designed life, the serviceability index could be diminished from 4.2 (the initial design serviceability index) to 1.5 (the terminal serviceability index). Basing on AASHTO 1993, this case study deals with a reliability of 95 percent and a combined standard error of 0.4.

$$\mathbf{log_{10}}(\boldsymbol{W}_{\mathbf{18}})=\boldsymbol{Z_R}\times\boldsymbol{S}_{\mathbf{0}}+\mathbf{7.35}\times\mathbf{log_{10}}(\boldsymbol{D}+\mathbf{1})-\mathbf{0.06}+\frac{\log_{10}(\frac{\Delta\mathrm{PSI}}{4.5-1.5})}{1+\frac{1.624\times10^{7}}{(D+1)^{8.46}}}+(\mathbf{4.22}-\mathbf{0.32}\boldsymbol{p_t})$$

$$\times\mathbf{log10}\left[\frac{(\mathrm{Sc}\prime)\ (\mathrm{C}_{d})(\mathrm{D}^{0.75}-1.132)}{215.63(\mathrm{J})\left(\mathrm{D}^{0.75}-\frac{18.42}{(\frac{\mathrm{Ec}}{\mathrm{k}})^{0.25}}\right)}\right]$$

This equation is from AASHTO for rigid pavement. This study used the equation for the slab thickness determination by using parameters in Table 6. The equation was confirmed by an experimental design from the field performance data. The equation built interrelationships between inputs and outputs of the data (FHWA 2006a).

The pavement thickness for CRCP was determined to be around 11 inches (~28 centimeters).

$$(54{,}326{,}933) = -\,1.645 \times 0.4 + 7.35 \times (\mathrm{D} + 1) - 0.06 + \frac{\log_{10}(\frac{2.7}{4.5-1.5})}{1+\frac{1.624\times10^{7}}{(D+1)^{8.46}}} +$$

$$(4.22 - 0.32 \times 4.2) \times \mathbf{log}10\left[\frac{(750)\ (1.0)(\mathrm{D}^{0.75}-1.132)}{215.63(2.6)\left(\mathrm{D}^{0.75}-\frac{18.42}{(\frac{4{,}500{,}000}{250})^{0.25}}\right)}\right]$$

D = 10.605 inches

Table 6. Pavement Design Parameters for Pavement Thickness

Variables	**Descriptions**	**Values**	**Notes**
W_{18}	Predicted number of 80 Kilo-Newton (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 0.4 to 0.5 for flexible pavements and 0.35 to 0.4 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.
Pt	Terminal serviceability index	1.5	Pt ranges from 1.5 to 3.0 based on the usage of the roads. The default Pt is 1.5, the bottom line of the end-of-life value.
ΔPSI	Different between P0 and Pt	2.7	The indicator of the pavement performance
Sc'	Modules of rupture of PCC	5.2MPa (750 psi*)	Assumed
C_d	Drainage coefficient	1.0	The default value per AASHTO (1993)
J	Load transfer coefficient	2.6 for CRCP	The average value per AASHTO (1993)
Ec	Elastic modulus of PCC	31,026MPa (4,500,000 psi)	Assumed; Ec = 57,000fc where $F'c$ = PCC compressive strength
k	Modulus of subgrade reaction	67.5MPa/m (250 pci)	K estimates the support of the layer underneath the surface layer. Typically, it ranges from about 50pci (13.5MPa/m) for the weak support, to over 1,000pci (270MPa/m) for the strong support

4.3 Quantity Takeoff of CRCP

CRCP thickness is 0.2794 meters (11 inches). CRCP needs two types of reinforcing bars; one is No.5 at 1.22 meters (48 inches) for transverse reinforcing steel. The other one is No.6 bar at 60.96 centimeters (24 inches) for longitudinal reinforcing steels. However, reinforcing bars are not considered in this research. This study considered concrete as the only input value.

Total volume of Concrete:

1000 meters (long) * 3.7 meters (wide) * 0.2794 meters (thickness) = 1033.78 meters * (1+10%) = 1137.16 meters (including 10% waste)

4.4 Price Information to Estimate for EIO-LCA

The reliable cost data used in this study is from each material company such as CTS Cement Manufacturing Corporation, Knife river aggregates, Trinity-expanded shale & clay, Headwaters resources, Boral, http://www.nationalslag.org, and http://www.slagcement.org. These companies were recommended by Chang-Seon Shon, Ph.D., who was the assistant research scientist in materials and pavement division at Texas A&M Transportation Institute (TTI). Since EIO-LCA has the 2002 model data base, this study needed to adjust the cost difference between 2013 and 2002. The unit cost needed to be converted with consumer price index. The following Table 7 was adapted in this study.

Table 7. Price Information of Main Concrete Components in 2013

Year	**Products**	**$**	**Unit**
2013	Fast Setting Hydraulic Cement	0.325	/kg
2013	Type I,II Cement	0.08	/kg
2013	Type III Cement	0.117	/kg
2013	Slag	0.018	/kg
2013	Fly ash	0.035	/kg
2013	Coarse aggregate	0.023	/kg
2013	Fine aggregate	0.023	/kg

5 DATA ANALYSIS

5.1 Data Utilize for Input Value

The EIO-LCA online model offers the U.S. producer price model for year 2002 as the most recent database. Therefore, achieving the unit price of concrete elements in 2002 is a significant process.

Table 8. Consumer Price Index (Statistics 2014)

Year	**Index**
2002	179.9
2003	184
2004	188.9
2005	195.3
2006	201.6
2007	207.342
2008	215.303
2009	214.537
2010	218.056
2011	224.939
2012	229.601
2013	233.049

This study obtained the prices in 2002 by utilizing Consumer Price Index (CPI) which applies the inflation between years 2013 and 2002. The Table 8 indicates CPI from year 2002 to year 2010. And Table 9 contains price information for 2002, which will be converted into the prices in 2013 using CPI.

Table 9. Price Information of Concrete and Components In 2002

Year	**Products**	**$**	**Unit**
2002	Fast Setting Hydraulic Cement	0.251	/kg
2002	Type I,II Cement	0.062	/kg
2002	Type III Cement	0.09	/kg
2002	Slag	0.014	/kg
2002	Fly ash	0.027	/kg
2002	Coarse aggregate	0.017	/kg
2002	Fine aggregate	0.017	/kg

The prices have to take the same standards for the comparison of the impacts of four types of concrete. Therefore, this study followed the standards: 1) 3.7 meters of width, 2) 0.2794 meters of thickness, 3) 1 lane-kilometer of length. Based on the standards, every concrete type has the same volume. The Table 10, Table 11, Table

12, and Table 13 reveal the 2002 price that costs for each 1 lane-km pavement listed by concrete types.

`

Table 10. 2002 Price Information of Portland Cement Concrete

Products	**Unit Quantity (kg/m3)**	**Price ($/m3)**	**Price ($/1lane KM)**
Type I.II Cement	112	10.12	11,502.95
Fly ash	0	0	0
Slag	112	1.56	1,769.69
Coarse aggregate	1,127	19.57	22,259.32
Fine aggregate	831	14.43	16,413.03

Table 11. 2002 Price Information of Fast Setting Hydraulic Cement Concrete

Products	**Unit Quantity (kg/m3)**	**Price ($/m3)**	**Price ($/1lane KM)**
FSHC	390	97.84	111,263.69
Fly ash	0	0	0
Slag	0	0	0
Coarse aggregate	900	15.63	17,775.86
Fine aggregate	215	3.73	4,246.45

Table 12. 2002 Price Information of RSC without Type III Portland Cement

Products	**Unit Quantity (kg/m3)**	**Price ($/m3)**	**Price ($/1lane KM)**
Type I,II Cement	448	27.67	31,461.07
Fly ash	0	0	0
Slag	0	0	0
Coarse aggregate	1,070	18.58	21,133.52
Fine aggregate	613	10.65	12,107.33

Table 13. 2002 Price Information of RSC with Type III Portland Cement

Products	**Unit Quantity (kg/m3)**	**Price ($/m3)**	**Price ($/1lane KM)**
Type III Cement	442	39.92	45,395.59
Fly ash	48	1.3	1,474.74
Slag	0	0	0
Coarse aggregate	778	13.51	15,366.24
Fine aggregate	776	13.48	15,326.74

To conduct Hybrid EIO-LCA online tool, dollar amounts spent per 1 lane-kilometer price data were applied as input value. Table 14 shows the input values for sector 327320 Ready mixed concrete. In this model, the values of other sectors are adjusted automatically based on these input values.

Table 14. Input Values for Concrete Sections in 2002 Dollars

Input	**PCC**	**FSHCC**	**RSC** (W/O Type III)	**RSC** (W/Type III)
Concrete	$ 51,945	$ 133,286	$ 64,701.92	$ 77,563.3

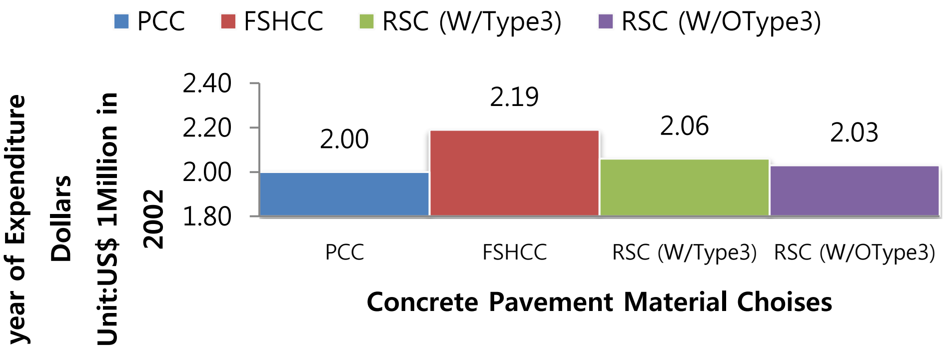
5.2 EIO-LCA Analysis

The results of EIO-LCA comes with eight outputs: Economic transaction, Global warming potential and greenhouse gases emissions, Energy use, Hazardous waste, Toxic release, Water withdrawal, Transportation movement, and Land use. The eight outputs can be divided into three categories of impacts: environmental, economic, and social. The eight outputs for assessment results are summarized below.

5.2.1 Economic Transaction

The Economic Activity assesses the economic value of each concrete type. The output shows that important interaction exists between economic value and the cement depending on the different types of cement. Thus, it could result in economic costs that varies according to the cement type. Figure 6 and Figure 7 show that PCC had the highest economic value with its lowest cost. On the contrary, FSHCC is the least economical as it is notably more expensive than others. So, PCC is the most economical option for highway rehabilitation.

Figure 6. Total Economic Transaction Results of Four Type of Concrete



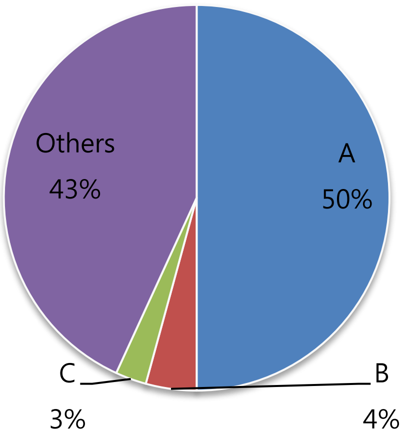
The Top Three Sectors are

A - Other nonresidential structure

B - Architectural and engineering

C - Ready mix concrete manufacturing

Figure 7. Top 3 Contributing Sectors of Economic Transaction



5.2.2 Global Warming Potential and Greenhouse Gases

The Global Warming Potential (GWP) and Greenhouse Gases assess the amount of greenhouse gases released into the air (Shine et al. 2005). The metric ton of carbon dioxide equivalent emission (tCO2e) is the unit of GWP. In the sector of greenhouse gases, outputs are CO2 fossil, CO2 process, methane (CH4), nitrous dioxide (N2O), and other gases such as Hydro Fluoro Carbons (HFC) and Per Fluoro Compounds (PFCs). In other words, the CO2 fossil and process cause the emission of CO2 into the atmosphere. Since the heavy use of cars for transportation, the greenhouse gas emissions are about 90 percent in the United States (EPA 2011). According to the results, over 45 percent of the tCO2e of the total GWP comes from cement manufacturing and other nonresidential structure sectors, followed by power generation and supply, and oil and gas extraction. Figure 8, Figure 9, Figure 10, and Figure 11 shows that PCC has a smaller amount of GWP than others, whereas FSHCC has the most amount of GWP among four types of concrete.

Figure 8. Total Greenhouse Gases Emissions Results of Four Type of Concrete

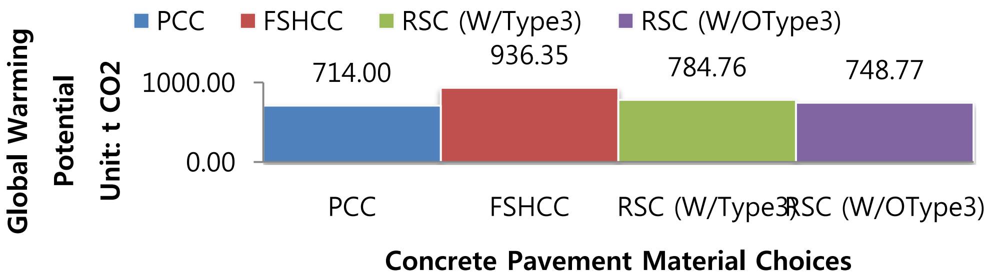


Figure 9. CO2 Emissions Results of Four Type of Concrete

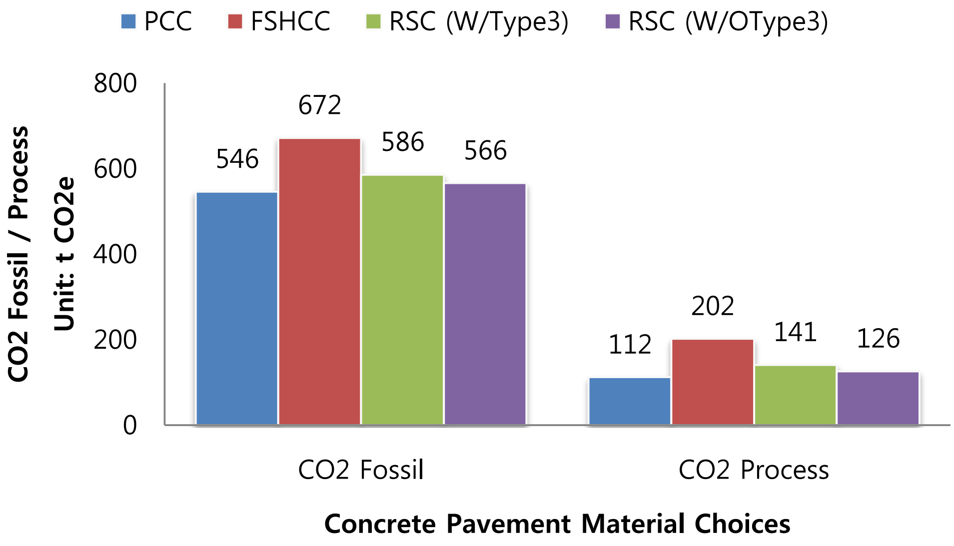
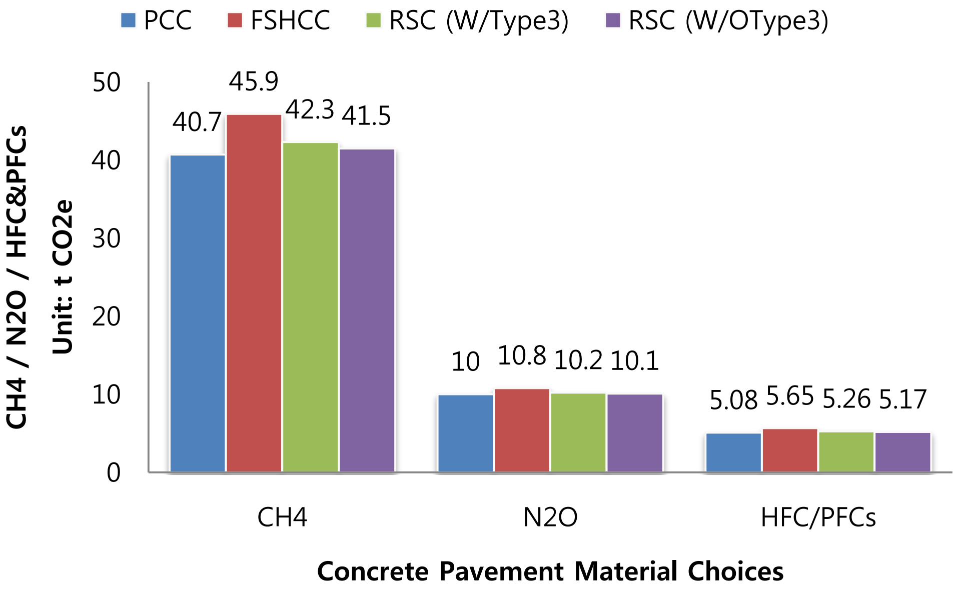


Figure 10. Others Greenhouse Gases Emissions Results of Four Type of Concrete



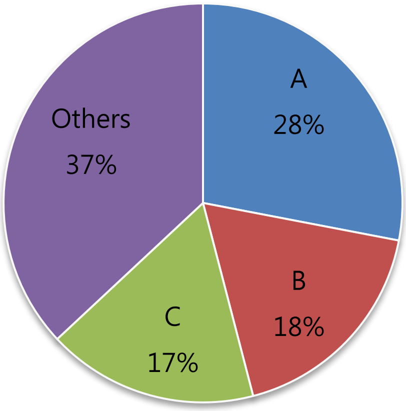
The top three sectors are

A - Other nonresidential structure

B – Cement manufacturing

C – Power generation and supply

Figure 11. Top 3 Contributing Sectors of Greenhouse Gases Emissions



5.2.3 Energy Use

The Energy Expenditure assesses the amount of entire energy consumed by all the fuels and electricity needed for concrete manufacturing. Terajoules (TJ) are used as unit of total energy use. According to the Figure 12, Figure 13, and Figure 14, in general, PCC uses a small quantity of energy when compared to the three concrete options for rehabilitation. In all the kinds of energy, the petroleum-based fuel is used more than the rest.

Figure 12. Total Energy Use Results of Four Type of Concrete

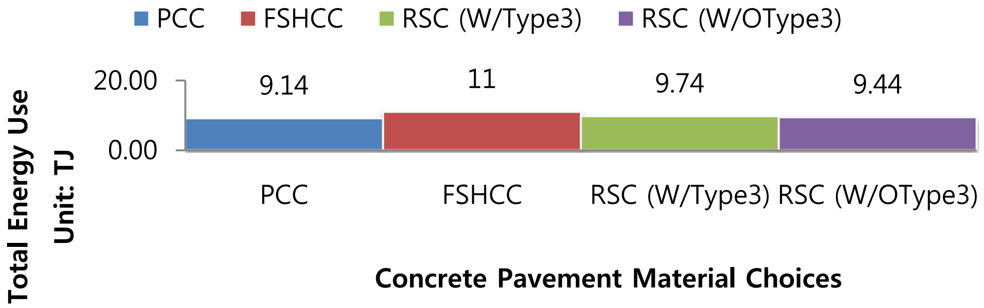
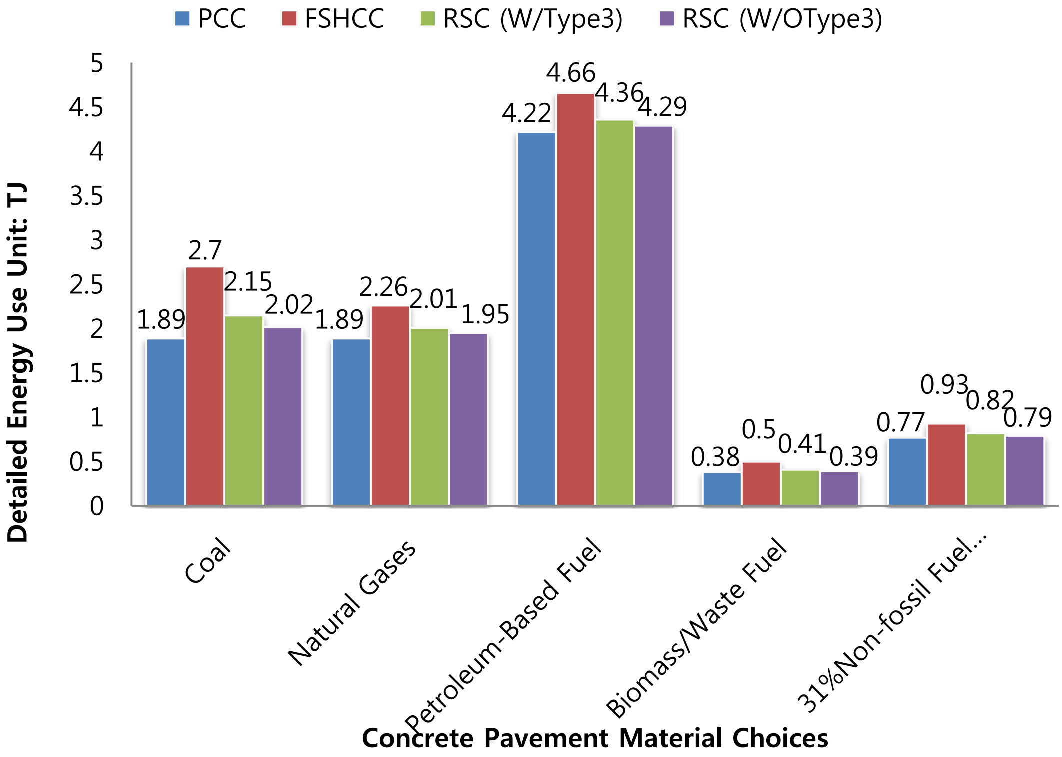


Figure 13. Detailed Energy Use Results of Four Type of Concrete



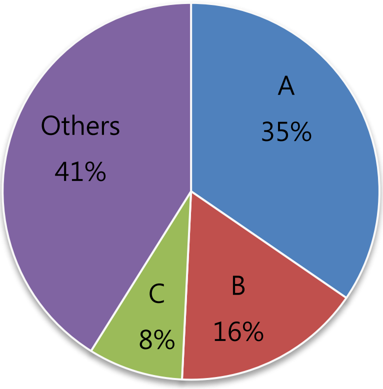
The top three sectors are

A - Power generation and supply

B - Cement manufacturing

C - Other nonresidential structure

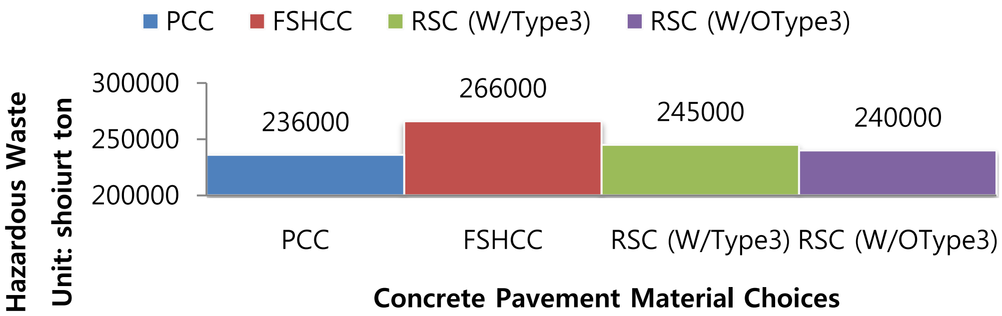
Figure 14. Top 3 Contributing Sectors of Energy Use



5.2.4 Hazardous Waste

According to the Resource Conservation and Recovery Act (RCPA), the environment and human beings are affected negatively by hazardous waste occurring in various forms from every phase of product (EPA 2011). Figure 15 and Figure 16 indicates that PCC creates the least amount of hazardous waste, whereas FSHCC creates the most hazardous waste.

Figure 15. Total Hazardous Waste Results of Four Type of Concrete



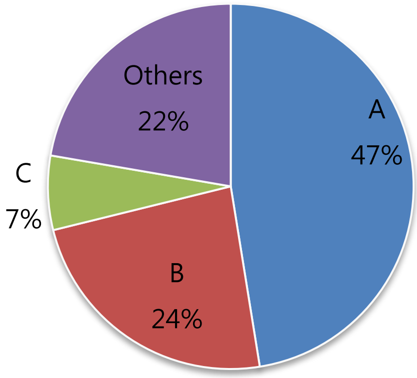
The top three sector are

A - Petroleum refineries

B - Other basic organic chemical manufacturing

C - Iron and steel mills

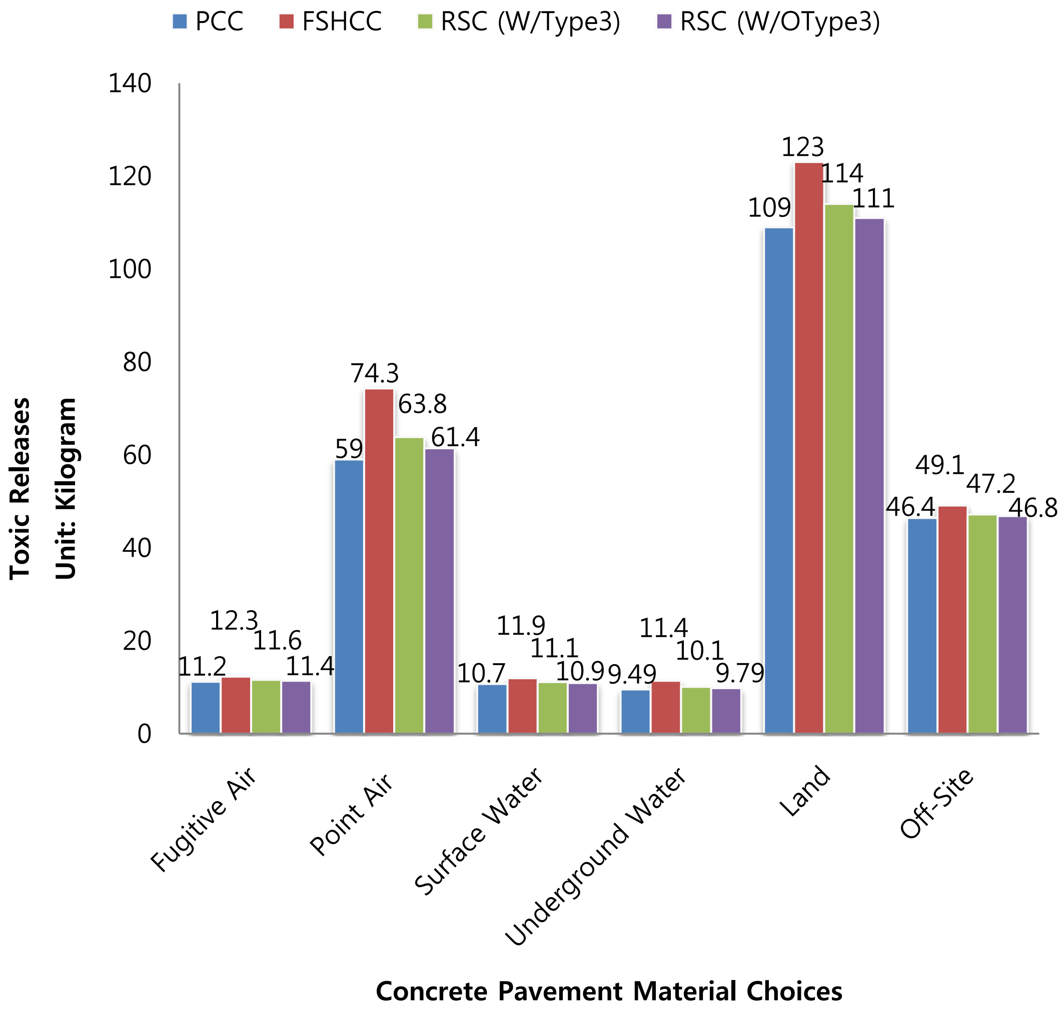
Figure 16. Top3 Contributing Sectors of Hazardous Waste



5.2.5 Toxic Release

This sector assesses all kinds of toxic release without their impacts. There are six types of release: fugitive air, point air, surface water, underground water, land, and off-site. Fugitive air is the released air from unconfined air streams, such as equipment leaks, ventilation system, and evaporative losses from surface impoundments and spills. Point air is released from confined air streams with stacks, vents, ducts, or pipes. In water, release is divided into surface water and underground water. Land release is on-site waste buried in landfills and soil waste. Off-site release is every chemical activity with the disposal, recycling, and combustion for energy reuse or transaction (CMUGDI 2014). According to the Figure 17 and Figure 18, on the list of toxic release, land, point air, and off-site have amounts of toxic release at least five times more than others. From these outputs, specific information on toxic release is provided. However, the CMU advises that it is not a reasonable approach in identifying the impact of toxic release (CMUGDI 2014).

Figure 17. Toxic Release Results of Four Type of Concrete



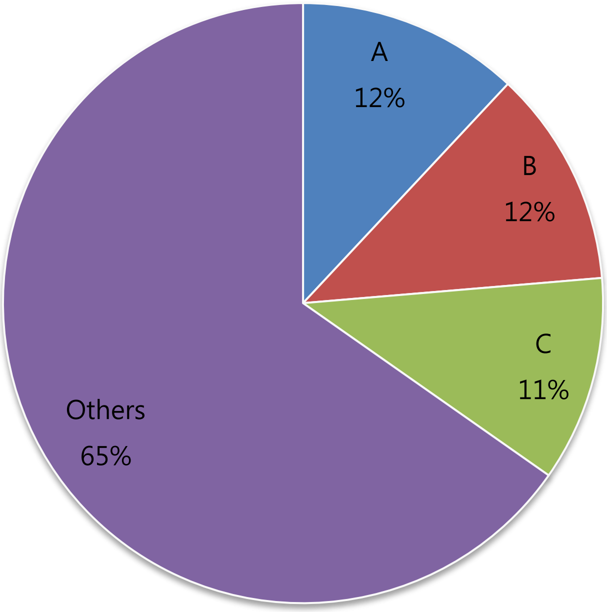
The top three sectors are

A - Other basic organic chemical manufacturing

B - Petroleum refineries

C - Plastic pipe and pile fitting manufacturing

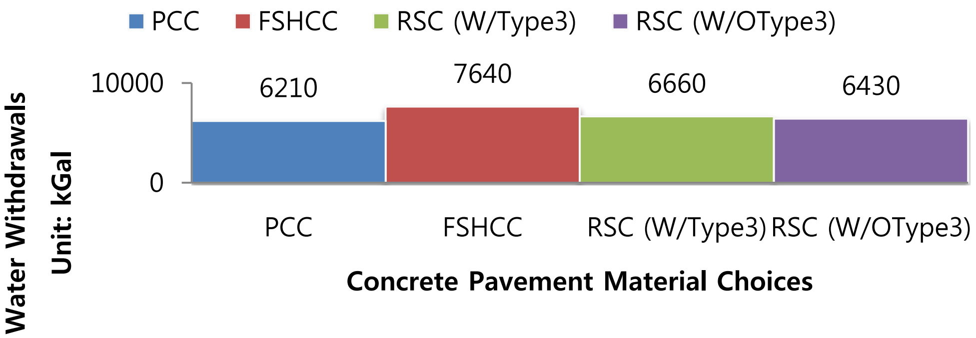
Figure 18. Top3 Contributing Sectors of Toxic Release



5.2.6 Water Withdrawal

Water withdrawal is the process of diverting water from surface and ground water. It is calculated in thousands of gallons (kGal). The Figure 19 and Figure 20 indicate that among all water withdrawal sectors, power generation and supply take over 50 percent of water, followed by paint and coating manufacturing and grain farming. The results also indicate that PCC withdraws less water than others.

Figure 19. Water Withdrawal Results of Four Type of Concrete



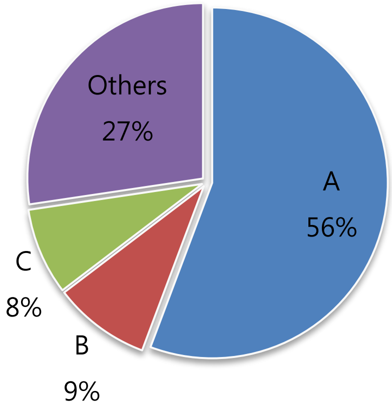
The top three sectors are

A - Power generation and supply

B - Paint and coating manufacturing

C - Grain farming

Figure 20. Top3 Contributing Sectors of Water Withdrawal



5.2.7 Transportation Movement

In this sector, there are eight types of transportation movement: air, oil pipe, gas pipe, rail, water, international air, and international water. The Figure 21 and Figure 22 and Figure 23 shows that among all transportation movement, international water takes more than half of the total transportation movement. PCC requires a small amount of transportation movement. On the contrary, FSHCC needs more transportation movement than others.

Figure 21. Total Transportation Movement Result of Four Type of Concrete

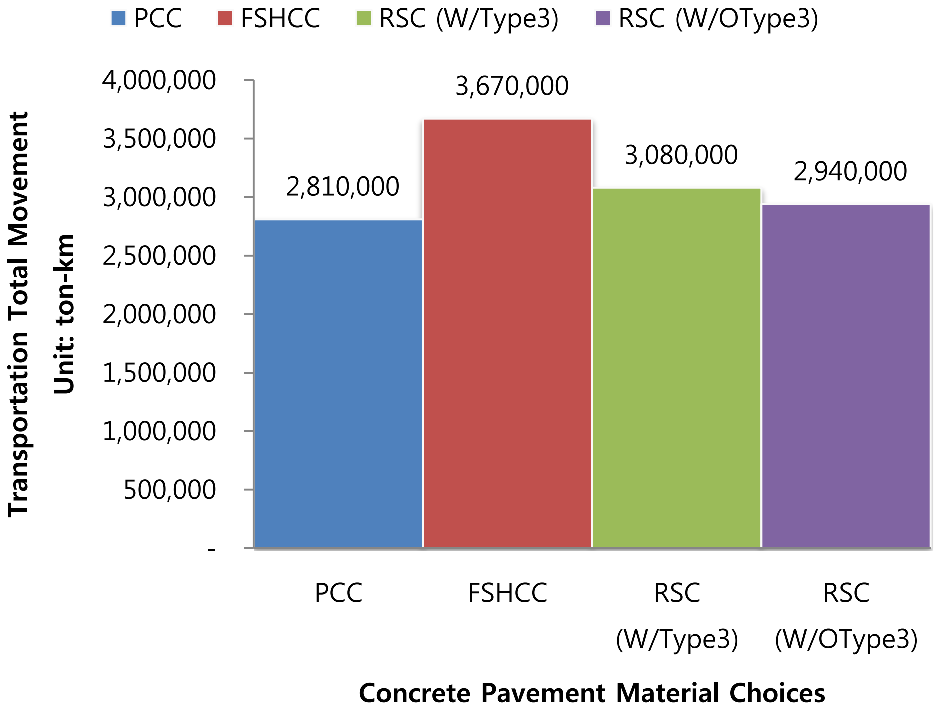
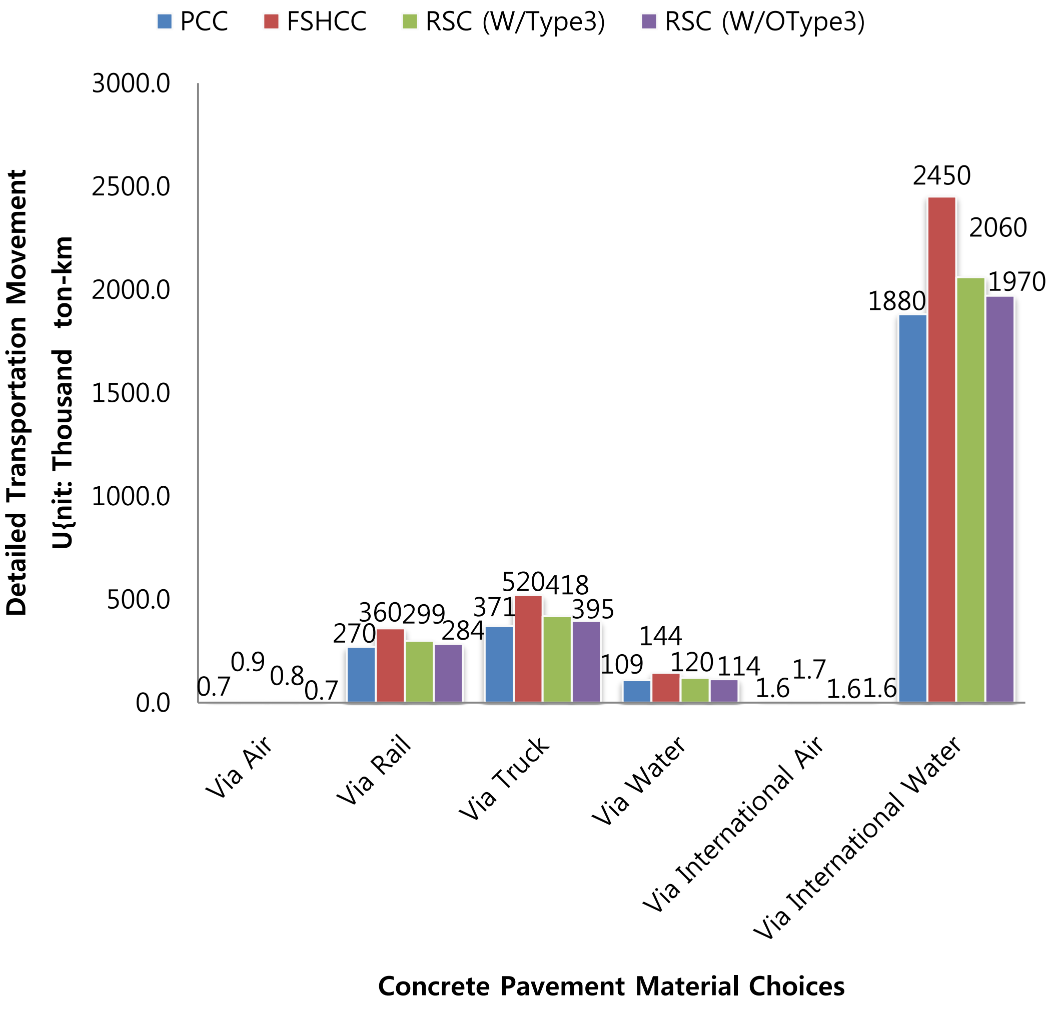


Figure 22. Detailed Transportation Movement Results of Four Type of Concrete



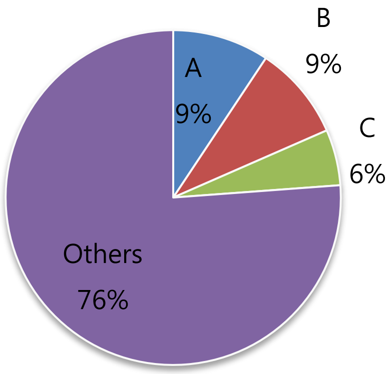
The top three sectors are

A - Ready mix concrete manufacturing

B - Other basic organic chemical manufacturing

C - Plate work and fabricated structural product manufacturing

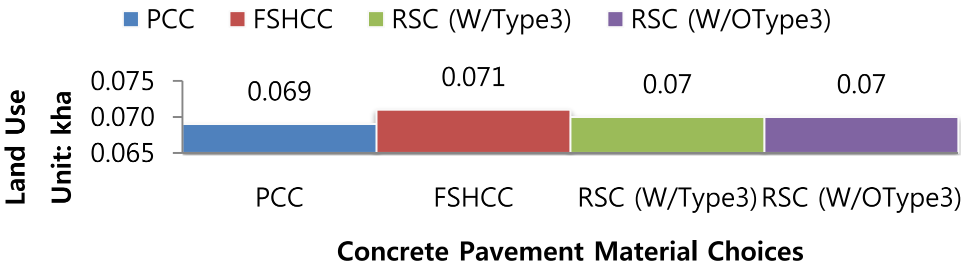
Figure 23. Top3 Contributing Sectors of Transportation Movement



5.2.8 Land Use

Some projects related to transportation affect public communities, business, and land use directly or indirectly. Therefore, when planning the transportation projects, the land use is considered as a significant social impact. Land use sector only deal with spatial demand. The Figure 24 and Figure 25 reveal the results of land use.

Figure 24. Land Use Results of Four Type of Concrete



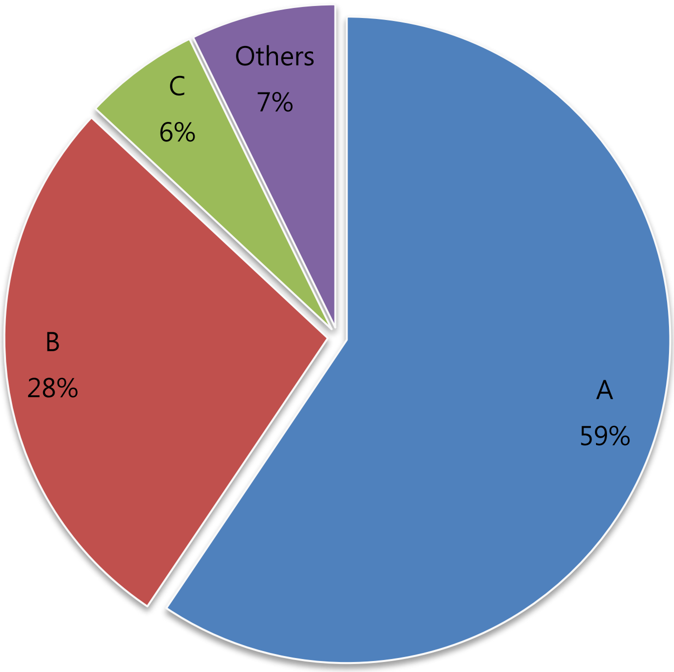
The top three sectors are

A - Logging

B - Forest nurseries, forest products, and timber tracts

C - All other crop farming

Figure 25. Top3 Contributing Sectors of Land Use



5.3 Summary of All Eight Assessments

Typically, according to the outputs of all eight assessments, different types of cement have considerable effects on determining the amounts of economic, environment, and social impacts. Following Table 15 shows the quantity of all eight assessment outputs. The top five contributors of each impact category are shown in Table 16 below. The orders of activities are a slightly different depending on the types of concrete. However, ordering of activities are almost the same. From the results, PCC is a sustainable selection when compared with other concrete pavements, although FSHCC has more negative impacts on economic, environment, and social than others.

Table 15. EIO-LCA for Concrete Pavement Rehabilitation alternatives

EIO-LCA analysis results for concrete pavement rehabilitation strategies							
Impact		**Unit**	**Type**	**Concrete Pavement Rehabilitation Strategies**			
				PCC	**FSHCC**	**RSC (W/Type III)**	**RSC (W/O Type III)**
Economic Impact	Year of Expenditure Dollars	$1 million in 2002	Year of Expenditure Dollars	2.00	2.19	2.06	2.03
Social Impact	Transportation Movement	ton km	Transportation Movement	2,810,000	3,670,000	3,080,000	2,940,000
	Land Use	kha	Land Use	0.069	0.071	0.07	0.07
Environmental Impact	Greenhouse Gases Emission	tCO2e	Global Warming Potential	714.00	936.35	784.76	748.77
			CO2 Fossil	546	672	586	566
			CO2 Process	112	202	141	126
			CH4	40.7	45.9	42.3	41.5
			N2O	10	10.8	10.2	10.1
			HFC/PFCs	5.08	5.65	5.26	5.17
	Energy Use	TJ	Total Energy	9.14	11	9.74	9.44
			Coal	1.89	2.7	2.15	2.02
			Natural Gases	1.89	2.26	2.01	1.95
			Petroleum-Based Fuel	4.22	4.66	4.36	4.29
			Biomass/Waste Fuel	0.375	0.495	0.412	0.393
			31%Non-fossil Fuel	0.765	0.934	0.818	0.792
	Hazardous Waste	short ton	Hazardous Waste	236,000	266,000	245,000	240,000
	Toxic Releases	kg	Fugitive Air	11.2	12.3	11.6	11.4
			Point Air	59	74.3	63.8	61.4
			Surface Water	10.7	11.9	11.1	10.9
			Underground Water	9.49	11.4	10.1	9.79
			Land	109	123	114	111
			Off-Site	46.4	49.1	47.2	46.8
	Water Withdrawals	kgal	Water Withdrawals	6210	7640	6660	6430

Table 16. Top 5 Decisive Activities on Each Analysis Categories

Ordering	**1**	**2**	**3**	**4**	**5**
Economic Transaction	Other nonresidential structures	Architectural and engineering services	Ready-mix concrete manufacturing	Wholesale trade	Management of companies and enterprises
Greenhouse Gases	Other nonresidential structures	Cement manufacturing	Power generation and supply	Oil and gas extraction	Iron and steel mills
Energy Use	Other nonresidential structures	Power generation and supply	Cement manufacturing	Petroleum refineries	Iron and steel mills
Hazardous Waste	Petroleum refineries	Other basic organic chemical manufacturing	Iron and steel mills	Plastics material and resin manufacturing	Other nonresidential structures
Toxic Release	Other basic organic chemical manufacturing	Petroleum refineries	Plastics Pipe and Pipe Fitting Manufacturing	Plate work and fabricated structural product manufacturing	Plastics material and resin manufacturing
Water Withdrawal	Power generation and supply	Paint and coating manufacturing	Grain farming	Stone mining and quarrying	Sand, gravel, clay, and refractory mining
Transportation Movement	Ready-mix concrete manufacturing	Other basic organic chemical manufacturing	Plate work and fabricated structural product manufacturing	Paint and coating manufacturing	Leather and hide tanning and finishing
Land Use	Logging	Forest nurseries, forest products	All other crop farming	Cattle ranching and farming	Grain farming

6 CONCLUSION

Sustainability is critical in delivering highway rehabilitation projects. This study handled the EIO-LCA to analyze the economic, environment, and social impacts for the four main concrete pavements: PCC, FSHCC, RSC with type III Portland cement, and RSC without type III Portland cement. These four concretes are specialized in pavement rehabilitation projects. The quantities of concrete were calculated based on the ASHTTO guide for design of pavement structures. Concrete Price for each alternative was estimated based on 2002 prices because the EIO-LCA model provides the 2002 database. Therefore, to avoid the price difference between 2013 and 2002, this study adjusted the price consulting with the using consumer price index. In this study, 30 years was assumed as the life cycle term for the analysis boundary, because it only applied CRCP, which has a 30 year life cycle as a pavement design. This study conducted the hybrid EIO-LCA models using the 2002 U.S. national purchaser price model. For the input data, the costs of each pavement alternatives were used, which was followed by explanation of the outputs were explained.

According to the assessment results, mainly depending on the types of cement, the quantity of impact in each output was influenced. It means that there exists a relationship between the types of cement and their economic, environmental, and social impacts. According to the Marceau (2007), minor ad-mixtures such as chemicals, consist less than 1 percent of the concrete. In other words, the ad-mixture has nearly no economic, environmental and social impact. However, ad-mixtures, such as fly-ash and slag cement, can reduce the three impacts as a cement substitute. Thus, in the case of general cement use, it is desirable to include these two ad-mixtures in the concrete. However, since PCC, FSHCC and two types of RSC almost never incorporate the fly-ash and slag cement. Therefore, fly-ash and slag cement are not a main concern. These two ad-mixtures have no effect on the results of this study. The price of concrete is affected by the types of cement because the unit price of each cement has a larger gap than any other material. Overall, PCC had the least negative impacts in all eight assessment outputs. Therefore, in case of rehabilitation project, using the PCC is the most economically, environmentally, and socially friendly alternative. If a rehabilitation project were to be done within 4 to 8 hours, agencies will have FSHCC as the only option because only FSHCC can be cured in 4 to 8 hours to reach the satisfactory strength. However, the PCC is recommended as the most sustainable option for the highway rehabilitation project because of its least amount of negative impacts economically, environmentally, and socially. In cases where there is a limited amount of time for a rehabilitation project, the agencies should pay closer attention in choosing a most appropriate alternative pavement type.

The findings of the assessment are followed below:

- In terms of economic impacts, architectural, engineering, and other nonresidential structure sectors cause 50 percent negative effects than others.
- With respect to the environmental impacts, cement is the main cause of greenhouse gas release. Over 45 percent of GWP and energy use comes from cement manufacturing, power generation and supply, and other nonresidential structures. In addition, hazardous waste and toxic release are mainly results from petroleum refineries and other basic organic chemical manufacturing. More specifically, under toxic release categories, the main contributors are land, off-site, and point air. Thus, to reduce of the toxic release, suitable management is needed for storage, landfill, and soil waste.
- In terms of social impact, most transportation movement occurs in international waters for ready mix manufacturing. Therefore, using local materials can reduce international water transportation. Under land use categories, PCC consumed the least land use than the rest.

Lastly, this study reveals that the EIO-LCA could be beneficial to the STAs in their decision making by offering fast and dependable output with economic, environmental, and social impacts. Hence, this study demonstrates that EIO-LCA is an efficient way to evaluate the pavement alternatives for the highway rehabilitation project.

REFERENCES

AASHTO (American Association of State Highway and Transportation Officials). (1993). "Guide for Design of Pavement Structures." American Association of State Highway and Transportation Officials, Washington, DC.

AISI (American Iron and Steel Institute). (2012). “Continuously reinforced concrete pavement: roads for this generation and the next.” *AISI*, <http://www.steel.org/en/The%20New%20Steel/~/media/Files/SMDI/Construction/CRCP%20-%20Marketing%20-%20CRCP%20Brochure.ashx> (Assessed Apr. 8, 2014).

BTS (Bureau of Transportation Statics). (2004). National Transportation Statistics. <http://www.bts.gov/publications/national_transportation_statistics/> (Assessed Apr. 10, 2014).

Berthiaume, R., and Bouchard, C. (1999). “Energy analysis of the environmental impact of paving material manufacture.” *Transactions of the Canadian Society for Mechanical Engineering*, 23(1B), 187–96.

Bloomquist, D., G. Diamond, M. Oden, B. Ruth, and M. Tia. (1993). “Engineering and Environmental Aspects of Recycled Materials for Highway Construction.” - Final Report. Report No. FHWA-RD-93-088. Washington, DC:U.S. Department of Transportation, Federal Highway Administration, and U.S. Environmental Protection Agency.

Caltrans (California Department of Transportation) (2007). "Life-cycle cost analysis procedures manual." C. D. o. Transportation, ed., Secramento, CA.

Clatrans (California Department of Transportation). (2011). “Construction analysis for pavement rehabilitation strategies Caltrans ‘rapid rehab’ software.” *Caltrans*, <http://www.dot.ca.gov/research/roadway/ca4prs/index.htm> (Assessed Sep. 5, 2014)

Caltrans (California Department of Transportation). (2012). “Price index for selected highway construction items.” *Caltrans*, <http://www.dot.ca.gov/hp/esc/oe/contract_progress/cost-index-`summary.pdf> (Assessed May, 23, 2014)

Carnegie Mellon University Green Design Institute. (2014). “Economic Input-Output Life Cycle Assessment (EIO-LCA) Model”, <http://www.eiolca.net/> (Accessed Feb. 22, 2014)

Choi, K., and Kwak, Y.H. (2012). “Decision-support model for incentives/disincentives time-cost tradeoff.” *International Journal of Automation in Construction*, 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.” *Journal of Construction Engineering and Management*, 138 (3), 323-330.

Chou, J. S., and Le, T. S. (2011). "Reliability-based performance simulation for optimized pavement maintenance." *Reliability Engineering & System Safety*, 96(10), 1402-1410.

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

EPA (Environmental Protection Agency). (2011). “Defining life cycle assessment.” <http://www.gdrc.org/uem/lca/lca-define.html> (Accessed Aug. 30, 2014)

Eccleston, C. H., and March F. (2011). *Global environmental policy concepts, principles, and practice*, CRC Press, Boca Raton, FL.

Embacher, R. A., and Snyder, M. B. (2001). "Life-Cycle Cost Comparison of Asphalt and Concrete Pavements on Low-Volume Roads; Case Study Comparisons." *Transportation Research Record: Journal of the Transportation Research Board*, 1749, 28-37.

FHWA (Federal Highway Administration). (1998). *Life cycle cost analysis in pavement design demonstration project 115 –participant handbook*, Washington, DC.

FHWA (Federal Highway Administration). (2006a). “Geotechnical aspects of pavements.” Washington, DC.

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

FHWA (Federal Highway Administration) (2008). "Highway Statistics 2008." FHWA. ed., <http://www.fhwa.dot.gov/policyinformation/statistics/2008/>. (Accessed Aug. 30, 2014)

FHWA (Federal Highway Administration) (2011). "Our Nation's Highway.", FHWA. ed., Washington D. C.

Gopalakrishnan, K. (2011). *Sustainable Highways, Pavements and Materials,* Transdependenz LLC.

Horvath, A. (1997). "Estimation of Environmental Implications of Construction Materials and Designs Using Life-Cycle Assessment Techniques." PhD Diss., Carnegie Mellon University.

Herbsman, Z., Chen, W. T., and Epstein, W. C. (1995). "Time is money: Innovative Contracting Methods in Highway Construction." *Journal of Engineering and Management,* ASCE, Vol.121, No. 3 273-281.

Horvath, A., and Hendrickson, C. (1998a). "Steel versus steel-reinforced concrete bridges: Environmental assessment." *Journal of Infrastructure Systems*, 4(3), 111-117.

Horvath, A., and Hendrickson, C. (1998b). "Comparison of environmental implications of asphalt and steel-reinforced concrete pavements." *Transportation Research Record: Journal of the Transportation Research Board*, 1626 (13), 105-113.

Hendrickson, C., Horvath, A., Joshi, S., and Lave, L. (1998). "Economic input-output models for environmental life-cycle assessment." Environmental Science and Technology, 32(7), 184-191.

Hendrickson, C., Lave, L. and Matthews, H. (2006). *Environmental life cycle assessment of goods and services: an input-output approach*. Washington, DC: Resources for the Future, Print.

ISO (International Organization for Standardization). (1997). Environmental management- Life Cycle Assessment-Principles and Framework. ISO 14040:1997. Geneva:ISO

IRF (International Road Federation). (2010). *World road statistics 2010*, Geneva, Switzerland *National Academy of Engineering, Grand Challenges for Engineering*. <http://www.engineeringchallenges.org/cms/8996/9221.aspx> (Accessed Aug. 1, 2014)

Kucukvar, M., and Tatari, O. (2011). “Ecologically based hybrid life cycle analysis of continuously reinforced concrete and hot-mix asphalt pavements.” Transportation research Part D: Transport and Environment.

Kim, B., Lee, H., Park, H., and Kim, H. (2012). “Framework for estimating greenhouse gas emissions due to asphalt pavement construction.” *Journal of Construction Engineering and Management*, 138(11), 1312-1321.

Lane, D. S. (1998). “Evaluation of Concrete Characteristics for Rigid Pavements.” Charlottesville: Virginia Transportation Research Council.

Long-life. (2007). “Long-life Pavement Rehabilitation Strategies,” California Department of Transportation at <http://www.dot.ca.gov/research/roadway/llprs/indes.htm> (Accessed Aug. 30, 2014)

Lee, E. B., and Ibbs, C. (2005). "Computer simulation model: Construction analysis for pavement rehabilitation strategies." *Journal of Construction Engineering and Management*, 131, 449.

Lee, E. B., J. R. Roesler, J. T. Harvey, and C. W. Ibbs. (2002). “Case Study of Urban Concrete Pavement Reconstruction on Interstate 10,” *Journal of Construction Engineering and Management, ASCE*, Vol. 128(1), pp. 49–56.

Lange, D., and Roesler, J. (2006). “Value Engineering for OMP Pavement Design.” University of Illinois.

Labi, S., and Sinha, K. C. (2005). "Life-cycle evaluation of flexible pavement preventive maintenance." *Journal of Transportation Engineering*, 131, 744.

Muga, H., Mukherjee, A., mihelcic, J., and Kueber, M. (2009). “An integrated assessment of continuously reinforced and jointed plane concrete pavements.” *Journal of Engineering Design Technology*, 7(1), 81-98.

Marceau, M., Nisbet, M. A., Van Geem, M. G., and Association, P. C. (2007). *Life Cycle Inventory of Portland Cement Concrete*, Portland Cement Association.

Mindess., Sidney., and Francis, Y. j. (1981) *Concrete*. Englewood Cliffs, N.J.: Prentice-Hall, Print.

Nemati, K. M., Uhlmeyer, J., Pierce, L., and Powell, J. (2003). "Accelerated Construction of Urban Intersections with Portland Cement Concrete Pavement (PCCP)." *Final Report, Federal Highway Administration.*

Ochoa, L., Hendrickson, C., and Matthews, H. (2002). "Economic input-output life-cycle assessment of US residential buildings." *Journal of Infrastructure Systems*, 89(4), 132-139

Pavement Consultancy Services. (1991). *Guidelines and Methodologies for the Rehabilitationof Rigid Highway Pavements Using Asphalt Concrete Overlays.* Beltsville, ML.

Park, K., Hwang, Y., abd Seo, H.(2003). “Quantitative assessment of environmental impacts on life cycle of highways.” *Journal of Construction Engineering and Management*, 129, 25.

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

Rogers, M. (2003). *Highway engineering*, Wiley-Blackwell Ltd., Malden, MA.

SAIC (2006). "Life Cycle Assessment: Principles and Practice." N. R. M. R. Laboratory, ed., the US Environmental Protectuon Agency (EPA).

Sathiyakumari, K. (2010). “A tree based model for high performance concrete mix design,” *International Journal of Engineering Science and Technology*, 2(9), 4640-4646.

Statistics, B. o. L. (2014). “Consumer Price Index: All Urban Consumers (CPI-U).” <ftp://ftp.bls.gov/pub/special.requests/cpi/cpiai.txt> (Accessed Aug. 30, 2014).

Salem, O., AbouRizk, S., and Ariaratnam, S. (2003). "Risk-based life-cycle costing of infrastructure rehabilitation and construction alternatives." *Journal of Infrastructure Systems,* 9, 6

Sugar, R. S., and California. (2001). *Rapid strength portland cement concrete*. Sacramento, Calif.: California Dept. of Transportation.

Shine, K. P., Fuglestvedt, J.S., Hailemariam, K., and Stuber, N. (2005). “Alternatives to the global warming potential for comparing climate impacts of emissions of greenhouse gases.” *Climate Change*, 68(3), 281-302.

Santero, N. J., Harvey, J., and Horvath, A. (2011). "Environmental policy for long-life pavement." *Transportation Research Part D: Tansport and Environment,* 16(2), 129-136

TxDOT (Texas Department of Transportation) (2011). "Pavement Design Guide." T. D. o. Transportation, ed., Austin, TX.

Treloar, G. J., Love, P. E. D., and Crawford, R. H. (2004). “Hybrid life-cycle inventory for road construction and use.” *Journal of Construction Engineering and Management*, 130, 43.

U.S. DOT (U.S. Department of Transportation). (1993). A Study of the Use of Recycled Paving Material: Report to Congress. Report FHWA-RD-93-147, EPA/600/R-93/095. Washinton, DC: Federal Highway Adminisration

Uhlmeyer, J., and Russell, M. (2013). *Dowel Bars for New and Existing Concrete Pavements* (No. 13-01-0001702). Construction Division State Materials Laboratory , Washington State Department of Transportation.

Viljoen, P. S. (1981). Incentive Management Techniques for Pavement Rehabilitation Construction. Ph. D. Dissertation, University of California at Berkley, Berkeley, CA.

Vesgisky, D., and Nickerson R. L. (1993). Highway Bridges: Life Cycle Costs versus Life Cycle Performance. Better Roads May:33-35.

WCED, (1987), *Our Common Future,* Brundtland Report, World Commission on Environment and Development, Oxford University Press, Oxford

WSDOT (Washington State Department of Transportation). (2011). “WSDOT pavement guide.” *WSDOT,* <http://training.ce.washington.edu/wsdot/> (Accessed Aug. 24, 2014)

Weiland, C., and Muench, S. T. (2010). “Life-Cycle Assessment of Reconstruction Options for Interstate Highway Pavement in Seattle, Washington.” Transportation Research Record: *Journal of the Transportation Research Board*, 2170(-1), 18-27.

Zapata, P. and Gambatese, J.A. (2005). “Energy consumption of asphalt and reinforced concrete pavement materials and construction.” *Journal of Infrastructure Systems*, 11(1), 9–20.