DEVELOPMENT OF THE MATERIALS, CONSTRUCTION, AND MAINTENANCE PHASES OF A LIFE CYCLE ASSESSMENT TOOL FOR PAVEMENTS

BY

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THESIS

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ABSTRACT

The heightened interest in sustainability applied to the roadway industry has highlighted the need for suitable quantitative analysis tools for assessing the environmental impact of sustainability, including economic and societal impacts. At present, there are qualitative tools to assess sustainability, such as the Infrastructure Voluntary Evaluation Sustainability Tool (INVEST), and a few researchers are producing life cycle assessment (LCA) tools to quantitatively assess the environmental side of sustainability in terms of impacts such as global warming potential and total energy demand. This research study details the creation of a regionalized LCA tool, particularly for concrete pavements, focusing on the methodology of the construction and maintenance/rehabilitation phases with collaborative studies investigating the materials, use, and end-of-life phases.

A tool verification study investigated the environmental impacts of the materials, construction, and maintenance/rehabilitation phases for a rigid pavement roadway. Cement, which had the highest impact for concrete in the materials phase, can be replaced with supplementary cementitious materials (SCMs) such as fly ash or ground granulated blast furnace slag (GGBFS) to reduce total energy and emissions by 14% to 29% for cement replacements of 35%. Construction impacts were relatively low compared to the materials phase, but practices such as two-lift paving can impact the materials phase and reduce total energy and global warming potential by 13.9% and 23.8%, respectively, when the bottom lift utilizes significant amounts of SCMs and recycled aggregates. The maintenance phase was found to be a significant contributor to the life cycle impacts, mainly because of the materials required for the activities, which accounted for 90% of the total energy and global warming potential, in the maintenance phase. Many of these results from the verification study were supported by previous findings reported in the literature.

A hypothetical case study comparing continuously reinforced (CRCP) and jointed plain (JPCP) concrete pavements was performed to demonstrate the capabilities of the LCA tool in the materials, construction, and maintenance phases. The total energy and global warming potential were found to be 10.6% and 4.9% higher, respectively, for the CRCP design relative to the JPCP alternative, when considering the full life cycle, i.e., 78 and 62 year service life, respectively. When the results were annualized to a per year basis, the CRCP design was 12.5% and 19.6% lower than the JPCP design in terms of total energy and global warming potential, respectively.

The results of this case study indicate that CRCP can be a sustainable pavement alternative relative to JPCP under certain design conditions. The use phase impacts should not be neglected as they have been shown to be a significant contributor in the life cycle. This LCA tool has been shown to provide a quantitative assessment of the environmental impacts of a roadway, in the materials, construction and maintenance phases, that can be used in conjunction with life cycle cost analysis to make more sustainable decisions.

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CHAPTER 1 INTRODUCTION

1.1 Roadway Life-Cycle Assessment

In recent years, there has been an increased demand to consider sustainability for infrastructure projects and more specifically, the pavement system. Roadway construction and maintenance are labor, equipment, and material intensive processes that use an abundance of natural resources and energy. In addition, the use of the roadway has a significant impact on vehicle energy/fuel usage and emissions. With the higher focus on sustainability leading to conservation of natural resources and emissions reductions, it is important to evaluate the various steps in a roadway's life cycle to determine areas of improvement. This begins with planning and designing a roadway utilizing sustainable practices, and continues with sustainable construction, maintenance, rehabilitation, and end of life strategies.

Sustainability is not a term that applies solely to emissions and energy consumption, but it is a balance of economic, environmental and societal impacts as displayed in Figure 1-1. Many times in designing a sustainable roadway, optimizing one of the three aforementioned impact factors will have positive effects on the others, but not always. For example, recycled materials and waste materials are typically less expensive than virgin materials, which make them economically attractive for utilization in new pavements. Utilization of recycled materials reduces the emissions and energy consumption associated with production of virgin materials. The use of recycled materials can be limited by two factors. The first factor is performance, as an increase in recycled material may decrease the service life of a roadway, resulting in increased maintenance intervals and reduced rehabilitation life. The second factor is the availability of quality recycled materials. If recycled materials are not locally available, and a surplus of equivalent virgin material is locally available, then the benefits of using recycled materials may be negligible compared to the impact of transporting it to the area. Other factors may contribute to sustainable pavement choices like shipping high quality aggregates large distances to increase skid resistance, which has a negative environmental and economic impact but is highly valued as a societal safety factor.

Figure 1-1 Sustainability is a Balance of Choices Considering Economic, Environmental, and Societal Impacts

Designing a sustainable roadway requires many considerations. In addition to the initial pavement design, it is necessary to consider the maintenance and rehabilitation activities that the pavement will require to reach the desired design life. Beyond the pavement, there are other considerations that can affect sustainability such as lighting, noise walls, bridges, barriers, drainage pipes, and ditches which all provide necessary functions but can be impacted or influenced by the pavement design. These can all have an impact on the sustainability of the roadway as a whole. While the economic impacts of creating a roadway can be reasonably well-defined through the use of life-cycle cost analysis (LCCA), characterizing the environmental and societal effects can be much more difficult. One methodology used to define the environmental impact of a product is life-cycle assessment (LCA). LCA analyzes and quantifies the environmental impacts of a product, beginning with the extraction or creation of the raw materials of the product and continuing all the way through the end of the product's life, or simply, "from cradle to grave." This method can be used to help consider the environmental impacts of the product's whole life in the design phase. LCA can also be applied to consider the environmental impact of the structures (bridges, noise, walls, barriers) and drainage (ditches, drainage pipes) aspects of the roadway.

LCAs quantify the environmental impact of creating and using a product by calculating the energy consumption and emissions associated with the product (e.g., pavement structure), and it either outputs or uses these values to calculate grouped impact factors, such as global warming potential and toxicity, through the process of life-cycle impact assessment. The purpose of impact factors is to simplify and categorize the numerous emissions and consumed energy into simple and comparable factors. While energy consumption and emissions are closely linked, they are not necessarily the same. Cleaner sources of energy, such as natural gas relative to diesel fuel, can produce fewer emissions and lessen the environmental impact. The various impact factors aggregate emission outputs so that designs can be compared without analyzing individual emission quantities. Application of LCA to pavement design, construction, maintenance and rehabilitation, and end of life considerations can be a valuable process to evaluate environmental sustainability of a set of design decisions.

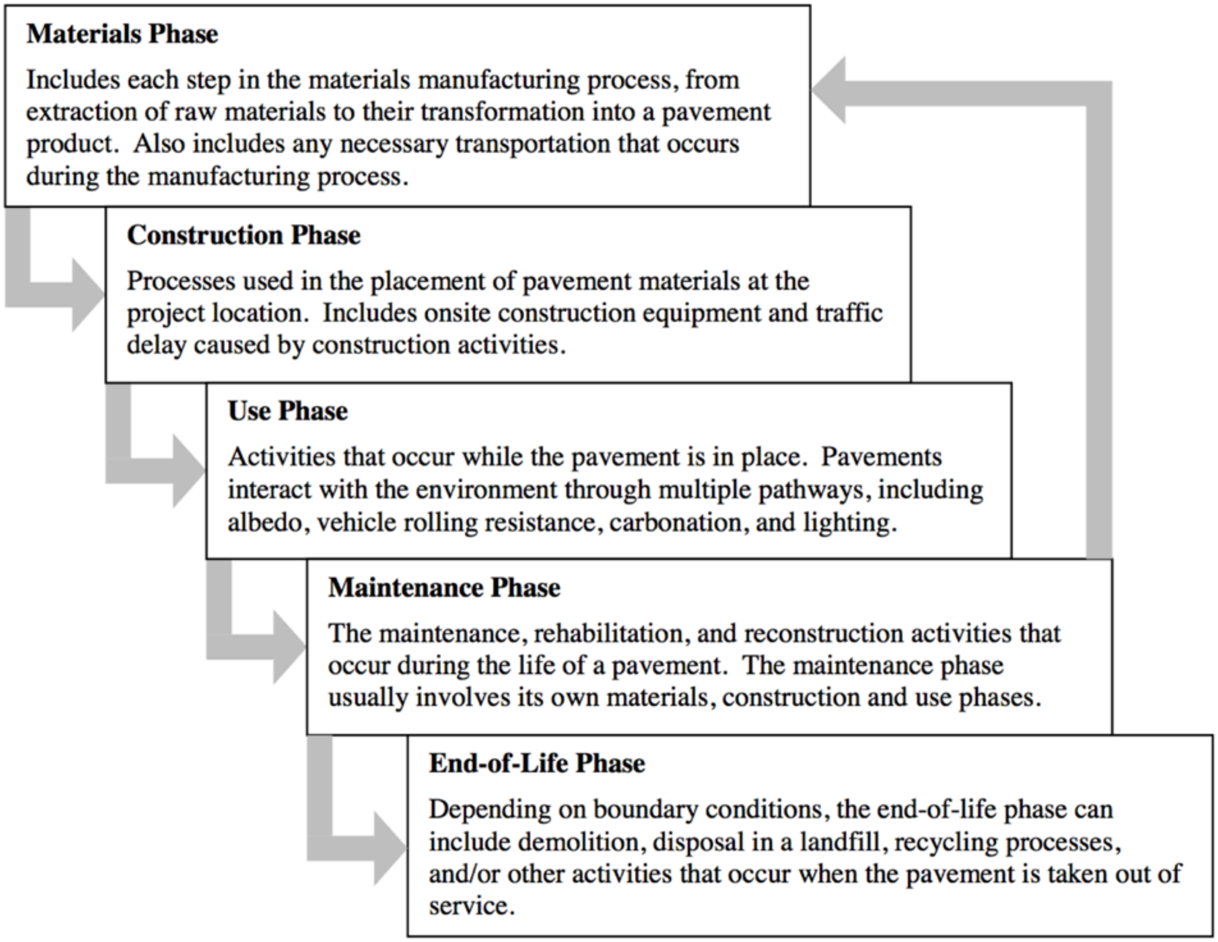
An LCA typically takes the form of literature or software analysis (SANTERO, 2009). Santero (2009) compiled an evaluation of a number of LCAs and concluded that most literature LCAs are actually life-cycle inventories (LCIs) which may quantify the environmental impact of one or two designs of a roadway but does not actually go through a life-cycle impact assessment (LCIA) to produce impact factors. This is a required step of LCA based on the methodological framework set down by International Organization for Standardization (ISO) 14040 (1997). Many of these examples studied the energy consumption and emissions associated with building a roadway with one or two pavement designs. A literature LCA typically analyzes a few specific cases or designs of a product and can many times be categorized more as a Life Cycle Inventory (LCI). A software-based LCA uses inventory data to calculate the energy and emissions from the life-cycle of a product and then outputs impact factors through the LCIA. Software-based LCAs can be designed such that any pavement design can be evaluated and multiple maintenance and rehabilitation plans can be applied to see the environmental impact of different policies.

LCAs have five major phases which include materials, construction, use, maintenance and end-of-life. A basic breakdown of the phases can be seen in the Figure 1-2. The boundary between the phases is not always clear and must be explicitly defined when evaluating products. Each LCA phase with respect to the roadway is briefly described as follows:

1. Materials Phase - extraction and production of the raw materials for the creation of the product. For a roadway, this would include the quarrying of aggregates and the extraction and creation of asphalt binder and cement.

2. Construction Phase - assembles the raw materials to the product's final usable form. This would be the initial construction of the roadway, including clearing the site, preparing the subgrade, placing the base and subbase and paving the surface layers.

3. Use Phase - energy and emissions associated with the product while it is in use. The use phase of a roadway includes such items as the lighting of the roadway and the vehicle emissions because of tire-pavement interaction (rolling resistance).
4. Maintenance and Rehabilitation Phase - minor repairs applied to keep the product functional. An effectively maintained roadway may have a number of patches, overlays, and other minor maintenance activities, such as filling potholes and sealing cracks and joints, during the pavement life-cycle. Materials utilized during the maintenance phase must be quantified in this phase such as asphalt or concrete mixes for patching or overlays.
5. End-of-life Phase - recycling and/or landfilling of the product for reuse or disposal. Removal and demolition of the existing roadway structure to be used as a new unbound layer (e.g., recycled concrete aggregate (RCA) as a granular subbase layer) and/or to produce materials for partial reuse in a new stabilized layer such as reclaimed asphalt pavement (RAP) in asphalt surface or binder layer.



Materials Phase

Includes each step in the materials manufacturing process, from extraction of raw materials to their transformation into a pavement product. Also includes any necessary transportation that occurs during the manufacturing process.

Construction Phase

Processes used in the placement of pavement materials at the project location. Includes onsite construction equipment and traffic delay caused by construction activities.

Use Phase

Activities that occur while the pavement is in place. Pavements interact with the environment through multiple pathways, including albedo, vehicle rolling resistance, carbonation, and lighting.

Maintenance Phase

The maintenance, rehabilitation, and reconstruction activities that occur during the life of a pavement. The maintenance phase usually involves its own materials, construction and use phases.

End-of-Life Phase

Depending on boundary conditions, the end-of-life phase can include demolition, disposal in a landfill, recycling processes, and/or other activities that occur when the pavement is taken out of service.

Figure 1-2 Phases of the pavement life-cycle (SANTERO, 2009)

As previously discussed, the pavement is only one part of the larger roadway infrastructure. A roadway LCA can encompass the life-cycle of all components including the pavement structure, lighting, noise walls, structures (bridges, barriers, etc.), and drainage components (ditches, piping, etc.). This research assists in the development of a roadway software-based LCA tool to determine the overall impact of creating, maintaining, and utilizing a roadway with a focus on the concrete material production, construction, and maintenance phases. Other details on the development of this software-based LCA tool are described in studies by Kang (2013) and Yang (2014), which are briefly overviewed later in Chapter 1.

The software-based LCA tool is being developed for the Illinois State Toll Highway Authority (Tollway) to assess the progress of developed and adopted sustainable roadway practices. The goal of this tool is to illustrate major impacts of creating new innovative roadway designs in comparison to the Tollway's standard practices in past years. One specific example is the use of fractionated reclaimed asphalt pavement (FRAP) as a partial replacement of coarse aggregate in concrete as well as FRAP in asphalt concrete shoulders and stabilized base layers. The LCA tool can be utilized by designers to show the increased sustainability of new designs, construction and maintenance practices, as well as their impact on the use of the pavement to relative previous standards and practices.

1.2 Formation of Regionalized LCA

There are a number of available tools to assess sustainability. Some of these tools are qualitative, such as the Leadership in Energy and Environmental Design (LEED) and the Infrastructure Voluntary Evaluation Sustainability Tool (INVEST) and perform as sustainability rating systems. A few of the tools are quantitative such as the Athena Institute Estimator for Highways and PaLate. The quantitative tools, which take the form of LCAs, are typically not regionalized tools and occasionally use outdated inventory databases. The purpose of creating a regionalized LCA tool is to more accurately calculate the environmental burden for the Illinois region's practices of road building. This can highlight areas in which the region is excelling in sustainability, in addition to identifying areas where certain processes can be improved.

To create a regionalized LCA, significant data must be collected and interpreted from local suppliers of aggregates, cementitious materials, and bituminous materials, in addition to the process and equipment contractors use to build and/or maintain the roadway. Any improvement in one of these components could impact the sustainability of the roadway and thus must be quantified. This data makes up the life cycle inventory database of the LCA.

The creation of this LCA tool is a vast undertaking and takes a team of researchers working on different parts of the tool. Kang's (2013) study provides an in depth look at the regionalized materials LCI database including data collection and inventory analysis for various pavement materials. Yang's (2014) study details the creation of an asphalt binder model for the materials LCI database while also describing the development of the framework for this LCA tool. This research study provides details on the data collection for the construction, maintenance and rehabilitation LCI database for the LCA tool. In addition, this study includes case studies to demonstrate the capabilities of the developing LCA tool. The case studies investigate the effects of utilizing various materials in concrete layers, construction maintenance activities, and compares full-scale studies using jointed plain concrete pavement (JPCP) and continuously reinforced concrete pavement (CRCP) with prescribed maintenance plans.

1.3 Literature Review/Previous Work

There are a number of different studies detailing the development of LCAs and LCI databases and a few programs that have been developed that can be used to perform roadway or pavement LCAs. Many of these pavement LCAs are not full LCAs as most leave out one or more of the phases typically because of a lack of necessary data. There are a few detailed summaries of existing pavement LCA literature including the studies by Kang (2013) and Santero (2009) in addition to a two-part review by Santero et al. (2011a; 2011b). This section details a few of the current LCA programs, and highlights certain benefits and disadvantages of each. In addition a brief discussion of some of the literature-based studies is included.

1.3.1 Athena Impact Estimator for Highways

The Athena Impact Estimator for Highways (2013) is an LCA software developed by the Athena Sustainable Materials Institute. It is designed for use in the North American region. It encompasses four of the five LCA stages including material manufacturing, roadway construction, maintenance, and use phases. Typically the use phase is the most neglected because of the relative lack of information and data. To analyze the impacts of the use-phase, pavement vehicle interactions models are required. This is done by taking into account the roadway roughness, in the form of IRI, and deflection modulus of the pavement system. Athena excludes the end-of-life phase because of the long service life of the highways to be evaluated.

1.3.2 Pavement Life-cycle Assessment Tool for Environmental and Economic Effects (PaLate)

PaLate is an Excel-based LCA tool that was originally developed at the University of California in 2003 (Horvath, 2003). The tool encompasses the material, construction, maintenance, and end-of-life phases and reports energy use, water consumption, and various emissions. In 2012 this tool was superseded by the web based tool Roadprint Online (Lin & Muench, 2012). The new version of the tool reports only energy use and global warming potential (GWP).

1.3.3 Project Emission Estimator (PE-2)

The Project Emission Estimator (PE-2) is an online LCA tool that encompasses the material, construction, use, and maintenance phases or a roadway and reports greenhouse gas (GHG) emissions (Mukherjee & Cass, 2012). In addition to the end-of-life phase being omitted, the use phase does not account for rolling resistance component of the pavement-vehicle interaction.

1.3.4 Literature Case Studies

One of the popular subjects for case studies is the comparison of concrete versus asphalt pavements. Stripple (2001) studied four LCA phases (excluding the use phase) and compared 40-

year life cycles of concrete and asphalt given a 1-kilometer long pavement section. Stripple (2001) found the asphalt design to be more environmentally friendly based on lower energy and CO_2 emissions. The study also estimated the energy consumption of the traffic assuming an ADT of 5,000 which resulted in greater energy consumption than either the asphalt or concrete pavement designs. Santero (2009) and Häkkinen and Mäkelä (1996) also found traffic impacts to be significant with the latter study finding that the traffic and lighting had the greatest environmental impact.

A study by Zhang et al. (2008) also compared asphalt and concrete in addition to a fiber reinforced composite. The asphalt design had the highest energy consumption (nearly twice that of concrete) and the greenhouse gas emissions were relatively similar. Similarly, a study by the Athena Institute (2006) found concrete to be advantageous in both energy consumption and global warming potential.

Much of the difference between the concrete and asphalt environmental burden can be attributed to the structural designs used in the analysis and the inventory data applied. It is not uncommon for multiple studies to use the same inventory data, which ultimately leads to similar results.

While there are numerous studies on the environmental differences between asphalt and concrete pavements, there has been little study devoted to the differences in concrete pavement types (i.e. jointed plain [JPCP] and continuously reinforced concrete pavement [CRCP]). One study investigated the LCA and life-cycle cost of JPCP relative to CRCP (Muga et al., 2009). This study considered the materials extraction, construction, and maintenance phases of LCA but primarily focused on the materials extraction. The study also investigated the impacts of the use of fly ash and slag as replacements of cement finding significant reductions in emissions with the use of both supplementary cementitious materials. JPCP was found to have almost 32.7 to 62 percent less emissions than CRCP in the materials phase primarily because of the increased steel content.

CHAPTER 2 LIFE-CYCLE ASSESSMENT PHASE DEVELOPMENT

This chapter presents the development of a few of the phases of the life-cycle assessment (LCA) tool. The first section presents the data validation for the materials phase related to concrete materials. The second section explains the creation of the construction and maintenance phases of the LCA tool, detailing the methodological approach behind this phase.

2.1 Concrete Materials Phase Data Collection and Validation

Concrete materials typically include crushed and natural aggregates, recycled aggregates (reclaimed asphalt pavement [RAP] and recycled concrete aggregate [RCA]), cement, and supplementary cementitious materials (SCMs) such as fly ash and ground granulated blast furnace slag (GGBFS). The formation of these construction materials is accounted for by tracking them to their initial raw material stages, i.e. extraction from the quarry or other by-product processes. Since cement is the most energy intensive material used to construct concrete pavements (kiln heating process reaches approximately 1500 ^{o}C [Mindess et al., 2003]), it is important to have accurate regional data for its embodied energy and emissions.

The data for the LCA tool is based on literature data in addition to regionalized questionnaire data. All questionnaire data was scrutinized to determine plausibility and validity. Any questions that arose from the questionnaire data were addressed by further inquiry to the questioned party to ensure accuracy. The complementary studies by Kang (2013) and Yang (2014) provide details on the data collection and analysis for the materials phase. Yang’s study provides the most up to date information on the data for the materials phase in the tool. Table 2-1 provides a succinct look at the data origin for the inventory database from Yang’s study (2014).

Table 2-1 Concrete Materials Phase Data Sources (Adapted from Yang, 2014)

Material	**Unit**	**Major Source**
Cement	tn.sh	PCA (2007)
GGBFS	tn.sh	Chen et al (2010), Purinski et al (2004)
Fly Ash	tn.sh	Chen et al (2010)
Sealant	tn.sh	US-EI 2.2
Reinforcing Steel	tn.sh	US-EI 2.2
Crushed Aggregate	tn.sh	US-EI 2.2
Natural Aggregate	tn.sh	US-EI 2.2
RAP	tn.sh	Questionnaire
RCA	tn.sh	Same as RAP
Ready Mix Concrete	CY	Questionnaire
Hauling	tn.sh-mile	MOVES (2013) (regionalized)
Illinois Electricity	kWh	eGRID (2012) (regionalized)

The source for the cement data is from two studies by the Portland Cement Association (2006; 2007). Obtaining regional data for fly ash and GGBFS is difficult because they are by-products with many plants not having detailed information on the allocation of energy consumption and emissions. For this reason, a study by Chen et al (2010) was used for fly ash and GGBFS and a study by Purinski et al (2004) was also added for GGBFS. Data for crushed and natural aggregates was obtained from the US Eco-Invent 2.2 database (2010). A cut-off approach was used for the recycled materials, RAP and RCA, which means only the burdens derived from the processing and handling of the recycled material after removal from the existing pavement is attributed to them. Data for concrete plants was also obtained from regional questionnaire data. The data for material hauling and electricity were obtained from Environmental Protection Agency programs, Motor Vehicle Emission Simulator (MOVES) (EPA, 2013) and eGRID (EPA, 2012), respectively, with each utilizing regionalized data.

2.2 Construction and Maintenance Phases Development Methodology

In order to regionalize the construction and maintenance phases, questionnaires were distributed regional contractors in order to accurately characterize the practices and equipment used in the region. Unfortunately, no questionnaires were returned and thus the construction and maintenance phases are currently only populated with literature data. The organization of these two phases allows for the incorporation of regionalized questionnaire data as it is obtained in the future.

This section breaks down the construction and maintenance phase hierarchy shown in Figure 2-1. The first subsection explains the purpose and development of construction tasks for the initial pavement design. The second subsection describes the creation of the construction equipment database used in the life-cycle inventory (LCI). The third section expands the construction equipment database to include more detailed emission factors from construction equipment. The final section groups the individual construction equipment's emissions into reported impact factors.

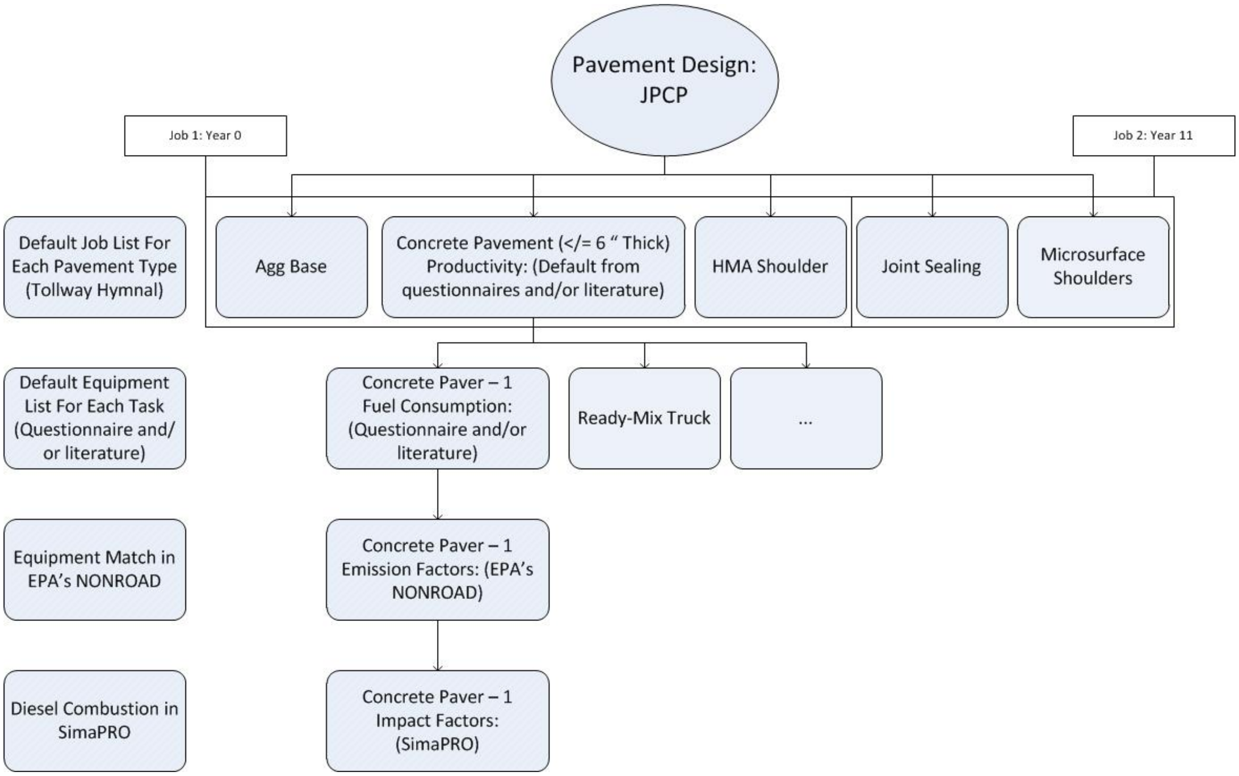


Figure 2-1 Construction and Maintenance Module Hierarchy

2.2.1 Construction and Maintenance Tasks Development

The most important input into the LCA tool is the pavement structural design, which affects every phase of the LCA. In the materials phase, it determines the type, component, source, and amount of materials required to build the pavement. Concrete pavement and asphalt pavement share aggregate as a similar material but the asphalt and cement components have vastly different production processes, which in turn generate very different emissions levels. In the construction phase, the pavement design determines which equipment will need to be used to transform the individual materials into layered systems and ultimately a single product. Concrete paving requires specialized equipment such as a slip-form paver and saws while asphalt pavement construction requires equipment such as an asphalt paver and material transfer device. The pavement design also impacts the use phase of the LCA, since concrete and asphalt pavements have different interactions with vehicles because of the rigidity, smoothness, and surface texture of the pavement. Maintenance and rehabilitation activities will differ with the pavement type and design with some pavements requiring more frequent maintenance work in the form of crack sealing, addressing localized distress, and minor overlays. Finally, the pavement design dictates how the pavement can be recycled. Pavements can be crushed or cold milled into recycled aggregates (RCA and RAP), landfilled, or utilized as a support layer for a structural overlay.

In this tool, the pavement design determines what tasks need to be performed to transform the construction materials and site into pavement layers, and what tasks need to occur throughout the pavement life cycle to meet its performance requirements. Tasks group individual construction equipment to perform a specific construction or maintenance activity. The tasks in this LCA tool are based on the construction task framework described in NCHRP *Fuel Usage Factors in Highway and Bridge Construction Report 744* (Skolnik et al., 2013). Additional tasks specifically used by the Tollway have also been developed. Examples of tasks include crack sealing and paving a certain thickness of concrete or asphalt. The paving tasks include the equipment needed by that task to transform the concrete or asphalt into a pavement layer. Multiple tasks are used to build the pavement structure as each layer requires at least one task to be built. The tasks can be classified into one of the following groups: paving, clearing, pavement removal, finishing, marking, stripping, stabilization, granular layer, earthwork, patching, grinding, cracks, surfacing, and joints. Table 2-2 summarizes the current task list and the associated groupings used in the LCA tool.

Table 2-2 Summary of Construction, Maintenance and Rehabilitation Tasks

Task	Grouping
Clearing – Light	Clearing
Clearing – Medium	Clearing
Clearing – Heavy	Clearing
Grading (Dirt) - Off Road - Long Haul	Grading
Grading (Dirt) - Off Road - Short Haul	Grading
Grading (Dirt) - On Road	Grading
Grading (Rock) - Off Road - Long Haul	Grading
Grading (Rock) - Off Road - Short Haul	Grading
Grading (Rock) - On Road	Grading
Fine Grading	Grading
Milling (<2")	Milling
Milling (2-4")	Milling
Pavement Removal – Asphalt	Pavement Removal
Pavement Removal – Concrete	Pavement Removal
Reinforcing Steel	Reinforcing Steel
Roadbed Finishing	Finishing
Pavement Marking	Marking
Strip Topsoil	Stripping
Topsoil Strip & Stockpile	Stripping
Asphalt Stabilized Sub-base 3"	Stabilization
Porous Granular Embankment 12"	Granular Layer
Earthwork	Earthwork
Patch - Pavement Surface	Patching
Diamond Grind Surface	Grinding
Rout and Seal Cracks	Cracks
Microsurface	Surfacing
Seal Joints	Joints
Base Stone	Paving
Concrete Pavement (</=6" Thick)	Paving
Concrete Pavement (> 6" Thick)	Paving
Two-Lift JPC Pavement 12"	Paving
Single-Lift JPC Pavement 12"	Paving
HMA - Leveling Course	Paving
HMA - Structural Course	Paving
HMA - Surface Course	Paving
Full-Depth HMA Pavement 12"	Paving

Tasks can be combined to perform construction or maintenance jobs. A job is a collection of tasks that is performed at a specific time in the pavement’s life. The entire initial construction would be counted as one job as it would require a number of tasks such as paving the concrete or asphalt and laying the base and/or subbase layers. Tasks also make up jobs scheduled throughout the pavement's life based on the maintenance and rehabilitation schedule. Ten total jobs can be scheduled including initial construction and nine maintenance and rehabilitation activities.

Individual construction tasks are developed to combine the equipment required to build and maintain the pavement. For example, a task such as paving a hot-mix asphalt (HMA) leveling course requires multiple pieces of equipment. A truck transports the HMA material to the site. A material transfer vehicle stores and maintains uniformity of the HMA material on the construction site. The asphalt paver uniformly places the asphalt down on the roadway. A water truck and multiple rollers are used to compact to the specified density and achieve a smooth, durable surface. These six pieces of equipment make up a single task, as each of the pieces of equipment contribute to the creation of the HMA pavement layer. Multiple tasks are combined to define the building and maintaining of the pavement section over its life cycle based on the original construction plan and the maintenance plan for the roadway throughout its life-cycle. The equipment assigned to each task in Table 2-2 can be seen in Appendix Table - 1.

Each task has a productivity based on the equipment utilized. The productivities are based on the historical data reported in NCHRP Report 744 (Skolnik et al., 2013) and collected from the Tollway. The construction task productivity can have a number of different units, such as cubic yards, square yards, tons or longitudinal feet per hour. The productivity is based on the performance of the equipment involved in the task with some equipment playing a larger role than others in increasing or decreasing the task productivity. For this reason, default productivity have been selected for each task based on the historical data in NCHRP Report 744 (Skolnik et al., 2013), and changing the individual equipment will not change the productivity of the task. This results because of the complexity of construction tasks, relying on multiple pieces of equipment that have different production units, along with the Excel constraints of the LCA tool. However, the task productivity can be changed manually to reflect a change in equipment.

The productivity of each of the tasks is linked with the amount of material that needs to be "processed." For example, a given amount of HMA is required to pave a certain thickness, width and length of a roadway. From the density of the HMA, this can be quantified as either tons of HMA or square yards of a given thickness. With the quantity of material being used and the task productivity both known, the amount of hours to complete each task can be determined.

2.2.2 Construction and Maintenance Equipment Database

To determine how much fuel is used by each task while it is processing the material, an equipment database was compiled. The equipment database summarizes all equipment used by the various tasks. Details on all of the equipment are required to determine the energy (typically diesel fuel) consumed and, in turn, emissions released while performing each task. Details of each type of equipment were gathered from various sources to create the equipment database. The important information required by the equipment database is the productivity and fuel/energy consumption. The primary sources of equipment information are the Athena Impact Estimator for Highways (2013), PaLate (Horvath, 2003), a road emissions optimization software (ROADEO) (World Bank, 2011), NCHRP Report 744 (Skolnik et al., 2013), and EPA's Nonroads (2008). The fuel or energy consumption for each construction task can be determine from the equipment fuel efficiency and the number of hours it takes to perform each task which is calculated based on the material quantity.

2.2.3 EPA's NONROADs Emissions Integration

Most construction equipment sources do not have readily available information on their emissions data. To translate the energy consumption data into multiple emission factors, the

Environmental Protection Agency's (EPA) construction equipment emissions software NONROAD (2008) model is utilized. The software provides emissions for a variety of construction equipment, at varying horsepower, including total hydrocarbons (THC), carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NO_x), sulfur dioxides (SO_2), particulate matter (PM), and Crankcase. This model also includes emission data from several years and a variety of months to give a representation of how emission regulations have changed emission output for multiple pieces of equipment. This is important to determine how sustainability has changed in the construction and maintenance and rehabilitation phases because of construction equipment over the years.

The NONROAD model provided information on some, but not all, construction equipment required by the LCA tool. For this reason, it was important to build a database of construction equipment and their productivities and fuel and energy consumptions that could be used in conjunction with the NONROAD model to obtain the emissions of all relevant construction equipment. A list of the pertinent construction equipment featured in the NONROAD model can be seen in the Table 2-3.

Table 2-3 Roadway construction equipment from EPA's NONROADs software (EPA, 2008)

Diesel Construction Equipment	Horsepower Categories (hp)
Pavers	25, 40, 50, 75, 100, 175, 300, 600
Tampers/Rammers	6
Compactors	6, 11, 16, 25
Rollers	6, 11, 16, 25, 40, 50, 75, 100, 175, 300, 600
Scrapers	75, 175, 300, 600, 750, 1000,
Paving Equipment	6, 11, 16, 25, 40, 50, 75, 100, 175, 300, 600
Surfacing Equipment	11, 16, 25,40, 50, 75, 100, 175, 300, 600, 750, 1000, 1200, 2000
Signal Boards	6, 11, 16, 25, 40, 50, 75, 100, 175, 300
Trenchers	6, 11, 16, 25, 40, 50, 75, 100, 175, 300, 600, 750, 2000
Bore/Drill Rigs	11, 16, 25, 40, 50, 75, 100, 175, 300, 600, 750, 1000, 1200, 2000
Excavators	6, 11, 16, 25, 40, 50, 75, 100, 175, 300, 600, 750, 1000, 1200, 2000, 3000
Concrete/Industrial Saws	11, 25, 40, 50, 75, 100, 175, 300
Cement & Mortar Mixers	6, 11, 16, 25, 40, 50, 75, 100, 175, 300, 600, 750
Cranes	25, 40, 50, 75, 100, 175, 300, 600, 750, 1000, 1200
Graders	40, 50, 75, 100, 175, 300, 600, 750
Off-highway Trucks	175, 300, 600, 750, 1000, 1200, 2000, 3000
Crushing/Proc. Equipment	25, 40, 50, 75, 100, 175, 300, 600, 750, 1000
Rough Terrain Forklifts	16, 25, 40, 50, 75, 100, 175, 300, 600
Rubber Tire Loaders	11, 16, 25, 40, 50, 75, 100, 175, 300, 600, 750, 1000, 1200, 2000, 3000
Tractors/Loaders/Backhoes	16, 25, 40, 50, 75, 100, 175, 300
Crawlers Tractors	40, 50, 75, 100, 175, 300, 600, 750, 1000, 1200, 2000
Skid Steer Loaders	11, 16, 25, 40, 50, 75, 100, 175
Off-highway Tractors	175, 300, 600, 750, 1000, 1200, 2000, 3000
Dumpers/Tenders	11, 16, 25, 40, 50, 75, 100, 175
Other Construction Equipment	11, 16, 25, 40, 50, 75, 100, 175, 300, 600, 750, 1000, 1200

The equipment from the NONROAD model was first matched with the existing literature equipment information collected to populate the tasks based on the name of the equipment. If there was not an exact or close match, the “Other Construction Equipment” category was used for emissions. With each piece of equipment in the database paired with its NONROAD’s counterpart, the horsepower was selected based on the NONROAD’s fuel consumption and the fuel consumption from the existing literature sources in the database. The NONROAD’s emissions data was then used to populate the equipment database. However, for LCA, reporting emissions is not the final step. Impact factors must also be reported.

2.2.4 Integration of SimaPro Impacts

With the emissions known for all of the construction equipment, impact factors were determined to simplify and aggregate the emission data into acceptable standard quantities. To do this the commercial LCA software SimaPro 7.3.3 (Pre., 2012) was used. SimaPro is not a tool geared towards pavement or roadway LCA, but its framework and a built in process for a general building machine burning diesel equipment. SimaPro enables aggregation of emissions data to obtain impact factors for each piece of equipment. The impacts from SimaPro utilized in the LCA tool are from TRACI (Bare, 2012) impact factors. TRACI, or Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts, is developed by the EPA to assist in impact assessment for LCA and other sustainability methodologies. This process combines substance emissions, including ammonia, benzo(a)pyrene, cadmium, carbon dioxide (CO_2), carbon monoxide (CO), chromium, copper, dinitrogen monoxide, dioxin, waste heat, methane, nickel, nitrogen oxides (NO_x), non-methane volatile organic compounds, polycyclic aromatic hydrocarbons, particulates (PM), selenium, sulfur dioxide, and zinc, into ten primary impact factors: global warming potential (GWP), ozone depletion, smog, acidification, eutrophication, carcinogenics, non carcinogenics, respiratory effects, fossil fuel depletion, and ecotoxicity in addition to tracking the depletion of renewable and non-renewable energy. The TRACI impact factors were utilized to calculate the total energy and global warming potential (GWP). The other environmental impacts were normalized to a uniform reference unit using normalization factors from Lautier et al. (2010) and weighted by significance based on Bare et al. (2006) and were then summed to create a “single score.”

2.2.5 Construction and Maintenance Phases Overview

The construction and maintenance phases utilize the construction tasks to build and maintain the pavement structure. The various construction tasks group equipment from the software's equipment database to perform a certain process, e.g., build a concrete pavement layer. The equipment database is made up of construction equipment that utilize emissions data from EPA's NONROADs model to compile impact factors such as global warming potential to be outputted by the LCA tool.

CHAPTER 3 VERIFICATION CASE STUDIES AND ANALYSIS

3.1 Concrete Materials Case Studies

To assess the functionality of the LCA tool’s materials phase with respect to concrete, a number of concrete mix designs were tested with a fixed pavement design. These mix designs utilized supplementary cementitious materials (SCMs), such as ground granulated blast furnace slag (GGBFS) and fly ash, as partial replacements of cement. The mixes also investigated the effects of using recycled aggregates, such as fractionated reclaimed asphalt pavement (FRAP) and recycled concrete aggregate (RCA), as partial and full replacement of the coarse aggregate in the mixes.

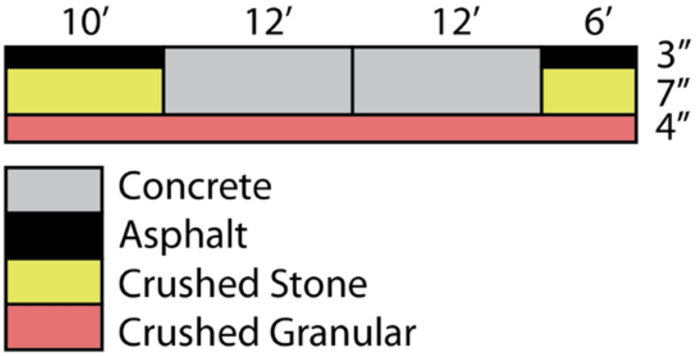
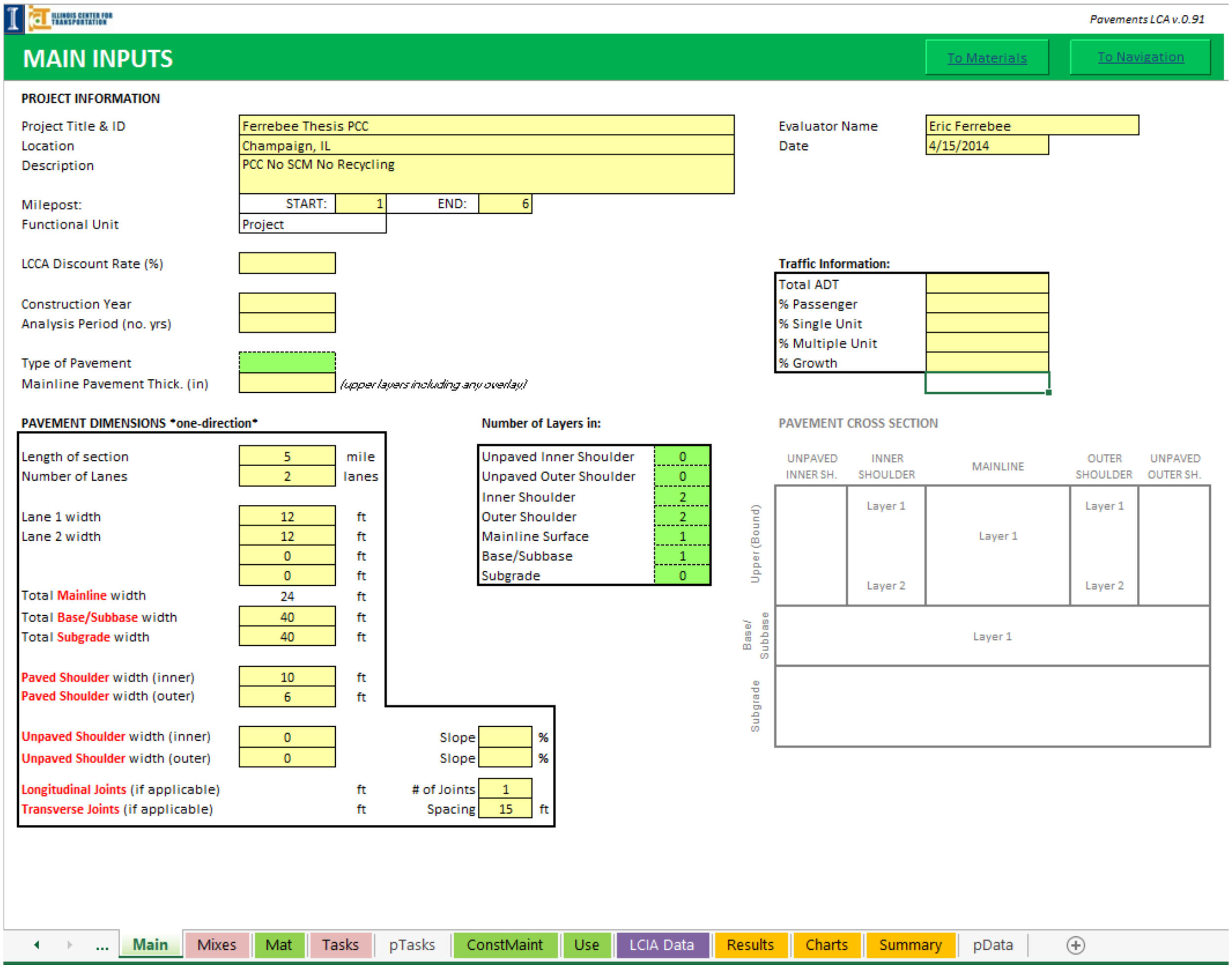


Figure 3-1 General Pavement Design

The pavement design that was selected for the concrete material analysis can be seen in Figure 3-1. The design consisted of a two lane, 10-inch concrete pavement, with each lane being 12 feet wide. The joint spacing was 15 feet. The various mix designs were applied to the concrete layer. The inside and outside shoulders were evaluated with widths of 10 feet and 6 feet, respectively. The shoulder was composed of a 3-inch hot-mix asphalt binder course over a 7-inch crushed aggregate layer. The asphalt mix was held constant for all cases. The entire 40-foot cross section was placed on a 4-inch layer of crushed granular subbase. A project length of five miles was chosen as the functional unit. These project details were inputted into the LCA tool as shown in Figure 3-2. This pavement design may not be representative of all agency's actual practices, but it is a theoretical pavement design to help demonstrate the LCA tool's capabilities and to assess some simple relationships within the materials phase.



MAIN INPUTS

PROJECT INFORMATION

Project Title & ID	Ferrebee Thesis PCC
Location	Champaign, IL
Description	PCC No SCM No Recycling
Milepost:	START: 1 END: 6
Functional Unit	Project
LCCA Discount Rate (%)	
Construction Year	
Analysis Period (no. yrs)	
Type of Pavement	
Mainline Pavement Thick. (in)	*(upper layers including any overlay)*

Evaluator Name	Eric Ferrebee
Date	4/15/2014

Traffic Information:

Total ADT	
% Passenger	
% Single Unit	
% Multiple Unit	
% Growth	

PAVEMENT DIMENSIONS *one-direction*

Length of section	5	mile			
Number of Lanes	2	lanes			
Lane 1 width	12	ft			
Lane 2 width	12	ft			
	0	ft			
	0	ft			
Total Mainline width	24	ft			
Total Base/Subbase width	40	ft			
Total Subgrade width	40	ft			
Paved Shoulder width (inner)	10	ft			
Paved Shoulder width (outer)	6	ft			
Unpaved Shoulder width (inner)	0		Slope		%
Unpaved Shoulder width (outer)	0		Slope		%
Longitudinal Joints (if applicable)		ft	# of Joints	1	
Transverse Joints (if applicable)		ft	Spacing	15	ft

Number of Layers in:

Unpaved Inner Shoulder	0
Unpaved Outer Shoulder	0
Inner Shoulder	2
Outer Shoulder	2
Mainline Surface	1
Base/Subbase	1
Subgrade	0

Figure 3-2 Project Level Inputs

3.1.1 Supplementary Cementitious Materials Mixes

The first set of four mixes, seen in Table 3-1, analyzed the effects of adding SCMs, including GGBFS and fly ash, as binary and ternary cementitious blends with cement. All mixes featured 610 pounds of total cementitious material, constant aggregate proportions, and virgin aggregates.

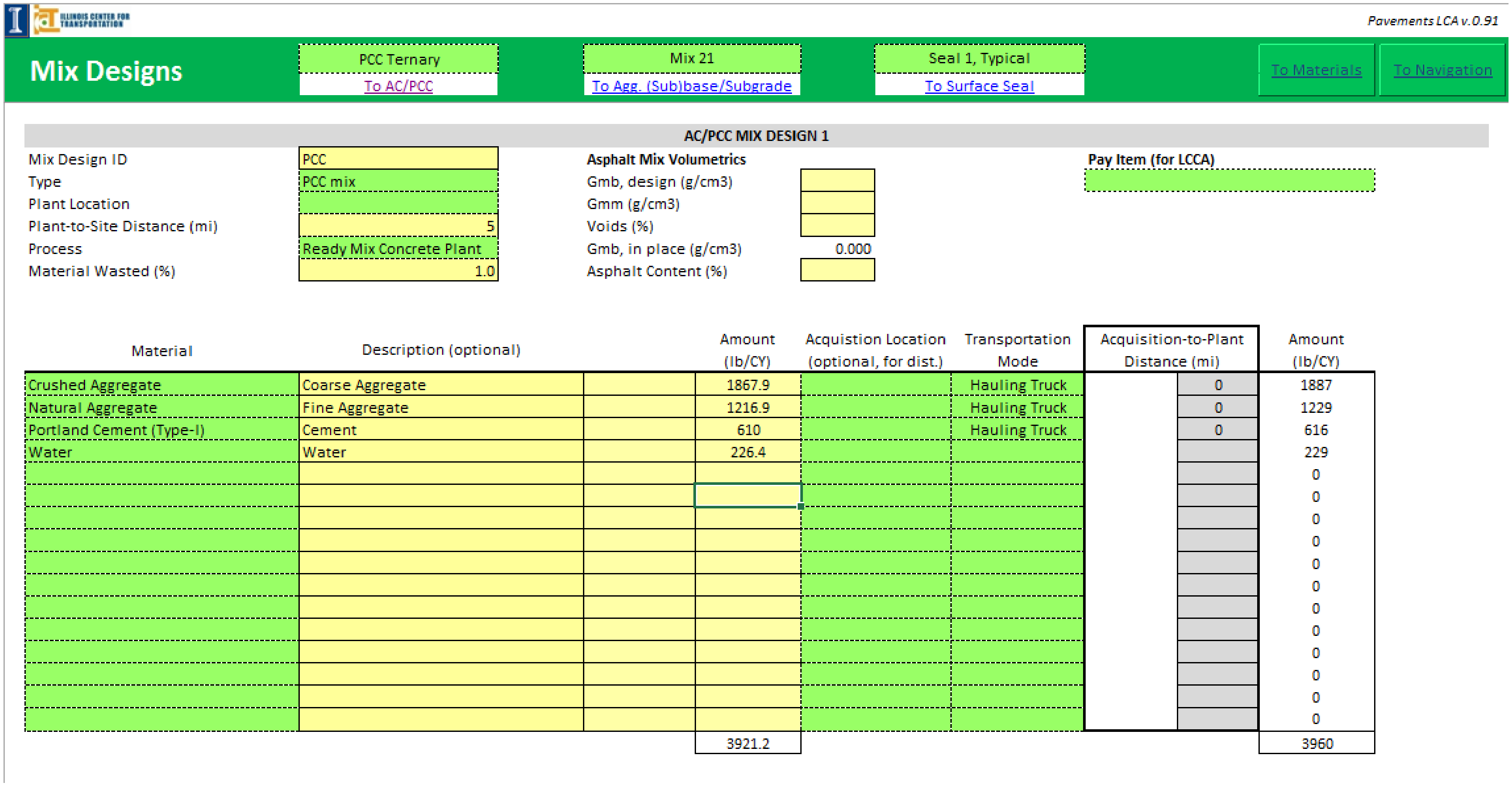
It should be noted that since weight replacement was used for SCMs these mixes are not precisely volumetrically equivalent. The first mix was a control concrete mix with cement and no SCMs. The second mix weight-replaced 35% of the cement with GGBFS. The third mix replaced 35% of the cement with fly ash. The final mix replaced 35% of the cement with GGBFS and 10% with fly ash.

Table 3-1 Concrete Mixes with Supplementary Cementitious Materials (lb/yd^3 (kg/m^3))

Mix	Virgin	35% GGBFS	35% Fly Ash	35% GGBFS and 10% Fly Ash
Virgin Coarse	1867.9 (1108.2)			
FRAP Coarse	0.0 (0.0)			
RCA Coarse	0.0 (0.0)			
Total Coarse	1867.9 (1108.2)			
Virgin Fine	1216.9 (722.0)	1216.9 (722.0)	1216.9 (722.0)	1216.9 (722.0)
Cement	610 (361.9)	396.5 (235.2)	396.5 (235.2)	335.5 (199.0)
GGBFS	0.0 (0.0)	213.5 (126.7)	0.0 (0.0)	213.5 (126.7)
Fly Ash	0.0 (0.0)	0.0 (0.0)	213.5 (126.7)	61.0 (36.2)
Total Cementitious	610 (361.9)			
Water	226.4 (134.3)			

Each mix was inputted into the “Mixes” section of the LCA tool to determine the energy and environmental impacts associated with the creation and transportation of each of the materials. The transportation of each material from acquisition to a ready-mix plant was assumed to be 0 miles to directly compare the impacts of the materials themselves in relation to the overall mix design rather than the hauling of the materials. The energy associated with running the ready-mix plant was also included to fully evaluate the changing environmental impact of concrete as a material, rather than individual components.

The input of the Virgin concrete mix to the LCA tool can be visualized in Figure 3-3. In addition to each of the concrete mixes, an asphalt mix and aggregate mixes were inputted for the shoulder and base layers, respectively. The virgin coarse aggregate and fine aggregate were assumed to be a crushed stone and natural sand aggregate, respectively.



Pavements LCA v.0.91

Mix Designs

PCC Ternary	Mix 21	Seal 1, Typical	To Materials	To Navigation
To AC/PCC	To Agg. (Sub)base/Subgrade	To Surface Seal		

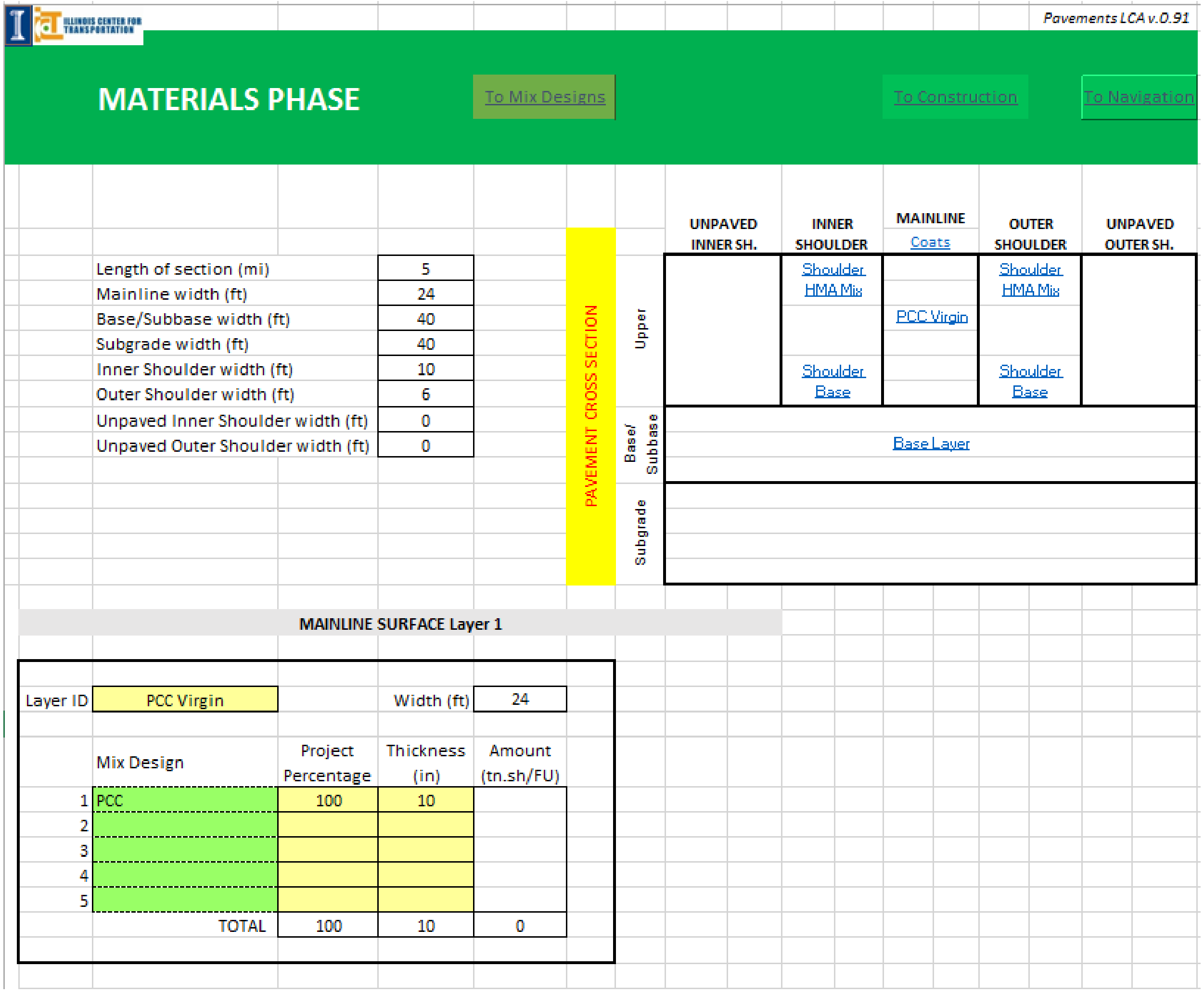
AC/PCC MIX DESIGN 1

Mix Design ID	PCC	**Asphalt Mix Volumetrics**		**Pay Item (for LCCA)**	
Type	PCC mix	Gmb, design (g/cm3)			
Plant Location		Gmm (g/cm3)			
Plant-to-Site Distance (mi)	5	Voids (%)			
Process	Ready Mix Concrete Plant	Gmb, in place (g/cm3)	0.000		
Material Wasted (%)	1.0	Asphalt Content (%)			

Material	Description (optional)		Amount (lb/CY)	Acquistion Location (optional, for dist.)	Transportation Mode	Acquisition-to-Plant Distance (mi)		Amount (lb/CY)
Crushed Aggregate	Coarse Aggregate		1867.9		Hauling Truck		0	1887
Natural Aggregate	Fine Aggregate		1216.9		Hauling Truck		0	1229
Portland Cement (Type-I)	Cement		610		Hauling Truck		0	616
Water	Water		226.4					229
								0
								0
								0
								0
								0
								0
								0
								0
								0
								0
								0
								0
			3921.2					3960

Figure 3-3 Virgin Concrete Mix Design Input

With the mix designs for all of the layers inputted, the mixes were assigned to their respective pavement layers. The materials interface in the LCA tool (see Figure 3-4) allows for multiple mix designs to be used within the same layer over the course of a project. For these examples, the mix designs remain constant over the five-mile example project.



Length of section (mi)	5
Mainline width (ft)	24
Base/Subbase width (ft)	40
Subgrade width (ft)	40
Inner Shoulder width (ft)	10
Outer Shoulder width (ft)	6
Unpaved Inner Shoulder width (ft)	0
Unpaved Outer Shoulder width (ft)	0

MAINLINE SURFACE Layer 1

Layer ID: PCC Virgin

Width (ft): 24

	Mix Design	Project Percentage	Thickness (in)	Amount (tn.sh/FU)
1	PCC	100	10	
2				
3				
4				
5				
	TOTAL	100	10	0

Figure 3-4 Mix Design Assignment to Pavement Layer

Once the mixes were assigned to layers, the LCA tool calculated the results for the materials phase. The results for the materials phase of the pavement design utilizing the Virgin concrete mix can be seen in Table 3-2. The main three outputs include the Single Score, Total Energy, and Global Warming Potential. Each of the indicators can be expanded to show the contributions from each of the pavement layers. Each layer can also be expanded to see the contribution from the individual materials within each layer.

Table 3-2 Materials Phase Results for Pavement Design Cross Section with Virgin Concrete Mix

	Indicator	Unit	Material Production
Indicators	Single Score	Pt	3.32E+02
	Total Energy	MJ	4.47E+07
	Global Warming Potential	kg CO2eq	6.19E+06
	Energy with Binder Feedstock	MJ	6.37E+07
	Ozone depletion	kg CFC-11 eq	2.26E-01
	Smog	kg O3 eq	4.68E+05
	Acidification	kg SO2 eq	2.65E+04
	Eutrophication	kg N eq	2.30E+03
	Carcinogenics	CTUh	4.94E-02
	Non carcinogenics	CTUh	5.36E-01
	Respiratory effects	kg PM2.5 eq	2.65E+03
	Ecotoxicity	CTUe	4.52E+06
	Fossil fuel depletion	MJ surplus	5.51E+06
	Energy, renewable primary, fuel	MJ	7.72E+04
	Energy, renewable primary, non fuel	MJ	1.35E+04
	Energy, renewable primary, total	MJ	9.07E+04
	Energy, non renewable primary, fuel	MJ	4.46E+07
	Energy, non renewable primary, non fuel	MJ	0
	Energy, non renewable primary, total	MJ	4.46E+07
	Use of secondary materials	kg	0
	Energy, renewable secondary, fuel	MJ	0
	Energy, non-renewable secondary, fuel	MJ	0
	Water resource depletion total [ILCD]	m3 water eq	8.54E+04
	Waste, hazardous	kg	0
	Waste, non hazardous	kg	0
	Waste, radio active	kg	0

While the presented values in Table 3-2 are the total values, they can be broken down by layer by the material components of each layer. Figure 3-5 shows the contribution of each layer to the total energy usage of the materials phase. Figure 3-6 shows the contribution of each layer to the global warming potential of the materials phase. These two figures display the prominent role that the concrete pavement layer plays within the materials phase for this assumed pavement structure. For this hypothetical design, the concrete layer makes up for 84% of the total energy used in the materials phase, with the next largest contributor being less than 10%. The concrete layer also accounts for 93% of the global warming potential. This is not surprising because the concrete layer makes up 20 ft^2 of the 46.67 ft^2 pavement cross section. Combine that with the fact that a concrete layer will naturally be more prominent than an aggregate layer due to the inclusion of cementitious materials which are typically energy and emission intensive to create.

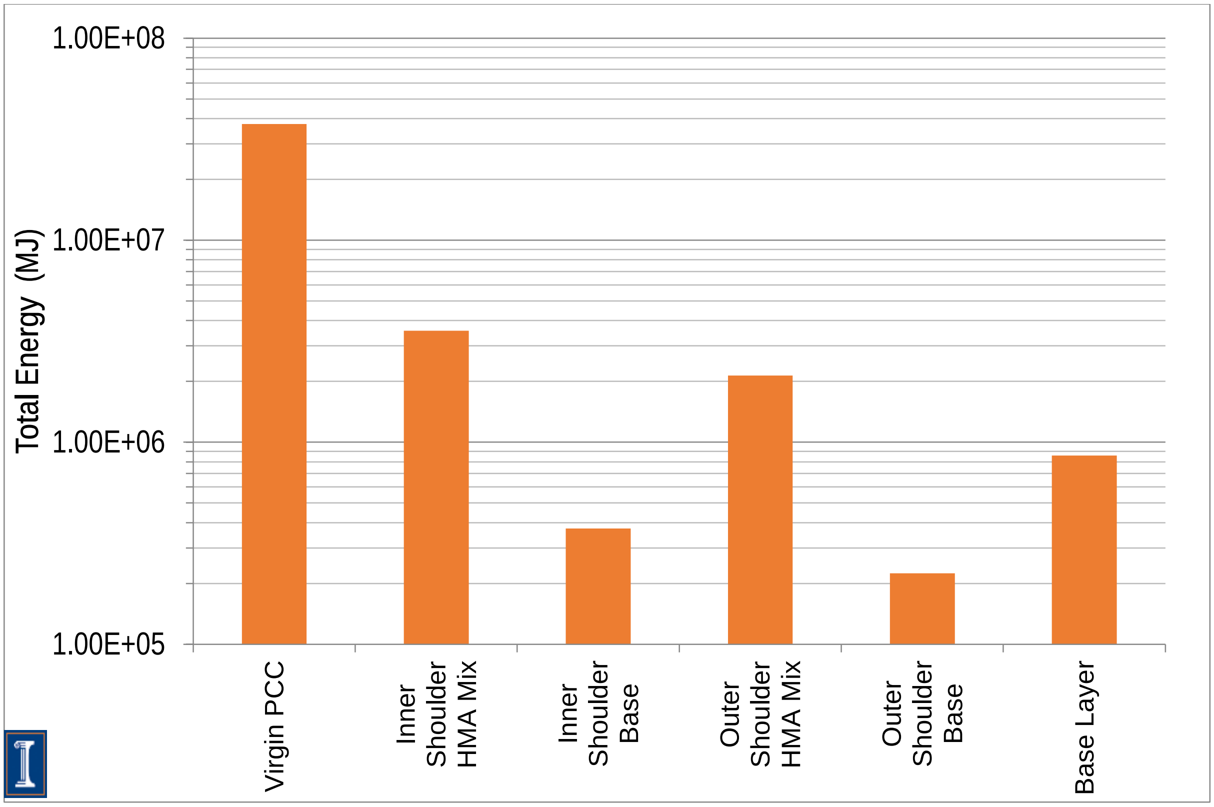


Figure 3-5 Breakdown of Total Energy Contribution by Pavement Layer for the Virgin Mix

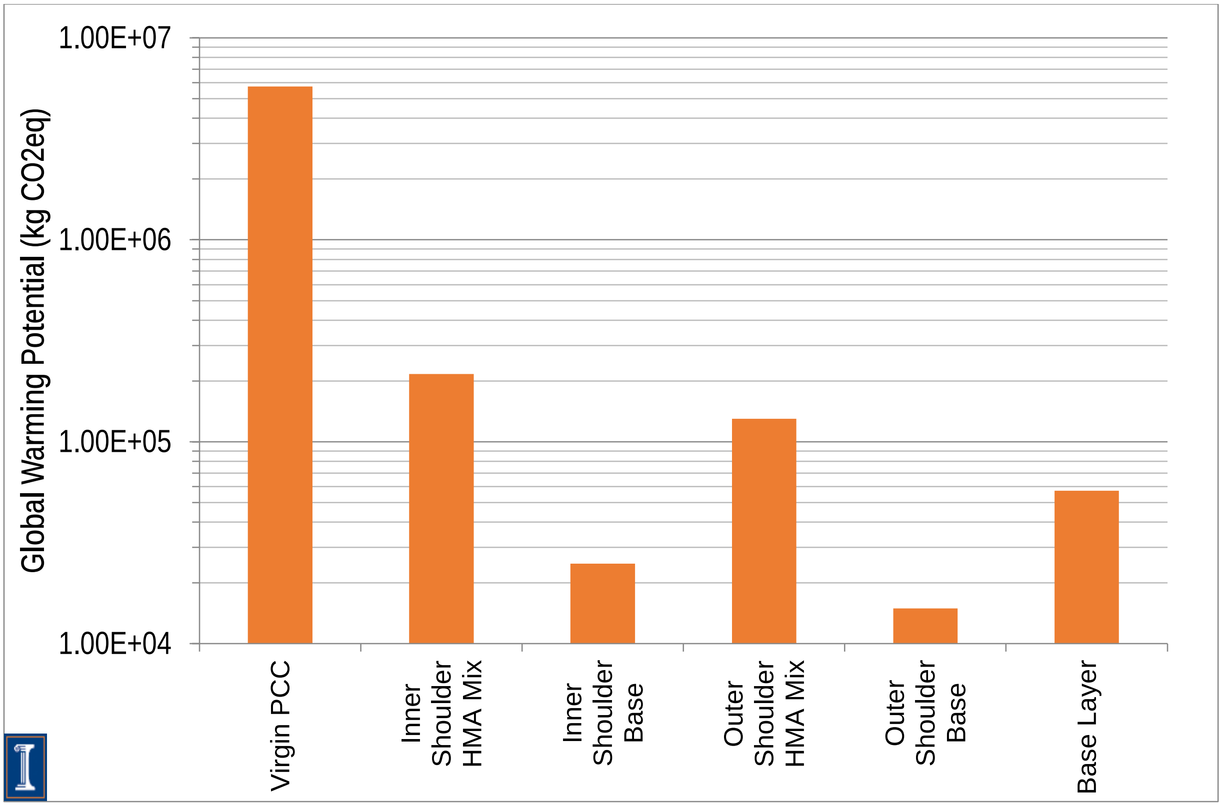


Figure 3-6 Breakdown of Global Warming Potential Contribution by Pavement Layer for the Virgin Mix

The contribution of the aggregates, cementitious materials and the ready-mix plant itself can be broken down to compare the energy and emissions of each concrete component. Figure 3-7 displays the contribution of each of the components in the concrete to the overall total energy in the materials phase while Figure 3-8 is the contribution of each of the components to the global warming potential of the materials phase. From these two figures, it is clear that the cement is the main contributor to both total energy usage and global warming potential. The other three components, including the creation of the crushed and natural aggregates, as well as the mixing at the concrete at the plant, are all insignificant in comparison to the creation of cement, which accounts for 92% of the total energy usage and 96% of the global warming potential of the concrete layer with this given mix design.

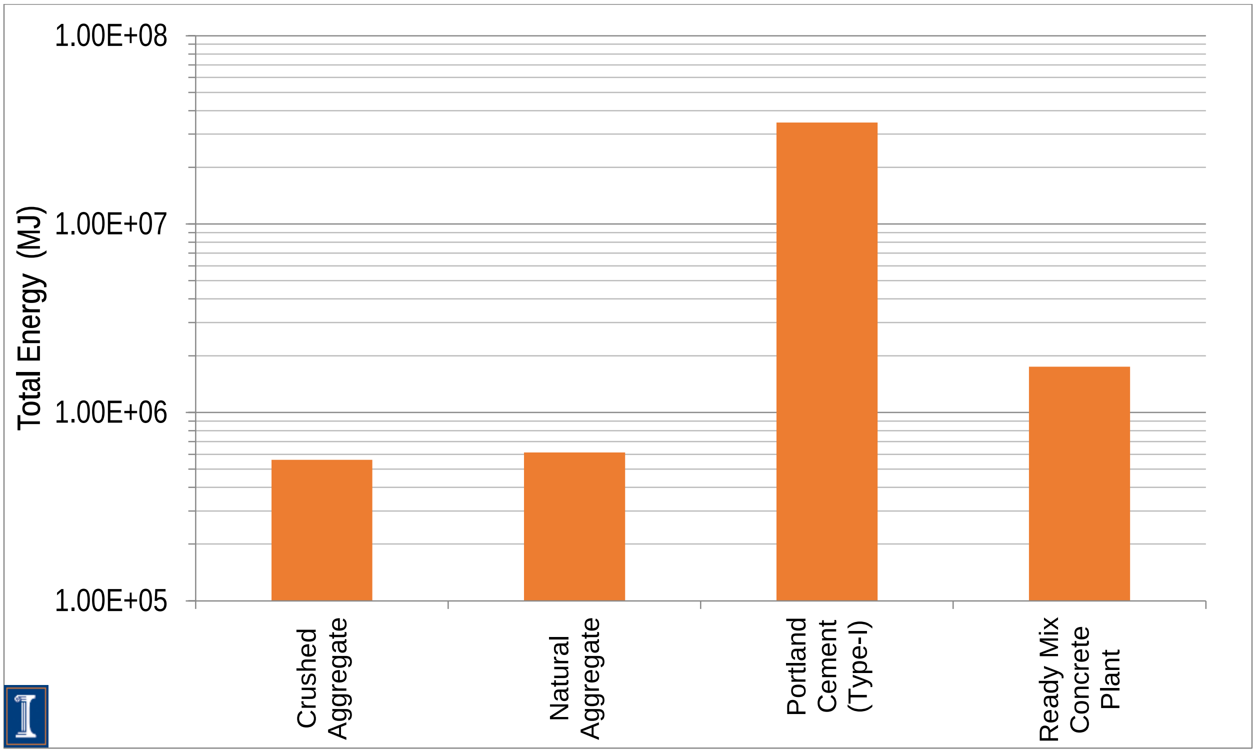


Figure 3-7 Materials Phase Energy by Constituent of Concrete Layer for the Virgin Mix

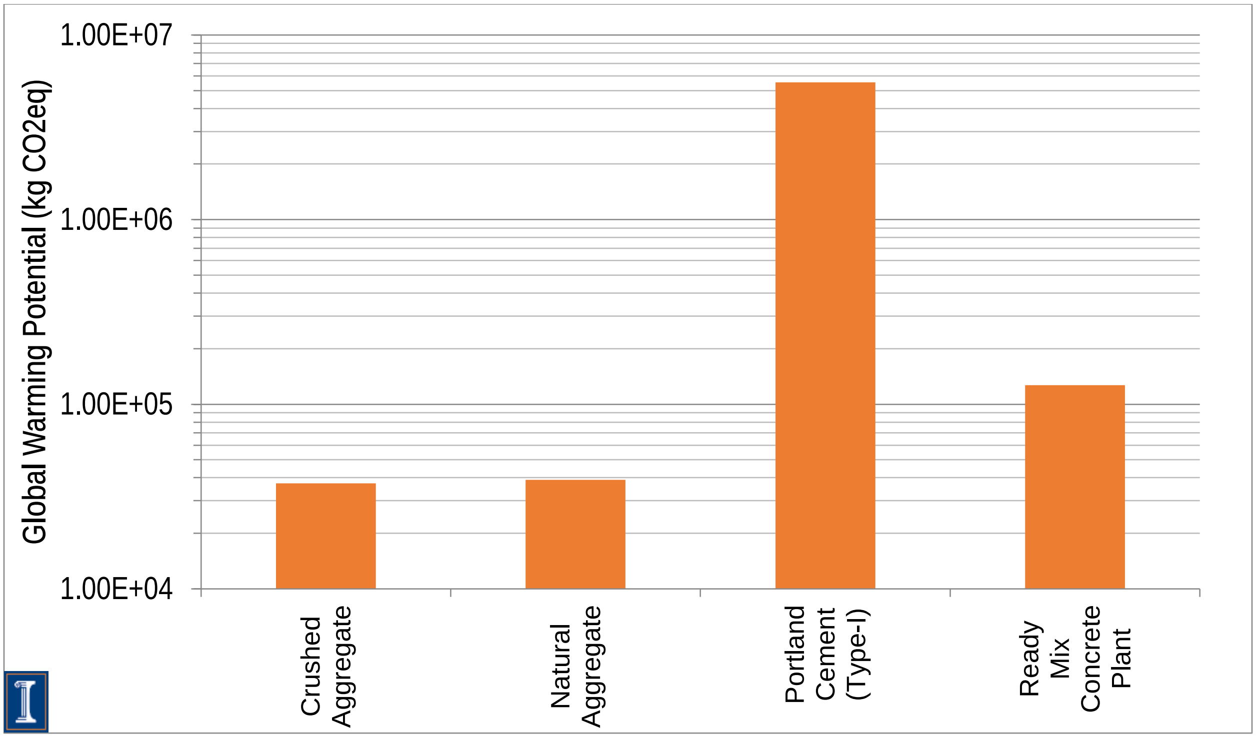


Figure 3-8 Materials Phase Global Warming Potential by Constituent of Concrete Layer for the Virgin Mix

The results have shown the total energy usage and global warming potential associated with a standard concrete mix. It is common practice for paving mixes to utilize fly ash, GGBFS, or both. To evaluate the effects of replacing cement with SCMs, the other mix designs were used in place of the Virgin mix. A comparison of total energy used by material in the concrete layer is displayed in Figure 3-9. As expected, the total energy and GWP do not change with respect to the aggregates and ready-mix plant since they have remained fixed. In reality, there would be a slight decrease in energy because the volume of paste increases with addition of SCM weight replacement of cement. As seen in Figure 3-9, the use of GGBFS, fly ash or both as a partial replacement of cement does decrease the total energy consumed for the material layer. The use of 35% GGBFS results in a 17% decrease in total energy, the use of 35% fly ash results in an even greater decrease in total energy at 26%, and using 35% GGBFS and 10% fly ash results in a decrease of 24% in total energy usage. These values are not unexpected as a number of other studies including Muge et al. (2009), Zapata & Gambatese (2005), and Hendrickson and Horvath (1998) found similar environmental trends when using SCMs such as fly ash and GGBFS.

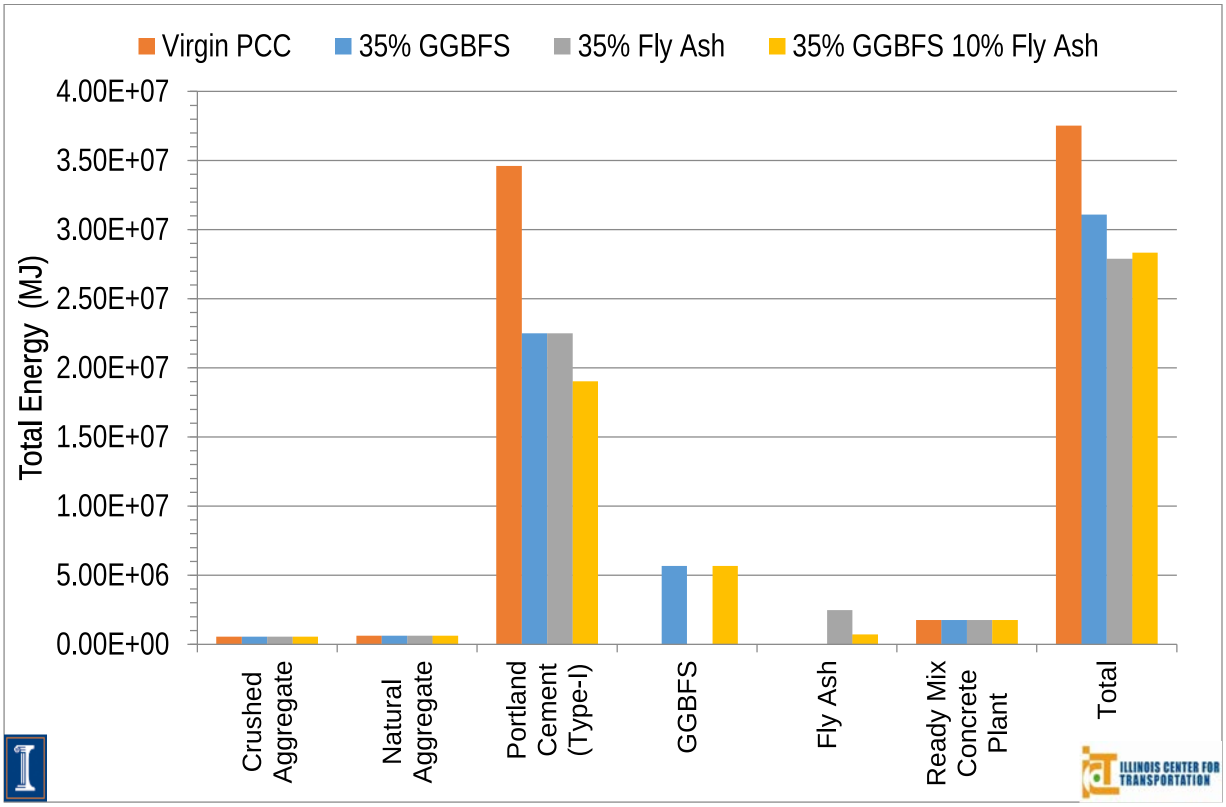


Figure 3-9 Total Energy Usage by Material Component for Concrete Layer with SCMs

The global warming potential produced by each material in the concrete mix is displayed in Figure 3-10. As with total energy usage, the utilization of GGBFS and fly ash both resulted in a decrease in the global warming potential. The GGBFS produced higher levels of global warming potential than fly ash, which was also seen with total energy usage. The decrease in global warming potential with the use of 35% GGBFS was found to be 28%, and the decrease with the use of 35% fly ash was found to be 32%. The decrease when a mix of 35% GGBFS and 10% fly ash was used was found to be 37%. This shows a deviation in the trend that was found with the total energy usage where the use of GGBFS and fly ash resulted in a higher total energy usage than when higher doses of fly ash were used. This trend deviation indicates that while total energy usage and global warming potential results can be similar, they are not completely the same. GGBFS is more beneficial in terms of savings in global warming potential than it is in energy usage relative to fly ash. The difference between fly ash and GGBFS is because of the weighting of the emissions for the global warming impact factor as defined by the TRACI impact factors.

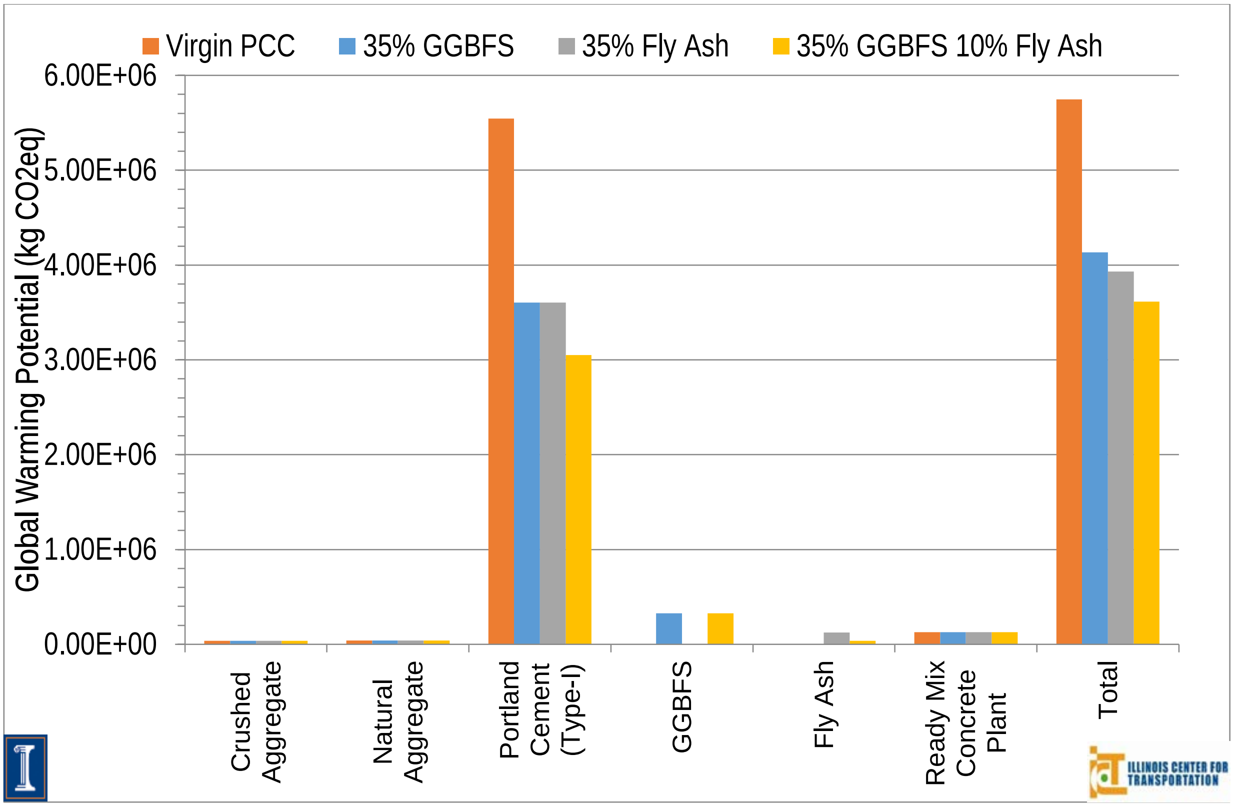


Figure 3-10 Global Warming Potential by Material Component for Concrete Layer with SCMs

If the materials phase is considered with the entire pavement structure, the total energy and global warming potential are reduced when adding SCMs. Table 3-3 shows the single score, total energy, and global warming potential values produced by the LCA tool for the four concrete mixtures. Table 3-3 shows the reduction in total energy relative to the virgin concrete mixture ranges from 14% to 22%, while the reduction in global warming potential is even greater, ranging from 26% to 34%.

Table 3-3 Materials Phase Results for Pavement Design using SCMs

	Single Score		Total Energy		Global Warming Potential (kg CO2eq)	
Mix	Points	% Reduction	MJ	% Reduction	(kg CO2eq)	% Reduction
Virgin	332	-	4.47E+07	-	6.19E+06	-
35% GGBFS	271	18%	3.51E+07	22%	4.37E+06	29%
35% Fly Ash	282	15%	3.83E+07	14%	4.58E+06	26%
35% GGBFS 10% Fly Ash	265	20%	3.55E+07	21%	4.06E+06	34%

3.1.2 Recycled Aggregate Concrete Mixes

To assess the effects of using recycled aggregates in concrete, a second set of mixes was simulated with the LCA tool. The mix with 35% GGBFS and 10% fly ash was taken as the control mix since it had the best performance of all the SCM combinations in terms of global warming potential. Additional mixes, shown in Table 3-4, were proposed to investigate the effects of adding coarse fractionated reclaimed asphalt pavement (FRAP) and coarse recycled concrete aggregate (RCA) as partial or full replacements of the coarse aggregate. The first mix utilized FRAP to replace 45% of the virgin coarse aggregate. The second mix replaced all of the virgin coarse aggregate with RCA. The third mix replaced 100% of the virgin coarse aggregate with 55% RCA and 45% FRAP. The total coarse aggregate weight across all the mixes, shown in Table 3-4, is not the same because the recycled aggregate replacements were by volume.

Table 3-4 Concrete Mixes with Recycled Aggregates in lb/yd^3 (kg/m^3). Source: Brand et al. (2013)

Mix	Control	45% FRAP	100% RCA	55% RCA/ 45% FRAP
Virgin Coarse	1867.9 (1108.2)	1002.3 (594.6)	0.0 (0.0)	0.0 (0.0)
FRAP Coarse	0.0 (0.0)	820.0 (486.5)	0.0 (0.0)	776.2 (460.5)
RCA Coarse	0.0 (0.0)	0.0 (0.0)	1696.2 (1006.3)	948.7 (562.8)
Total Coarse	1867.9 (1108.2)	1822.3 (1081.1)	1696.2 (1006.3)	1724.9 (1023.3)
Virgin Fine	1216.9 (722.0)			
Cement	335.5 (199.0)			
GGBFS	213.5 (126.7)			
Fly Ash	61.0 (36.2)			
Total Cementitious	610 (361.9)			
Water	226.4 (134.3)			

The concrete mixes in Table 3-4 were inputted into the LCA tool like the first set of mixes. The shoulder layers and base layers were held constant. Figure 3-11 and Figure 3-12 show the total energy usage and global warming potential for the concrete layer, respectively. From these two figures, it is very difficult to discern the effect of using FRAP, RCA or a combination of the two. There appears to be a small decrease in the total energy and global warming potential when the recycled aggregates are used but this reduction was found to be less than 1%. This indicates that any reduction in energy usage or global warming potential is masked by the significantly larger impacts created by the creation of the cementitious materials and the running of the ready-mix plant. This does not mean that recycled materials offer limited benefit since they can produce a cost saving for a project when virgin aggregates are replaced especially in the hauling during the construction phase (Smith et al., 2014). Since the hauling distances were set at a constant value, the benefit of having a local, readily-available recycled material, which can decrease costs and environmental impacts, is not accounted for in this example.

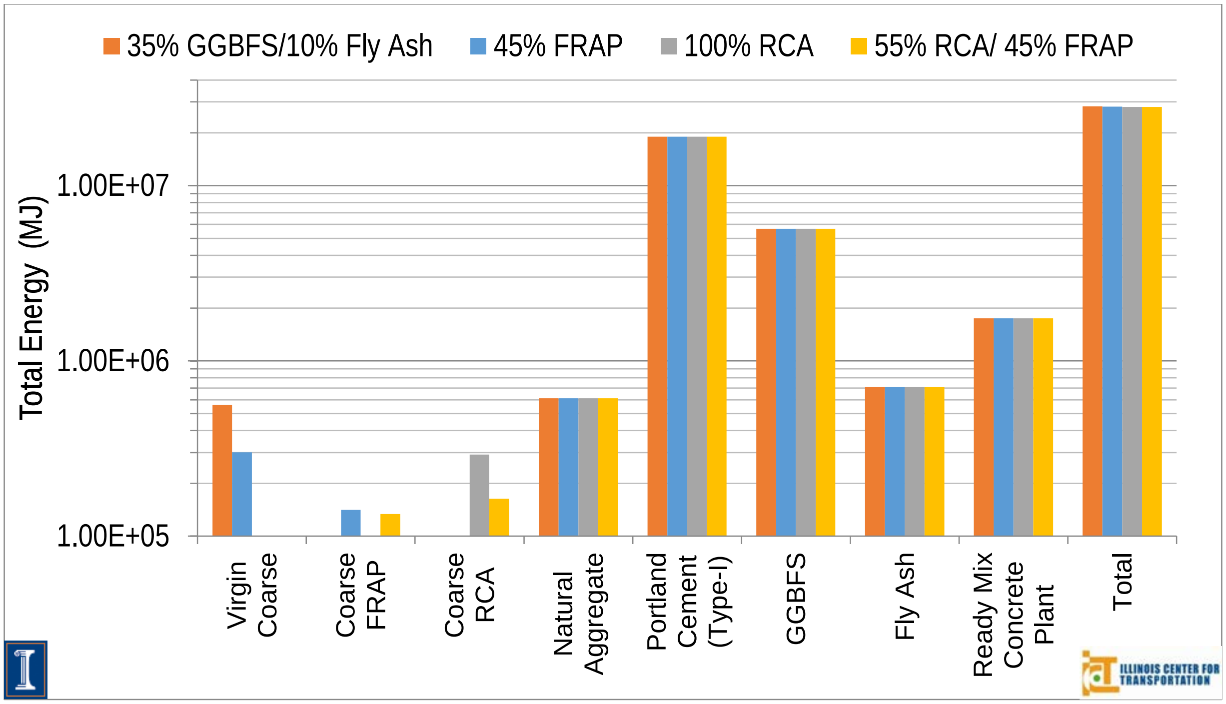


Figure 3-11 Total Energy Usage by Material Component for Concrete Layer with Recycled Aggregates

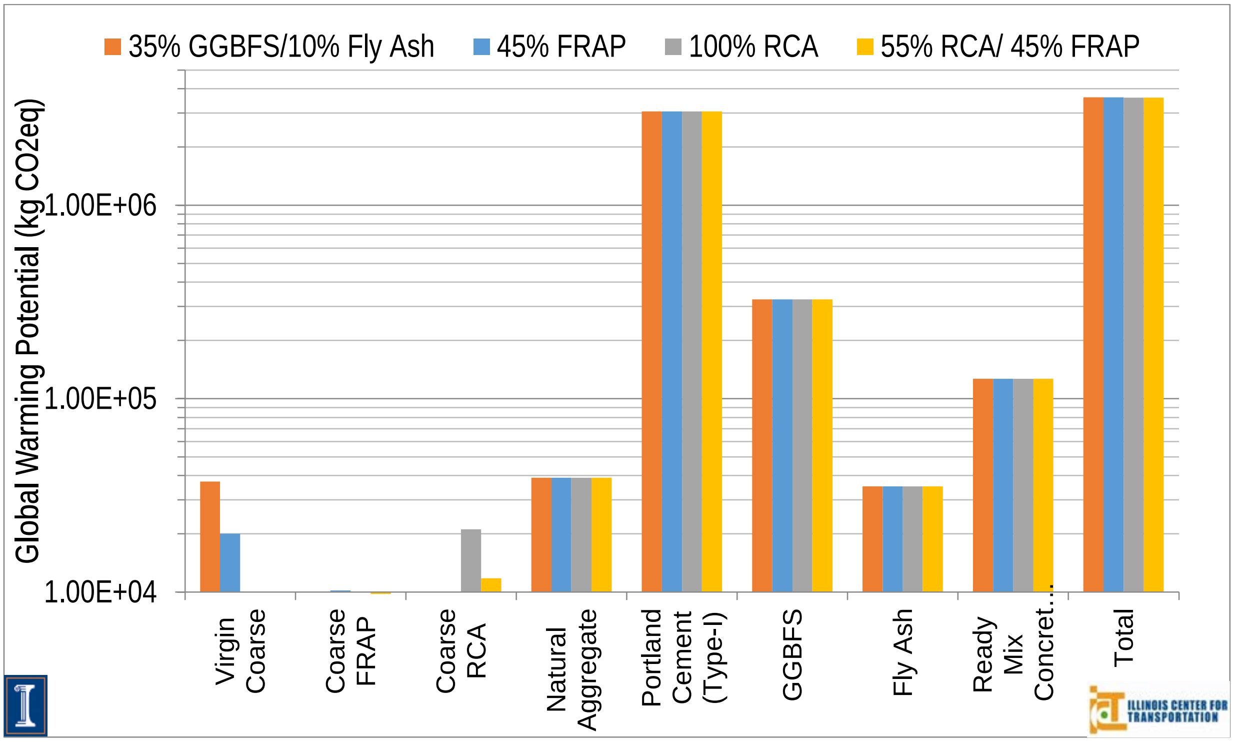


Figure 3-12 Global Warming Potential by Material for Concrete Layer with Recycled Aggregates

Figure 3-13 and Figure 3-14 display the reduction in total energy usage and global warming potential, respectively, by replacing the coarse aggregate with recycled aggregates. As shown, there are benefits of using recycled aggregates over virgin aggregates. The greatest reductions in energy and global warming potential, as expected, are achieved when 100% of the coarse aggregate is replaced with recycled aggregates. Using 100% RCA rather than a mixture of 45% RCA and 55% FRAP, results in the largest reduction of both energy and global warming potential because of the slightly more energy-intensive creation process for FRAP. The percent energy and GWP savings for the recycled aggregates relative to the control mix can be seen in Table 3-5. The less than 2% difference in GWP in 100% RCA relative to 45% RCA and 55% FRAP means the two aggregate recycling processes are not significantly different.

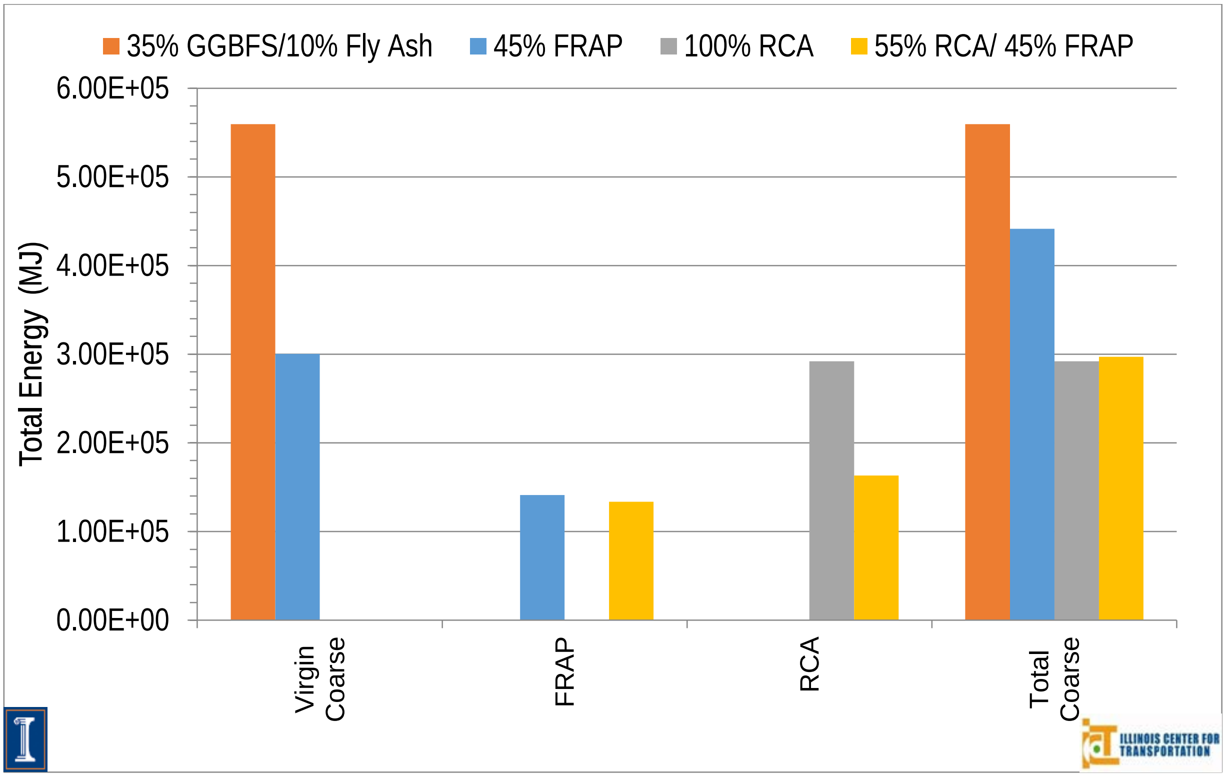


Figure 3-13 Total Energy Usage for Coarse Aggregates in Various Mixtures for Concrete Layer

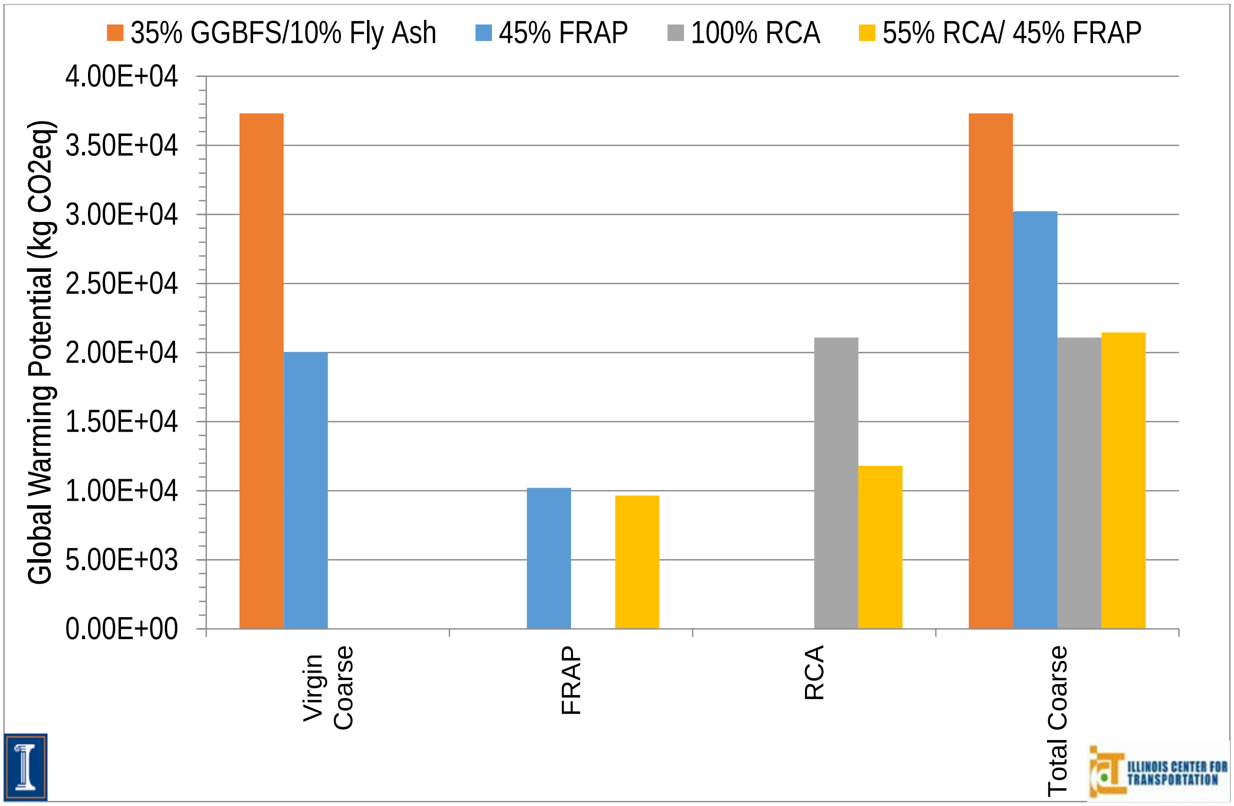


Figure 3-14 Global Warming Potential for Coarse Aggregates in Various Mixtures for Concrete Layer

Table 3-5 Percent Savings for Replacement of Coarse Aggregate with Recycled Aggregates in Concrete

		35% GGBFS/ 10% Fly Ash	45% FRAP	100% RCA	45% RCA/ 55% FRAP
Total Energy	MJ	5.59E+05	4.41E+05	2.92E+05	2.97E+05
	% Reduction	-	21%	48%	47%
Global Warming Potential	kg CO2eq	3.73E+04	3.02E+04	2.11E+04	2.15E+04
	% Reduction	-	19%	43%	43%

The overall pavement structure results for the materials phase, including single score, total energy, global warming potential and percent reduction relative to the control mix, can be seen in Table 3-6. Changing the aggregate type alone does not have a significant impact on the overall project scores in the material phase as other manufacturing processes are significantly more energy and emission intensive. However, utilizing recycled aggregates in pavement layers can significantly impact the cost of the project both in the materials and construction phases by reducing material transport costs if the recycled aggregate is locally available.

Table 3-6 Material Phase Results for Concrete Mixes with Recycled Aggregates

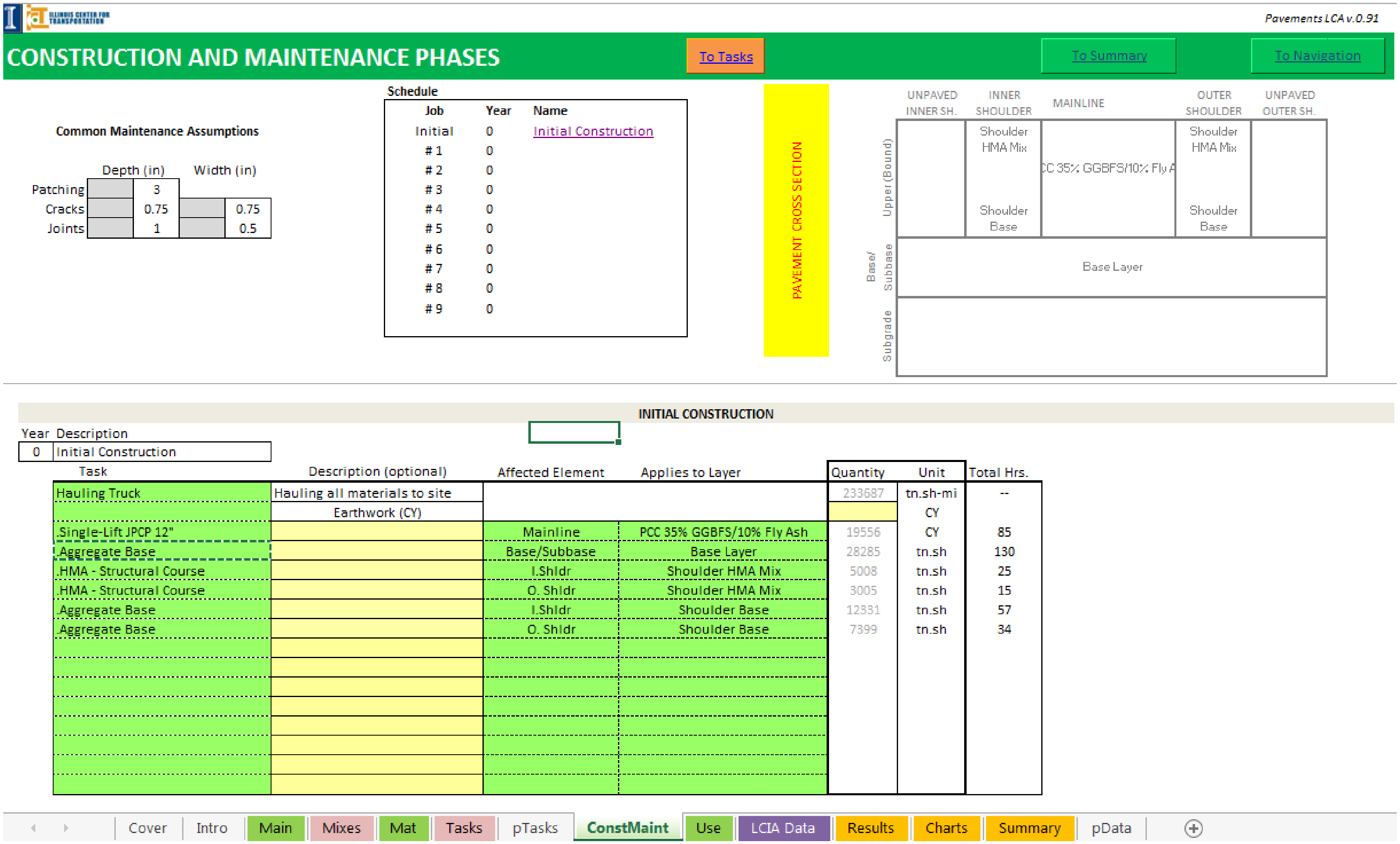
	Single Score		Total Energy		Global Warming Potential (kg CO2eq)	
Mix	Points	% Reduction	MJ	% Reduction	(kg CO2eq)	% Reduction
35% Slag/10% Fly Ash	264.7	-	3.55E+07	-	4.06E+06	-
45% FRAP	263.4	0.5%	3.54E+07	0.3%	4.05E+06	0.2%
100% RCA	261.9	1.1%	3.52E+07	0.8%	4.04E+06	0.4%
45% RCA/ 55% FRAP	261.9	1.1%	3.52E+07	0.7%	4.04E+06	0.4%

3.2 Concrete Construction and Maintenance Case Studies

The pavement structure assumed in Section 3.1 was also utilized to assess the construction and maintenance phase of the pavement LCA. The construction and maintenance phases are set up such that the amount of material being “processed” determines the amount of fuel required to perform a specific task. Minor deviations in mix design have little effect on the fuel required by various machineries. For this reason, the mix proportions utilized for the non-concrete layers in Section 3.1 are fixed for this section. The concrete mix design with 35% GGBFS and 10% fly ash without recycled aggregate will be used for a majority of this section.

3.2.1 Initial Construction Phase Case Studies

With the creation of the paving materials (e.g., concrete or asphalt layer or aggregate base layer), the pavement structure now has to be constructed through a series of tasks. Each task performs several actions to construct the pavement into its final form. Construction of each pavement layer requires at least one task, as shown in the tool screenshot in Figure 3-15. Each task may have multiple construction processes and equipment needed to complete. For example a base layer may require placement and compaction. All construction materials have a transportation task to haul from the plant to the construction site. This hauling distance was assumed to be five miles for all materials. As seen in Figure 3-15, the same task may be repeated multiple times in order to construct the same paving material and layer in different lanes. The tasks used for this pavement structure include a single lift JPCP layer, two HMA structural courses and two aggregate bases to account for the shoulders. The equipment associated with these tasks can be seen in Appendix Table - 1.



CONSTRUCTION AND MAINTENANCE PHASES

Common Maintenance Assumptions

		Depth (in)		Width (in)
Patching		3		
Cracks		0.75		0.75
Joints		1		0.5

Schedule

Job	Year	Name
Initial	0	Initial Construction
# 1	0	
# 2	0	
# 3	0	
# 4	0	
# 5	0	
# 6	0	
# 7	0	
# 8	0	
# 9	0	

INITIAL CONSTRUCTION

Year	Description
0	Initial Construction

Task	Description (optional)	Affected Element	Applies to Layer	Quantity	Unit	Total Hrs.
Hauling Truck	Hauling all materials to site			233687	tn.sh-mi	--
	Earthwork (CY)				CY	
.Single-Lift JPCP 12"		Mainline	PCC 35% GGBFS/10% Fly Ash	19556	CY	85
.Aggregate Base		Base/Subbase	Base Layer	28285	tn.sh	130
.HMA - Structural Course		I.Shldr	Shoulder HMA Mix	5008	tn.sh	25
.HMA - Structural Course		O. Shldr	Shoulder HMA Mix	3005	tn.sh	15
.Aggregate Base		I.Shldr	Shoulder Base	12331	tn.sh	57
.Aggregate Base		O. Shldr	Shoulder Base	7399	tn.sh	34

Figure 3-15 Initial Construction Task Assignment to Layers

With tasks assigned to all layers, the LCA tool automatically calculates the total energy and GWP. For the construction phase, the total energy was found to be 1,531,839 MJ and the global warming potential was found to be 112,741 kg CO2eq. The breakdown of total energy by pavement layer in the initial construction can be seen in Figure 3-16. The global warming potential breakdown by pavement layer in the initial construction is displayed in Figure 3-17. The base layer, which extends the entire length of the pavement, and the material transportation (hauling trucks) are most prominent factors in terms of total energy and global warming potential for the initial construction. The biggest contributor in the materials phase was not the most significant process during the construction phase. Hauling the materials to the construction site accounted for 27% and 30% of the total energy and global warming potential, respectively. Clearly, the most important factors to the construction phase is locating and utilizing the materials that can meet the minimum requirements for each pavement layer including consideration of recycling the old pavement layers. Additionally, strategically locating staging can significantly impact energy, costs, and emissions (Smith et al. 2014).

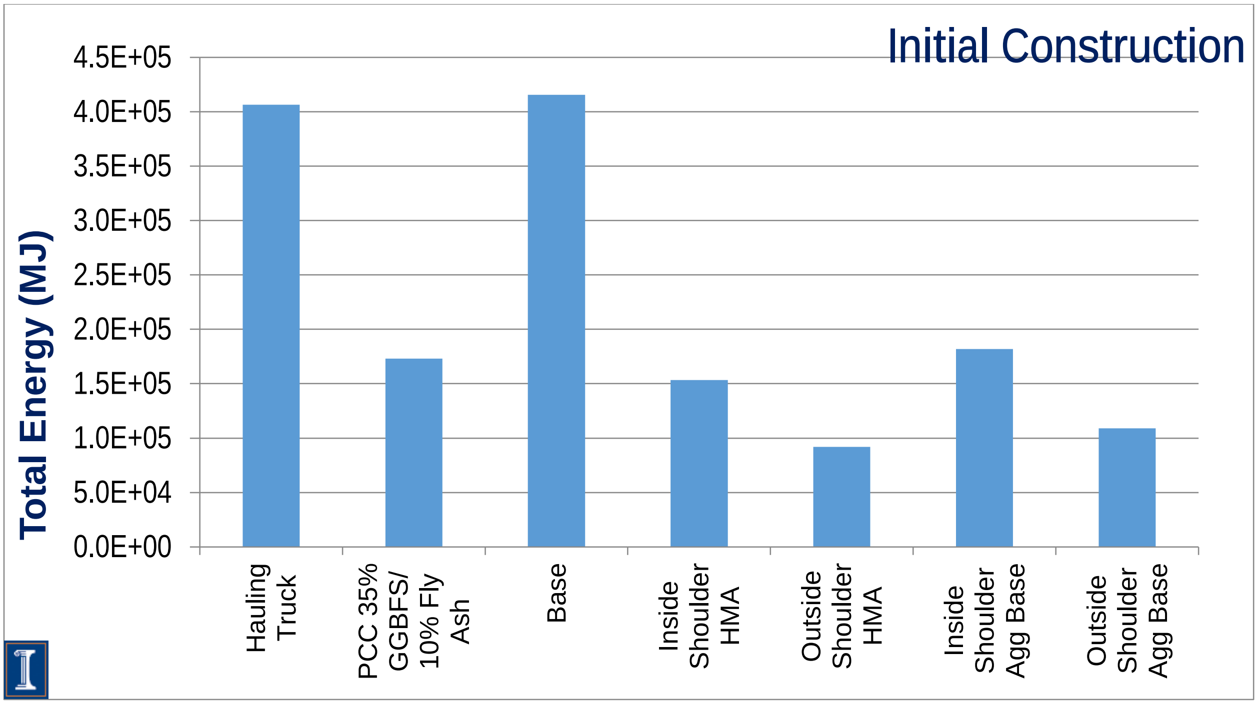


Figure 3-16 Energy Usage by Pavement Layer for Initial Construction

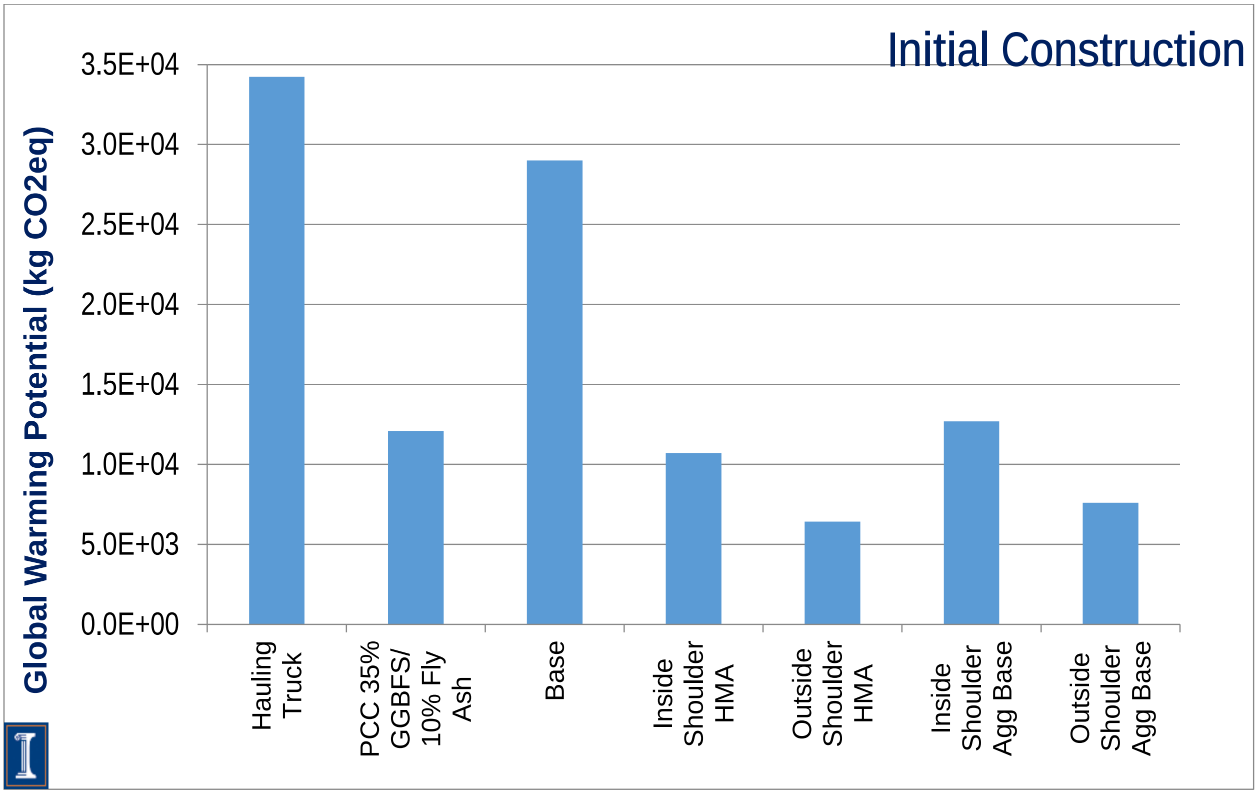


Figure 3-17 Global Warming Potential by Pavement Layer for Initial Construction

Table 3-7 displays the single score, total energy and global warming potential results from the LCA tool for the materials and construction phases for the assumed pavement structure. The construction phase is largely insignificant in comparison to the materials phase. In all three of the major categories, the construction phase fails to account for more than 5% of the combined materials and construction phase totals.

Table 3-7 Materials and Construction Phases Results Summary

	Single Score (Points)		Total Energy (MJ)		Global Warming Potential (kg CO2eq)	
Phase	Materials	Construction	Materials	Construction	Materials	Construction
Concrete Mix	134.4	0.5	2.83E+07	1.73E+05	3.61E+06	1.21E+04
Shoulder HMA Mix	74.8	0.5	3.57E+06	1.53E+05	2.17E+05	1.07E+04
Shoulder Base	2.7	0.6	3.74E+05	1.82E+05	2.50E+04	1.27E+04
Shoulder HMA Mix	44.9	0.3	2.14E+06	9.20E+04	1.30E+05	6.42E+03
Shoulder Base	1.6	0.3	2.24E+05	1.09E+05	1.50E+04	7.61E+03
Base Layer	6.2	1.3	8.58E+05	4.16E+05	5.72E+04	2.90E+04
Material Hauling	-	1.3	-	4.07E+05	-	3.42E+04
Phase Total	264.7	4.8	3.55E+07	1.53E+06	4.06E+06	1.11E+05
% of Project Total	98.2%	1.8%	95.9%	4.1%	97.3%	2.7%
Project Total	269.5		3.70E+07		4.17E+06	

While the construction phase may not itself have a very significant environmental impact on the overall results of the LCA, there are construction options that can impact other phases. One such option is two-lift concrete paving, which is the practice of paving two lifts of concrete in a “wet-on–wet” process. This method allows for a homogeneous concrete slab to be made up of two separate concrete mixes. The bottom lift permits usage of larger quantities of recycled or waste materials such as SCMs or lower quality aggregates. To illustrate the benefits of using this process in the construction phase, the previous case was compared to a case utilizing two-lift paving with one mix design and a case utilizing two-lift paving with two mix designs. The top lift was taken as 3 inches and the bottom lifts as 7 inches, making up the 10-inch concrete thickness of the original pavement design. Table 3-8 presents which concrete mixes were assigned to each lift.

Table 3-8 Concrete Mix Design in Each Paving Lift

Case	One Lift	Two-Lift - One Mix Design	Two-Lift - Two Mix Designs
Top Lift	No SCMs No Recycled Aggregate	No SCMs No Recycled Aggregate	No SCMs No Recycled Aggregate
Bottom Lift	-	No SCMs No Recycled Aggregate	35% GGBFS/ 10% Fly Ash - 55% RCA/ 45% FRAP

Figure 3-18 and Figure 3-19 display the total energy and global warming potential, respectively, for the three cases in the construction phase. As expected, the two-lift cases increases the energy and GWP over single lift paving because of the additional equipment used to process both lifts of concrete. The decrease in the hauling truck is only because of the slight difference in unit weight between the bottom lift concrete mix designs. This difference is not reflected in the concrete layer construction because the two-lift task is based on cubic yards paved rather than hauling weight. The total energy usage and global warming potential results for two-lift paving were all between 10% and 12% greater than the single-lift construction. The total energy for initial construction increased to 1,705,041 MJ and 1,696,441 MJ for the two-lift one mix design and two mix designs construction, respectively. The global warming potential for initial construction increased to 124,826 kg CO2eq and 124,102 kg CO2eq for the two-lift one mix design and two mix designs construction plans, respectively.

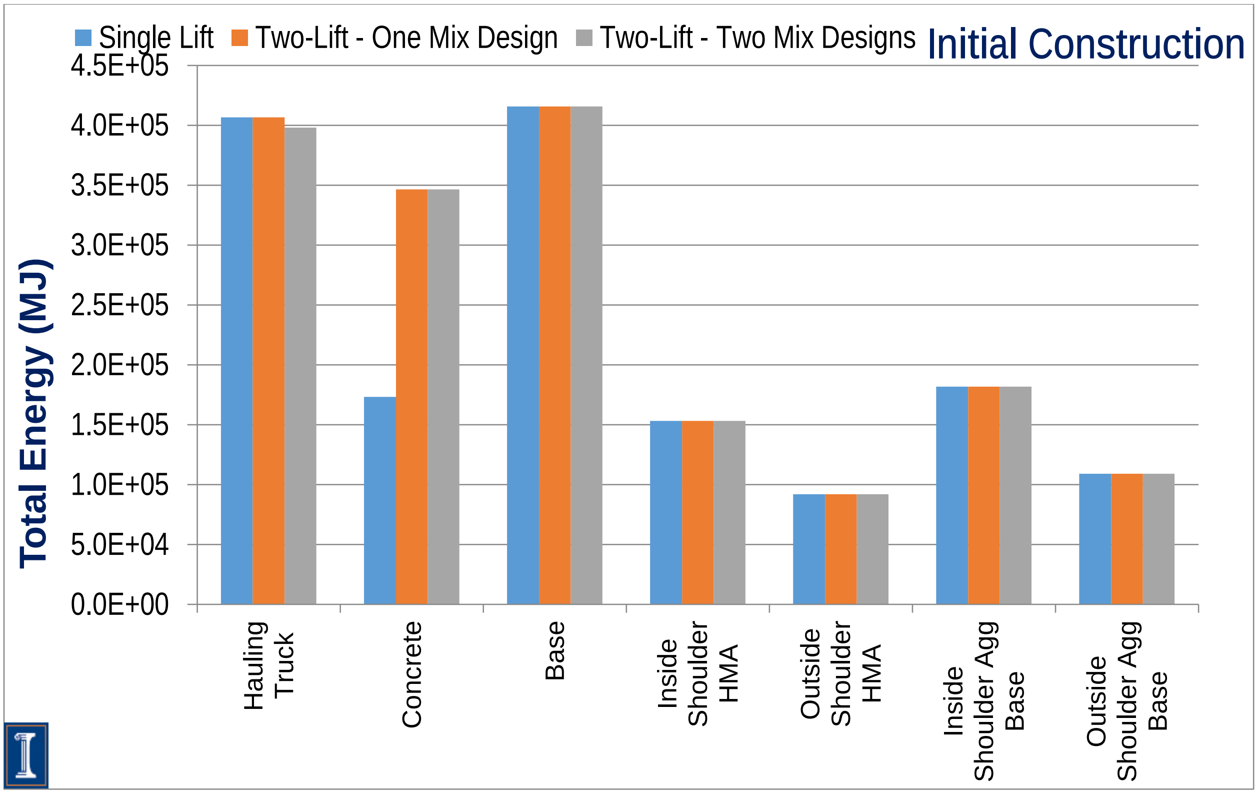


Figure 3-18 Total Energy Usage for Single versus Two-Lift Initial Construction

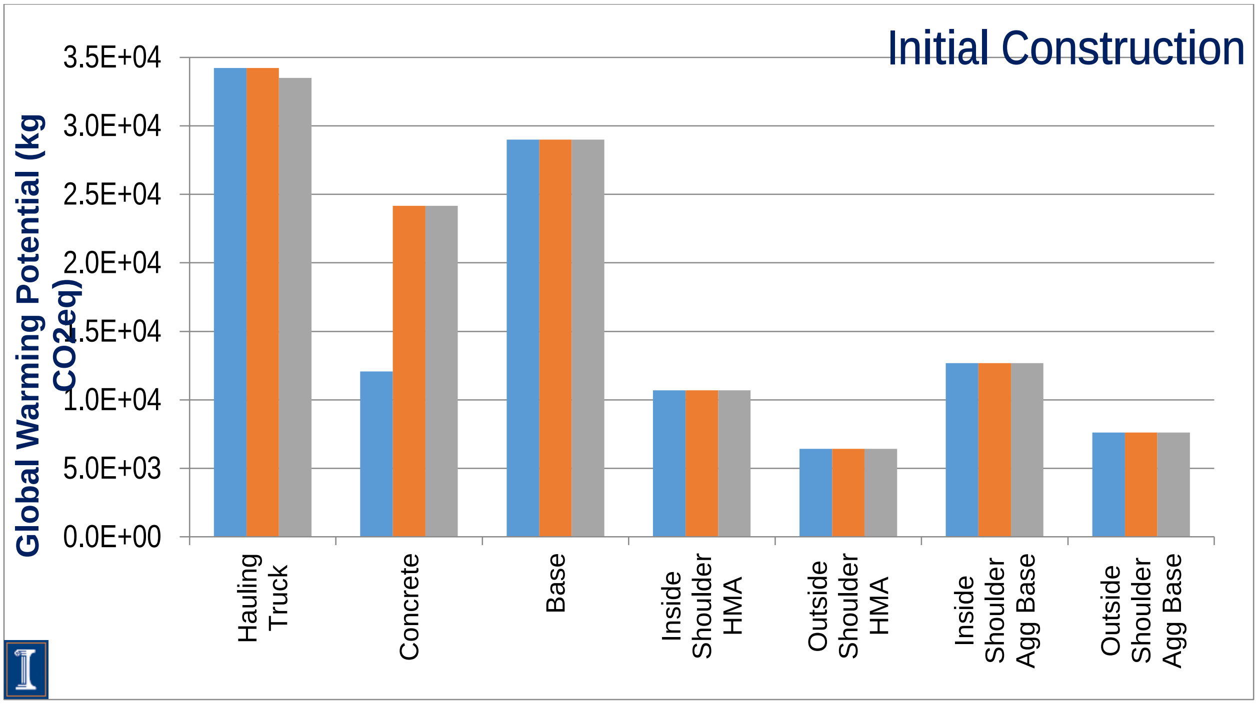


Figure 3-19 Global Warming Potential for Single versus Two-Lift Initial Construction

The increase in the construction phase with two-lift paving option may indicate that it is not the most viable option for increasing sustainability. However, a pavement LCA analysis considering the material phase as well and the utilization of SCMs and recycled aggregates can be used to holistically determine the actual impact of using this construction method. Table 3-9 displays the total energy and global warming potential for the materials and construction phases as well as the combined value for the overall project (detailed summary can be seen in Appendix Table - 2). From Table 3-9, the increase in the construction values is offset by the savings in the materials phase when SCMs and recycled aggregates are used as a replacement for cement and virgin aggregates in the bottom lift. The savings could be further compounded if higher dosages of SCMs were utilized in the bottom lift. The potential for increasing sustainability in a two-lift pavement is viable because of the ability to use a lower quality material in the bottom lift while the top lift is held to a higher performance level. Additionally, recycled aggregates can typically be found close to the construction site. If this reduces hauling distances then the savings in energy and emissions will increase as found in a recent study by Smith et al. (2014). Furthermore, utilizing recycled material limits the disposal impacts of shipping materials to a landfill or recycling center.

Table 3-9 Summary Results for Single Lift and Two-Lift Case Studies

	Total Energy (MJ)			Global Warming Potential (kg CO2eq)		
	Materials	Construction	Project	Materials	Construction	Project
Single Lift	4.47E+07	1.53E+06	4.62E+07	6.19E+06	1.13E+05	6.31E+06
Two-Lift - One Mix Design	4.47E+07	1.71E+06	4.64E+07	6.19E+06	1.25E+05	6.32E+06
Two-Lift - Two Mix Designs	3.81E+07	1.70E+06	3.98E+07	4.69E+06	1.24E+05	4.81E+06

3.2.2 Maintenance and Rehabilitation Case Studies

To study the effects of the maintenance and rehabilitation phase, the initial construction case study from Section 3.2.1 was employed. Various maintenance and rehabilitation techniques were applied to the pavement structure to determine the effects on the sustainability of the pavement structure. Five maintenance and rehabilitation tasks were applied to a single analysis period to determine their relative impacts. The five tasks included sealing joints (longitudinal), patching 3.5% of the surface area, diamond grinding the surface, placing a 4-inch HMA overlay, and transporting the asphalt material for the HMA overlay. Typically these tasks would not all be performed in the same analysis period, but will be evaluated in the same analysis period in order to directly compare the impacts of these common maintenance and rehabilitation tasks.

The total energy usage and global warming potential for the equipment in the five tasks is displayed in Figure 3-20 and Figure 3-21, respectively. Placement of the 4-inch HMA overlay had the highest impact on both the total energy and global warming potential. The total equipment values for all five processes for energy and global warming potential were 1,178,153 MJ and 84,668 kg CO2eq, respectively. These values do not include the material related energy and emissions for the maintenance and rehabilitation processes. These processes are only applied to the mainline with the shoulders remaining untouched.

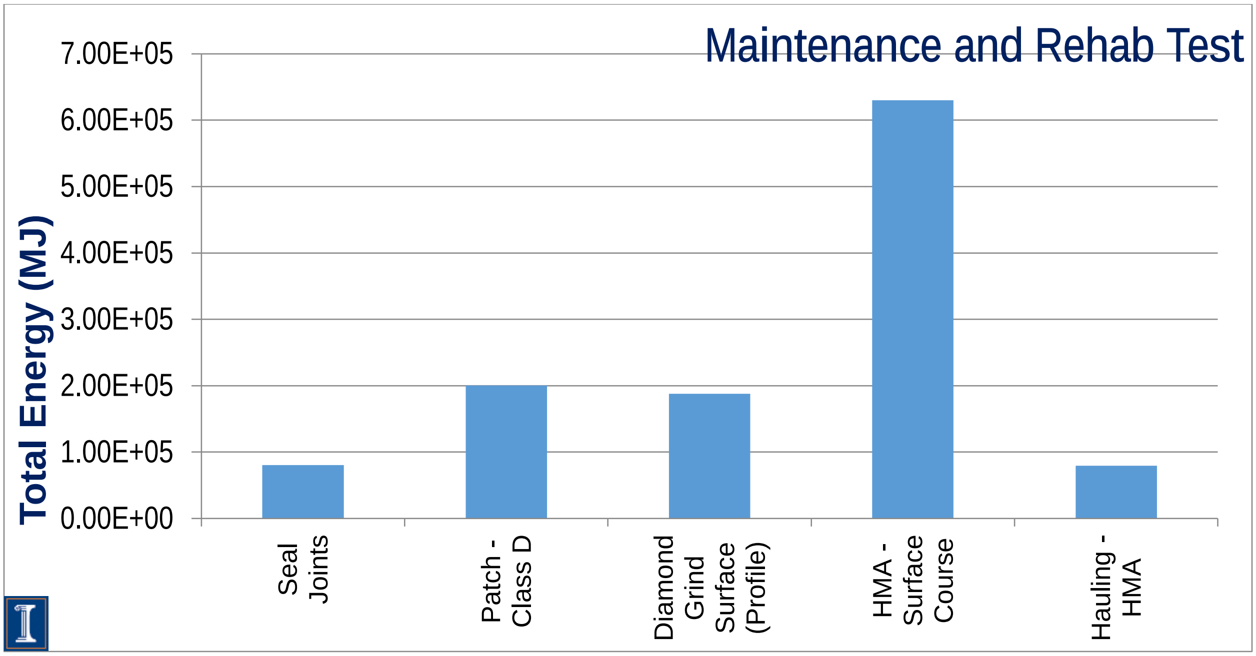


Figure 3-20 Total Energy Usage by Maintenance and Rehabilitation Task Equipment

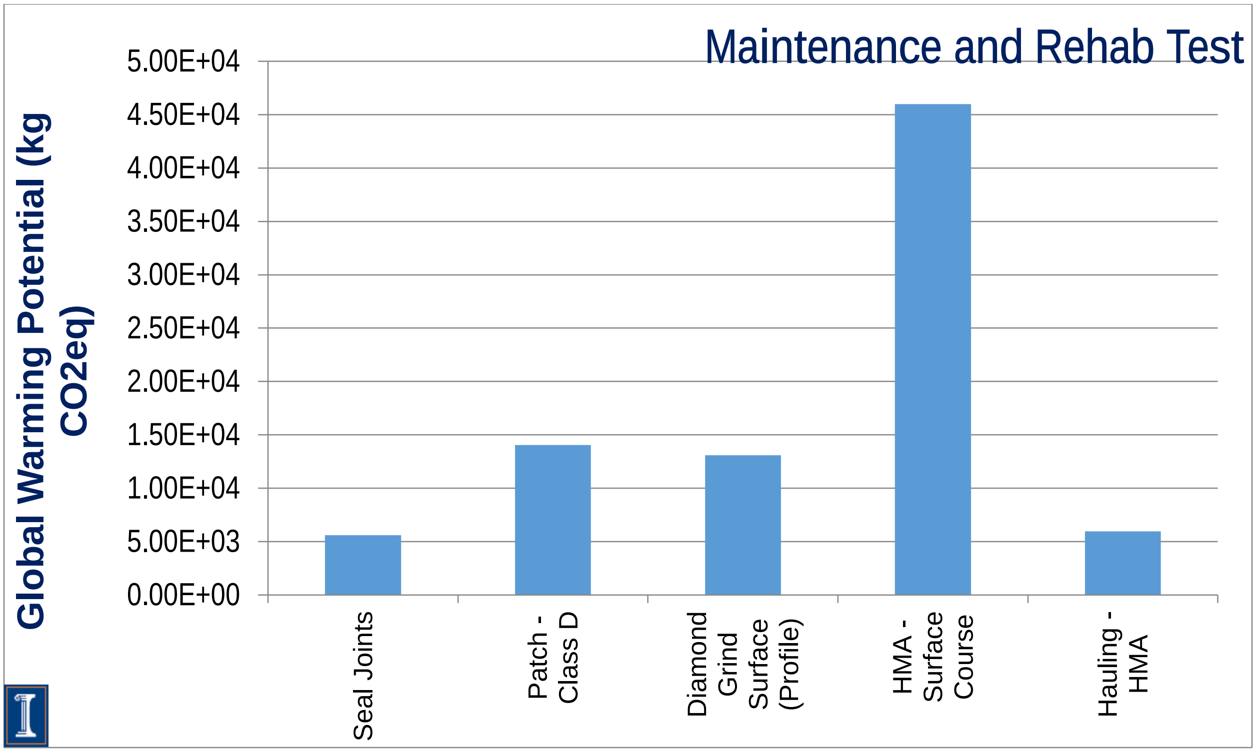


Figure 3-21 Global Warming Potential by Maintenance and Rehabilitation Task Equipment

There is also a materials aspect to the patching and overlay tasks since a concrete patch requires concrete materials and an asphalt overlay requires bituminous materials. The materials used for the concrete layer were also used for the patch materials, while the mix used for the original asphalt shoulder was also applied to the 4 inch HMA overlay of the mainline. The total energy and global warming potential for both the maintenance and rehabilitation equipment and materials are summarized in Table 3-10. For this LCA analysis, the HMA overlay material is the most significant contributor to the total energy and global warming potential for the maintenance and rehabilitation phases.

Table 3-10 Maintenance and Rehabilitation Phase Energy and Global Warming Potential Breakdown

	Total Energy (MJ)	Global Warming Potential (kg CO2eq)
Maintenance and Rehabilitation Task Equipment	1.18E+06	8.47E+04
HMA Mix	1.14E+07	6.94E+05
PCC 35% GGBFS/ 10% Fly Ash	2.98E+05	3.80E+04
Sealant	1.98E+04	1.16E+03
Total Maintenance and Rehabilitation Phase	1.29E+07	8.18E+05

A summary of the single score, total energy and global warming potential for the materials, construction and maintenance and rehabilitations phases is presented in Table 3-11 with the detailed results listed in Appendix Table - 3. From Table 3-11 it can be seen that the production of paving materials (for initial construction and maintenance and rehabilitation) accounts for between 95% to over 98% of the major impacts when considering these three LCA phases. In order to make significant reductions in total energy and emissions for a project accounting only for the material, construction, and maintenance and rehabilitation phases, improvements in the material phase energy and emission would need to take place. Improvements in energy efficiency and emission reductions should be weighted against any potential decrease in the performance life of the pavement material and/or layer.

Table 3-11 Summary of Results for Materials, Construction and Maintenance and Rehabilitation Phases

	Single Score		Total Energy		Global Warming Potential	
	Points	% of Project	MJ	% of Project	kg CO2eq	% of Project
Materials Phase	264.7	51.4%	3.55E+07	71.1%	4.06E+06	81.4%
Construction Phase	4.8	0.9%	1.53E+06	3.1%	1.13E+05	2.3%
Maintenance and Rehabilitation Equipment	3.7	0.7%	1.18E+06	2.4%	8.47E+04	1.7%
Maintenance and Rehabilitation Materials	241.6	46.9%	1.17E+07	23.5%	7.33E+05	14.7%
Total Project	514.9		4.99E+07	-	4.99E+06	-

3.3 Verification Case Study Conclusions

The findings from this verification case study demonstrate the materials phase importance among the three pavement life cycle phases studied. Energy and GWP savings in this phase for concrete pavements can be the result of using SCMs or recycled aggregates. SCMs have a much larger impact because of the reduction in required cement, which is energy and emissions intensive. The initial construction phase and the maintenance and rehabilitation phase make up a much smaller portion of the pavement life cycle assessment. The materials used in the maintenance and rehabilitation phase can account for a significant portion of the pavement energy usage and GWP. This will be compounded, as many pavement structures will have multiple maintenance and rehabilitation tasks over the lifecycle of the structure. The planning of pavement type and subsequent maintenance and rehabilitation tasks should be chosen carefully because of their effect on the pavement LCA.

Decisions at each phase of a pavement’s life cycle can have a significant impact on the energy and emissions in other phases. Choosing a longer life pavement in the initial construction of a pavement can lead to high energy and emissions in the initial materials and construction phases. However it may reduce the need for maintenance and rehabilitation activities later in the pavement’s life. Another example is the use of carbon sequestering cement. This could have a high impact in the material phase but throughout the life of the pavement the specialized cement could sequester more emissions that was initially required to make the cement. Santero (2009) found that a 12-inch deteriorated, crushed concrete pavement could sequester up to 110 Mg of CO_2 for one mile of pavement. It is important to consider the impacts of initial decisions on the energy and emissions throughout the life cycle of the pavement.

CHAPTER 4 CONCRETE PAVEMENT LCA CASE STUDY

This hypothetical case study analyzed a project representative of an actual principal arterial with two different concrete pavement types. The study applied representative paving mix designs to all layers. Full service life maintenance plans supplied by the Illinois Tollway were also applied to analyze the effects of each of the pavement types throughout their life cycles.

4.1 Project Background and Pavement Structure

The project was a 4.6-mile segment of a major principal arterial roadway. The pavement structure consisted of four lanes in one direction with widths of 12 feet, 12 feet, 12.5 feet and 13.5 feet from the inside to outermost lane, respectively. The two pavement cross sections are displayed in Figure 4-1. The mainline was constructed with two layers: a 11-inch continuously reinforced concrete pavement (CRCP) over a 4-inch asphalt base layer. The inner and outer paved shoulders widths are 12.67 feet and 11 feet, respectively. Both paved shoulders consisted of a 2-inch asphalt surface layer over a 4-inch asphalt base layer. An aggregate base layer extended under both shoulders and the mainline lanes with an average thickness of 6 inches. A 4-inch unpaved aggregate shoulder extended 4 feet beyond the outer paved shoulder. The second surface type was a 12-inch jointed plain concrete pavement (JPCP) with 15-foot joints with the rest of the structure remaining constant. These values were inputted into the LCA tool as seen in Figure 4-2. The CRCP and JPCP pavement structures were designed to have a total service life of 78 years and 62 years, respectively, with 9 maintenance and rehabilitation periods, each throughout the life of the pavements. These are based on estimates provided by the Illinois Tollway's maintenance plans. At the end of life for each pavement type, reconstruction is required.

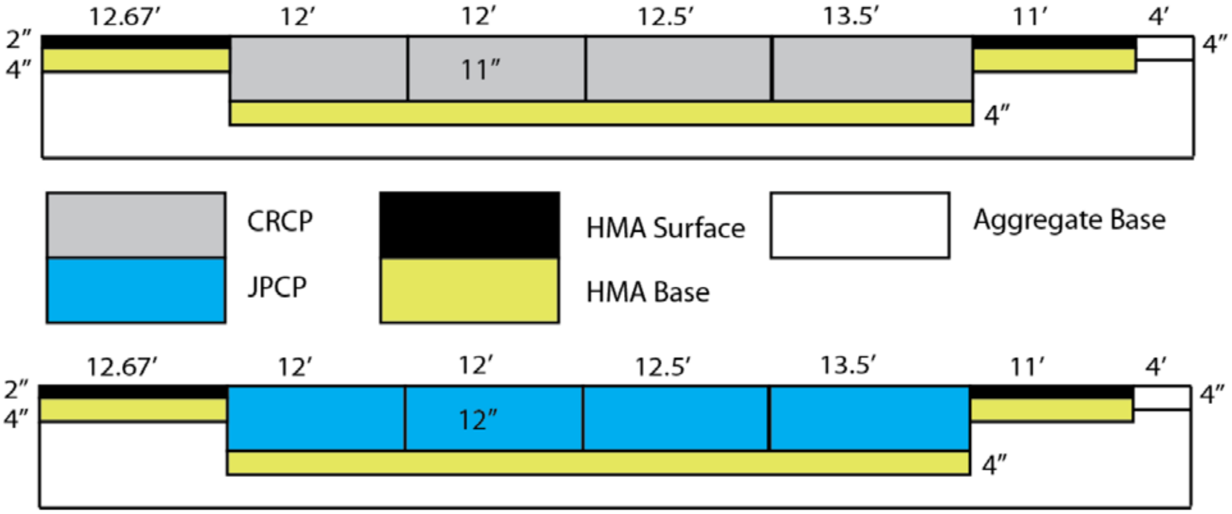
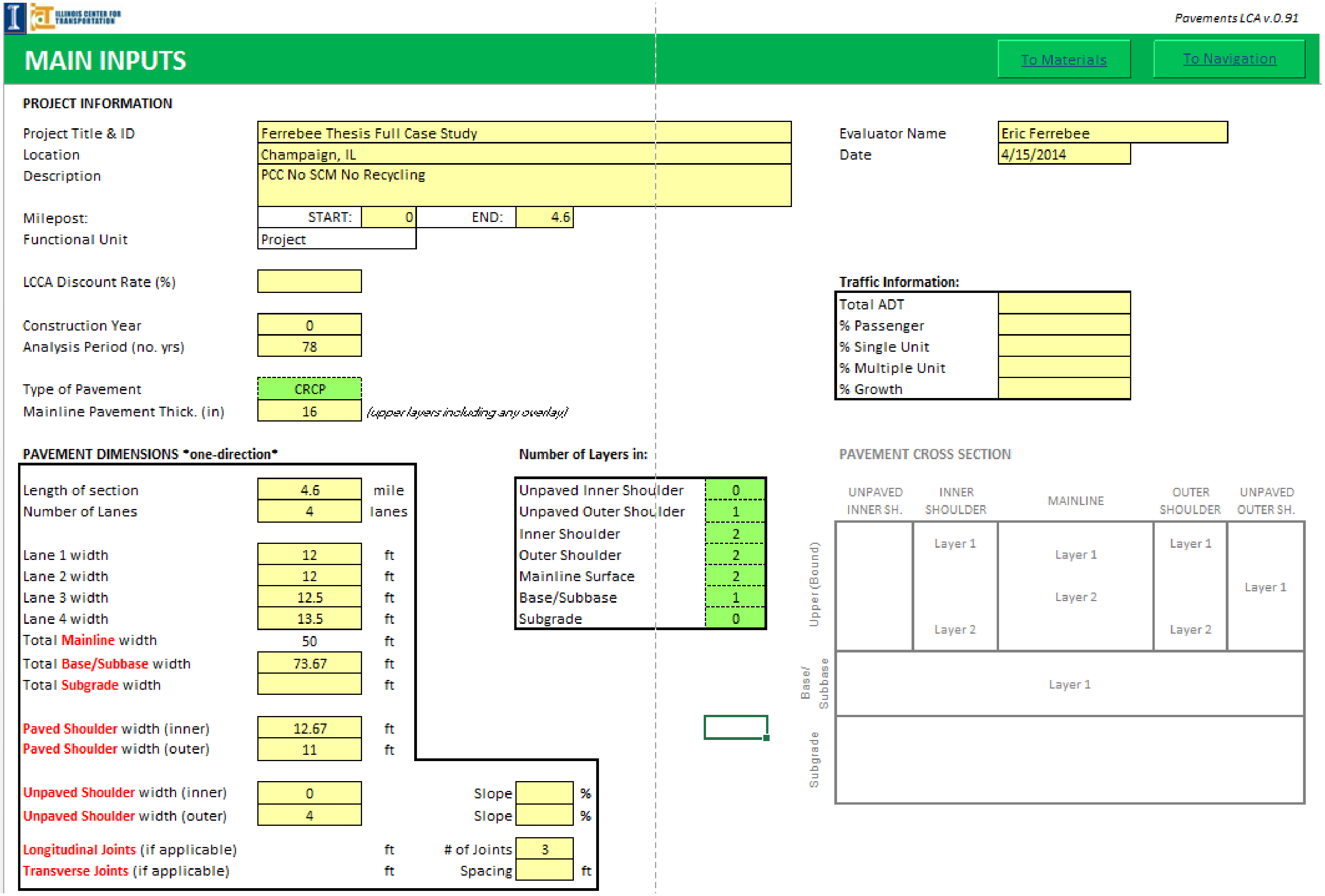


Figure 4-1 Pavement Structures for Continuously Reinforced and Jointed Plain Concrete Pavement Alternatives, Respectively



Pavements LCA v.0.91

MAIN INPUTS

PROJECT INFORMATION

Project Title & ID	Ferrebee Thesis Full Case Study		
Location	Champaign, IL		
Description	PCC No SCM No Recycling		
Milepost:	START: 0	END: 4.6	
Functional Unit	Project		
LCCA Discount Rate (%)			
Construction Year	0		
Analysis Period (no. yrs)	78		
Type of Pavement	CRCP		
Mainline Pavement Thick. (in)	16	*(upper layers including any overlay)*	

Evaluator Name	Eric Ferrebee
Date	4/15/2014

Traffic Information:

Total ADT	
% Passenger	
% Single Unit	
% Multiple Unit	
% Growth	

PAVEMENT DIMENSIONS *one-direction*

Length of section	4.6	mile			
Number of Lanes	4	lanes			
Lane 1 width	12	ft			
Lane 2 width	12	ft			
Lane 3 width	12.5	ft			
Lane 4 width	13.5	ft			
Total Mainline width	50	ft			
Total Base/Subbase width	73.67	ft			
Total Subgrade width		ft			
Paved Shoulder width (inner)	12.67	ft			
Paved Shoulder width (outer)	11	ft			
Unpaved Shoulder width (inner)	0		Slope		%
Unpaved Shoulder width (outer)	4		Slope		%
Longitudinal Joints (if applicable)		ft	# of Joints	3	
Transverse Joints (if applicable)		ft	Spacing		ft

Number of Layers in:

Unpaved Inner Shoulder	0
Unpaved Outer Shoulder	1
Inner Shoulder	2
Outer Shoulder	2
Mainline Surface	2
Base/Subbase	1
Subgrade	0

Figure 4-2 Project Information and Pavement Structure Inputs for CRCP Surface

4.2 Paving Mix Designs

Two mix designs were assigned to the concrete layers and are shown in Table 4-1. The first mix was used for 81.5% of the project and the second mix was used for 18.5% of the total project. Two Tollway representative mixes are used for different parts of the project as this is not considered to be a two-lift project. The haul distance for each material to the plant is also included in Table 4-1. The concrete plant is taken as 3.8 miles from the construction site. In addition to these materials, steel is required for both the CRCP and JPCP pavements. A reasonable steel content for CRCP is 0.7% by volume, which requires an estimated 3.82 million pounds of steel for the project, assuming a density of steel of 490 lb/ft^3. A similar approximation for JPCP is 0.058% steel by volume (assuming dowels and tie bars), which results in a required 345,311 pounds of steel for the project. All steel was assumed to be five miles from the construction site.

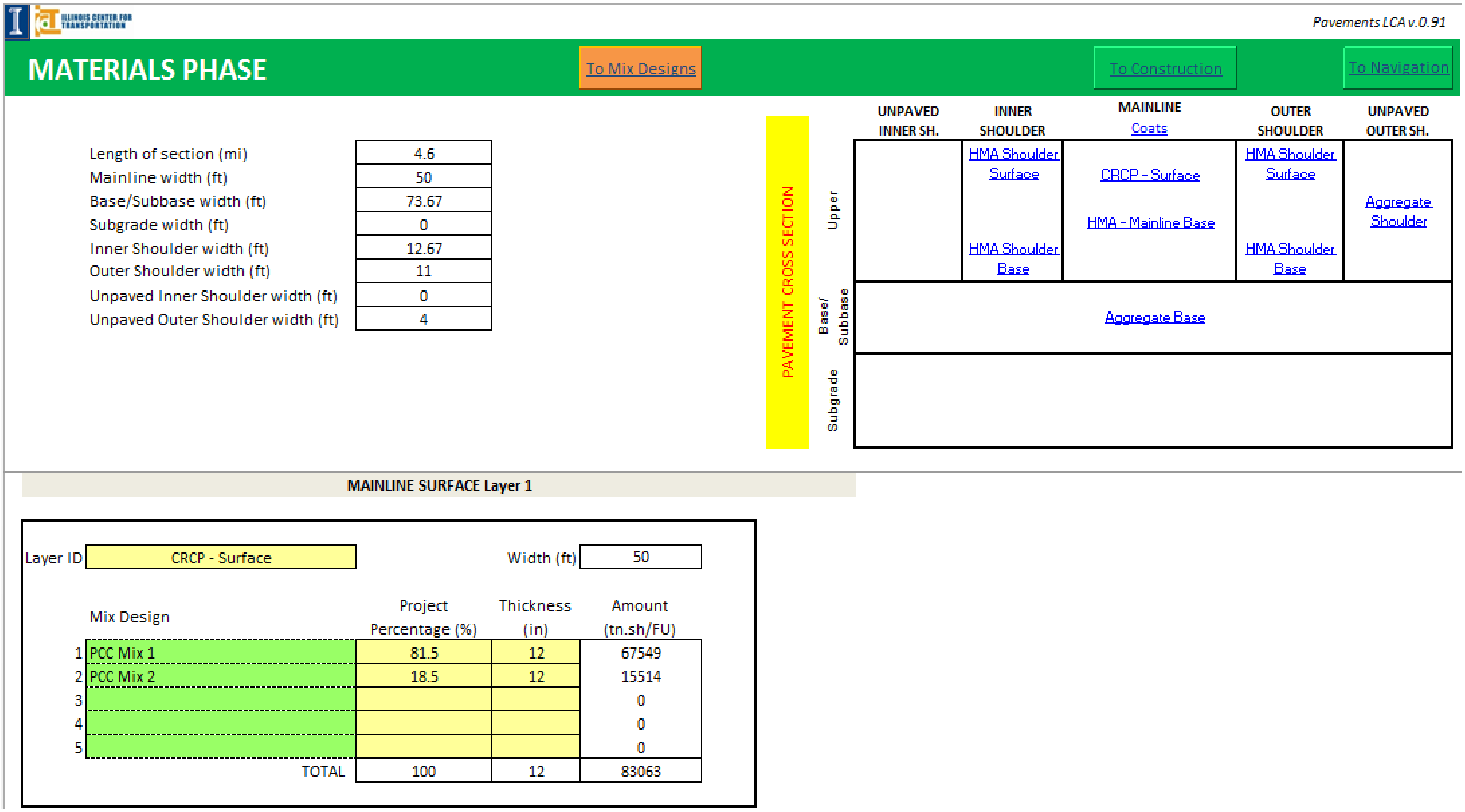
Table 4-1 Concrete Mix Designs and Material Haul Distances

	PCC Mix 1 (lb/CY)	PCC Mix 2 (lb/CY)	Material Source to Plant Distance (mile)
Coarse Aggregate	1901	1800	31.4
Fine Aggregate	1178	1375	21.6
Cement	435	517	64.9
Fly Ash	135	-	36.2

Three asphalt mixes were used for the asphalt layers. The amount of each material by percent of mix is shown in Table 4-2. The distances for material hauling to the plant are also included in Table 4-2. The two fine aggregates had different locations which created variable hauling distances from material source acquisition to plant. The FRAP was assumed to have 5% recycled binder contributing to the overall asphalt content of the mix. The FRAP was taken from the existing pavement, so the material acquisition to plant distance was assumed to be zero. For this analysis, the asphalt plant is assumed to be 3.8 miles from the construction site. The mix designs were assigned to their corresponding layer with thicknesses as shown in Figure 4-3, which completed the required inputs for the materials phase.

Table 4-2 Asphalt Mix Designs by Percent of Mix and Material Haul Distances

	Mainline Base	Shoulder Binder	Shoulder Surface	Material Source to Plant Distance (mile)
Virgin Coarse	64.0%	67.0%	59.6%	31.4
Fine Aggregate 1	9.0%	18.0%	17.9%	31.4
Fine Aggregate 2	11.0%	-	20.0%	21.6
Mineral Filler	1.0%	-	2.5%	48
FRAP	15.0%	15.0%	-	0
Asphalt Binder	4.7%	4.6%	5.7%	51.7



Length of section (mi)	4.6
Mainline width (ft)	50
Base/Subbase width (ft)	73.67
Subgrade width (ft)	0
Inner Shoulder width (ft)	12.67
Outer Shoulder width (ft)	11
Unpaved Inner Shoulder width (ft)	0
Unpaved Outer Shoulder width (ft)	4

MAINLINE SURFACE Layer 1

Layer ID CRCP - Surface

Width (ft) 50

	Mix Design	Project Percentage (%)	Thickness (in)	Amount (tn.sh/FU)
1	PCC Mix 1	81.5	12	67549
2	PCC Mix 2	18.5	12	15514
3				0
4				0
5				0
	TOTAL	100	12	83063

Figure 4-3 Mix Design and Layer thickness Assignment for CRCP Materials Phase

4.3 Construction and Maintenance

The initial construction was set to be at year zero. Nine major tasks were required to transform the individual materials to the final pavement structure. Table 4-3 displays the necessary construction tasks along with the layer to which each task was applied. These initial construction tasks were required for both the CRCP and JPCP types.

Table 4-3 Initial Construction Tasks for CRCP and JPCP Surfaces

Task	Description	Affected Element	Applies to Layer
Hauling Truck	Hauling all materials to site	-	-
Single-Lift PCC	Paving Concrete Layer	Mainline	Concrete - Surface
HMA - Leveling Course	Pave HMA Base	Mainline	HMA - Mainline Base
Aggregate Base	Agg Base Layer	Base/Subbase	Aggregate Base
HMA - Surface Course	Pave HMA Shoulder Surface	Inside Shldr	HMA Shoulder Surface
HMA - Leveling Course	Pave HMA Shoulder Base	Inside Shldr	HMA Shoulder Base
HMA - Surface Course	Pave HMA Shoulder Surface	Outside Shldr	HMA Shoulder Surface
HMA - Leveling Course	Pave HMA Shoulder Base	Outside Shldr	HMA Shoulder Base
Aggregate Base	Agg Shoulder	Unpaved Shldr	Aggregate Shoulder

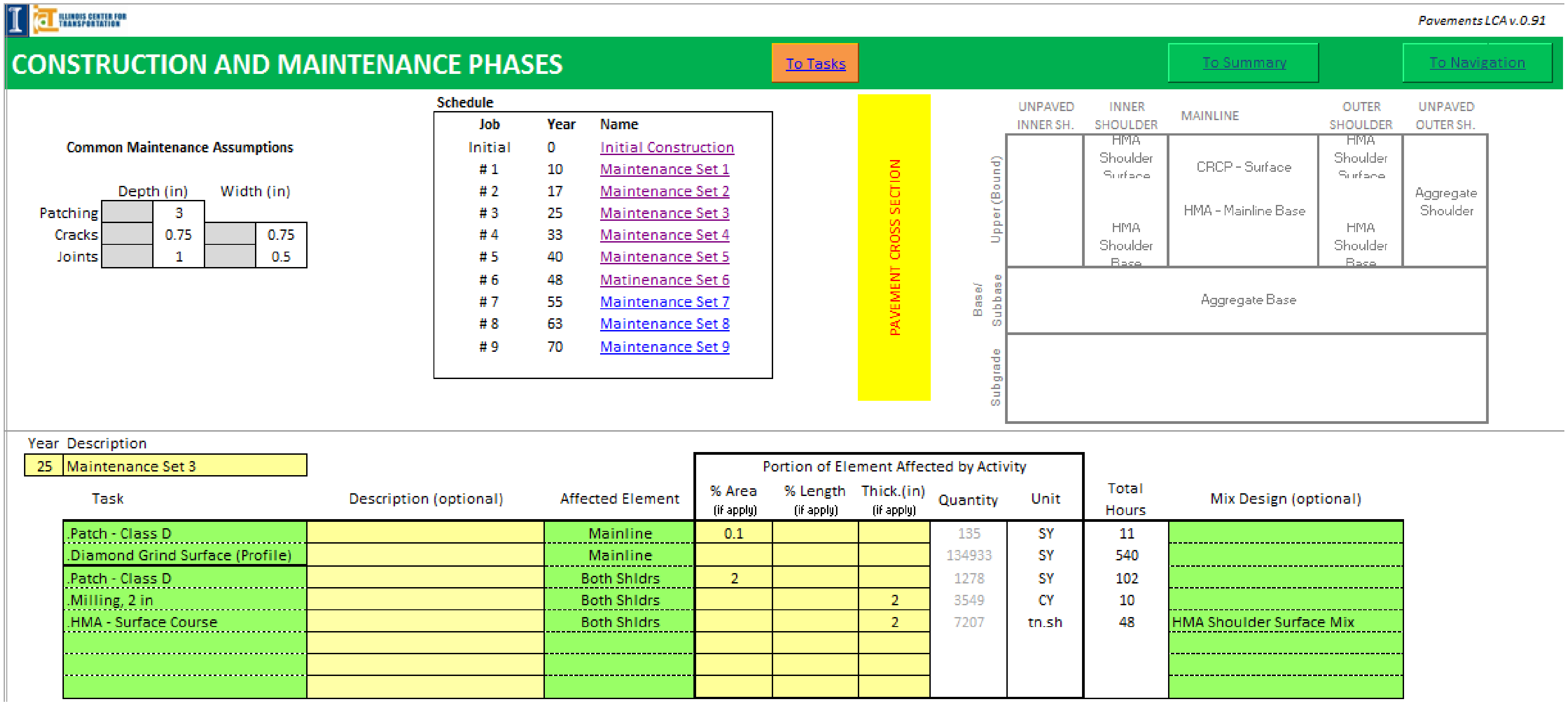
Typical Tollway maintenance plans for CRCP and JPCP surfaces were utilized for the maintenance and rehabilitation schedule (Illinois Tollway, 2013). Each schedule consisted of nine maintenance and rehabilitation activities that extended to 70 years and 58 years, respectively, after the CRCP and JPCP initial construction. The end-of-life for these maintenance plans was scheduled for year 78 and year 62 of the original CRCP and JPCP construction, respectively, when they would require complete reconstruction. As the end-of-life phase is not yet implemented within this tool, the final maintenance activities are the last thing considered for each of the pavements. The maintenance plan for CRCP and JPCP are presented in Table 4-4 and Table 4-5, respectively. The HMA overlays utilized the HMA shoulder surface mix design. A representative set of grouped maintenance activities is presented in Figure 4-4. As can be seen from these two maintenance plans, the JPCP requires more patching and more crack sealing in addition to having a shorter life span than the CRCP surface.

Table 4-4 CRCP Maintenance Schedule (Illinois Tollway, 2013)

Year	Maintenance Set	Mainline Activity	Shoulder Activity
0	Initial Construction		
10	1	Patch 0.1%	Rout and Seal Cracks (2 x CL Longitudinal, 2 x CL Transverse
		-	Microsurface
17	2	-	Rout and Seal Cracks (2 x CL Longitudinal, 2 x CL Transverse
		-	Microsurface
25	3	Patch 0.1%	Mill 2-inch
		Diamond Grind Surface	Patch 2%
		-	HMA Overlay 2-inch
33	4	Patch 1%	HMA Overlay 4-inch
		HMA Overlay 4-inch	-
40	5	Rout and Seal Cracks (100 % Longitudinal + 50% Random)	Rout and Seal Cracks (2 x CL Longitudinal, 2 x CL Transverse
48	6	Mill 4-inch	Rout and Seal Cracks (2 x CL Longitudinal, 2 x CL Transverse
		Patch 0.5%	Microsurface
		HMA Overlay 4-inch	-
55	7	Rout and Seal Cracks (100 % Longitudinal + 50% Random)	Rout and Seal Cracks (2 x CL Longitudinal, 2 x CL Transverse
63	8	Mill 4-inch	Mill 2-inch
		Patch 0.5%	Patch 2%
		HMA Overlay 4-inch	HMA Overlay 2-inch
70	9	Rout and Seal Cracks (100 % Longitudinal + 50% Random)	Rout and Seal Cracks (2 x CL Longitudinal, 2 x CL Transverse
78	Reconstruction		

Table 4-5 JPCP Maintenance Schedule (Illinois Tollway, 2013)

Year	Maintenance Set	Mainline Activity	Shoulder Activity
0	Initial Construction		
11	1	Seal Joints	Rout and Seal Cracks (2 x CL Longitudinal, 2 x CL Transverse
			Microsurface
18	2	Seal Joints	Rout and Seal Cracks (2 x CL Longitudinal, 2 x CL Transverse
		Patch 3.5%	Microsurface
25	3	Patch 2.5%	Mill 2-inch
		Diamond Grind Surface	Patch 2%
		Seal Joints (100% Longitudinal)	Overlay 2-inch
32	4	Patch 4%	HMA Overlay 4-inch
		HMA Overlay 4-inch	-
38	5	Rout and Seal Cracks (100% Longitudinal, 100% Transverse)	Rout and Seal Cracks (2 x CL Longitudinal, 2 x CL Transverse
44	6	Mill 4-inch	Rout and Seal Cracks (2 x CL Longitudinal, 2 x CL Transverse
		Patch 4%	Microsurface
		HMA Overlay 4-inch	-
49	7	Rout and Seal Cracks (100% Longitudinal, 100% Transverse)	Rout and Seal Cracks (2 x CL Longitudinal, 2 x CL Transverse
54	8	Mill 4-inch	Rout and Seal Cracks (2 x CL Longitudinal, 2 x CL Transverse
		Patch 4%	Microsurface
		HMA Overlay 4-inch	-
58	9	Rout and Seal Cracks (100% Longitudinal, 100% Transverse)	Rout and Seal Cracks (2 x CL Longitudinal, 2 x CL Transverse
62	Reconstruction		



Common Maintenance Assumptions

	Depth (in)	Width (in)
Patching	3	
Cracks	0.75	0.75
Joints	1	0.5

Schedule

Job	Year	Name
Initial	0	Initial Construction
# 1	10	Maintenance Set 1
# 2	17	Maintenance Set 2
# 3	25	Maintenance Set 3
# 4	33	Maintenance Set 4
# 5	40	Maintenance Set 5
# 6	48	Matinenance Set 6
# 7	55	Maintenance Set 7
# 8	63	Maintenance Set 8
# 9	70	Maintenance Set 9

Year	Description
25	Maintenance Set 3

Task	Description (optional)	Affected Element	Portion of Element Affected by Activity			Quantity	Unit	Total Hours	Mix Design (optional)
			% Area (if apply)	% Length (if apply)	Thick.(in) (if apply)				
.Patch - Class D		Mainline	0.1			135	SY	11	
.Diamond Grind Surface (Profile)		Mainline				134933	SY	540	
.Patch - Class D		Both Shldrs	2			1278	SY	102	
.Milling, 2 in		Both Shldrs			2	3549	CY	10	
.HMA - Surface Course		Both Shldrs			2	7207	tn.sh	48	HMA Shoulder Surface Mix

Figure 4-4 Representative Set of Maintenance Tasks for CRCP

4.4 Results

With the cross-sectional features, mix designs, materials phases, construction and maintenance and rehabilitation phases inputted into the LCA tool, the impact factor results for each pavement surface type were obtained.

4.4.1 Materials Phase

The total energy consumed by the CRCP and JPCP projects in the materials phase was 143,473,275 MJ and 116,829,562 MJ, respectively, which is equivalent to a 19% reduction for JPCP relative to CRCP. The total global warming potential for the CRCP and JPCP projects in the materials phase was 14,571,028 kg CO2eq and 13,244,251 kg CO2eq, respectively, which is equivalent to a 9% reduction for JPCP relative to CRCP. The total energy and global warming potential for the materials phase for the CRCP and JPCP projects broken down by layer can be seen in Figure 4-5 and Figure 4-6, respectively. As can be seen from these figures, the concrete surface layers have the largest impact on the materials phase. The change in total energy and global warming potential for the two concrete layers is because of the difference in the amount of steel in each pavement type and the difference in thickness. All of the other layers energy and GWP remained the same between JPCP and CRCP since the inputs and layers were the same.

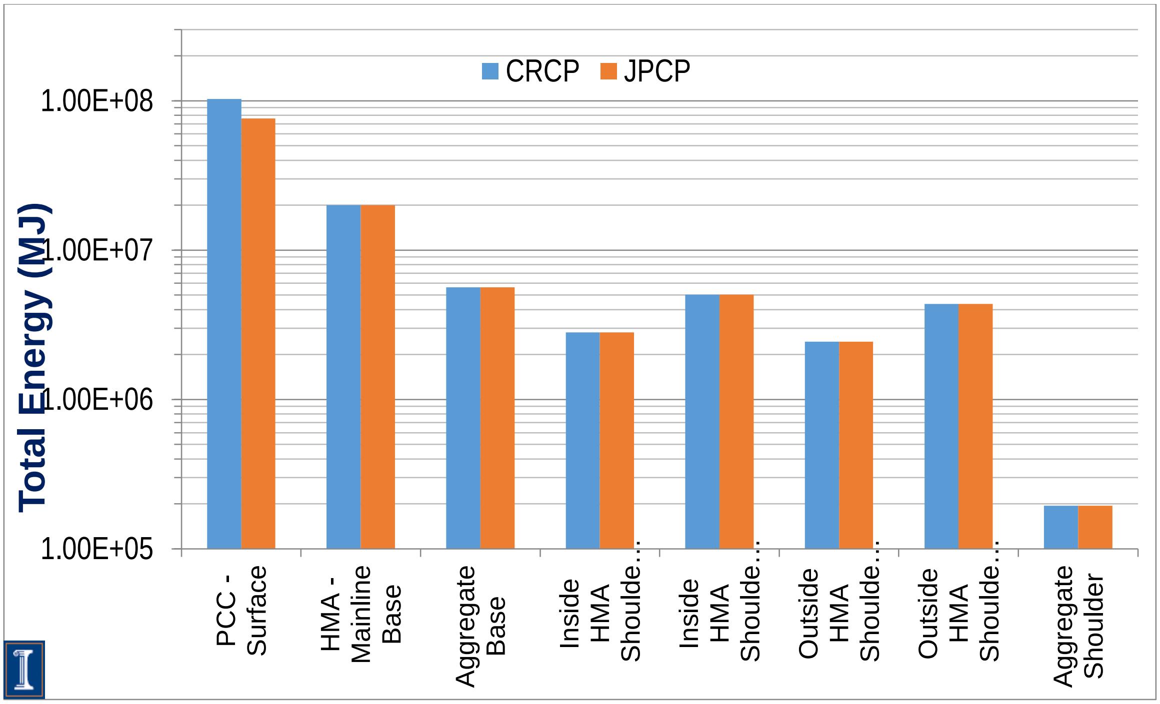


Figure 4-5 Total Energy by Pavement Layer for Materials Phase

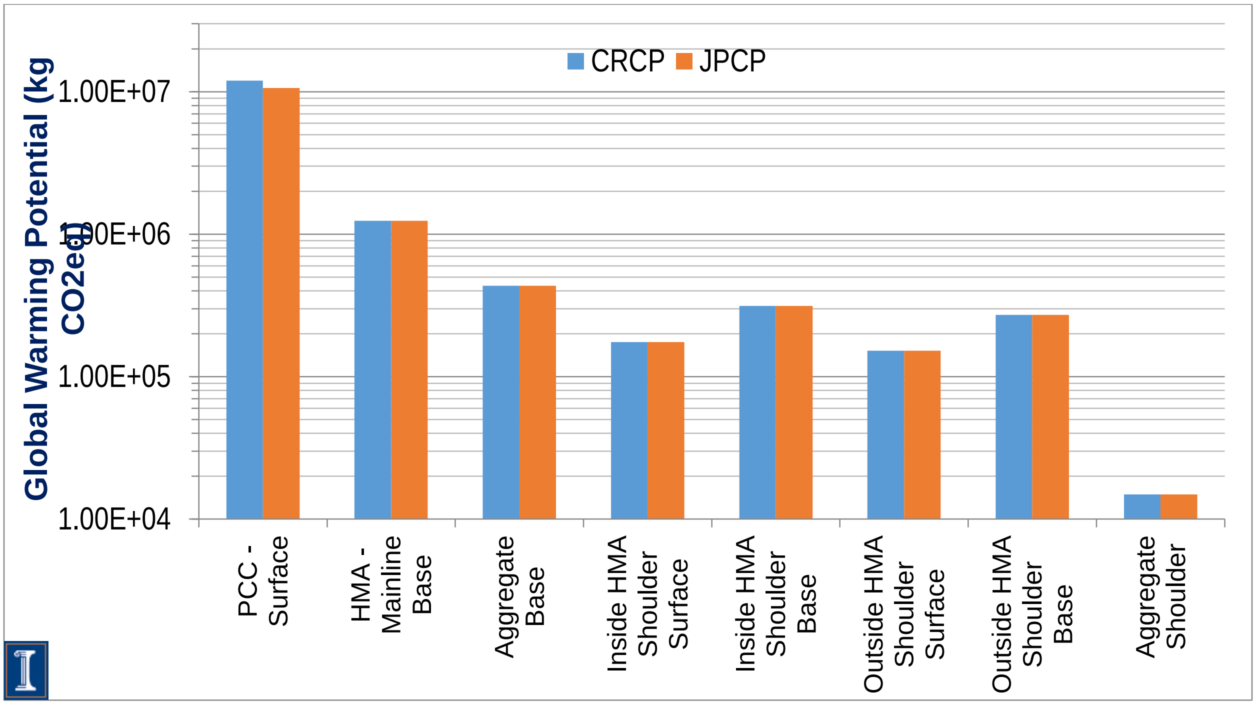


Figure 4-6 Global Warming Potential by Pavement Layer for Materials Phase

To visualize the impact of the steel in the CRCP and JPCP surfaces, Figure 4-7 and Figure 4-8 display the breakdown of total energy and global warming potential, respectively, by material in the concrete layers. The steel accounts for roughly two-thirds as much energy as the cement in the CRCP layer whereas it is more on the order of magnitude of the other constituents in the JPCP layer. The steel does not have quite the same impact in terms of global warming potential where it is less than one-third of the GWP as the cement in the CRCP surface.

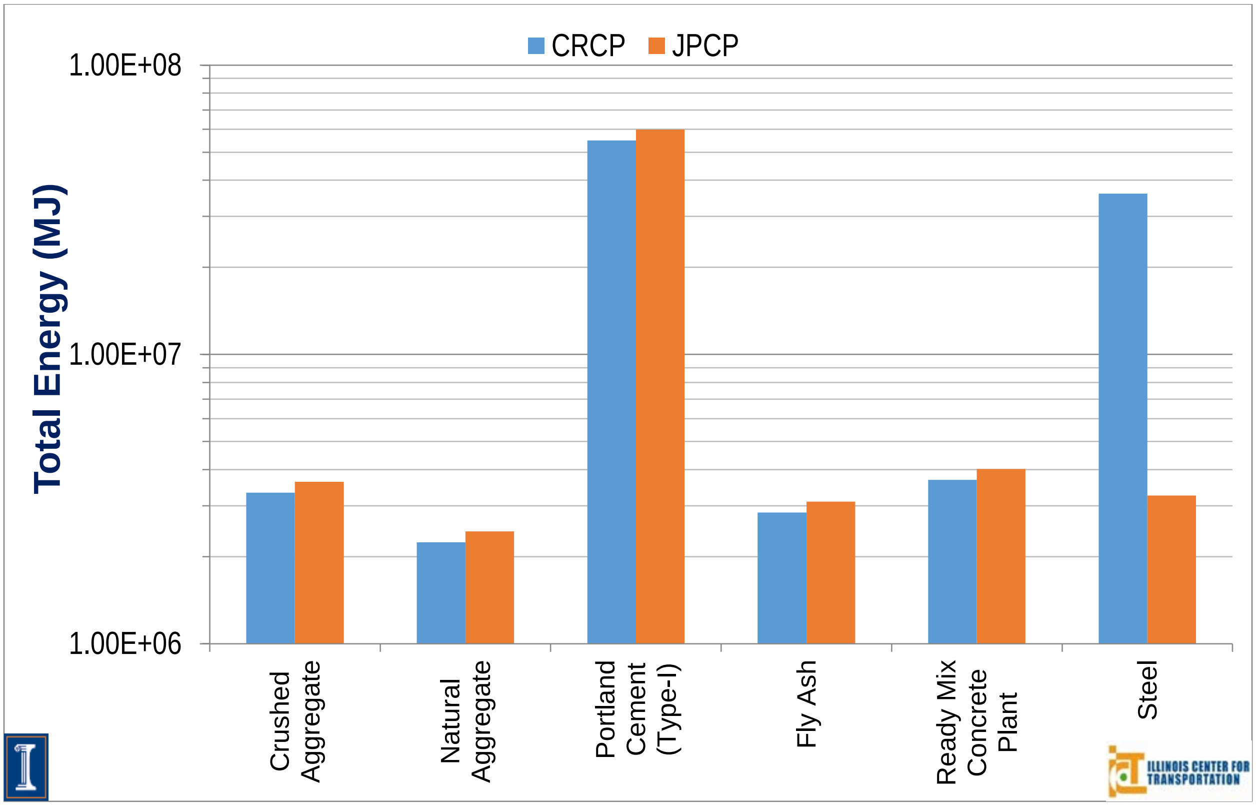


Figure 4-7 Total Energy for Concrete Layer Materials

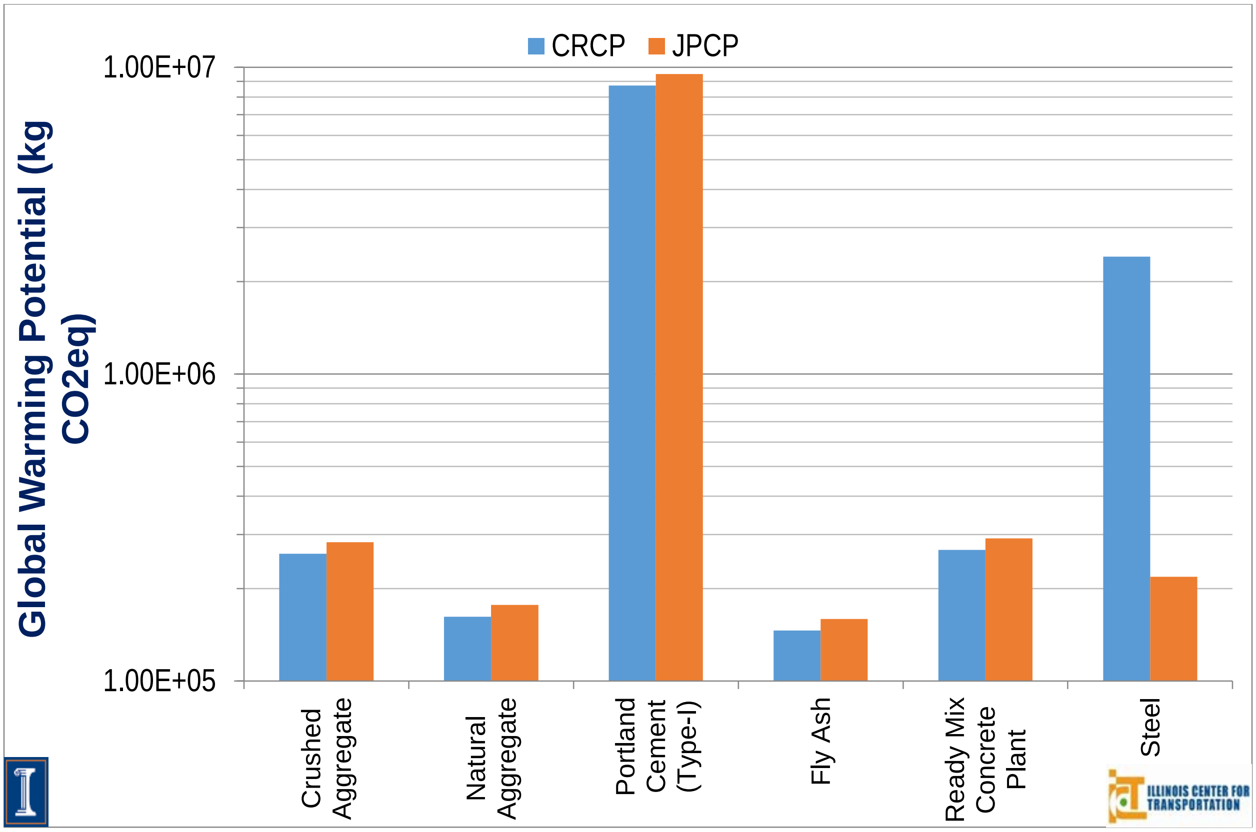


Figure 4-8 Global Warming Potential for Concrete Layer Materials

4.4.2 Construction Phase

A summary of the construction results for the CRCP and JPCP cases can be seen in Table 4-6, which indicates that there is little difference between the two construction phases. The main difference comes from hauling the steel to the construction site and hauling the extra material for the extra thickness of the JPCP layer. The placement of the steel is typically done by hand and thus does not carry any energy usage or emissions with it.

Table 4-6 Construction Phase Summary

	Total Energy (MJ)	Global Warming Potential (kg CO2eq)
CRCP	5.65E+06	4.07E+05
JPCP	5.72E+06	4.13E+05
Difference	1.24%	1.33%

4.4.3 Maintenance Phase

The CRCP and JPCP maintenance plans differ significantly based on the Illinois Tollway policies. The maintenance phase for the JPCP surface is more intensive with the pavement assumed not to have as long as service life compared to CRCP. The total energy and global warming potential for the equipment in the maintenance phase for the pavement structures can be seen in Figure 4-9 and Figure 4-10, respectively, based on the maintenance plans specified in Table 4-4 and Table 4-5. There are three sets of maintenance activities (4, 6, and 8) that contribute significantly to the total energy and global warming potential the pavement structures. These sets of activities include milling and a structural asphalt overlay, which requires the transportation and placement of large quantities of materials.

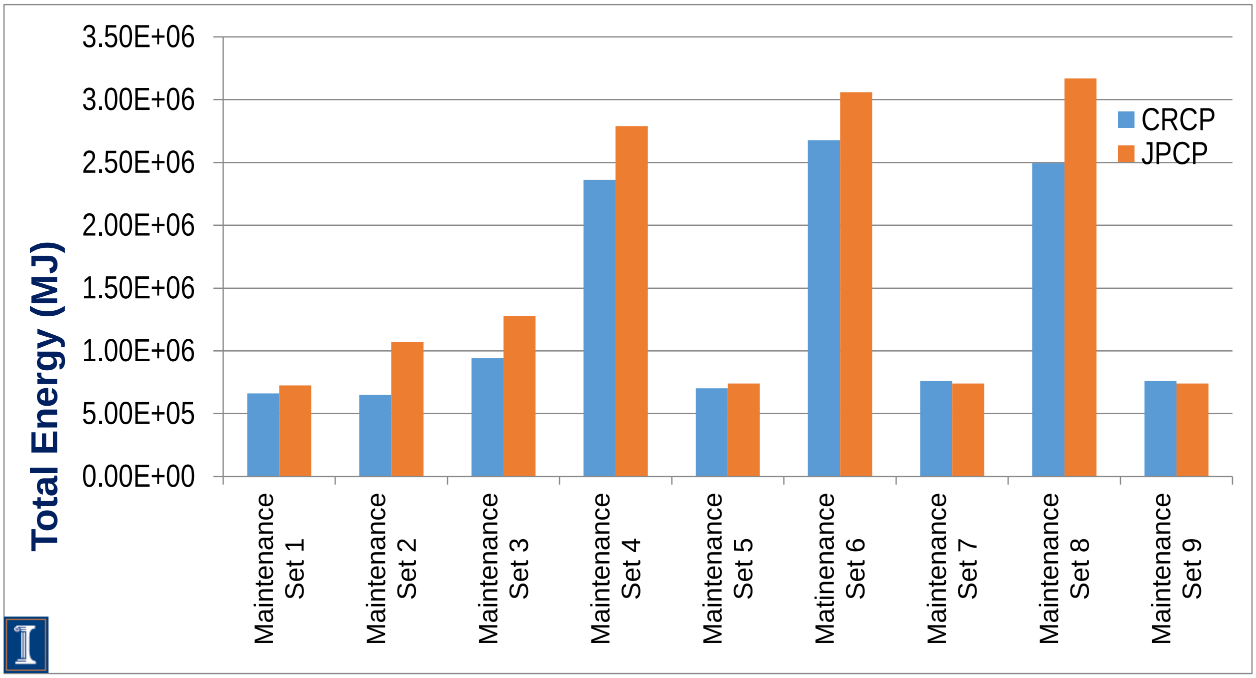


Figure 4-9 Total Energy Usage by Equipment in Maintenance Phase

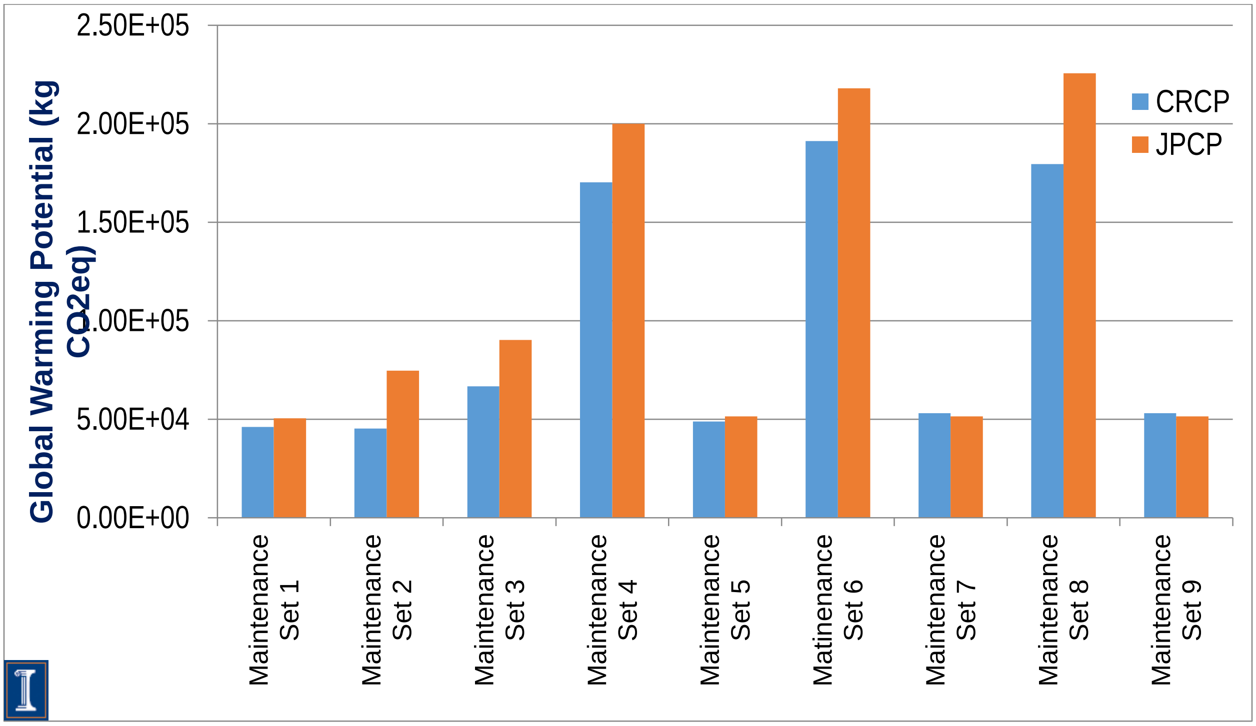


Figure 4-10 Global Warming Potential by Equipment in Maintenance Phase

The total energy and global warming potential for the materials production in the maintenance phase is summarized in Figure 4-11, Figure 4-12 and Table 4-7. While similar trends can be seen between the equipment usage and material production values for the individual maintenance sets, it is clear that there are a number of differences. A number of the maintenance sets have very low energy or global warming potential associated with them, such as crack sealing and patching, when compared to the maintenance sets that require structural asphalt overlays. From Table 4-7, the maintenance phase of the CRCP and JPCP structures nearly balance out in terms of total energy and global warming potential.

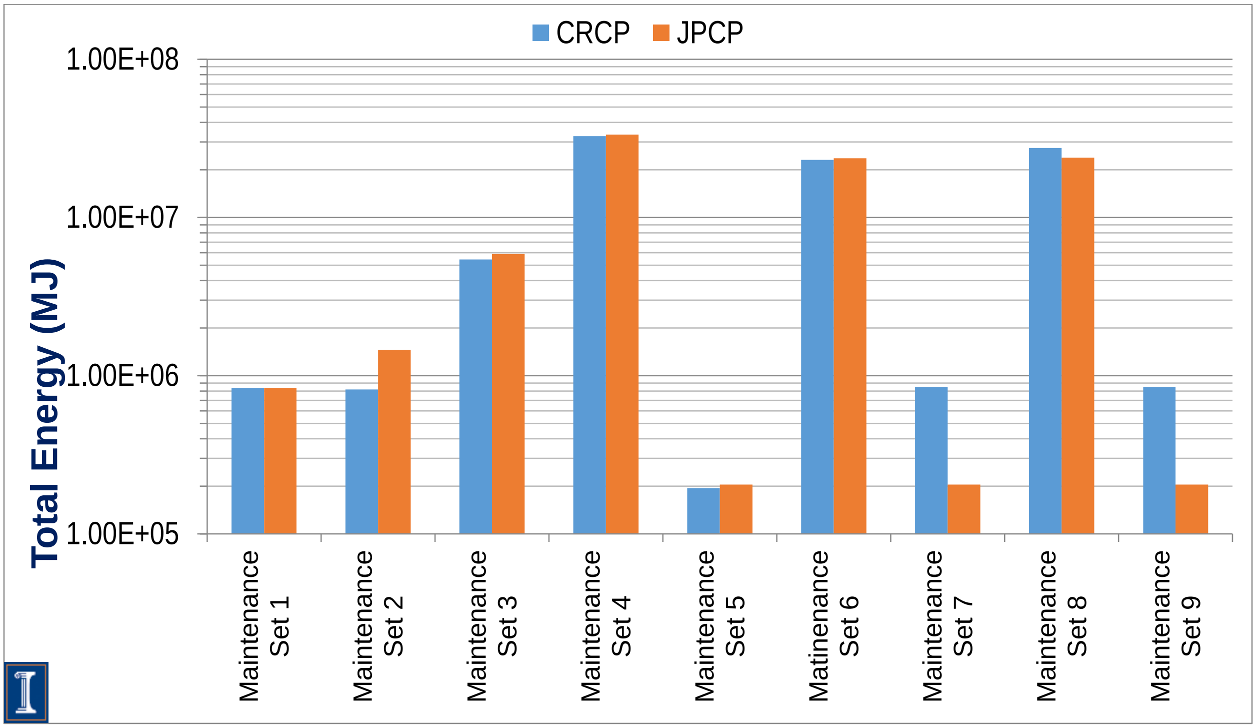


Figure 4-11 Total Energy for Material Production in Maintenance Phase

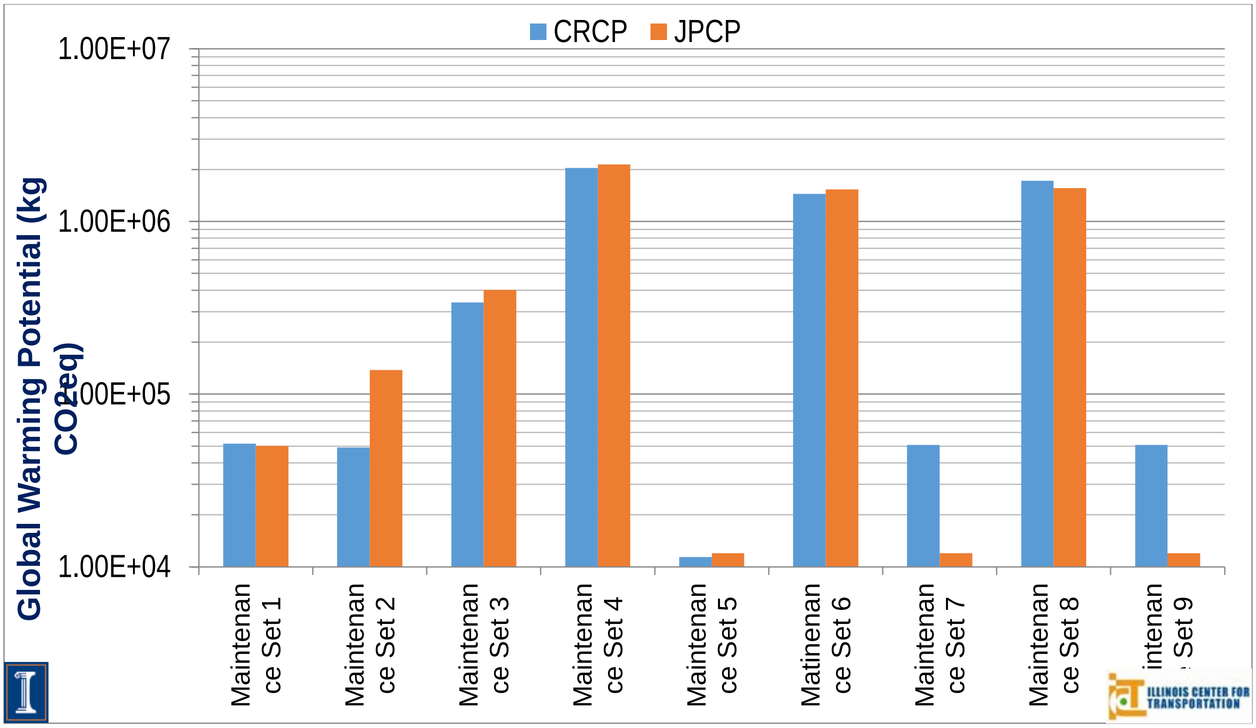


Figure 4-12 Global Warming Potential for Material Production in Maintenance Phase

Table 4-7 Maintenance Phase Summary for CRCP and JPCP Comparison

	CRCP		JPCP	
	Total Energy (MJ)	Global Warming Potential (kg CO2eq)	Total Energy (MJ)	Global Warming Potential (kg CO2eq)
Maintenance Equipment	1.20E+07	8.55E+05	1.43E+07	1.01E+06
Maintenance Materials	9.24E+07	5.77E+06	8.99E+07	5.86E+06
Maintenance Totals	**1.04E+08**	**6.62E+06**	**1.04E+08**	**6.88E+06**

4.4.4 Material, Construction, Maintenance & Rehabilitation Results

The summarized results for the materials, construction, and maintenance phases are displayed in Table 4-8. The CRCP structure has higher values for the main three evaluation categories. The CRCP full project values are 29.2%, 10.6% and 4.9% greater than the JPCP values in the main categories of single score, total energy and global warming potential, respectively. Nearly all of this difference is because of the production of the steel. The differences would be greater if not for the increased thickness of the JPCP and the difference in maintenance schedules. If the concrete thickness for CRCP was 80% of the JPCP thickness than these full project impact factors for the two concrete pavement types may be even closer. A summary of all results for both cases can be seen in Appendix Table - 4 and Appendix Table - 5.

Table 4-8 Summarized Project Results

	CRCP			JPCP		
	Single Score (Points)	Total Energy (MJ)	Global Warming Potential (kg CO2eq)	Single Score (Points)	Total Energy (MJ)	Global Warming Potential (kg CO2eq)
Materials	2126.0	1.43E+08	1.46E+07	1061.4	1.17E+08	1.32E+07
Construction	17.8	5.65E+06	4.07E+05	18.0	5.72E+06	4.13E+05
Maintenance Equipment	37.9	1.20E+07	8.55E+05	45.3	1.43E+07	1.01E+06
Maintenance Materials	1777.9	9.24E+07	5.77E+06	1679.9	8.99E+07	5.86E+06
Full Project	3959.6	2.54E+08	2.16E+07	2804.6	2.27E+08	2.05E+07

While the CRCP values presented in Table 4-8 are greater than those for the JPCP counterpart, it is important to remember that the service lives of the two structures are different with the CRCP having a 78 year service life and the JPCP having a 62 year service life. Factoring in these results, Table 4-9 presents the results normalized by the service life of each of the individual pavement structures. From this table, it can be seen that the extra service life gained by the extra steel used in the CRCP structure proves to make the per-year energy and global warming potential more beneficial than the JPCP structure. By delaying the reconstruction of the pavement, the CRCP's viability increases with 12.5% and 19.6% less total energy and global warming potential than the JPCP alternative but still 10.9% greater single score. Therefore, accounting for the difference in CRCP and JPCP service life, the environmental impact factors can be more favorable for CRCP.

Table 4-9 Summary of Project Results Normalized to a Single Year of Service for CRCP vs. JPCP

	CRCP			JPCP		
	Single Score (Points)	Total Energy (MJ)	Global Warming Potential (kg CO2eq)	Single Score (Points)	Total Energy (MJ)	Global Warming Potential (kg CO2eq)
Materials	27.3	1.84E+06	1.87E+05	17.1	1.88E+06	2.14E+05
Construction	0.2	7.24E+04	5.22E+03	0.3	9.23E+04	6.65E+03
Maintenance Equipment	0.5	1.54E+05	1.10E+04	0.7	2.31E+05	1.64E+04
Maintenance Materials	22.8	1.18E+06	7.39E+04	27.1	1.45E+06	9.46E+04
Full Project	**50.8**	**3.25E+06**	**2.77E+05**	**45.2**	**3.66E+06**	**3.31E+05**

4.4.5 Use Phase Impacts and Considerations

The current LCA tool and case study has only taken into account the materials, construction, maintenance and rehabilitation phases of a LCA. The use phase can be one of the largest contributors to LCA analysis and at this stage only a qualitative impact analysis on the pavement LCA can be done. Pavement smoothness is one of the important factors in the use phase energy consumption and global warming potential calculations, as has been noted by a number of studies including Santero (2009). Typically, it can be assumed that a CRCP surface retains its smoothness much longer than a JPCP surface. This leads to the conclusion that CRCP would have lower energy usage and global warming potential during the use phase, which would further increase its environmental performance over its life-cycle relative to JPCP.

4.5 Case Study Conclusions

Two project level case studies compared the environmental impacts in the materials, construction, maintenance and rehabilitation phases for a continuously reinforced concrete pavement (CRCP) and a jointed plain concrete pavement (JPCP). For the set of inputs, with the prescribed maintenance plans for each pavement type, the CRCP alternative resulted in the higher total energy and global warming potential over the life cycle by 10.6% and 4.9%, respectively. This reflects the trend found by Muga et al. (2009) where CRCP alternative had 32.7-62% higher emissions relative to a JPCP design. When the values of the case study were normalized annually (based on the expected design lives of 78 years and 62 years for CRCP and JPCP, respectively), the CRCP alternative became more sustainable option as it had energy and global warming potentials that were 12.5% and 19.6% lower than the values of the JPCP design.

The LCA results determined between CRCP and JPCP pavements will change if the pavement structure or the materials used in the pavement layers is altered. Additionally, since this is not a complete LCA, as the use and end of life phases were omitted, the actual environmental impacts could vary significantly because the use phase is one of the highest contributors to a pavements environmental burden.

The results of the case study indicate that the LCA tool can be effectively used to identify the environmental impacts of various concrete pavement structures over the materials, construction and maintenance and rehabilitation phases. The differences found between the CRCP and JPCP structures indicate the tradeoffs between upfront energy usage and global warming potential relative to later more frequent maintenance and rehabilitation tasks periodically overall the pavement life span. This parallels the decision that must be made in terms of upfront cost versus life cycle cost as pavement structures such as CRCP will tend to have a higher upfront cost (or energy input), relative to JPCP, but may minimize the overall life cycle cost by reducing the future maintenance and rehabilitation costs. While project level case studies were useful, it is important to also consider the effects of the use and end-of-life phases as well when making decisions. The use phase can have one of the greatest impacts on a pavement LCA and it should not be ignored when considering various pavement structure options with an LCA tool.

CHAPTER 5 SUMMARY AND CONCLUSIONS

Through a collaborative effort, a software-based Life Cycle Assessment (LCA) tool for pavements was developed to account for the materials, construction and maintenance and rehabilitation phases. The use and end-of-life phases are still under development and were not included in this study of the LCA analysis tool. Life cycle inventory data was extracted from the literature, gathered from existing tools, and collected from regional materials suppliers for the materials and construction database. Alternative sustainability tools and literature provided regionalized data as well. The life cycle inventory data collected from regional suppliers and the literature were analyzed for accuracy before populating the new LCA tool. The construction data was organized into tasks that can be used to build and maintain the roadway for the LCA tool simulation.

The three LCA phases covered in the software were tested with a hypothetical concrete pavement design. Eight mix designs, with varying levels of supplementary cementitious materials (SCMs), such as ground granulated blast furnace slag (GGBFS) and fly ash, and recycled aggregates [e.g., reclaimed asphalt pavement (RAP) and recycled concrete aggregate (RCA)] were used to test the LCA software's materials phase and calculate the three main environmental impact factors: total energy, global warming potential (GWP), and single score. Four mix designs investigated the use of SCMs with both fly ash and GGBFS significantly reducing the environmental impacts relative to straight cement mixtures as expected. Fly ash and GGBFS reduced total energy by 14% and 22%, respectively, and global warming potential by 26% and 29%, respectively, when substituted for cement at 35% replacement level. Mixture designs substituting recycled aggregates (RAP and RCA) reduced total energy and GWP relative to virgin aggregates. For the material phase, the impact of using recycled aggregates was not nearly as significant (less than 2%) as the use of SCMs to replace portland cement (greater than 14%).

The construction phase of the LCA was independently tested using the basic tasks required to create the hypothetical pavement design used in the materials phase. The tasks that had the largest impact in the construction phase were the hauling of the materials to the site and base layer construction. For the combined impacts of the materials and construction phases, the materials phase accounted for 95% of the environmental impact (both total energy and global warming potential). This is consistent with past material and construction phase LCA research for pavements. Even though the construction phase had a minor environmental impact relative to the total impact, certain decisions in the construction phase, such as two-lift paving, can lead to a reduction in environmental impact in the materials phase by allowing higher amounts of SCMs and recycled aggregates in the lower paving lift. Two-lift paving was found to decrease total energy and global warming potential by 13.9% and 23.8%, respectively, for the materials and construction phases, over a single-lift paving operation with no SCMs or recycled aggregates.

The influence of the maintenance and rehabilitation phase was tested in the LCA tool with several predefined tasks. Not surprisingly, HMA overlays had a greater impact than simple tasks such as sealing joints and patching. Because some maintenance and rehabilitations tasks can also carry a significant materials component, the maintenance and rehabilitation phase can produce a significant portion of the life-cycle impacts that is even higher than the construction phase. For this case study, the materials portion of the maintenance and rehabilitation activities accounted for 90.9% and 89.6% of the total energy and global warming potential.

A hypothetical case study evaluating the materials, construction, and maintenance and rehabilitation phases was performed to compare the life cycle impacts of continuously reinforced

(CRCP) and jointed plain (JPCP) concrete pavements with realistic inputs and maintenance and rehabilitation plans. The reinforcing steel for the CRCP resulted in a significantly higher environmental impact for the material phase (19% higher in total energy and 9% higher in global warming potential), which was expected based on past studies (Muga et al., 2009). The initial construction phase for the two designs was very similar with only a slight difference because of the 1-inch difference in slab thickness between the CRCP and JPCP designs. The applied maintenance plan schedules were different with assumed performance lives of 78 and 62 years, respectively, for CRCP and JPCP based on Illinois Tollway practice. The CRCP had total energy and global warming potential values 10.6% and 4.9%, respectively, higher than JPCP over the entire life cycle, but when these impacts were annualized to a per year basis, the CRCP resulted in 12.5% and 19.6% lower values for total energy and global warming potential, respectively. The maintenance phase and task assumptions at various future years can greatly influence the LCA environmental burden. While this study found that CRCP is a viable option in terms of total energy and global warming potential because of its longer service life relative to JPCP, the maintenance and rehabilitation phase and the design life must be taken into account to justify the additional steel required by the structure.

This LCA research, with some regionalized data from Illinois, has shown the environmental impacts of pavement design, construction, and maintenance are primarily dominated by the material phase, followed by the maintenance and rehabilitation phase, and finally by the construction phase. To further improve the overall environmental impact of a pavement design, assuming it this is the design objective, structural designs that reduce energy intensive maintenance activities should be selected as well as materials which continue to reduce the energy and GWP of this phase without reducing the performance life of the roadway.

Additionally, these findings should be contextualized in light of the impact of the use phase, which is highly dependent on the pavement surface and structure. A life-cycle cost analysis should be used to balance environmental impacts with the economics of the design as well as societal impacts. Future research should further investigate the effects of the use phase including the pavement vehicle interactions especially as the pavement structure deteriorates with time. Additionally, new technologies, such as sequestering CO_2 in the cement production, could help to offset the significant emissions associated with a concrete pavement LCA.

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APPENDIX

Appendix Table - 1 Construction Tasks and Associated Equipment

Task	Base Stone	Clearing - Light	Clearing - Medium	Clearing - Heavy	Concrete Pavement (</=6" Thick)	Concrete Pavement (> 6" Thick)
Category	Paving	Clearing	Clearing	Clearing	Paving	Paving
Default Productivity	217	1089	847	726	60	45
	tn.sh	SY	SY	SY	SY	SY
Equipment	Truck - Water	Dozer	Dozer	Dozer	Backhoe	Backhoe
	Dozer	Excavator	Dozer	Dozer	Paver - Slipform	Paver - Slipform
	Grader	Tub Grinder	Excavator	Excavator	-	-
	Roller - Vibratory	-	Tub Grinder	Tub Grinder	-	-
	Portable Screening/ Crushing	-	-	-	-	-

Task	Grading (Dirt) - Off Road - Long Haul	Grading (Dirt) - Off Road - Short Haul	Grading (Dirt) - On Road	Grading (Rock) - Off Road - Long Haul	Grading (Rock) - Off Road - Short Haul	Grading (Rock) - On Road
Category	Grading	Grading	Grading	Grading	Grading	Grading
Default Productivity	285.6	215.32	233.38	240	215.32	140
	CY	CY	CY	CY	CY	CY
Equipment	Truck - Water	Truck - Water	Truck - Water	Truck - Powder	Truck - Powder	Truck - Powder
	Dozer	Dozer	Dozer	Truck - Water	Truck - Water	Truck - Water
	Haul Truck	Haul Truck	Excavator	Dozer	Dozer	Dozer
	Excavator	Excavator	Grader	Haul Truck	Haul Truck	Loader - R/T [Medium]
	Grader	Grader	Roller - Soil	Loader - R/T	Loader - R/T	Grader
	Roller - Soil	Roller - Soil	-	Grader	Grader	Dril - Track
	-	-	-	Dril - Track	Dril - Track	-

Task	HMA - Leveling Course	HMA - Structural Course	HMA - Surface Course	Milling (<2")	Milling (2-4")	Pavement Removal - Asphalt
Category	Paving	Paving	Paving	Milling	Milling	Pavement Removal
Default Productivity	130	200.06	150	6250	6250	50
	tn.sh	tn.sh	tn.sh	SY	SY	CY
Equipment	Truck - Distributor	Truck - Distributor	Truck - Distributor	Truck - Water	Truck - Water	Milling Machine
	Truck - Water	Truck - Water	Truck - Water	Dozer	Dozer	Broom
	Roller	Roller	Roller	Milling Machine	Milling Machine	-
	Roller - Pneumatic	Roller - Pneumatic	Roller	Broom	Broom	-
	Paver - Asphalt	Paver - Asphalt	Roller - Pneumatic	-	-	-
	MTV	MTV	Paver - Asphalt	-	-	-
	-	-	MTV	-	-	-

Task	Pavement Removal - Concrete	Reinforcing Steel	Roadbed Finishing	Pavement Marking	Strip Topsoil	Two-Lift JPC Pavement 12"
Category	Pavement Removal	Reinforcing Steel	Finishing	Marking	Stripping	Paving
Default Productivity	66	1	400	10560	120	5500
	CY	tn.sh	SY	Long. FT	CY	SY
Equipment	Loader - R/T	Crane - Hydraulic	Dozer	Truck - Paint	Dozer	Spreader - Aggregate
	Excavator	-	Scrapper	-	Scrapper	Paver - Slipform
	-	-	Grader	-	-	-

Task	Single-Lift JPC Pavement 12"	Asphalt Stabilized Sub-base 3"	Full-Depth HMA Pavement 12"	Porous Granular Embankment 12"	Earthwork	Fine Grading
Category	Paving	Stabilization	Paving	Granular Layer	Earthwork	Grading
Default Productivity	5500	4000	1500	3800	2600	2000
	SY	SY	SY	SY	CY	SY
Equipment	Spreader - Aggregate	Roller	Roller	Roller - Soil	Roller - Soil	Grader
	Paver - Slipform	Paver - Asphalt	Paver - Asphalt	Grader	Dozer	-
	-	-	-	Loader - R/T	Loader - R/T	-
	-	-	-	Dozer	Dozer	-
	-	-	-	Truck - Water	Truck - Water	-

Task	Topsoil Strip & Stockpile	Patch - Pavement Surface	Diamond Grind Surface	Rout and Seal Cracks	Microsurface	Seal Joints
Category	Stripping	Patching	Grinding	Cracks	Surfacing	Joints
Default Productivity	2000	12.5	149.5	41	1000	41
	SY	SY	SY	Long. FT	SY	Long. FT
Equipment	Dozer	Black Topper	Diamond Grinder	Silicone Sealant Equipment	Micro-surfacing Truck	Silicone Sealant Equipment
	-	Roller	-	Saw	Augered Screed Box	Saw
	-	-	-	Air Compressor	-	Air Compressor

Appendix Table - 2 Full Results for Construction Tests Utilizing Two-Lift Paving

Case		Single Lift			Two-Lift - One Mix Design			Two-Lift - Two Mix Designs		
Phase		COMPLETE PROJECT	Material Production	Construction	COMPLETE PROJECT	Material Production	Construction	COMPLETE PROJECT	Material Production	Construction
Single score	Pt	337.1	332.3	4.8	337.6	332.3	5.4	288.4	283.0	5.4
Total Energy	MJ	4.62E+07	4.47E+07	1.53E+06	4.64E+07	4.47E+07	1.71E+06	3.98E+07	3.81E+07	1.70E+06
Global Warming Potential	kg CO2eq	6.31E+06	6.19E+06	1.13E+05	6.32E+06	6.19E+06	1.25E+05	4.81E+06	4.69E+06	1.24E+05
Energy with Binder Feedstock	MJ	6.53E+07	6.37E+07	1.53E+06	6.55E+07	6.37E+07	1.71E+06	5.88E+07	5.71E+07	1.70E+06
Ozone depletion	kg CFC-11 eq	0.24	0.23	0.02	0.25	0.23	0.02	0.23	0.21	0.02
Smog	kg O3 eq	4.85E+05	4.68E+05	1.70E+04	4.87E+05	4.68E+05	1.92E+04	4.22E+05	4.03E+05	1.91E+04
Acidification	kg SO2 eq	2.71E+04	2.65E+04	6.20E+02	2.72E+04	2.65E+04	6.97E+02	2.39E+04	2.32E+04	6.94E+02
Eutrophication	kg N eq	2.38E+03	2.30E+03	7.81E+01	2.39E+03	2.30E+03	8.73E+01	1.99E+03	1.91E+03	8.69E+01
Carcinogenics	CTUh	4.94E-02	4.94E-02	4.38E-05	4.94E-02	4.94E-02	4.72E-05	4.12E-02	4.11E-02	4.67E-05
Non carcinogenics	CTUh	0.54	0.54	0.00	0.54	0.54	0.00	0.45	0.45	0.00
Respiratory effects	kg PM2.5 eq	2.71E+03	2.65E+03	6.12E+01	2.72E+03	2.65E+03	6.90E+01	2.38E+03	2.31E+03	6.88E+01
Ecotoxicity	CTUe	4.54E+06	4.52E+06	1.88E+04	4.54E+06	4.52E+06	2.00E+04	4.56E+06	4.54E+06	1.98E+04
Fossil fuel depletion	MJ surplus	5.72E+06	5.51E+06	2.18E+05	5.75E+06	5.51E+06	2.43E+05	5.65E+06	5.41E+06	2.42E+05
Energy, renewable primary, fuel	MJ	7.87E+04	7.72E+04	9.70E+02	7.88E+04	7.72E+04	1.08E+03	6.61E+04	6.44E+04	1.07E+03
Energy, renewable primay, non fuel	MJ	1.39E+04	1.35E+04	3.11E+02	1.39E+04	1.35E+04	3.46E+02	1.15E+04	1.11E+04	3.45E+02
Energy, renewable primary, total	MJ	9.25E+04	9.07E+04	1.28E+03	9.27E+04	9.07E+04	1.43E+03	7.76E+04	7.55E+04	1.42E+03

Case		Single Lift			Two-Lift - One Mix Design			Two-Lift - Two Mix Designs		
Phase		COMPLETE PROJECT	Material Production	Construction	COMPLETE PROJECT	Material Production	Construction	COMPLETE PROJECT	Material Production	Construction
Energy, non renewable primary, fuel	MJ	4.61E+07	4.46E+07	1.53E+06	4.63E+07	4.46E+07	1.70E+06	3.97E+07	3.80E+07	1.70E+06
Energy, non renewable primary, non fuel	MJ	0	0	0	0	0	0	0	0	0
Energy, non renewable primary, total	MJ	4.61E+07	4.46E+07	1.53E+06	4.63E+07	4.46E+07	1.70E+06	3.97E+07	3.80E+07	1.70E+06
Use of secondary materials	kg	0	0	0	0	0	0	0	0	0
Energy, renewable secondary, fuel	MJ	0	0	0	0	0	0	0	0	0
Energy, non-renewable secondary, fuel	MJ	0	0	0	0	0	0	0	0	0
Water resource depletion total [ILCD]	m3 water eq	8.66E+04	8.54E+04	1.21E+03	8.68E+04	8.54E+04	1.35E+03	7.65E+04	7.51E+04	1.34E+03
Waste, hazardous	kg	0	0	0	0	0	0	0	0	0
Waste, non hazardous	kg	0	0	0	0	0	0	0	0	0
Waste, radio active	kg	0	0	0	0	0	0	0	0	0

Appendix Table - 3 Full Results for Maintenance and Rehabilitation Case Study

Phase	Unit	COMPLETE PROJECT	Material Production	Construction	Maintenance	Maintenance Materials
Single score	Pt	5.15E+02	2.65E+02	4.85E+00	3.73E+00	2.42E+02
Total Energy	MJ	4.99E+07	3.55E+07	1.53E+06	1.18E+06	1.17E+07
Global Warming Potential	kg CO2eq	4.99E+06	4.06E+06	1.13E+05	8.47E+04	7.33E+05
Energy with Binder Feedstock	MJ	1.07E+08	5.46E+07	1.53E+06	1.18E+06	5.00E+07
Ozone depletion	kg CFC-11 eq	3.32E-01	2.08E-01	1.86E-02	1.43E-02	9.14E-02
Smog	kg O3 eq	4.51E+05	3.87E+05	1.70E+04	1.37E+04	3.39E+04
Acidification	kg SO2 eq	2.93E+04	2.23E+04	6.20E+02	4.94E+02	5.92E+03
Eutrophication	kg N eq	2.26E+03	1.77E+03	7.81E+01	6.11E+01	3.54E+02
Carcinogenics	CTUh	8.09E-02	3.77E-02	4.38E-05	3.02E-05	4.32E-02
Non carcinogenics	CTUh	8.62E-01	4.10E-01	1.69E-03	1.20E-03	4.49E-01
Respiratory effects	kg PM2.5 eq	3.19E+03	2.51E+03	6.12E+01	5.48E+01	5.67E+02
Ecotoxicity	CTUe	1.32E+07	4.55E+06	1.88E+04	1.25E+04	8.66E+06
Fossil fuel depletion	MJ surplus	1.30E+07	5.38E+06	2.18E+05	1.68E+05	7.22E+06
Energy, renewable primary, fuel	MJ	6.00E+04	6.12E+04	9.70E+02	7.46E+02	7.90E+03
Energy, renewable primay, non fuel	MJ	1.13E+04	1.09E+04	3.11E+02	2.39E+02	1.65E+03
Energy, renewable primary, total	MJ	7.13E+04	7.21E+04	1.28E+03	9.85E+02	9.56E+03
Energy, non renewable primary, fuel	MJ	4.99E+07	3.54E+07	1.53E+06	1.18E+06	1.17E+07
Energy, non renewable primary, non fuel	MJ	0	0	0	0	0
Energy, non renewable primary, total	MJ	4.99E+07	3.54E+07	1.53E+06	1.18E+06	1.17E+07
Use of secondary materials	kg	0	0	0	0	0
Energy, renewable secondary, fuel	MJ	0	0	0	0	0
Energy, non-renewable secondary, fuel	MJ	0	0	0	0	0
Water resource depletion total [ILCD]	m3 water eq	1.13E+05	7.48E+04	1.21E+03	9.34E+02	3.56E+04
Waste, hazardous	kg	0	0	0	0	0
Waste, non hazardous	kg	0	0	0	0	0
Waste, radio active	kg	0	0	0	0	0

Appendix Table - 4 Full Results for CRCP Case Study

		Materials	Construction	Maintenance Equipment	Maintenance Materials	TOTAL
Single score	Pt	2126.0	17.8	37.9	1777.9	3959.6
Total Energy	MJ	1.43E+08	5.65E+06	1.20E+07	9.24E+07	2.54E+08
Global Warming Potential	kg CO2eq	1.46E+07	4.07E+05	8.55E+05	5.77E+06	2.16E+07
Energy with Binder Feedstock	MJ	2.26E+08	5.65E+06	1.20E+07	3.71E+08	6.14E+08
Ozone depletion	kg CFC-11 eq	7.21E-01	6.88E-02	1.46E-01	7.39E-01	1.67E+00
Smog	kg O3 eq	1.06E+06	6.63E+04	1.41E+05	2.85E+05	1.55E+06
Acidification	kg SO2 eq	7.09E+04	2.39E+03	5.08E+03	4.51E+04	1.23E+05
Eutrophication	kg N eq	5.98E+03	2.94E+02	6.26E+02	2.80E+03	9.70E+03
Carcinogenics	CTUh	6.66E-01	1.41E-04	2.90E-04	3.14E-01	9.81E-01
Non carcinogenics	CTUh	3.03E+00	5.64E-03	1.17E-02	3.28E+00	6.33E+00
Respiratory effects	kg PM2.5 eq	8.76E+03	2.39E+02	5.60E+02	4.20E+03	1.38E+04
Ecotoxicity	CTUe	2.63E+07	5.75E+04	1.17E+05	6.34E+07	8.98E+07
Fossil fuel depletion	MJ surplus	2.13E+07	8.05E+05	1.71E+06	5.27E+07	7.66E+07
Energy, renewable primary, fuel	MJ	4.27E+05	3.58E+03	7.60E+03	6.33E+04	3.84E+05
Energy, renewable primay, non fuel	MJ	8.36E+04	1.15E+03	2.44E+03	1.35E+04	7.76E+04
Energy, renewable primary, total	MJ	5.11E+05	4.72E+03	1.00E+04	7.68E+04	4.62E+05
Energy, non renewable primary, fuel	MJ	1.43E+08	5.65E+06	1.20E+07	9.23E+07	2.53E+08
Energy, non renewable primary, non fuel	MJ	0	0	0	0	0
Energy, non renewable primary, total	MJ	1.43E+08	5.65E+06	1.20E+07	9.23E+07	2.53E+08
Use of secondary materials	kg	0	0	0	0	0
Energy, renewable secondary, fuel	MJ	0	0	0	0	0
Energy, non-renewable secondary, fuel	MJ	0	0	0	0	0
Water resource depletion total [ILCD]	m3 water eq	8.47E+05	4.48E+03	9.52E+03	2.72E+05	1.13E+06
Waste, hazardous	kg	0	0	0	0	0
Waste, non hazardous	kg	0	0	0	0	0
Waste, radio active	kg	0	0	0	0	0

Appendix Table - 5 Full Results for JPCP Case Study

		Materials	Construction	Maintenance Equipment	Maintenance Materials	TOTAL
Single score	Pt	1061.4	18.0	45.3	1679.9	2804.6
Total Energy	MJ	1.17E+08	5.72E+06	1.43E+07	8.99E+07	2.27E+08
Global Warming Potential	kg CO2eq	1.32E+07	4.13E+05	1.01E+06	5.86E+06	2.05E+07
Energy with Binder Feedstock	MJ	1.99E+08	5.72E+06	1.43E+07	3.50E+08	5.70E+08
Ozone depletion	kg CFC-11 eq	6.87E-01	6.96E-02	1.74E-01	7.08E-01	1.64E+00
Smog	kg O3 eq	1.02E+06	6.70E+04	1.70E+05	3.01E+05	1.56E+06
Acidification	kg SO2 eq	6.35E+04	2.41E+03	6.12E+03	4.41E+04	1.16E+05
Eutrophication	kg N eq	5.26E+03	2.98E+02	7.50E+02	2.79E+03	9.10E+03
Carcinogenics	CTUh	1.90E-01	1.44E-04	3.32E-04	2.96E-01	4.87E-01
Non carcinogenics	CTUh	1.68E+00	5.74E-03	1.35E-02	3.09E+00	4.79E+00
Respiratory effects	kg PM2.5 eq	6.61E+03	2.41E+02	7.09E+02	4.06E+03	1.16E+04
Ecotoxicity	CTUe	2.04E+07	5.88E+04	1.32E+05	5.93E+07	7.99E+07
Fossil fuel depletion	MJ surplus	2.02E+07	8.15E+05	2.04E+06	4.95E+07	7.25E+07
Energy, renewable primary, fuel	MJ	1.76E+05	3.62E+03	9.06E+03	6.29E+04	2.22E+05
Energy, renewable primay, non fuel	MJ	3.31E+04	1.16E+03	2.91E+03	1.33E+04	4.46E+04
Energy, renewable primary, total	MJ	2.09E+05	4.78E+03	1.20E+04	7.61E+04	2.66E+05
Energy, non renewable primary, fuel	MJ	1.17E+08	5.72E+06	1.43E+07	8.98E+07	2.26E+08
Energy, non renewable primary, non fuel	MJ	0	0	0	0	0
Energy, non renewable primary, total	MJ	1.17E+08	5.72E+06	1.43E+07	8.98E+07	2.26E+08
Use of secondary materials	kg	0	0	0	0	0
Energy, renewable secondary, fuel	MJ	0	0	0	0	0
Energy, non-renewable secondary, fuel	MJ	0	0	0	0	0
Water resource depletion total [ILCD]	m3 water eq	2.79E+05	4.53E+03	1.13E+04	2.60E+05	5.55E+05
Waste, hazardous	kg	0	0	0	0	0
Waste, non hazardous	kg	0	0	0	0	0
Waste, radio active	kg	0	0	0	0	0