CAIT-UTC-052

Environmental Assessment of Airport Pavement Design and Construction Alternatives

Final Report
February 2016

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In cooperation with
Rutgers, The State University of New Jersey
And
State of New Jersey
Department of Transportation
And
U.S. Department of Transportation
Federal Highway Administration

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TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No. CAIT-UTC-052	2. Government Accession No.	3. Recipient's Catalog No.

4. Title and Subtitle Environmental Assessment of Airport Pavement Design and Construction Alternatives	5. Report Date February 2016 6. Performing Organization Code CAIT/Rutgers
7. Author(s) Hao Wang	8. Performing Organization Report No. CAIT-UTC-052
9. Performing Organization, Name and Address Rutgers University Piscataway, NJ 08854	10. Work Unit No. 11. Contract or Grant No. DTRT12-G-UTC16
12. Sponsoring Agency Name and Address Center for Advanced Infrastructure and Transportation Rutgers, The State University of New Jersey 100 Brett Road Piscataway, NJ 08854	13. Type of Report and Period Covered Final Report 7/01/14 - 12/31/2015 14. Sponsoring Agency Code

15. Supplementary Notes

U.S Department of Transportation/Research and Innovative Technology Administration
1200 New Jersey Avenue, SE
Washington, DC 20590-0001

16. Abstract

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17. Key Words Energy, GHG Emission, Airport Pavement, Life Cycle Assessment	18 Distributional Statement

19. Security Classification Unclassified	20. Security Classification (of this page) Unclassified	21. No. of Pages 29	22. Price

Form DOT F 1700.7 (8-09)

Summary

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1. INTRODUCTION

With the continuous increase of air traffic volumes and the development of heavy wide-body aircraft, airfield pavements require frequent maintenance and rehabilitation activities in order to provide sufficient structure capacity and satisfactory surface characteristics. Asphalt pavement and Portland cement concrete (PCC) pavement are commonly used in airfield pavements and overlays. The factors affecting the selection of pavement type and rehabilitation strategy may include agency experience, the long-term performance of alternatives, the impact on airport operations, construction and maintenance costs, and environmental and sustainability considerations (*1*). The life-cycle cost analysis (LCCA) has been mandated by the Federal Aviation Administration (FAA) Advisory Circular to be the part of the pavement type or treatment selection process (*2*). The LCCA is mostly used to aid airport planners in identifying the most cost-effective pavement construction and rehabilitation strategies.

Construction and rehabilitation of airfield pavements produce significant impacts on energy consumption and environmental pollution resulting from the production of large amounts of raw construction material and the operation of construction equipment. Airport authorities are interested in selecting a pavement strategy that considers economic and environmental factors over the life cycle of the pavement. Therefore, an assessment methodology is needed for airport authorities to properly quantify environmental sustainability in airport pavement design and construction processes.

Life-Cycle Assessment (LCA) is a technique to assess environmental sustainability associated with a product's life cycle with flexibility and comprehensiveness (*3*). There are three major types of LCA models available, which depend on the source of information used in the LCA. The first is Economic Input-Output model (EIO) based LCA, which is developed by Carnegie Mellon University. The EIO-LCA method is used to estimate the activities related to materials and energy resources and the environmental emissions resulting from the activities in the economy. This method can be applied to any transactions between industries related to the economy of the sectors. The second is process-based LCA, which is based on the methodology set by International Standards Organization (ISO) 14040 and 14044. The process-bases LCA considers material and energy inputs and environmental outputs of each process in the life cycle, such as manufacturing, assembling, maintaining, using and disposing of the product. The third method is Hybrid LCA, in which an EIO model is integrated with the process-based LCA to produce more comprehensive representations for environmental effects of the processes.

The process-based LCA method is mostly used for construction projects since the methodology can disaggregate the projects into individual processes or activities independently (*4*). The life-cycle of pavement can be divided into different stages including raw material extraction, material processing and manufacturing, transportation, construction, maintenance, and end-of-life. LCA can identify the material and process that cause a significant impact in the pavement life-cycle and help airport authorities incorporate sustainability metrics into decision making process.

LCA studies have been typically used to examine and compare the environmental impacts of different types of highway pavements (flexible vs. rigid) occurred at various stages. Literature review of previous LCA studies suggests mixed findings on environmental sustainability have been reported for the comparison between asphalt and concrete pavement design strategies and a lack of consistency was found among the results (*5-11*). The process-based, economic input-output-based, and hybrid approaches have been used for conducting pavement LCA. Most pavement LCA studies considered energy consumption and emissions in production of raw material, material mixing, transportation, and construction equipment. However, few studies have considered maintenance treatments along with the initial construction in LCA. The definition of analysis period varied from the pavement service life resulted from the initial construction only or a specific analysis period with scheduled maintenance treatments.

The comparison results vary when asphalt pavement is compared to concrete pavement, depending on energy or the type of emission. There are many factors that may affect the LCA results, such as system boundaries, quality and source of inventory data, inconsistent pavement designs, and geographic location. The type of concrete pavement (Jointed Plain Concrete Pavement [JPCP], Jointed Reinforced Concrete Pavement [JRCP], and Continuously Reinforce Concrete Pavement [CRCP]) was found having significant effects on the environment impact due to the existence of steel. The comparison was complicated by the assumption of pavement service life and maintenance history used in the analysis. Therefore, general conclusions derived from literature studies may not be applicable for specific pavement projects.

2. BACKGROUND

Runway 13R-31L at John F. Kennedy (JFK) International Airport was originally constructed during the 1940s. The current runway is 14,511-feet long and 150 feet wide. It is the second-longest commercial runway in North America. The original pavement section was 12-inch Portland cement concrete (PCC) on 6-inch crushed stone screenings. During the 1970s, the runway was overlaid with hot-mix asphalt (HMA). Over the years, the runway has been overlaid number of times and as a result, there was 16-inch HMA on top of the original PCC surface.

The aim of reconstruction/rehabilitation project at JFK airport was primarily to increase the airport capacity to accommodate new large aircrafts in Aircraft Design Group VI. Based on these studies and discussions with the FAA a number of required airfield modifications were identified including widening Runway 13R-31L from 150 feet to 200 feet. Another development that would impact the project scope was the significant growth in air traffic operations at JFK starting in 2005, which leads to additional regional airport delays. In response, the JFK Delay Reduction Program was developed for moving aircraft to and from the runways more efficiently. Runway 13R-31L taxiway entrance and exit modifications and relocated runway thresholds were included. The scope of the rehabilitation and widening project changed again to include delay reduction program components.

Economic and constructability studies were performed in 2007 for two pavement rehabilitation design alternatives: one is 9-inch thick HMA overlay with milling and overlays scheduled every eight years; and the other one is 18-inch PCC with minor concrete repair every eight years. The alternatives study consists of life-cycle cost analysis using a discount rate of 3.5% and 40-year analysis period. The results indicate that the initial cost for the HMA rehabilitation was 3% cheaper than the PCC reconstruction, but the life-cycle cost for the PCC construction was 35% cheaper than the HMA rehabilitation. However, the alternatives study did not consider noneconomic factors or environmental sustainability metrics associated with raw materials, manufacturing processes, construction equipment in the pavement life cycle.

Figure 1 Runway 13R-31L at New York JFK Airport (Courtesy of PANY&NJ)

3. OBJECTIVE AND SCOPE

The objective of this study is to quantify energy and environmental sustainability impacts of asphalt and concrete runway pavements using LCA. The design alternatives include runway rehabilitation/reconstruction designs considered in the constructability study at the JFK airport and new runway surface layer designs conducted using the FAA pavement design methodology. Life-cycle inventory data were compiled from literature and field surveys to contractors. The data variations in the material-related energy and emission rates were considered for sensitivity analysis. The impact assessment focused on the cumulative energy demand (CED) and greenhouse gas (GHG) emission in the material, construction, and maintenance phases of pavement life-cycle. Both direct energy consumption and GHG emission and their corresponding upstream components related to process fuels were considered in the impact assessment. The study results can be used for decision making among different runway pavement design and rehabilitation alternatives by airport authorities.

4. RESEARCH METHODOLOGY

This study follows the basic steps of life cycle assessment: goal definition and scope, inventory analysis, impact assessment and interpretation (*3*). The goal is to quantify energy consumption and environmental impacts of airport pavement design alternatives. The study scope includes design alternatives for both new pavement design and pavement overlays on existing runway pavements. The pavement structures considered include the surface layer constructed with Portland cement concrete or asphalt concrete over base layers or existing pavement layers. The function unit is defined as one-mile runway with 200-ft width that is designed to carry the aircraft traffic mix in the analysis period at the major hub airport. The system boundary covers the material, construction and maintenance phases of the pavement life cycle. The end-of-life stage was not considered here due to the complexity involved between different pavement types. Concrete pavements are usually left in place as base layer for new overlays; while asphalt pavements are removed and recycled at different percentages.

The inventory analysis is limited to energy consumption and greenhouse gas emissions (GHG); as a result, the impact assessment determines the cumulative energy demand (CED) and global warming potential (GWP) of the GHG emissions based on their relative contribution. The greenhouse gases considered in this study include Carbon Dioxide (CO_2), Methane (CH_4) and Nitrous Oxide (N_2O). The global warming indicator of greenhouse gas is defined as the ratio of the time-integrated radiative forcing from the instantaneous release of 1 kilogram (kg) of a trace substance relative to that of 1 kg of a reference gas (*12*). The CO_2 was used as reference gas in this study, and the GWP weighted emissions were measured in CO_2 equivalent (CO_2 Eq.) using the GWP equivalency factors.

The unit inventory data for material-related energy consumption and GHG emission were extracted from up-to-dated articles and research papers and the uncertainty of data sources were analyzed. Contractor survey and field observations were conducted to obtain the operation efficiency of construction equipment for runway construction. Direct energy consumptions and GHG Emissions were obtained from fuel combustion and electricity consumption for various material acquisition and process operations in the system boundary. Consideration of energy and emissions associated with the production of process fuels and electricity in the upstream process was included to account for the indirect energy consumption and GHG emission.

5. LIFE-CYCLE INVENTORY

5.1 Material Acquisition and Production

In order to quantify energy consumption and emission of pavement, the first step is to determine the material components and manufacturing processes for each material or process in the pavement life- cycle. Materials are obtained in raw forms and then manufactured to the final form as required by the construction demand. For the asphalt pavement and jointed concrete pavement considered in this study, raw materials contain asphalt, cement, aggregate, slag cement, polymer additive, and steel. Manufacturing of material includes handling, drying, mixing and preparation of materials for placement, such as production of hot-mix asphalt and cement concrete. The manufactured material will then be transported to the construction site for placement. Placement of materials depends on types of construction requirement on the project site and it is accomplished using different types of equipment.

In this study, life inventory data of raw material and manufacturing process were collected from published reports from literature. Although multiple data sources are available for life-cycle inventory data of typical construction materials and processes for pavements, discrepancies may exit due to different geographic locations, technologies, and system boundaries. To address this, baseline analysis was conducted using the inventory data identified as the most appropriate for this analysis. The inventory data used in the baseline analysis were selected from the previous studies conducted in U.S. as compared to a relatively larger set of inventory data reported by European researchers. The extreme ranges of inventory data (minimum and maximum values) reported in the literature were also used analysis to investigate the sensitivity of analysis results to the inventory data. Table 1 lists the material-related life-cycle inventory data from various data sources, respectively, for energy consumption and GHG emission values.

Table 1 Material-Related Life-Cycle Inventory for Asphalt and Concrete Pavements

Material / Process	Baseline Value		Data from Literature	
	Energy Consumption (MJ/t)	Emissions CO_2 eq. (kg/t)	Energy Consumption (MJ/t)	Emissions CO_2 eq. (kg/t)
Asphalt Binder	5,810 (*13*)	480 (*13*)	6000 (*5*), 3634 (*14*), 5812 (*15*), 3980 (*16*)	330 (*5*), 173 (*14*), 377 (*15*), 244 (*16*)
Portland Cement	4,340 (*17*)	928 (*17*)	5350 (*5*), 4776 (*14*) , 5232 (*18*)	799 (*5*) ,806 (*14*), 670 (*18*)
Sand or Gravel	21 (*17*)	0.0728 (*17*)	24 (*5*), 6 (*14*), 68.6 (*18*)	1.74 (*5*), 0.07 (*14*), 6.1 (*18*)
Crushed Stone	32 (*17*)	1.42 (*17*)	52 (*5*), 38 (*14*)	2.0 (*5*), 6 (*18*)
Steel	21,520 (*19*)	1578 (*19*)	21,800 (14), 11,300 (18)	241 (*14*), 232 (*18*)
Polymer Additive	76742 (*16*)	3715 (*16*)	N/A	
Slag Cement	643.8 (*20*)	7.42 (*20*)	N/A	
HMA Manufacturing	266 (*21*)	16.4 (*21*)	485 (*5*), 432 (*14*)	34.8 (*5*), 21.9 (*14*), 15.1 (*22*)
PCC Manufacturing	18 (*23*)	0.72 (*23*)	40 (*14*), 110 (*18*), 56 (*24*)	1.67 (*14*), 7.70 (*18*), 9.54 (*24*)

5.2 Transportation and Construction

There are three transport stages in the pavement life-cycle: 1) transportation of raw materials from extraction site to processing facility, such as transport of crude oil to refinery; 2) transportation of processed material to manufacturing plant, such as transport of asphalt from refinery to the hot-mix asphalt plant, 3) transportation of manufactured material from production site to construction site. The first two transport stages were included in the life-cycle inventory of raw material or manufacturing process in most previous studies. Therefore, only transportation of hot-mix asphalt or cement concrete from the plant to the job site was separately considered in this study. The transportation of milled material from the existing asphalt pavement was negligible because the design allowed for reuse of the removed pavement as subbase materials for new taxiways instead of trucking it off site for recycling or disposal.

In the construction phase, the environmental burdens are due to the combustion-related emissions from construction equipment usage. The NONROAD (non-road engines, equipment, and vehicles) 2008 model developed by Environment Protection Agency (EPA) was used to calculate CO_2 emission for off-road equipment by its function, horsepower, and fuel type (*25*). Since NONROAD cannot directly provide energy consumption, the energy consumption was calculated based on the heating value of diesel fuel and the emission factors for non-highway vehicles, as shown in Equation 1 (*26, 27*). In order to calculate the energy consumption and emissions generated in the construction process, contractor survey and field observation were conducted to determine the operation hours for each type of equipment. Table 2 summarizes the construction activities with the equipment used and operation efficiency.

$$r_{energy} = r_{emission} \times \frac{HV}{f(emission)} \quad (1)$$

Where, r_{energy} is energy rate in MJ/hour;

$r_{emission}$ is emission rate in g/hour (obtained from NONROAD for CO_2);

HV is heating value, 138.451 MJ/gallon for diesel fuel; and

$f(emission)$ is fuel-specific emission factor for CO2, CH_4, or N_2O in g/gallon.

Table 2 Construction Equipment and Operation Efficiency for Pavement Construction

Construction activity		Equipment	Horsepower (hp) rating	Productivity
HMA	Paving	Vogele Super 2100-2	250	1,500-2,000 tons/12 hours
	Rolling compaction	HAMM HD+140	155	Same as paving (5-10 passes)
PCC	Front Paver (Placer/Spreader)	GOMACO PS-2600	275	275 yards/hour
	Middle Paver (Slip Form Paver)	GOMACO GP-4000	440	275 yards/hour
	Back Finishing Paver (Texture/Cure)	GOMACO TC-600	60	275 yards/hour
	Concrete Saw cutting	Edco SS-26 31D	31	8000 linear feet/10 hours
	Drilling Dowel Bar	EZ Drill 210B-4	20	800 bars/10 hours
	Joint Sealant		10	8000 linear ft./10 hours
General	Milling	Wirtgen 250i	990	1000 cubic yards/12 hours shift
	Grooving	Lincon Electric 10,000 Plus	23	10,000 square yards/ 12 hours
	Articulated Dump Truck	Caterpillar 740	445	40 tons capacity

5.3 Consideration of Upstream Components

The overall environmental impact of a process depends on both the combustion (direct) energy and emissions for operating equipment and vehicles, and the upstream energy requirements for producing and delivering the energy source. The upstream (indirect) emissions are generated from processing fuel consumed during various processes from material extraction to construction. Energy is required to produce fuels and electricity used in the downstream processes. Therefore, in addition to the energy use and emission of direct use of fuels and electricity, the energy and emissions associated with the production of these fuels and electricity were considered in the analysis.

To incorporate the upstream (indirect) values, the GREET 2013 model developed by Argonne National Laboratory was used. The GREET model is a life-cycle modeling tool to evaluate the impact of fuel use including all fuel production processes from oil exploration to fuel use (from well to wheels) (*28*) For process fuels such as coal, natural gas, gasoline, fuel oil, liquefied petroleum gases (LPG), etc., upstream values can be extracted for each specific fuel type. The mix of energy source for production of electricity was obtained for the northeast states of U.S. from the fuel cycle model in GREET and used to calculate the upstream values for electricity. Table 3 lists the energy usage profile for production of raw materials and manufacturing processes of PCC and HMA as reported by different literature sources (*16*, *17*, *20*, *21*, *29*, *30*). The process fuel used for transportation and construction can be directly determined from the fuel type used by the specific transport vehicle and construction equipment.

Table 3 Energy Usage Profiles for Production of Raw Materials and Manufacturing Processes of PCC and HMA

Process fuels	Asphalt (*29*)	Cement (*17*)	Sand (*17*)	Crushed Stone (*17*)	Steel (*30*)	Slag Cement (*20*)	Polymer (*16*)	HMA plant (*21*)	PCC plant (*17*)
Coal	0.04%	56.58%	0	1.89%	1.42%	0	9.75%	0	0
Diesel	0	0	0	0	0	0	0	0	0
Gasoline	1.05%	0.04%	3.41%	3.85%	0.25%	0	0	0	0
LPG	0.51%	0.02%	0	0	0	0	0	0	0
Natural Gas	72.54%	0.85%	6.87%	11.63%	33.2%	77.56%	53.9%	80%	39.3%
Distillate Fuel Oil	0.15%	3.45%	39.1%	42.40%	0	0.09%	36.35%	20%	26.2%
Petroleum Coke	18.39%	18.12%	0	0	18.4%	0	0	0	0
Residual Oil	0.47%	0.09%	9.46%	7.11%	2.23%	0	0	0	0
Nuclear Power	0	9.26%	0	0	0	0	0	0	0
Electricity	4.25%	11.58%	41.2%	33.1%	17.8%	22.35%	0	0	34.5%

The calculation of upstream energy consumption and emission for a particular material or process can be shown in Equation 2, where the unit upstream energy consumption and GHG emission extracted from the GREET 2013 model are then multiplied with the energy usage profile of process fuels and electricity.

$$UEE = \sum_{i=1}^{n} CE \cdot PE_i \cdot UEE_i \tag{2}$$

Where,

UEE = Upstream energy consumption (BTU/ton) or emission (g/ton);

CE = Combustion energy (MMBTU/ton);

PF_i = Percent of the i th type of energy in the energy matrix;

UEE_i = Upstream energy consumption (BTU/MMBTU) or emission (g/MMBTU) for the i th type of energy (calculated from GREET);

i = Type of energy including coal, diesel, gasoline, liquefied petroleum gas, natural gas, distillate oil, petroleum coke, residual oil, and electricity; and

n = Total number of energy type.

6. PAVEMENT DESIGN ALTERNATIVES

6.1 Pavement Rehabilitation Design Alternatives

Since differences in properties of asphalt concrete and cement concrete can have strong influences on pavement structure design and quantities of material usage, it is critical to conduct LCA of different pavement types with the same performance standard. In an early study sponsored by FAA in 2004, field data collected from 30 airports in U.S. concluded that flexible and rigid pavements designed based on FAA standards have structure condition index (SCI) values at or above 80 after 20 years. While the structural performance of flexible and rigid pavements was found comparable, differences in functional performance was noted (*31*).

In this study, the two design alternatives for resurfacing runway 13R-31L at JFK airport were based on the analysis of existing pavement condition data and the past experience of PANYNJ, as shown in Table 4. Each design alternative is expected to sustain the desired performance level over the runway's life cycle although they varied significantly due to consideration of pavement life and rehabilitation needs. The PANYNJ's experience with asphalt surfaced runway was no longer lasting over 10 years before rehabilitation was required. Hence, the asphalt pavement was designed to require significant overlay treatments every eight years in the 40-year design life. On the other hand, only concrete repair was required for concrete pavements every eight years.

Table 4 Design Alternatives for Resurfacing Runway Pavement

Stage	Year	Rigid Overlay	Flexible Overlay
Initial Construction	0	Milling 6-inch asphalt + overlay 2-inch asphalt	Milling 3-inch asphalt
	0	18-inch Concrete Overlay	9-inch Asphalt Overlay
Maintenance	8	Concrete Repair	Milling 3-inch + overlay 4-inch asphalt
	16	Concrete Repair	Milling 6-inch + overlay 7-inch asphalt
	24	Concrete Repair	Milling 3-inch + overlay 4-inch asphalt
	32	Concrete Repair	Milling 6-inch + overlay 7-inch asphalt

6.2 New Pavement Design Alternatives

In addition to overlay design, a series of typical new pavement designs were conducted using the aircraft traffic mix at JFK airport, respectively, for asphalt and concrete pavements. The design procedure outlined in FAA Advisory Circular 150/5320-6E is used for new pavement design using the FAA Rigid and Flexible Iterative Elastic Layered Design (FAARFIELD) software (*2*).

In the FAARFIELD, mechanistic-empirical design correlates critical pavement stresses and strains to empirical performance models. Although the fatigue damage at the bottom of asphalt surface layer can be calculated, the design control criteria is subgrade rutting caused by the vertical compressive strain on top of subgrade. For rigid pavements, failure is caused by the fatigue cracking affected by the ratio of tensile stress to the flexural strength of concrete. The pavement thickness was designed to have the cumulative damage factor (CDF) equal to one at the end of design life. It is noted that in the FAARFIELD, the elastic modulus of asphalt surface layer is set at 200,000 psi and the modulus of PCC layer is fixed at 4,000,000 psi. The flexural strength of PCC can be set in the range of 500 to 800 psi.

The runway pavement surface layers were designed over difference thickness combination of crushed stone base and plant mix macadam, considering the practice used by the PANYNJ. It is noted that the asphalt surface layer is designed with P401 surface layer with 200,000-psi modulus and P403 asphalt stabilized base layer with 400,000-psi modulus based on the recommendation from FAA Advisory Circular 150/5320-6E. Table 5 shows the design thickness of new runway pavement, respectively, for asphalt and concrete surface layer.

Table 5 Design Alternatives for New Runway Pavement

Layer	HMA Pavement	PCC Pavement
1	9-inch HMA	20-inch PCC
2	12-inch plant mix macadam	4-inch plant mix macadam
3	14-inch P-209 crushed stone	6-inch P-209 crushed stone

7. RESULTS AND ANALYSIS

7.1 Comparison between Different Pavement Materials

The material-related energy consumption and GHG emission were shown in Table 6, respectively, for combustion and upstream components of each raw material and manufacturing process (plant operation for producing mixtures). The analysis was conducted using the standard mixture designs that were used at airfield pavements by the PANYNJ and the baseline values in the life-cycle inventory database. The combustion (direct) values are generated in the processes for raw material acquisition and manufacturing process; while the upstream values are related to the type and quantify of process fuel that is consumed in the combustion process. The results show that the upstream components play a significant role in the total environmental burdens, although the exact values of upstream components vary depending on the percentage of process fuel and electricity.

For both hot-mix asphalt and Portland cement concrete, the binding agent (asphalt binder or Portland cement) with small mass percentages has the most significant component in the energy consumption and GHG emission for raw material. The typical process of producing asphalt binder is divided into four stages: crude oil extraction, transport, production in refinery, and storage (DOE). The manufacturing process of Portland cement mainly includes quarry and crush, raw meal preparation, pyroprocess, and finishing grind (PCA). It is noted that as compared to asphalt binder, Portland cement has roughly the same energy consumption but twice the GHG emission due to the clinker process in cement kilns.

Aggregates contribute to the total energy consumption and GHG emission in a much less degree as compared to asphalt binder or Portland cement. Aggregates contribute to the total energy consumption in a more significant role as compared to the GHG emission. Crushed aggregate requires mechanical breaking after acquisition or quarrying; while natural aggregates (sand or gravel) are obtained by dredging. On the other hand, the very small content of polymer has a significant impact in the total energy consumption and GHG emission of HMA due to the energy-demanding process for polymer manufacturing.

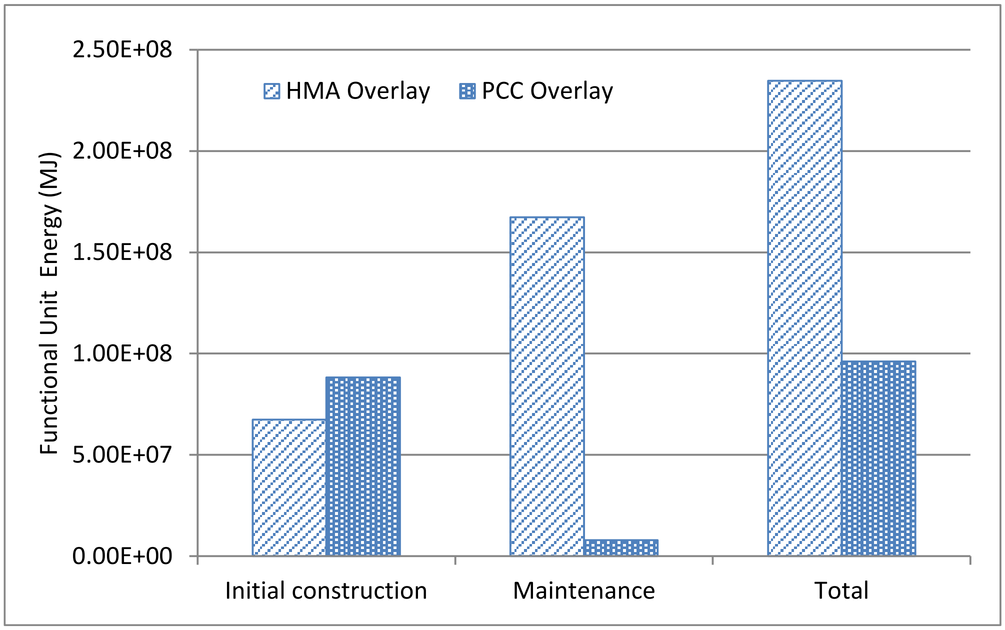
As expected, the manufacturing of HMA consumes much more energy and generates more GHG emission than the production of PCC. Asphalt production includes mixing of asphalt binder, aggregate and other additives at the required temperature, and energy consumption and emission are mainly generated from heating and mixing. The exact amount of heat energy varies depending on the moisture content in the aggregate and the discharge temperature of HMA. On other hand, concrete is produced by mixing cement with fine aggregate (sand), coarse aggregate (crushed stone), and water without heating. This causes much less energy consumption in the concrete plant as compared to the HMA plant. It is noted that energy consumption and GHG emission for steel production are counted separately for concrete pavement. Totally there are 24,000 dowel bars were used in the joints of concrete slabs, which causes significant amount of environmental burdens that cannot be neglected.

Table 6 Material-Related Energy Consumption and GHG Emssion for HMA and PCC

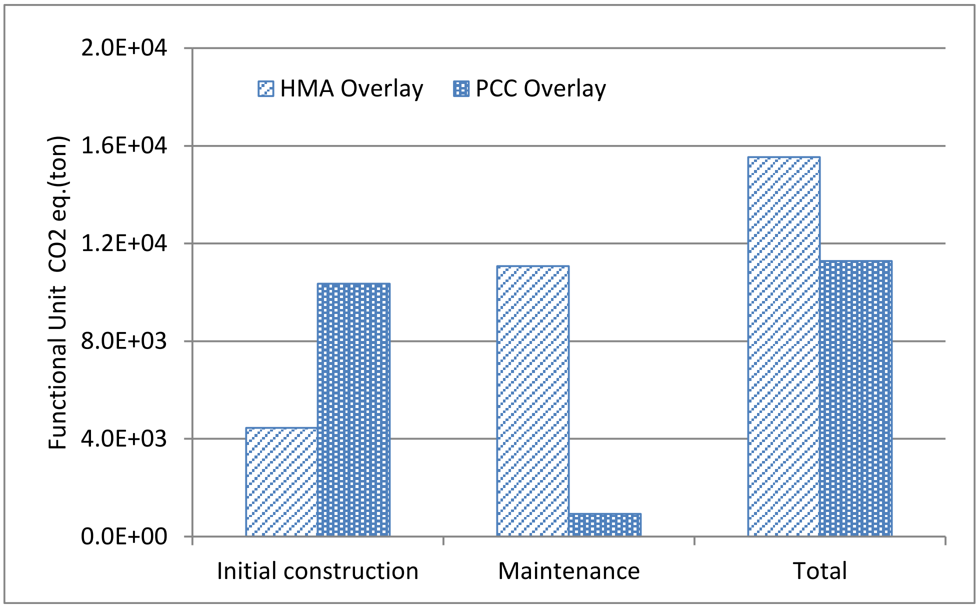
Material / Process		Energy consumption (MJ)		GHG emission (CO2 eq.)	
		Combustion	Upstream	Combustion	Upstream
For each ton of HMA					
Raw material extraction and production	Asphalt	286.4	87.7	23.7	6.1
	(4.93%)	*(48%)*	*(50%)*	*(62%)*	*(51%)*
	Aggregate	25.3	26.1	0.59	1.1
	(94.7%)	*(4%)*	*(15%)*	*(2%)*	*(9%)*
	Polymer	283.9	63.1	13.7	4.8
	(0.37%)	*(48%)*	*(36%)*	*(36%)*	*(40%)*
	Total	595.7	176.9	38	12
HMA manufacturing		266	58.9	16.4	4.7
For each ton of PCC					
Raw material extraction and production	Protland cement	265	93	56.7	8.2
	(6.08%)	*(87%)*	*(75%)*	*(99%)*	*(85%)*
	Slag cement	22	15	0.3	0.7
	(3.48%)	*(7%)*	*(12%)*	*(0.5%)*	*(8%)*
	Aggregate	17	17	0.6	0.7
	(58.58%)	*(6%)*	*(13%)*	*(1%)*	*(8%)*
	Water *(31.86%)*	Neglected			
	Total	304	125	58	10
PCC manufacturing		18	17	0.7	0.8

7.2 Comparison between Runway Rehabilitation Strategies

Figures 2 (a) and (b) compare the environmental impacts of two rehabilitation strategies with HMA and PCC, respectively, for energy consumption and GHG emission of one functional unit. The results using the baseline values in the life-cycle inventory database are show in the column values and the variation of results are displayed in error bars representing the minimum and maximum values. It is noted that this comparison was performed for two rehabilitation strategies in a 40-year analysis period that is different from the pure comparison between HMA and PCC. For example, the PCC rehabilitation design includes two-inch asphalt overlay after 6-inch milling of existing asphalt layer before placing the concrete overlay. The results show that the HMA overlay causes greater energy consumption and comparable GHG emission, as compared to the PCC overlay. The similar trend can be observed if the variations in the inventory data were considered. Maintenance stage constitutes the major component in the life-cycle energy consumption and GHG emission for the HMA rehabilitation strategy.



(a)



(b)

Figure 2 Environmental impacts of pavement rehabilitation strategies with HMA and PCC for (a) energy consumption and (b) GHG emission

The percentage distributons of energy consumption and GHG emission at different stages of initial construction were calculated, as shown in Figure 3. For both HMA and PCC overlays, the material-related environment impacts play the most significant role in the total energy consumption and GHG emission. The percentages of energy consumption and GHG emission caused by material-related components are 88-89% of for HMA overlay and 94-96% for PCC overlay. The acquisition and production of raw material consumes 85% of total energy and generates 92% of total GHG emission for PCC overlay; while only 63% of total energy and 62% of total GHG emission for HMA overlay.

The on-site transporation component is minor due to the short transport distrance to the HMA plant and the on-site concrete batch plant. The construction equipment causes 7% energy consumption for HMA overlay but only 4% for PCC overlay. This is because significant amount of milling and paving operation for multi-lifts of HMA overlay as compared to the one-lift slip-form paving process for PCC overlay.

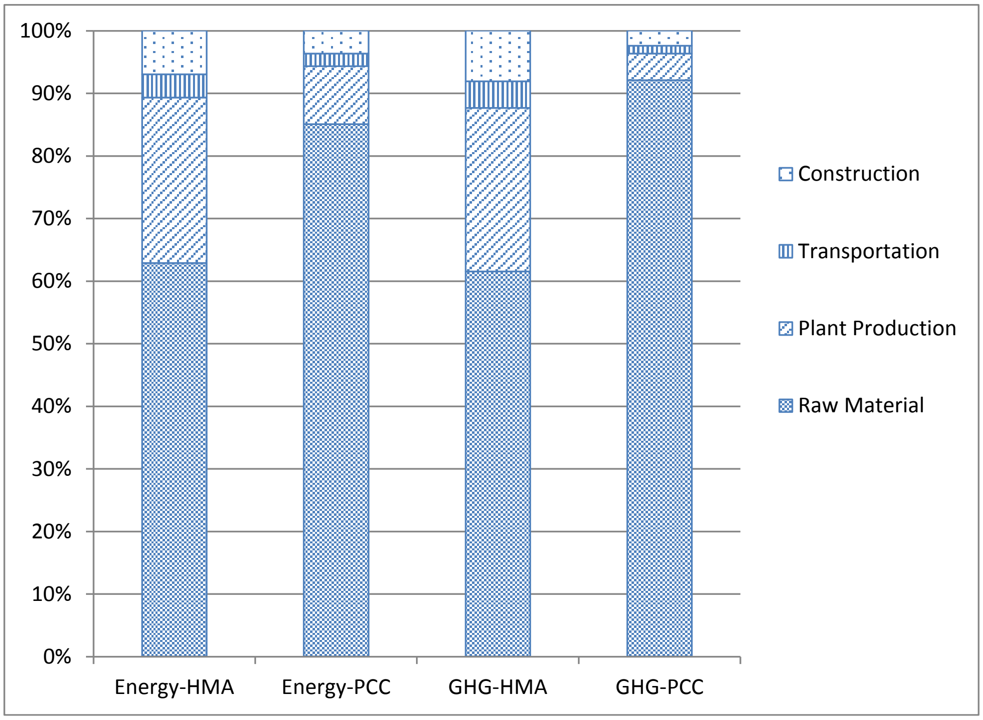
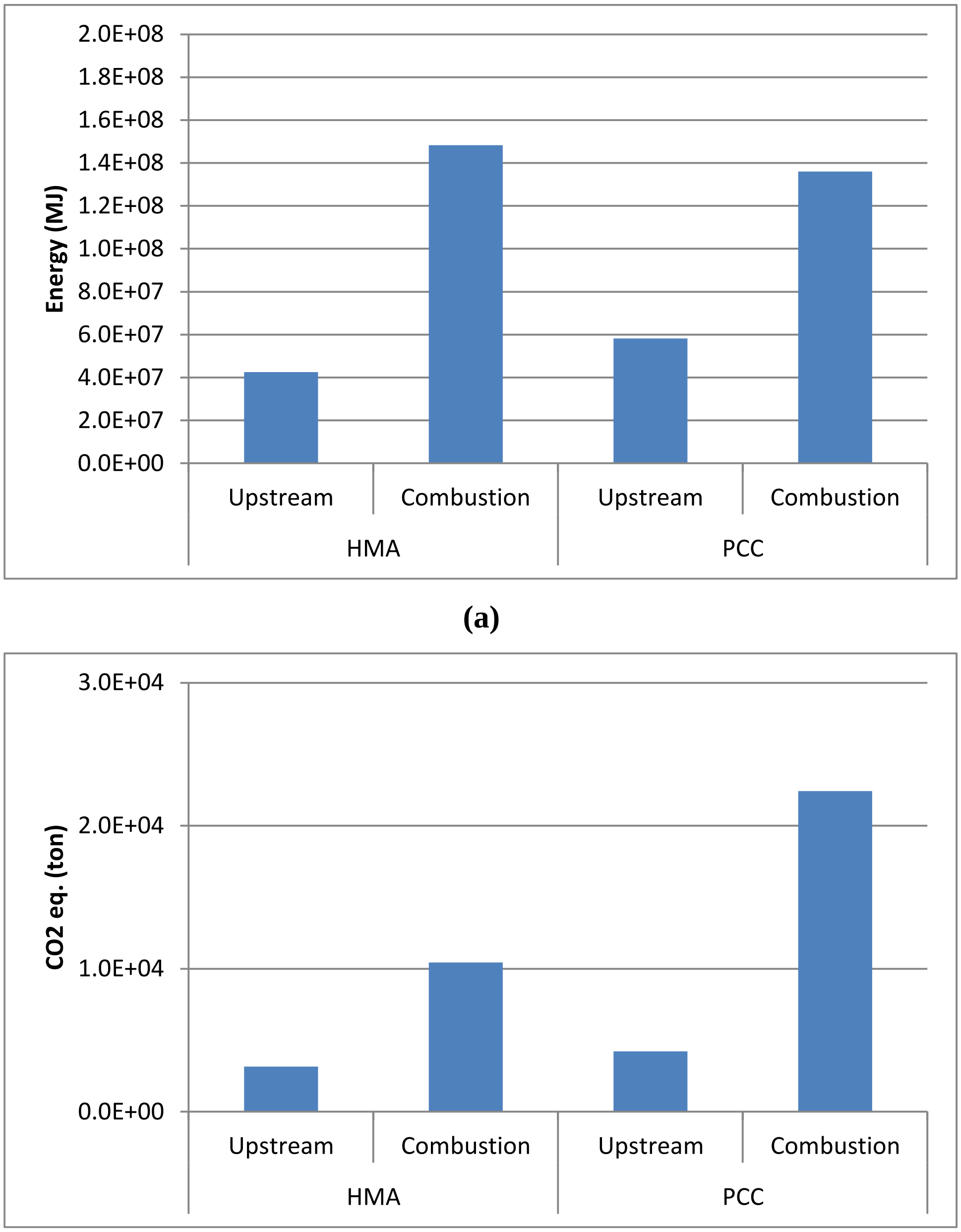


Figure 3 Percentage distributon of energy consumption and GHG emission at different stages of initial construction

7.3 Comparison between New Runway Pavement Designs

Figures 4(a) and (b) compare the environmental impacts of different new runway pavement designs with HMA and PCC, respectively, for energy consumption and GHG emission of one functional unit. The energy and emission quantities were calcualted for the whole pavement strucutre including surface, base, and subbase layer. No maintenance phase was considered in this case. No maintenance phase was considered in this case because these two pavement strucutres were designed to have the same design life without major rehabilitation.

The resutls indicate that the HMA pavement may consumes slightly smaller but comparable energy as compared to the PCC pavement. On the other hand, the HMA pavement generates less amounts of GHG emission. It is noted that the trends observed here are different from the comparison between runway rehabilitation design alternatives. The percentages of upstream components are 24-25% of total energy or emission quantities for HMA pavement and 21-37% for PCC pavement. This again emphasizes the importance of considering the upstream process in order to accurately quantify the life-cycle energy consumption and environmental impact.



(a)

(b)

Figure 4 Environmental impacts of new pavement designs with HMA and PCC for (a) energy consumption and (b) GHG emission

In the new runway pavement design, the HMA surface layer thickness is much smaller than the PCC surface layer thickness; while the thicknesses of base and subbase layer are much thicker in the HMA pavement structure. The design alternatives presented here are based on the practice at the PANYNJ and the design outputs of FAARFIELD. It is expected that different comparison results may be found as the design practice or geographic location changes. There is no unanimous estimation of the pavement life comparison between asphalt and concrete pavements subjected to the same traffic and environmental conditions.

8. CONCLUSIONS

This study assessed the cumulative energy demand (CED) and greenhouse gas (GHG) emission of different airport pavement design alternatives using LCA approach. The results indicate that the expected pavement service life and maintenance treatments significantly affect the comparison between HMA and PCC pavements. The consideration of energy and emissions associated with the production of process fuels and electricity in the upstream process cannot be neglected in the LCA. The implementation of LCA approach enables decision makers to quantify energy consumption and GHG emissions among alternative pavement designs.

The environmental impact among different pavement design alternatives significantly depend upon pavement type, design assumptions, and maintenance strategies. Although there are no general conclusions on pavement type selection, the comparison of energy consumption and GHG emission due to upstream, construction and maintenance stages brings awareness to the airport engineer on the differences between HMA and PCC pavements. The project-level analysis need be conducted for selecting the most appropriate design alternatives in the airport planning process. Airport agencies and contractors should work together to select the preferred pavement designs considering performance, economic cost, and sustainability.

The current analysis focused on the difference between asphalt and concrete pavement design scenarios for new runway pavements and overlay rehabilitations on existing pavements. Further analysis should consider the environmental impact of other sustainable pavement practices in the airport, such as recycled asphalt mixture or warm-mix asphalt, permeable pavements at runway or taxiway shoulders, and heated pavements at apron. The extra environmental burdens caused by airline delays due to construction activities in the airfield is analogy to traffic delay caused by work zones in highway projects, which should be considered in future work.

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