Environmental Assessment and Economic Analysis of Porous Pavement at Sidewalk

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ABSTRACT: This study aims to evaluate economic and environmental benefits of porous pavement surface using life-cycle cost analysis (LCCA) and life-cycle assessment (LCA). The research will focus on application of porous surface for sidewalk. The life-cycle inventory data were collected from literature search, online database, and project records. The comparison study was conducted between pervious paving systems and the conventional impermeable pavement with drainage system and Best Management Practices (BMPs) in storm water management. Three pavement alternatives are considered in this study, including conventional concrete, porous asphalt, and porous concrete. The study results can help quantify the environmental impacts and costs of using porous pavement surface at light traffic condition and select the sustainable pavement alternative.

1 INTRODUCTION

Porous pavement is one of the green infrastructures that reduce the negative environmental impact from storm water runoff in the urban area. In natural process, the rainfall will soak into the ground and gets filtered by vegetation and soil. However, in urban area with sufficient impermeable surface such as roofs and pavement, the storm water runoff releases contaminants into the nearby water bodies such as bacteria, trash, heavy metals and other pollutants making them one of the most important sources of water pollution (EPA, 2008). The major benefit of porous pavement is the storm water quality control and the potential to lower the requirement of Best Management Practices (BMPs), curbs, underdrainage system such as pipes, manhole, inlet and outlet, and gutters (FHWA, 2010). Recently, studies indicate that porous pavement can reduce the urban heat island effect under certain whether conditions (EPA, 2008). The cooling effect is mainly caused by absorbing heat for moisture evaporation. Studies also show that porous pavement can reduce tire noise by 2 to 8 decibels and increase surface friction by reducing hydroplaning risk at pavement surface (Lebens, 2012; EPA, 2008).

Porous pavement surfaces could be asphalt, concrete or interlock pavers. These pavements have been mainly used in light traffic areas such as parking lot, highway shoulder, sidewalk, and residential street and driveways (FHWA, 2010). Application of porous pavement on heavy traffic highway is also possible but less preferable due to the insufficient successful practice in the U.S. (Wang, 2010). In the cold region, winter maintenance of porous pavement may be problematic. Porous pavement experiences decreased durability due to the damage caused by freeze-thaw cycle (Lebens, 2012). At the same time, it is commonly acknowledged that less dense, open-graded porous pavement has inadequate structural support compared to traditional asphalt and concrete pavement (Rogge and Hunt, 1999). Other disadvantages of porous pavement include the potential clogging and raveling issues.

Although porous pavement as one of the storm water management practice has been widely accepted as an environmentally preferable, less expensive alternative to conventional pavement in light traffic areas, there is limited studies focus on the life-cycle environmental impacts and the life-cycle cost of porous pavement.

The objective of this paper is to conduct environmental assessment and economic analysis of porous pavements at sidewalk. The life-cycle assessment includes the definition of goal and scope, life-cycle inventory analysis, and impact assessment and interpretation. Due to the time and resource limitation, this study only focused on the environmental impact related to material acquisition and production. In addition, life-cycle cost analysis with simplified assumptions was conducted to compare different alternative pavement designs at sidewalk.

2 REVIEW OF PERTINENT STUDIES

Many states' and local departments of transportation (DOTs) have pavement design and construction requirements of sidewalk, trail, and bike lanes in their specifications and guidelines. Table 1 summarized examples of sidewalk design requirements and costs from case studies in Florida, Pennsylvania, and Washington. Most of previous researches about sidewalk focus on the safety, completeness, and accessibility of sidewalk, and the evaluation of satisfaction of pedestrian with different environmental elements of sidewalk. However, there are few studies on engineering design and construction of pavement at sidewalk, resulting in the lack of data of mix design and properties of sidewalk pavement material for both porous concrete and porous asphalt.

Table 1 Summary of Porous Pavement Design Requirements and Costs

	Structure design	Drainage system	Construction cost	Source & Location
Pervious Concrete Shoulder (Highway Traffic)	Thickness: 10" Reservoir layer:12"	Two collection slotted pipes were placed to document runoff volume and water quality analyses	1.5 times conventional paving method due to skilled labor to install the concrete layer	Wanielista & Chopra, 2007 Florida
Permeable Asphalt (Light Traffic)	Thickness: 3"	N/A	\$110 / sq. yard; full 8" including choker stone, Storage stone not included	Basch et.al, 2012 Philadelphia, PA
Pervious Asphalt (Minimal Traffic)	N/A	Combination of traditional curbs channel to receiving storm sewer and pervious asphalt	Cost of designing and installing slightly higher than traditional pavement due to innovative engineering	Basch et.al, 2012 Salem, OR
Permeable Concrete for Sidewalk	Length: 1500' Width: 5 1/2'	N/A	\$20/ sq. yard (bid price lower than expected), \$10000 additional engineering cost	Olympia, WA, 1999 Olympia, WA
Permeable Concrete for Bicycle Lanes Sidewalk	Bike lane 5' wide; Sidewalk 6' wide	Gutter slope and overflow basin to remove standing water into storm water facility	Pervious concrete lane: \$140 / sq. yard, Pervious Concrete Sidewalk: \$92.25 /sy	Tosomeen, 2008 Olympia, WA

Wang, Harvey, and Jones (2010) performed a preliminary life-cycle cost analysis and life-cycle assessment framework of different storm water management options based on the fully permeable pavement designs. Their study was to evaluate the present economic life-cycle cost of fully permeable pavement as compared to the conventional pavement with treatment BMP for two scenarios: 1) shoulder retrofit for high speed highway and 2) low-speed highway or parking lot. The analysis period used in their study was 40 years in which two constructions of BMPs and two to four replacements of fully permeable pavements were included. The typical discount rate used is 4% and the salvage value at the end of the analysis period was assumed to be zero. The result indicates that the fully permeable pavement is more cost-effective than the scenarios of shoulder retrofit and parking lot with BMPs.

Life-Cycle Assessment (LCA) is a method to quantify the life-cycle environmental impact of a product from cradle to grave with flexibility and comprehensiveness (ISO 14044, 2006). The phases generally start from the raw material production to the end of life of a product. Vares and Pulakka (2015) preformed LCA and LCCA for comparison of the conventional and permeable pavement walkways in Finland. The cost analysis used the present value including maintenance and repair costs over a period of 30 year. The conventional pavements include asphalt and concrete surfaces with built-in sewage system with pipes and manholes for storm water treatment. The pervious surface includes partly permeable pavement structure of concrete and fully permeable pavement structure of permeable concrete and porous asphalt. The report also provides a scenario for operation and maintenance periods of surfaces. Sensitivity analysis was conducted with 25% higher and lower cost in case of permeable structures. The result shows the life cycle costs of permeable structure pavement are more cost-effective, which is also supported by the sensitivity analysis. The life cycle assessment of pavement structures shows that pavement surface has the highest contribution of the GHG emission compared to other sub-bases. All permeable pavements have less carbon footprint than conventional pavement. The reason is that the two conventional pavement use drainage manholes with concrete tube and reinforcement have the biggest contribute to the difference of carbon footprint between permeable pavement and conventional pavement.

3 POROUS PAVEMENT DESIGNS

Three pavement alternatives are considered in this study, including conventional concrete, porous asphalt, and porous concrete design 1 and 2. Table 2 shows the structure design of conventional concrete sidewalk. For conventional sidewalk, underdrain system with pipes is needed. According to the New Jersey Standard Roadway Construction 2007, the conventional concrete sidewalk required 4-inch thick cement concrete surface with a slope 1/4” per foot. Detail information about high-density polyethylene drainage pipe including sizes (like inside and outside diameters), thickness, and weight were found from a manufacture’s product note.

Table 2 Conventional Concrete Sidewalk Structure Design

Conventional Concrete Sidewalk Structure		Layer Thickness (in)	Quantity (ton/mile)
Surface Layer	Cement concrete	4	41.85
Sub grade	Compacted earth	N/A	N/A
Drainage Pipes	4 (in.) in diameter	N/A	1.484

Porous paving sidewalk designs used in the study include porous concrete and asphalt surface course. The reservoir layer of uniformly graded coarse aggregate is placed on soil subgrade with certain drainage requirement. One of the important benefits of porous pavement is the potential to reduce or eliminate the use of underdrain pipes. With the reservoir layer, more rainfall amounts can be temporally stored under the pavement until fully infiltrated into the ground. The thickness of storage layer depends upon the required runoff storage volume, the typical rainfall amount in the area, and the permeability of soil underneath. The design of porous pavement follows New Jersey Storm Water Best Management Practices Manual - Standard for pervious paving system. Table 3 shows the structure design of porous paving sidewalk.

Table 3 Porous Pavement Sidewalk Structure Design

Porous Pavement Sidewalk Structure		Thickness (in)	Area (sq. in)	Quantity (ton/mile)
Surface	Porous Concrete Surface	4	-	38.00
	Porous Asphalt Surface	4	-	35.2
Bedding	Choker Course -AASHTO No. 57	1	-	7.10
Reservoir Layer	Coarse Aggregate- AASHTO No.2	12	-	88.00
Filter Layer	Non-Woven Geotextile	-	253440	-
Subgrade	Un-compacted Subgrade	-	-	-

The porous asphalt mixture designs were obtained from the technical report of Porous Asphalt Pavements (Wisconsin Asphalt Pavement Association, 2015). The porous concrete mixture design 1 and design 2 were obtained from lab experiments currently conducted at Rutgers University. The conventional concrete mixture design is from a sidewalk project of New Jersey Department of Transportation. The mix designs of different materials are shown in Table 4.

Table 4 Mixture design of conventional concrete, porous concrete and porous asphalt

Material (lbs/cu.yd)	Conventional Concrete	Porous Concrete design 1	Porous Concrete design 2	Porous Asphalt
Cement	405	635	465	N/A
Slag	175	N/A	155	N/A
Fine Agg./sand	1314	224	N/A	N/A
Coarse Agg.	1850	2430	2500	N/A
Water	283	209	165	N/A
Asphalt	N/A	N/A	N/A	194
Polymer	N/A	N/A	N/A	14
Fine Agg.	N/A	N/A	N/A	761
Coarse Agg.	N/A	N/A	N/A	2283

4 LCA CASE STUDY

4.1 LCA Goal and Scope

The LCA attempts to quantify the environmental impacts of three sidewalk pavements using a cradle-to-grave approach. The three pavements that are being studied include porous asphalt, porous concrete, and traditional concrete pavement. The functional unit is defined as one-mile sidewalk with four feet width. The system boundary covers material, initial construction, and maintenance stages. Due to the time and resource limitation, the construction and end-of-life stage is not considered in this study. Future study will include inventory of construction stage with detail information about construction equipment and working productivity.

The analysis period used to inventory the inputs and outputs is set to be 40 years in order to create a fair comparison between alternatives with different design life. Since there is limited data in the literature of the life span of sidewalk pavements, an effort was made in this study to conduct sensitivity analysis of pavement life with an assumption that reconstruction will take place at the end-of-life of pavement. The minor pavement repairs are neglected in this study.

The impact assessments include energy consumption and greenhouse gas (GHG) emission from the upstream and direct combustion processes of the activities. The greenhouse gases considered in this study include Carbon Dioxide (CO_2), Methane (CH_4) and Nitrous Oxide (N_2O), which are converted to CO_2 equivalent using the Global Warming Potential (GWP) in 100-year time horizon (Levasseur et al. 2009).

4.2 Life-Cycle Inventory Data

The inventory data of energy consumption and GHG emission of material and manufacturing process were collected from published article and government reports. Upstream or indirect energy consumption and greenhouse gas emission associated with the processes of different stages are considered. The combustion (direct) energy and GHG Emissions are due to the straight use of fuels and electricity; while the upstream (indirect) components are generated from processing fuel that is consumed during various processes from material extraction to production.

To consider the upstream values, GREET 2013 model was used to extract the unit upstream energy consumption and GHG emission. GREET 2013 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) (Wang, 1999). The equation shown below is developed to calculate the upstream energy consumption and GHG emission using the approach developed in the authors' previous work (Wang et al. 2016).

$$\mathrm{UEE} = \sum_{i=1}^{n} \mathrm{CE} \cdot \mathrm{PE_i} \cdot \mathrm{UEE_i} \quad (1)$$

Where, UEE = Upstream energy consumption (BTU/ton) or emission (g/ton); CE = Combustion energy (MMBTU/ton); and $\mathrm{PE_i}$ = Percent of the i_{th} type of energy in the energy matrix.

The life-cycle inventory data for the components of asphalt and concrete pavements and plant production can be found from the synthesis of literature (Yang, 2014; Marceau, et al., 2007; Marceau, et al., 2006; Marceau, et al., 2003; Prowell et al., 2014; Argonne National Laboratory, 2007). Since GREET model does not provide emission factor for HDPE (High Density Polyethylene) material for underdrain pipes, the emission factors for polypropylene were used as an estimation (Worrell et al. 2000).

4.3 LCA Comparisons between Different Pavement Materials

In order to reach the same performance level of storm water runoff quality control, instead of collecting the runoff and discharge into the nearby water bodies directly, the impermeable sidewalk pavements with BMPs are comparable with porous pavement. Although BMPs are considered in this study, due to the lack of detail data of the specific BMP's design, construction equipment, and productivities, the BMP is neglected in the LCA comparison part.

Table 5 presents the results of energy consumption and GHG emission of four alternatives for each structure layer of one-mile sidewalk pavement structure. The results cover combustion and upstream values associated with the material related activities of raw material acquisition and plant production. Regardless of maintenance activities, the results indicate that porous concrete design 1 requires more energy and releases more CO_2 eq. than conventional concrete pavement. It is noted that porous paving material that has less fine aggregate to achieve the higher rate of permeability usually requires more binding agent of cement (NJDEP, 2004). Moreover, small percentages of Portland cement and asphalt binder of the total paving material have the most critical contribution in the energy consumption and GHG emission in material acquisition and production phases. These reasons explain the difference of results between porous concrete and conventional concrete pavements. However, the use of slag cement as partial substitution of Portland cement considerably reduces energy consumption and GHG emission. For porous concrete design 2, 25% Portland cement is replaced by slag cement, significantly reducing the energy consumption comparing to porous concrete design 1.

The results also show that bedding and reservoir layer consist of aggregate has noticeably smaller impact on energy consumption and GHG emission; while drainage pipes, one of the plastic materials, has significant contribution in energy consumption of conventional concrete pavement. The porous asphalt with polymer modified binder, consumes similar energy consumption but generates much less GHG emission as compared to porous concrete design 1, which is the combined effect of raw material and plant production.

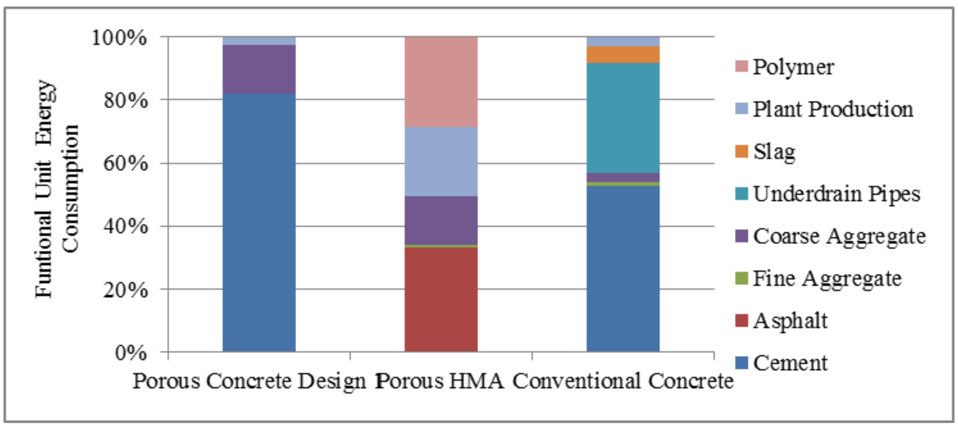
Table 5 Energy Consumption (MJ) of one-mile sidewalk pavement structure

Energy Consumption (MJ/mile)		Porous Concrete design 1	Porous Concrete design 2	Porous Asphalt	Conventional Concrete
1)	Surface	43535	34924	42569	31884
2)	Bedding	441	441	441	-
3)	Reservoir Layer	5469	5469	5469	-
4)	Subgrade	-	-	-	-
5)	Drainage Pipes	-	-	-	17137* (include feedstock energy)
Total		49446	40834	48480	49021

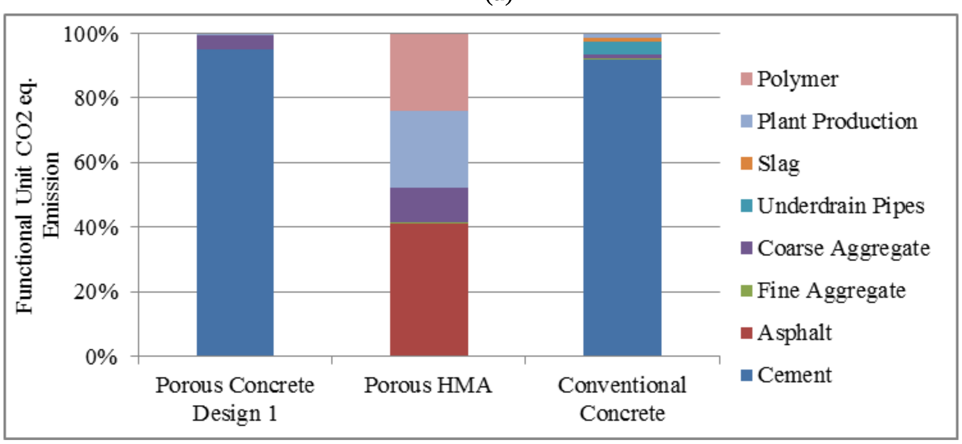
Table 6 CO_2 eq. Emission (Kg) of one-mile sidewalk pavement structure

CO2 eq. Emission (kg/mile)		Porous Concrete design 1	Porous Concrete design 2	Porous Asphalt	Conventional Concrete
1)	Surface	7456	5559	2839	5073
2)	Bedding	20	20	20	-
3)	Reservoir Layer	243	243	243	-
4)	Subgrade	-	-	-	-
5)	Drainage Pipes	-	-	-	191
Total		7719	5822	3102	5264

Figure 1 presents the percentage distribution of energy consumption and CO_2 eq. emission based on the initial construction of one-mile sidewalk with different materials. The results cover plant production and raw material used in pavement construction including polymer, cement, asphalt, aggregate, slag, and underdrain pipes. It is apparent that, compared to cement concrete production, manufacturing of porous asphalt pavement consumes more energy and release the greater amount of CO_2 eq. as well. The difference in plant production is mainly due to the amount of heating energy used to dry aggregate and to mix asphalt binder with aggregate at certain discharge temperature, usually around 160 ℃. With higher moisture content in aggregate, more energy is required to remove moisture from it before mixing. On the other hand, cement, aggregate, and water are mixed without extra heating energy for production of cement concrete. Another noticeable component is the impact of polymer in asphalt binder. The use of 0.43% polymer of the total weight of porous asphalt contributes to 20% of energy consumption and CO_2 eq. emission.



(a)



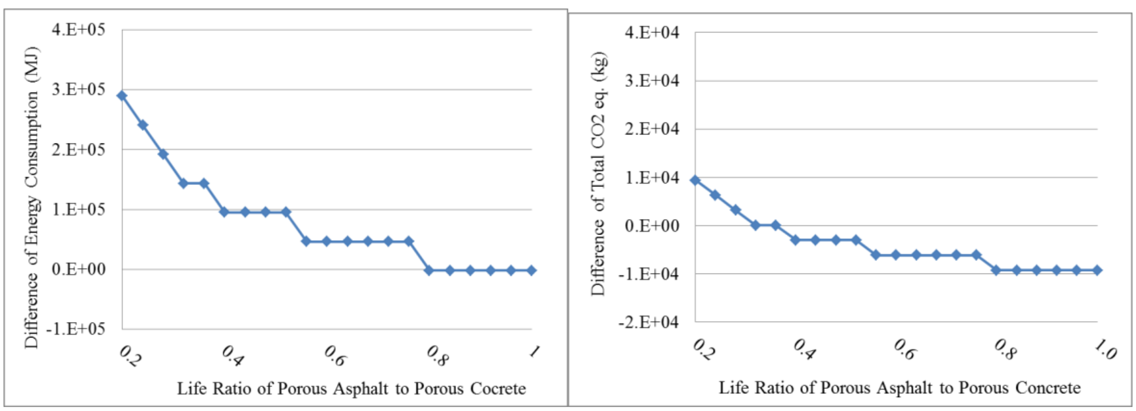
(b)

Figure 1 Percentage Distributions of (a) Energy Consumption and (b) CO_2 eq. Emission for Porous Concrete, Porous HMA, and Conventional Concrete

4.4 LCA Comparison with Different Life Span Ratios

The literature data show that the life span of porous asphalt and porous concrete is from 15 years to 40 years without major repair. However, the life estimations cannot be specific without convincing evidence of field data. In order to avoid the arbitrary selection of life span of sidewalk pavement alternatives, sensitivity analysis of pavement life span was considered in this study assuming pavements need reconstructions after reaching the end of life during the analysis period of 40 years. For example, the analysis results show that the environmental burden of porous asphalt is similar or smaller than porous concrete design 1. If the life span of porous asphalt pavement is shorter than porous concrete pavement, the environmental benefits of using porous asphalt will be offset by the need for more frequent reconstruction activities.

In the LCA, only the initial construction and reconstruction were considered due to the lack of life cycle inventory data for porous pavement maintenance. The time effect (discount rate) was not considered for energy consumption and GHG emission. Figure 2 (a) shows the breakeven point of pavement life ratio between porous asphalt and porous concrete is around 0.8 when the life of porous concrete is assumed to be 25 years. It means that with the life span of porous asphalt of 20 years and the porous concrete of 25 years, porous asphalt with one reconstruction has the same energy consumption with porous concrete in the 40-year analysis period. When the life ratio is smaller than 0.8, porous asphalt needs more than one reconstruction activities will results in more energy consumption than porous concrete; when the life ratio is bigger than 0.8, porous asphalt will have less energy consumption than porous concrete within the analysis period. Figure 2(b) shows that the breakeven point of life ratio between porous asphalt to porous concrete is around 0.32 for CO_2 eq. emission.



(a) (b)

Figure 2 Breakeven points of pavement life ratios between porous asphalt and porous concrete (design 1 with slag cement) for (a) energy consumption and (b) CO2 eq. emission (the life of porous concrete is assumed to be 25 years in 40-year analysis period)

5 LIFE CYCLE COST ANALYSIS

In order to be consistent with LCA results, the analysis period of LCCA conducted in this study is set to be 40 years, and the uncertainty of life spans of pavement alternatives will be considered in the life-cycle cost analysis. Three comparison alternatives are porous concrete, porous asphalt, and conventional concrete pavements. In order to reach the same performance level of storm water runoff control, instead of collecting and discharging the runoff into the nearby water bodies directly, the impermeable sidewalk pavements with drainage pipes and BMPs are comparable with porous pavement with reservoir layer.

The cost data is primarily obtained from the project biding records of New Jersey DOT in the recent three years and the summary of cost data from literature. The construction cost of BMPs is from Preliminary Data Summary of Urban Storm Water Best Management Practices (EPA, 1999). Figure 4 shows the initial construction cost of three pavement alternatives. Compared to asphalt pavement, conventional concrete pavements have the highest cost in the initial construction. It can be observed that underdrain pipes for conventional sidewalk pavement have significant contribution to the total cost.

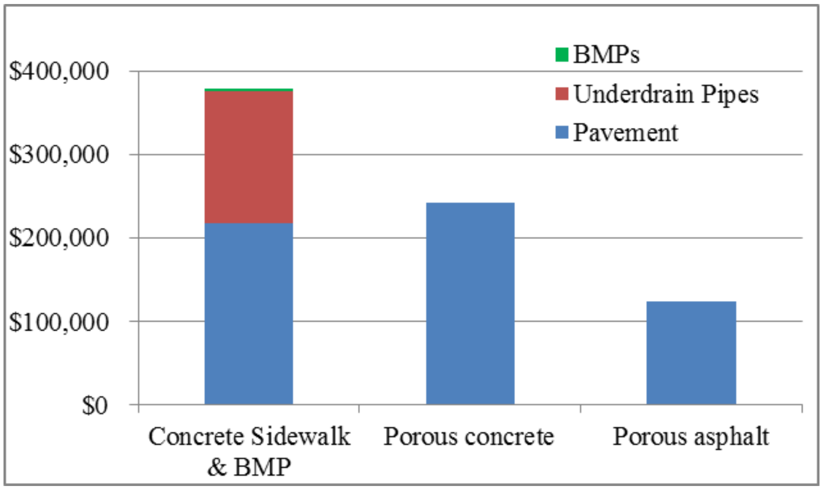
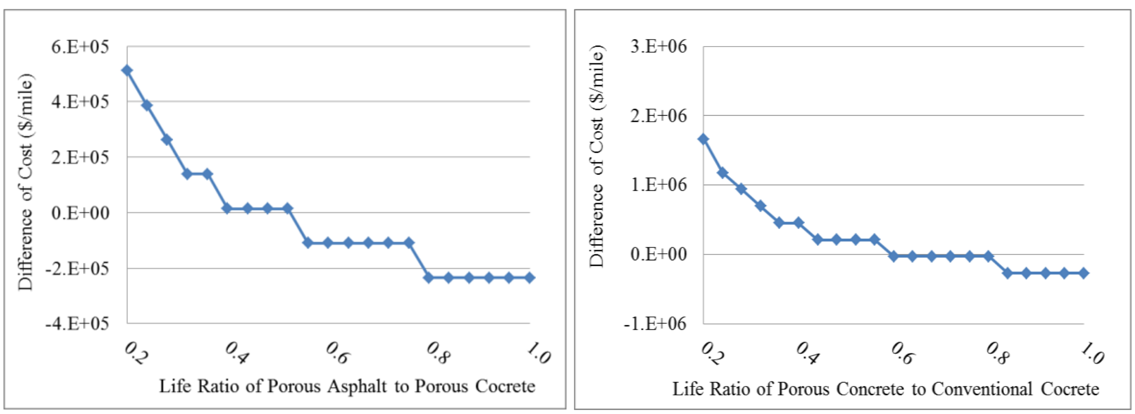


Figure 3 Initial construction cost ($/mile) of three sidewalk pavements

It is expected that the uncertainty of life spans of pavement alternatives will critically affect the result of life-cycle cost analysis. Since the cost of initial construction of each alternative is already known, the breakeven points of pavement life ratio can be calculated using the method discussed above. The annual maintenance costs of porous pavement and BMP were not considered due to lack of data, which was considered not significant based on experience. The discount rate is assumed to be 3% in the LCCA. In addition, the salvage value at the end of 40-year period is assumed to be zero due to uncertain life spans of four alternatives. Therefore, only the reconstruction cost at the end of life was considered in the LCCA. As shown in Figure 5, for the life-cycle cost, the breakeven points of life ratios were found being 0.6 between porous concrete and conventional concrete pavements, and 0.56 between porous asphalt and porous concrete pavements.



(a) (b)

Figure 4 Breakeven points of pavement life ratios between (a) porous asphalt and porous concrete and (b) porous concrete to conventional concrete for cost ($/mile) (the life of porous concrete is assumed to be 25 years in 40-year analysis period)

6 CONCLUSIONS

In the LCA comparison of different paving material of the initial construction phase, the results illustrate that mix designs of the pavement surface course greatly influence the LCA comparison results. Porous concrete pavement with slag cement requires less energy consumption than conventional concrete; porous asphalt pavement with polymer modified binder has higher energy consumption compared to the porous concrete with slag and conventional concrete surface. The sensitivity analysis of pavement LCA indicates that pavement life ratio can significantly affect the comparison results between different pavement types due to the reconstruction activities for the one with the shorter. For life cycle cost analysis, pavement life ratio and maintenance frequency are critical factors in the results. The result shows that underdrain pipes for conventional sidewalk pavement have significant contribution in the initial construction cost.

Preliminary results from this study indicate that porous pavement is not always environmentally preferable and less expensive when we use the life-cycle approach to quantify cost and environmental impact of energy consumption and GHG emission. For a more complete life cycle assessment, the construction and maintenance phase cannot be neglected. Detail information about sidewalk construction including equipment type and productivity should be collected and added to the life cycle inventory. It is also needed to consider the costs of construction and maintenance of porous pavements and BMPs which are included in the current life-cycle cost analysis. This study is in progress and future work will address these limitations.

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