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Environmental Assessment and Economic Analysis of Porous Pavement at Sidewalk

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Outline

- Introduction
- Porous Mixtures
- LCA Framework and Results
- LCCA Results and Ongoing Work
- Conclusions

Introduction

- Benefits of porous pavement
  - Reduce storm water system requirements and flooding risk
  - Reduce surface runoff and peak flows
  - Recharge ground water
  - Improve water quality by capturing pollutants
  - Potential reduction of heat island effects in urban areas

- Porous pavement surfaces could be asphalt, concrete or interlock pavers

- Porous pavement is mostly used for light-traffic applications, such as sidewalk, parking lot, residential street and driveway, highway shoulder or median

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Limitations and Concerns

- Prone to clogging and reduction of infiltration rate
- Periodic maintenance with high pressure washing and vacuum sweep is required
- Subsurface drainage may be required in less permeable soils
- Special care is needed to avoid compacting underlying parent soils
- Raveling due to water and deicing salts (porous asphalt)
- Requirements on handling and placement due to relatively stiff consistency (porous concrete)

Objectives and Scopes

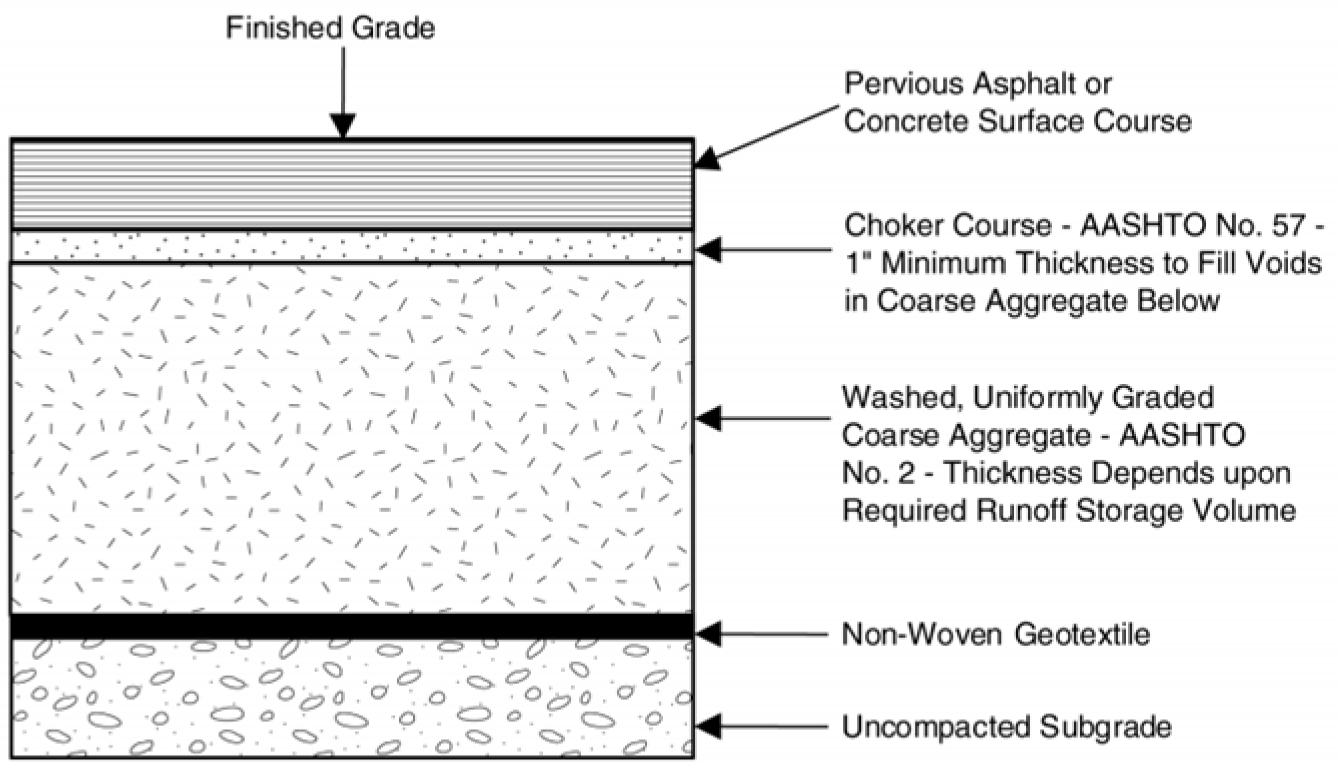
- Conduct environmental assessment of porous pavements as compared to conventional concrete for light traffic applications

- Conduct life-cycle cost analysis of different porous pavements

- Recommend porous concrete mix design based on engineering properties, life-cycle cost, and environmental impact that satisfy requirements of NJDOT

Porous Pavement Structure

Balance between structural adequacy and hydraulic performance



Hydraulic Design of Porous Pavement

- The design of the depth of reservoir layer underneath porous pavement surface depends on different storm events and the infiltration rate of soil which is the most hydraulically restrictive layer in porous pavement
- Follows New Jersey Storm Water Best Management Practices Manual by NJDEP

Underdrain needed (Stormwater Quality Design Storm 1.25 in/2-hr)				
Hydrologic Soil Group	general soil texture groups	Excellent Drainage	Good Drainage	Fair Drainage
A	Sands			
A-B	Sandy and silty soils			
B	Loams	√		
C-D	Clayey soils	√	√	
D	Sodic clayey soils	√	√	

Mixture Designs

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

LCA Framework

- Functional unit: one-mile sidewalk with four feet width
- System boundary: raw material and mixture production in initial construction and maintenance (reconstruction) stages within 40-year analysis period
  - Construction-related activities were not considered
- Life-cycle inventory data were compiled from literature and existing database
- Impact assessment: energy consumption and greenhouse gas (GHG) emission
  - Carbon Dioxide (CO_2), Methane (CH_4) and Nitrous Oxide (N_2O) were converted to CO_2 Eq. using GWP equivalency factors

Inventory Database for Material

- Asphalt: updated date from UIUC study; EIA PADD 1 (east coast) *(Yang et al. 2016)*
- Cement, crushed aggregate, sand or gravel: Portland Cement Association report *(Marceau, et al. 2007)*
- Polymer additive: European Bitumen Association report *(Eurobitume, 2011)*
- Slag cement: CTL report *(Marceau and VanGeem, 2003)*

- Hot-mix asphalt production: Plant energy and emission data from NCHRP 9-47A report *(Prowell et al., 2014)*
- Cement concrete production: Portland Cement Association report *(Marceau, et al., 2006)*

Indirect (Upstream) Energy and Emission

- In addition to energy and emissions of direct use of fuels and electricity, energy and emissions associated with the production of fuels and electricity are considered separately

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

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.

Energy Usage Profile

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

Comparison between Different Mixtures - Energy Consumption

Energy Consumption (MJ/mile)	Porous Concrete (no slag)	Porous Concrete (slag)	Porous Asphalt	Conventional Concrete (slag)
Surface	43535	34924	42569	31884
Bedding	441	441	441	-
Reservoir Layer	5469	5469	5469	-
Drainage Pipes	-	-	-	17137* (include feedstock energy)
Total	49446	40834	48480	49021

Comparison between Different Mixtures - GHG Emission

CO_2 eq. Emission (kg/mile)	Porous Concrete (no slag)	Porous Concrete (slag)	Porous Asphalt	Conventional Concrete (slag)
Surface	7456	5559	2839	5073
Bedding	20	20	20	-
Reservoir Layer	243	243	243	-
Drainage Pipes	-	-	-	191
Total	7719	5822	3102	5264

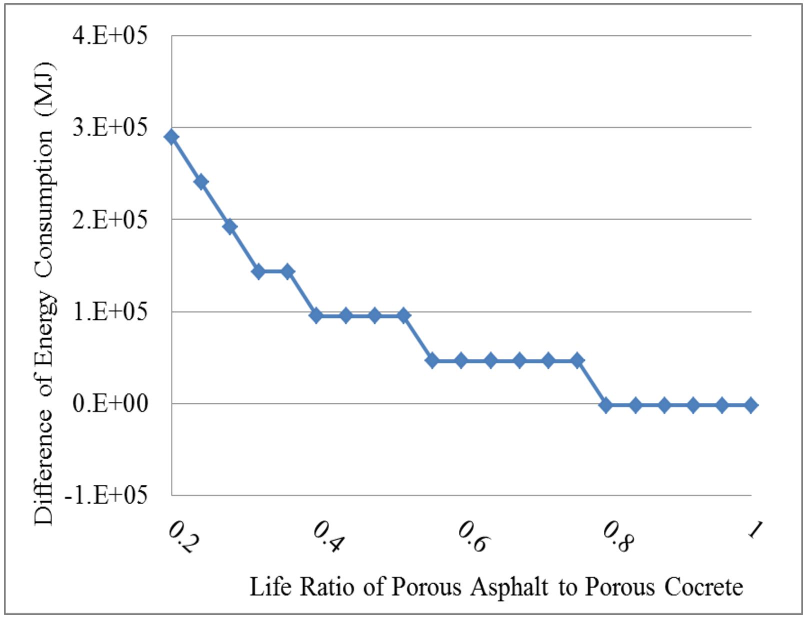
Field Performance of Porous Pavement

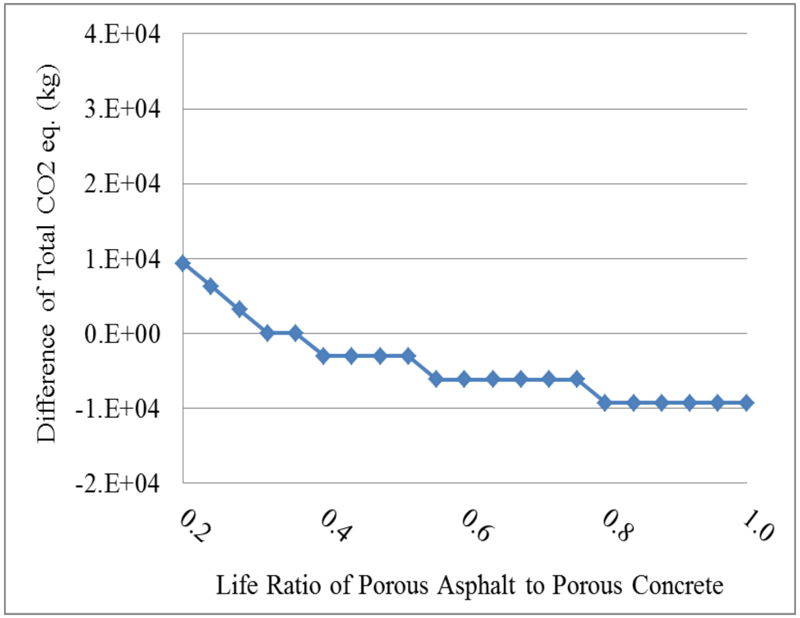
- Failure reasons of porous pavement
  - Clogging may originate from pavement wear due to tire friction, erosion from adjacent areas, vegetation, or sand application during winter maintenance
  - Drawdown of asphalt during hot days
  - Freezing-thaw damage

- In real practice, the lifespan is affected by construction procedure and maintenance frequency
  - Porous concrete: 20-30 years
  - Permeable asphalt: 15-20 years

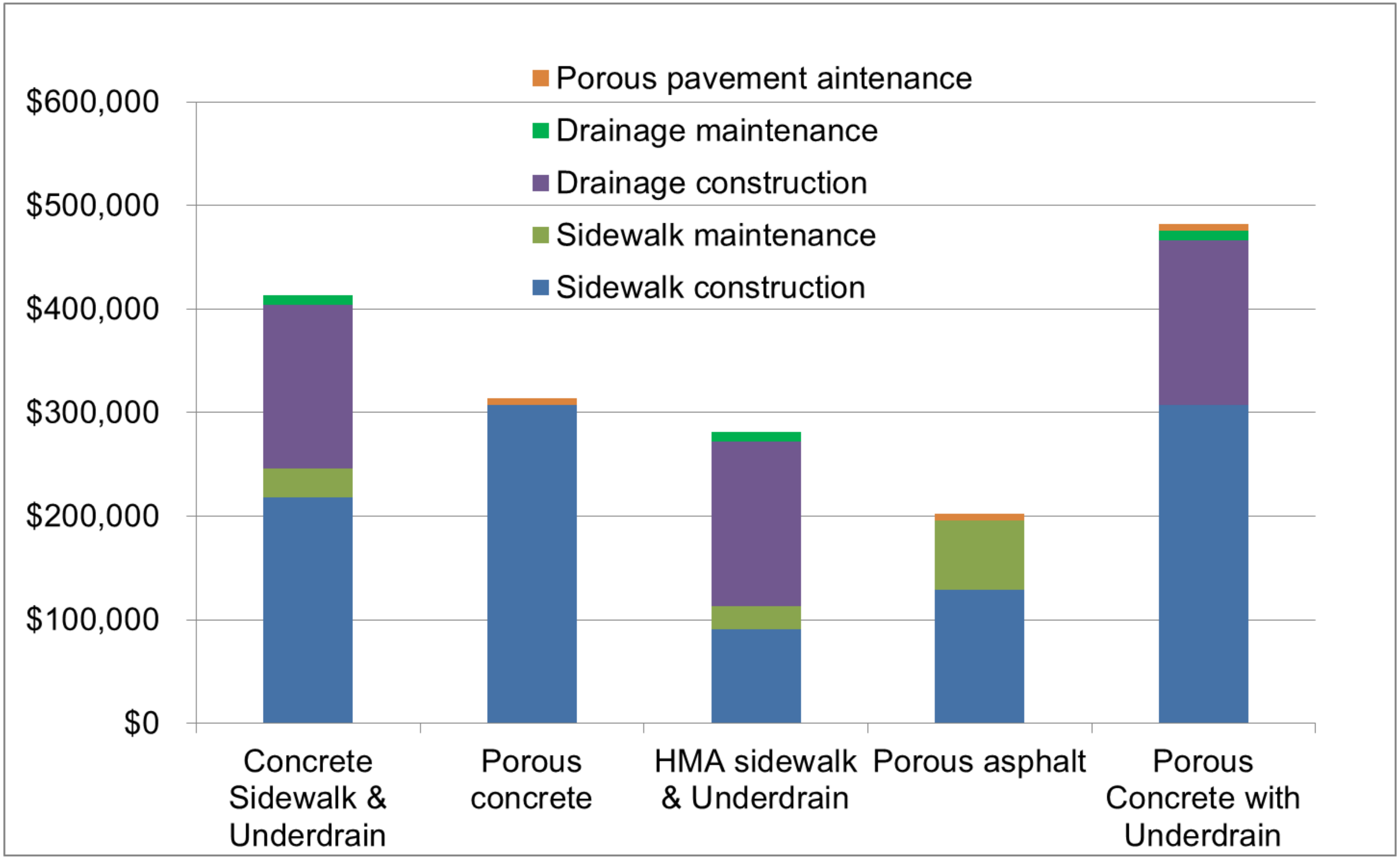
Comparison with Different Life Ratios

- The breakeven point of pavement life ratio between porous asphalt and porous concrete is around 0.8 (energy consumption) and 0.32 (CO_2 eq.) when the life of porous concrete (no slag) is assumed to be 25 years





Life-Cycle Cost Analysis



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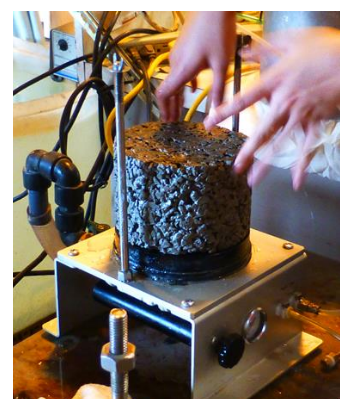
Laboratory Testing of Structural and Hydrological Properties of Porous Concrete

- Flexural Strength
- Splitting-Tensile Strength
- 7-Day and 28-Day Compressive Strengths
- Free Shrinkage
- 28-Day Elastic Modulus
- Freeze-Thaw Resistance
- Permeability



Mix Designs of Porous Concrete

Mix	Cement	3/8 Agg	1/4 Agg	Sand	Fly Ash	Slag	Water	W/CM Ratio	MRWR (SP)	HS	VMA	AE
PRC-1	635*	2430	---	224	---	---	209	0.33	---	---	---	---
PRC-2 (WELDON)	864	2430	---	---	---	---	236	0.27	1.9	1.9	---	0.8
PRC-3 (CLAYTON)	600	2835	---	---	---	---	162	0.27	1.9	1.9	---	0.8
PRC-4	620	2700	---	---	---	---	168	0.27	1.9	1.9	---	0.8
PRC-5	620	2700	---	---	---	---	168	0.27	1.9	1.9	2	0.8
PRC-6	620	1380	1380	---	---	---	168	0.27	1.9	1.9	---	0.8
PRC-7	525	2500	---	---	95	---	168	0.27	1.9	1.9	---	0.8
PRC-8	465	2500	---	---	---	155	168	0.27	1.9	1.9	---	0.8
PRC-9 (Silvi)	500		2700	---	---	---	165	0.33	1.9	1.9	---	0.8
PRC-10 (gravel)	600	2700	---	---	---	---	180	0.3	1.9	1.9	---	0.8
PRC-11 (gravel)	600		2700	---	---	---	180	0.3	1.9	1.9	---	0.8

**in lb/yd^3*

Highlighted mix designs were chosen for fabricating slabs

Field Slabs and Temperature Monitoring

Conclusions and Recommendations

- LCA results illustrate that mix designs of pavement surface course greatly influence comparison results between porous asphalt, porous concrete and conventional concrete
- The pavement life ratio can significantly affect comparison results between different pavement types due to the reconstruction activities
- LCCA results show that underdrain pipes for conventional sidewalk pavement have significant contribution
- The benefits of porous pavement on storm water management and urban heat island need to be considered in future LCA study

Thank You

Questions ?

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