The Application of Permeable Pavement with Emphasis on Successful Design, Water Quality Benefits, and Identification of Knowledge and Data Gaps

June 2015

A summary report from the National Center for Sustainable Transportation

Masoud Kayhanian, Department of Civil and Environmental Engineering, University of California, Davis

Peter T. Weiss, Department of Civil Engineering, Valparaiso University, Valparaiso, Indiana

John S. Gulliver and **Lev Khazanovich**, Department of Civil, Environmental, and Geo-Engineering, University of Minnesota, Minneapolis

National Center for Sustainable Transportation

University of Minnesota

ITS UCDAVIS INSTITUTE of TRANSPORTATION STUDIES

About the National Center for Sustainable Transportation

The National Center for Sustainable Transportation is a consortium of leading universities committed to advancing an environmentally sustainable transportation system through cutting-edge research, direct policy engagement, and education of our future leaders. Consortium members include: University of California, Davis; University of California, Riverside; University of Southern California; California State University, Long Beach; Georgia Institute of Technology; and University of Vermont. More information can be found at: ncst.ucdavis.edu.

Disclaimer

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated under the sponsorship of the United States Department of Transportation's University Transportation Centers program, in the interest of information exchange. The U.S. Government and the State of California assumes no liability for the contents or use thereof. Nor does the content necessarily reflect the official views or policies of the U.S. Government and the State of California. This report does not constitute a standard, specification, or regulation. This report does not constitute an endorsement by the California Department of Transportation (Caltrans) of any product described herein.

Acknowledgments

This study was funded by a grant from the NCST, which is supported by USDOT and by California Department of Transportation (Caltrans) through the University Transportation Centers program. The authors would like to thank the NCST and Caltrans for their support of university-based research in transportation, and especially for the funding provided in support of this summary report. Additional funding was provided by the Minnesota Department of Transportation (MnDOT) for the preparation of a state-of-the-art literature review.

NCST

The Application of Permeable Pavement with Emphasis on Successful Design, Water Quality Benefits, and Identification of Knowledge and Data Gaps

A National Center for Sustainable Transportation Summary Report

June 2015

Masoud Kayhanian, Department of Civil and Environmental Engineering, University of California, Davis

Peter T. Weiss, Department of Civil Engineering, Valparaiso University, Valparaiso, Indiana

John S. Gulliver and **Lev Khazanovich**, Department of Civil, Environmental, and Geo-Engineering, University of Minnesota, Minneapolis

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Acronyms and Abbreviations

A/C	aggregate to cement ratio
AASHTO	American Association of State and Highway Association
ACI	American Concrete Institute
ACPA	American Concrete Pavement Association
ACPI	American Concrete Pavement Institute
ASTM	American Standards and Testing Methods
BMP	best management practice
BOD	biological oxygen demand
Cd	cadmium
CDEA	Caltrans Division of Environmental Analysis
cm/s	centimeter per second
CN	curve number
COD	chemical oxygen demand
CRMCA	Colorado ready mixed concrete association
Cu	copper
DIN	dissolved inorganic nitrogen (comprised of nitrate, nitrite, and ammonia)
DVR	dissipated volumetric rate
EMC	event mean concentration
FHWA	Federal Highway Administration
FN	friction number
FWD	falling weight deflectometer
HMA	hot mix asphalt
HMA-O	hot mix asphalt-open graded
in/hr	inches per hour
K_{sat}	hydraulic conductivity-saturated
K_{unsat}	hydraulic conductivity-unsaturated
IRI	international roughness index
lb/ft^3	pound per cubic feet
lb/yd^3	pound per cubic yard
LCA	life cycle assessment
LCCA	life cycle cost analysis
ME	mechanistic empirical
mg/L	milligram per litter
MnDOT	Minnesota Department of Transportation
NAPA	National Asphalt Pavement Association
NCHRP	National Cooperative Highway Research Program
NCST	National Center for Sustainable Transportation
NPV	net present value
NRCS	National Resource Conservation Services
OGFC	open grade friction course
PA	porous asphalt

PAH	poly-aromatic hydrocarbon
Pb	lead
PC	pervious concrete
pcf	pound per foot
PICP	permeable interlocking concrete pavers
pfc	pound per cubic feet
RM	rational method
SR	surface roughness
TC	time of concentration
TDS	total dissolved solids
TKN	total Kajeldahl nitrogen
TN	total nitrogen
TP	total phosphorus
TPH	total petroleum hydrocarbon
TSS	total suspended solid
UCPRC	University of California Pavement Research Center
UDFCD	urban drainage and flood control district
UNHSC	University of New Hampshire Storm Center
USDOT	Unite States Department of Transportation
USEPA	United States Environmental Protection Agency
Zn	zinc

The Application of Permeable Pavement with Emphasis on Successful Design, Water Quality Benefits, and Identification of Knowledge and Data Gaps

EXECUTIVE SUMMARY

Permeable pavement presented in this paper is defined as a type of pavement that has ability to store stormwater until it infiltrates through the subgrade soil and can function as a conventional pavement to carry specific traffic load and speed. Hence, open graded friction course (OGFC) that is an overlay of open graded pavement installed over conventional pavements is not discussed in this paper. Depending on surface pavement, permeable pavements are generally grouped as porous asphalt (PA), pervious concrete (PC) and permeable interlocking concrete pavers (PICP). For permeable pavement to function well, regardless of the type of surface pavement, it is required to satisfy both the structural and hydrologic requirements. If designed and constructed well, then permeable pavement also can act as a best management practice and often viewed as an alternative low impact development option for urban areas.

Currently, the majority of the successful permeable pavement installations are related to parking lots and other commercial areas with low speed and light traffic load. During the past two decades tremendous progress has been made with regards to the application of permeable pavements with issues related to structural design, hydrologic design, water quality, and surface clogging. However, several important research questions remain unresolved and must be addressed before permeable pavements are fully integrated and implemented in urban roads; especially in highways with higher speeds and loads.

This paper focuses on successful application of permeable pavement design and performance with special emphasis on stormwater management, water quality benefits, and identification of knowledge and data gaps. The paper provides a summary of the current practice and design methods, discusses the potential application of permeable pavement for highway environment, summarizes the research progress documented in the literature related to mixed design, hydrologic performance, maintenance, water quality benefits, identifies knowledge gaps and unresolved issues, and explores the future direction in permeable pavement application.

The content of this report revealed that there have been many successful permeable pavement installations in the United States though mostly in parking lots and other commercial areas with low speed and light traffic load. However, only a handful of demonstration projects and simulations studies that evaluate the use of permeable pavement in highway environments and urban roads, which have higher vehicle speeds and heavier loads. One notable field study in this area was completed by Minnesota Department of Transportation. Results from this study showed a positive picture for permeable pavements based on overall structural and hydrologic (i.e., infiltration and water quality) performance. The University of California Pavement

Research Center and National Cooperative Highway Research Program have also completed simulation and feasibility studies on the performance of permeable pavements under highway conditions. Both studies produced promising results. While tremendous amount of progress has been made with this relatively new pavement technology, knowledge gaps remain in design, performance and maintenance evaluation.

1. Introduction

1.1. Background

Depending on the type of surface pavement, permeable pavement can be referred to as: porous asphalt, pervious concrete, or interlocking concrete pavers. Permeable pavement has several permeable layers and has the ability to store stormwater until it infiltrates through the subgrade soil or is collected by an underdrain. Because permeable pavements have the ability to reduce runoff volume, they are usually used as a low impact development (LID) design for stormwater best management practice (BMP). For permeable pavement to function effectively, there are many components that must perform and work well. These components include the physical and structural stability of surface pavement, the ability to handle traffic speed and loads, the ability to store stormwater within the aggregate beneath the pavement surface, the ability of the subgrade soil to infiltrate water, and the absence of clogging to ensure water infiltration and continuous functionality.

Design and construction of permeable pavement, regardless of the type of surface pavement, requires structural and hydrologic analysis with both requirements being satisfied in order for the pavement to function properly. Generally, the structural design of the pavement is performed to determine the thickness of the aggregate depths that are necessary to support the design traffic loads while protecting the subgrade from permanent deformation. The hydrological design determines the depth required to store a design volume of infiltrated water in order to achieve stormwater management objectives. An optimal permeable pavement design is one that is just strong enough to handle design traffic load and speed while maintaining the necessary porosity to provide sufficient porosity and stormwater management.

1.2. Expected Benefits and Potential Trade Offs

Numerous benefits are expected from the application of full depth permeable pavements installed in urban parking lots, commercial and residential driveways. These benefits usually include but are not limited to: noise reduction, stormwater runoff volume management, an increase in water quality, and improvement in thermal performance and urban heat island impact as summarized in Table 1. There might be several potential trade-offs with the application of permeable pavements compared to conventional pavement installations. These potential trade-offs include but are not limited to: extra cost, moisture damage, and ground water contamination as summarized in Table 2.

1.3. Objectives of the summary report

During the past two decades tremendous progress has been made with regards to the application of permeable pavements in parking lots and other commercial areas with low speed and light traffic load. However, there are still numerous unresolved issues related to structural design, hydrologic design, water quality, and surface clogging that must be addressed before permeable pavements are fully integrated and implemented in urban roads and highways with higher speeds and loads.

Table 1. Major Benefits Associated with the Application of Permeable Pavements

Major benefit	*Description*
Reduce noise	Noise pollution has become an increasing concern in urban areas (WHO 2013). Noise generated from vehicles operating on the pavement arises from different sources and one of them is related to tire passes over the pavement (tire/pavement noise). Tire/pavement noise depends heavily on pavement surface characteristics and pavement macrotexture (McDaniel and Thorton 2005; Sandberg 2001). Asphalt pavement with open-graded friction courses that have good raveling resistance (such as the rubberized open-graded asphalt concrete) have been determined to be a good candidate for noise reduction (Donavan 2006). The open-graded asphalt surfaces will sustain noise reducing properties as long as their surface air permeability is maintained (Reyes and Harvey 2011; Ongel et al. 2008).
Manage stormwater runoff volume	Conventional impermeable pavement surfaces cause precipitation to run off much faster than it does from vegetated or undeveloped surfaces. The runoff from impermeable surfaces is often directed to stormwater collection systems and thus is not absorbed into the nearby soil. In addition, the collection of runoff in this manner during high precipitation events can cause the stormwater collection system to overflow resulting in flooding and erosion due to high flow velocities. In contrast, permeable pavements allow a significant portion of the stormwater runoff volume to pass through the surface and be absorbed into the underlying ground and hence minimize or eliminate the need for stormwater collection and treatment systems. For these reasons, the United States Environmental Protection Agency (USEPA) (2010) cites the use of pervious concrete and porous asphalt pavements as a BMP for the management of stormwater runoff on a local and regional basis.
Improve water quality	Full depth permeable pavement generally provides water quality and related benefits in several ways that include, but are not limited to (1) a reduction in the temperature increase and pollutants discharged into nearby surface water and streams, (2) reduction of pollutant mass loads through runoff infiltration into the subgrade soil, and (3) recharge of groundwater table, particularly in arid areas. In addition, there are also reported water quality benefits from the use of open graded friction course (OGFC) pavements (Barrett et al., 2006; Bean et al., 2004; Roseen et al., 2012).
Improve thermal performance and reduce urban heat island impact	A heat island is a local area of elevated temperature located in a region and is often referred to as an urban heat island (UHI) because it most often occurs in urban areas (USEPA 2008). It is estimated that paved surfaces for travel and parking can account for 29 to 39 percent of the land surface area in urban areas, and as a result it has been theorized that solar reflectance of paving materials can contribute to the development of urban heat islands (Akbari et al., 1999; Rose et al., 2003; Millstein 2013). Permeable pavement generally is a lower contributor to the UHI effect in built environments located in regions that experience hot weather and are large enough to generate a heat island. In addition, permeable pavements can generally mitigate stormwater heating in biologically sensitive areas. Conventional pavements tend to be hotter and also have the potential to make the stormwater warmer during summer rainfall events. The warmer stormwater runoff may impact the biological communities in the receiving waters if their thermal regimes are altered. This would be a particular issue in locations that receive significant rainfall during hot seasons and where heated stormwater is not cooled before entering the biologically sensitive area. It should not be an issue in climate regions that have little or no summer rainfall.

As part of this ongoing effort and to increase our knowledge for broader implication of permeable pavement, the senior author of this summary report in collaboration with researchers from Valparaiso University and the University of Minnesota prepared a state of the art literature review for the Minnesota Department of Transportation (MnDOT) (Weiss et al., 2015). This summary report, in part, was prepared based on the MnDOT literature review report. The focus of this summary report is to assess the application of permeable pavement with an emphasis on successful mix design, water quality benefits, and identification of knowledge and data gaps for sustainable transportation. The summary report is organized into five sections: (1) introduction, (2) current practice and design methods, (3) potential application for highway land uses, (4) research progress documented in the literature, and (5) knowledge gaps, unresolved issues, and future directions.

Table 2. Potential Trade-offs Associated with the Application of Permeable Pavements

Potential tradeoffs	***Description***
Extra cost	The cost trade-off is generally related to the underlying aggregate water storage bed, which causes the pavements to be more expensive than conventional pavement construction. Another extra cost is the maintenance of the permeable surface, consisting of regular vacuum sweeping for removal of dust and other particles to prevent clogging, which is more expensive than conventional pavements (Levine 2011). Both of the above extra costs may be justified for certain permeable pavement application in urban areas. For example, typical stormwater management solutions usually rely on best management practices such as retention ponds that are difficult and very costly to accommodate in built-up urban areas. In addition, there will be a significant economic benefit for diverting any treatment and clean-up cost associated with portion of stormwater collection system commingled with the sanitary sewage, particularly when the system is overwhelmed during high precipitation events.
Moisture damage	Moisture damage in permeable asphalt concrete (AC) pavements is a complex phenomenon usually associated with (Hicks, 1991): (1) loss of adhesion and (2) loss of cohesion. The loss of adhesion is due to water getting between the asphalt and aggregate and stripping away the asphalt film. The loss of cohesion is due to softening of asphalt content in the presence of water, which weakens the bond between the asphalt and concrete aggregate. Moisture damage can be affected by a variety of contributing factors, including air-void content, pavement structure, cumulative rainfall, mix type, use of anti-strip additive (lime or liquid), and pavement age (Hicks, 1991). The moisture damage can be reduced by using less than optimum binder contents and by the addition of anti-strip additive (lime or liquid) treatment (Lu and Harvey, 2008) or using the high viscosity bitumen (Liu and Cao, 2009).
Groundwater contamination	In general, the natural filtering that occurs in the soil removes a majority of particle-bound inorganic and organic contaminates. There may be an increased risk of ground water contamination from regulated dissolved pollutants. A few researchers made conclusions on groundwater impact based on their results obtained from infiltrated water sampling and analysis (Van Seters, 2007; Boving et al., 2008). Presently, there is no experimental monitoring data available to verify long-term risk of groundwater contamination. However, the USEPA has been conducting long-term monitoring of porous asphalt, pervious concrete, and permeable concrete pavers (PICP) at a 100-car employee parking lot at its National Risk Assessment Laboratories in Edison, New Jersey (Rowe et al. 2010). When published, the results of this study could provide some insight into the fate of pollutants in soils and groundwater

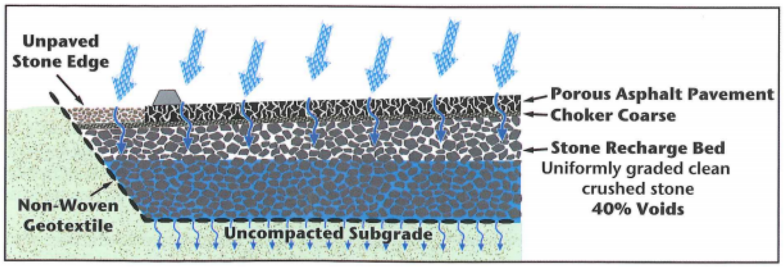
2. Current Practice and Design Methods

2.1 Typical Mix Design and Cross Section Layers

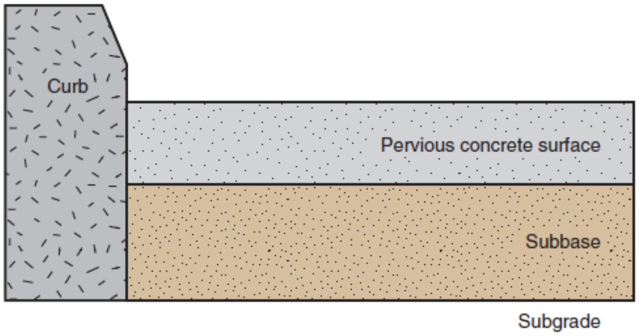
Generally speaking, no specific standard mix design and aggregate gradation is used among permeable pavement systems. Each industry has tried to compile available existing mix design information regarding the design and construction of a specific pavement. A typical cross section design with appropriate aggregate mix design suggested by the three leading permeable pavement industries is shown in Figure 1. As shown, generally a cross-section consists of the surface permeable pavement (asphalt, concrete or interlocking pavers) on top, a choker coarse, a stone subbase recharge bed, and uncompacted subgrade. A non-woven geotextile fabric can also be used to separate the reservoir bed with subgrade soil.

A typical cross section layer of porous asphalt is shown in Figure 1a. The thickness of surface permeable asphalt may vary depending on the application. For instance, the National Asphalt Pavement Association (NAPA) (2008) recommended minimum thickness of 2.5, 4, and 6 inch compacted porous asphalt surface when used for a parking lot (little or no trucks), residential traffic (some trucks), and heavy traffic (heavy trucks), respectively.

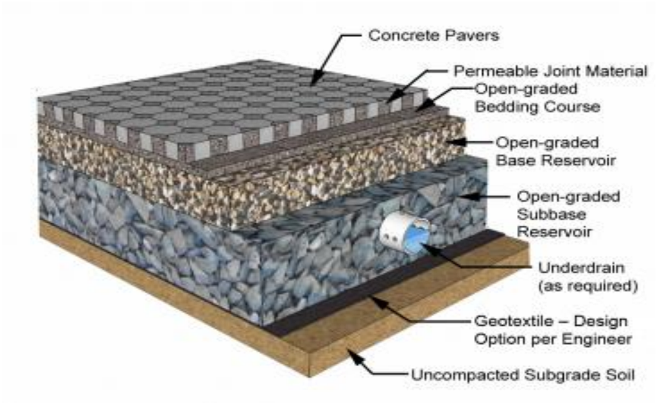
The aggregate used for the porous asphalt recharge bed should be clean, crushed stone with little to no fines and a minimum void ratio of 40%. For the recharge bed, typically, American Association of State and Highway Transportation Officials (AASHTO) No. 3 stone is specified but AASHTO No. 1 or 2 stones have also been used. When AASHTO No. 3 is used it has been found that AASHTO No. 57 works well for the choker course. To prevent fines from entering the subbase, geotextile filter fabric is typically placed between the subgrade layer and underlying soil. Finally, the subgrade is uncompacted to allow for infiltration. The gradation of choker and reservoir course based on AASHTO No. 3 and AASHTO No. 57 along with recommended gradation by the University of New Hampshire Stormwater Center (2009) for reservoir course based on AASHTO No. 5 is shown in Table 3.



(a) Porous asphalt pavement (NAPA, 2008)



(b) Pervious concrete pavement (ACPA 2009)
(Concrete surface layer, 15-25% voids; subbase layer, is 20-40% voids; and subgrade layer 5-20% voids)



(c) Permeable interlocking concrete paver system (Smith, 2011)

Figure 1. Typical Cross Section Layers Proposed by Different Permeable Pavement Industries

Table 3. Recommended Aggregate Gradations (UNHSC 2009)

U.S. Standard Sieve Size Inches (mm)	Percent Passing		
	Chocker Course AASHTO No. 57	Reservoir Course AASHTO No. 3	Reservoir Course (alternative) AASHTO No. 5[a]
6 (150)	--		--
2½ (63)	--	100	--
2 (50)	--	90-100	--
1½ (37.5)	100	35-70	100
1 (25)	95-100	0-15	90-100
¾ (19)	--	--	2-55
½ (12.5)	25-60	0-5	0-10
3/8 (9.5)	--	--	0-5
#4 (4.75)	0-10	--	--
#8 (2.36)	0-5	--	--
#200 (0.075)	--	--	--
%Compaction	95	95	95

[a] Alternative gradation (e.g. AASHTO No. 5) may be accepted upon Engineer's approval

The asphalt mix may consist of polymer-modified asphalt and sometimes includes fibers to reduce draindown and help to improve resistance to scuffing at high temperatures. The term "draindown" refers to the phenomenon in which pavement infiltration capacity reduces over time. In addition, a study conducted by the University of New Hampshire Stormwater Center (UNHSC 2009) recommended that below the porous asphalt layer there should be a 4 to 8 inch choker layer (8 inch is preferred), an 8 to 12 inch filter course layer of poorly graded sand, a 3 inch (minimum thickness) filter blanket (i.e. pea gravel), and a reservoir of course, crushed stone. The optional bottom layer is recommended only for aquifer protection or to eliminate infiltration.

A typical cross-section of pervious concrete is shown in Figure 1b. As shown, the subbase is a stone reservoir that can store a finite volume of water and drain tiles (not shown) can be added below the pavement to convey water downstream in the stormwater management system. The American Concrete Institute (ACI) states that aggregate is typically single sized or course aggregate between 3/8 inch and 3/4 inch and all aggregates should meet ASTM D448 and C33/C33M (ACI 2010). Rounded and crushed aggregate, both normal and lightweight have been used but flaky or elongated aggregate should not be used. Aggregates should also be hard, clean, and have no coating. Portland cement conforming to ASTM C150/C150M, C595/C595M, or C1157/C1157M should be used as the main binder with supplementary materials such as fly ash, blast-furnace slag, and silica fume. Kevern et al. (2008) recommended that fly ash use be restricted to 10% and silica fume to 5% replacement. Water-to-cement ratios should be low and typically range from 0.26 to 0.40; specifically targeted 0.32 to improve workability and density Kevern et al. (2008). Finally, water-reducing, retarding, accelerators, and air-entraining admixtures can be used but should meet all relevant requirements and ASTM standards. Typical mix proportions for pervious concrete are 450 to 700 lb/yd^3 of cementitious materials, 2000 to 2500 lb/yd^3 of aggregate, at water to cement ratio of 0.27 to 0.34, aggregate to cement ratio of 4 to 4.5:1, and a fine to coarse aggregate ratio of zero to 1:1 (Tennis et al. 2004). ACI (2010) suggested repeated trial-and-error efforts that involve developing different mix proportions under laboratory settings and testing them in the field until the desired behavior is achieved. Overall, the goal would be to obtain a balance between voids, strength, paste content, and workability.

Permeable interlocking concrete pavers (PICP) have joints or openings that are filled with permeable material that allows water to infiltrate across the pavement surface. The joints and/or openings typically cover about 5% to 15% of the total pavement surface area. A typical cross-section of a PICP system is shown in Figure 1c. As shown, the PICP layers, from top to bottom, consist of the concrete pavers, open-graded bedding course, open-graded base reservoir, open-graded subbase reservoir (with underdrain, if necessary), geotextile fabric (optional), and the subgrade soil. The open-graded bedding course is usually 2 inches thick, consists of small size aggregate (usually ASTM No. 8 or smaller) that allows infiltration, and provides a level bed for the pavers. The open-graded base reservoir is usually 4 inches thick and consists of crushed stones from 0.5 to 1.0 inch in size. The open-graded subbase reservoir usually consists of stones from 2 to 3 inches in size and the thickness of this layer depends on water storage requirements and traffic loads. If the native soils underlying the PICP system do not provide adequate infiltration, the open-graded subbase reservoir may include a perforated underdrain (as shown) to convey water out of the system. Finally, a geotextile fabric may be placed between the open-graded subbase layer and the uncompacted subgrade soil. The purpose of the geotextile layer is to separate the sub-base reservoir from the natural soil and to prevent fines from migrating into the layers above.

2.2. Structural Design Methods

Several methods are currently used to perform the structural analysis of permeable pavements as summarized in Table 4. The analysis methods are based on the conventional pavements that may require some modifications and field validation as will be discussed in subsequent sections under current research progress and knowledge gaps.

Table 4. Summary of Structural Design Methods Used for Porous Asphalt, Pervious Concrete, and Permeable Interlocking Concrete Pavers

Pavement type	Structural design method
Porous asphalt	Porous pavement is structurally designed based on The American Association of State Highway and Transportation Officials (AASHTO) structural design guidelines for flexible pavements (AASHTO 1993).
Pervious concrete	The American Concrete Pavement Association (ACPA) has adopted a structural design methodology and incorporated it into software called PerviousPave. This software determines the minimum required thickness of the pervious concrete layer and the required thickness of the subbase/reservoir layer. PerviousPave uses the enhanced concrete fatigue model that was developed for StreetPave (a software package for the structural design of conventional concrete pavements). ACPA details the design process, which assumes fatigue is the sole failure criteria for structural design. This approach was also suggested by a publication at the 2007 Annual Meeting of the Transportation Research Board and a 2008 publication in the Journal of Green Building.
Interlocking concrete pavers	The Interlocking Concrete Pavement Institute (ICPI) prepared structural and hydrologic design software called Permeable Design Pro. The structural inputs and calculations rely on the AASHTO structural design guidelines for flexible pavements (AASHTO 1993, Smith 2011). Recently, the University of California Pavement Research Center (UCPRC) has conducted a pilot-scale load testing for ICPI on a test track with three cross-sections of (unstabilized) subbase aggregates. The test track was on a very weak clay subgrade and loading was generated with a heavy vehicle simulator (HVS) under repetitive passes using dual wheel path tires at 25 kN, 40 kN, and higher loads. A mechanistic design model as well as design charts were summarized in final report (Li et al., 2014).

2.3. Hydrological Design Methods

Hydrologic design is an integral and important aspect of any permeable pavement design and must be performed in order to determine an adequate aggregate depth that is large enough to provide the necessary storage capacity for the design runoff volume. Hydrologic design is typically based on the storage volume provided to temporarily store stormwater runoff. The storage capacity of the entire permeable pavement system includes the capacity within the permeable pavement layer, the capacity within the base course and, in some circumstances, it may also include above ground storage due to curbs and/or underground storage tanks. In general, the hydrologic design process determines the required thickness of the permeable reservoir layers within the permeable pavement system so that the pavement structure will have the capacity to temporarily store runoff from the design runoff event. Once obtained, the thickness is compared to the thickness obtained from the structural design and the more conservative value (i.e. thicker permeable reservoir) is selected. Additionally, the pavement reservoir layer should also be designed so that it can infiltrate the design runoff volume within the desired time.

At present, there is not a standard hydrologic design being used by permeable pavement industries. Rather, different hydrologic design methods have been suggested or proposed as summarized in Table 5. It is important to note that the subgrade reservoir capacity is heavily impacted by the infiltration capacity of on-site native soils. Although a higher infiltration rate is desirable, the minimum infiltration rates of 0.5, 0.1, and 0.5 in. /hr are suggested by ACPA (2009), NAPA (2008), and ICPI (Smith 2011), respectively. Also, depending on the infiltration capacity of the native soil, permeable pavement systems may contain underdrains located in the aggregate reservoir layer to collect and convey infiltrated water out of the permeable pavement structure. In addition, when calculating total runoff volume for hydrological design capacity, different methodologies have been employed that are briefly described below.

Curve number (CN): Leming et al. (2007) suggested using the National Resources Conservation Service (NRCS) (1986) rainfall distribution and CN method to calculate the reduced runoff volume from pervious concrete pavements. NAPA (2008) also recommended CN method for porous pavement design. With regards to the CN method, hydrologic soil groups (HSG) A and B are listed as best suited for permeable pavements, but it is also stated that soil groups C and D can be used with special care (e.g. drain tiles, etc.). In a non-industry publication, Schwartz (2010) used CN and presented pervious concrete design criteria for freeze-thaw protection and water drawdown.

Rational method: The rational method (RM) is generally not recommended for determining runoff volumes when designing permeable pavements (NAPA 2008). However, Leming et al. (2007) stated that the RM may provide accurate results when used for estimating the peak runoff flow rates onto simple pervious concrete systems, but may not be acceptable for a complex pervious pavement systems design and analysis since some of the advantages of hydrological features of using pervious concrete will not be captured. When using the RM, the duration of the design storm is recommended to be equal to the time of concentration (TC).

ICPI method: The runoff volume for a permeable interlocking concrete pavement (PICP) system is calculated based on the surface area of PICPs that is considered 100% pervious because, when functioning properly, all water that lands on the surface will infiltrate (Smith 2011). Under this method the maximum allowable storage time is assumed to ensure that the subgrade will not be saturated for too long. For example, the effective fill time for NRCS Type II storms is generally assumed to be 2 hours. With this time limit and the value of final infiltration rate into the soil, the maximum allowable base/subbase depth is estimated. If the depth of pavement required exceeds the maximum depth of pavement allowed, then the design process is modified to estimate the number of underdrains.

Table 5. Summary of Hydrological Design Methods Used for Porous Asphalt, Pervious Concrete, and Interlocking Concrete Pavers

Pavement industry	Hydrologic design method
Porous asphalt	No specific hydrologic design method is specified by NAPA (2008) when calculating the reservoir capacity; NAPA only suggests general items that must be considered.
Pervious concrete	The American Concrete Paving Association (ACPA 2009) has made available a computer program, PerviousPave, which incorporates a hydrologic design process based on the Los Angeles County Method (LADPW 2002). The required concrete thickness (as determined by the structural design) is maintained during the hydrologic design and the subbase thickness is adjusted until the entire system can store the design storm water volume. The user can choose whether the entire design volume will be stored in the voids of the subbase layer or if the void spaces of the pervious concrete layer and storage volume available above the pervious concrete up to the curb height will be used for storage. Given the infiltration rate into the soil, the program also checks to make sure the system can infiltrate the design volume in the desired time.
Interlocking concrete pavers	The ICPI developed an event-based hydrologic model from a non-proprietary FHWA model called Drainage Requirements in Pavements or DRIP (Mallela et al. 2002). The software includes pipe designs for detention/outflow in low infiltration soils and enables calculation of runoff volumes contributed from adjacent surfaces. The program includes a library of rainfall data for the U.S. and Canada, and an option for user input of various rainfall frequencies.

Computer modeling method: Various computer models are being used for hydrologic design and they are operated based on two methods: (1) event-based hydrograph estimation, or (2) continuous simulation modeling programs. Examples of computer modeling methods include the Watershed Hydrology Program (WinTR-20), Small Watershed Hydrology (Win TR-55), Santa Barbara Unit Hydrograph (SBUH), HEC-1 Flood Hydrograph Package, HydroCAD Stormwater Modelling (HydroCAD), and HYDRUS that was used in a simulation study performed by the researchers at the University of California (Chai et al. 2012, Li et al. 2012).

2.4. Maintenance Practice Methods

Regular maintenance actions for permeable pavements are recommended by all industries to decrease surface clogging and thereby ensure continuous surface infiltration. However, there is no standard maintenance or cleaning methods currently available. Typical cleaning methods used include pressure washing and vacuuming. Mechanical sweeping is generally not recommended because the particles will be crushed and pushed farther into the pavement. No specific frequency of cleaning is suggested, although at least once per year is recommended. A higher cleaning frequency may be needed depending on site and weather conditions. In addition, to avoid potential clogging, the application of sand is typically not recommended.

3. Potential Application for Highway Land Uses

As indicated previously, nearly all installations of permeable pavements are currently related to low traffic and slow speed application. As the application of permeable pavements continues to increase, there is a more desire to use them in highway environment with higher traffic speeds and higher loads. The information available in this type of application is very limited. Several studies attempt to explore the use of porous asphalt and pervious concrete in highway land use that is discussed in this section of the paper.

3.1 MnROAD Permeable Pavement Test Cells Demonstration Project

3.1.1. Description of Test Cells

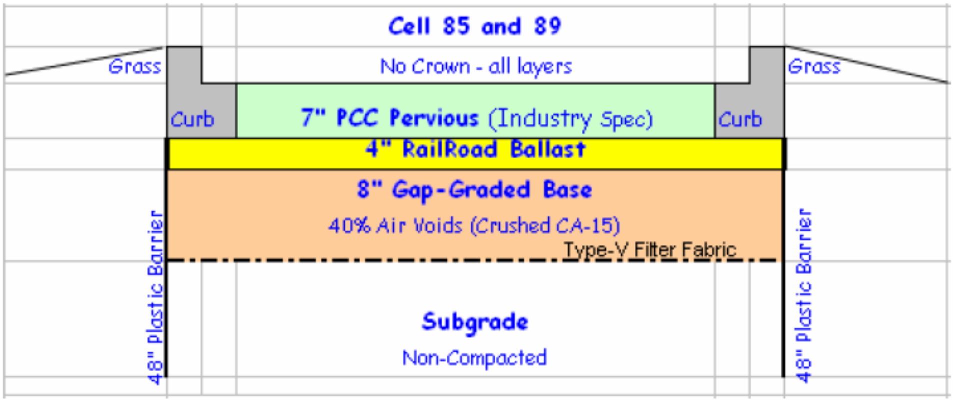
Porous asphalt and pervious concrete pavement test cells were constructed, based on the industry standards, at the Minnesota Department of Transportation MnROAD research facility. The test cells were part of a 2.5 mile, 2 lane low volume closed loop road segment (see Figure 2). To simulate high load and low volume traffic, one 18 wheel, 5 axle truck with trailer was driven on the inside lane for 80 laps every day during the course of the study. The outer lane was not subject to significant traffic loading. This allowed to determining the performance differences between the inner and outer lanes attributed to the impact of environmental and traffic loading effects (inner lane) versus the impact of only the environment (outer lane).

Figure 2. MnROAD Test Facility and Cell Location Cell 85 = pervious concrete on sand, cell 86 = porous asphalt on sand, cell 87 = pervious controls, cell 88 = porous asphalt on clay, cell 89 = pervious concrete on clay, cell 39 = pervious concrete overlay. (Izevbekhai and Akkari 2011).

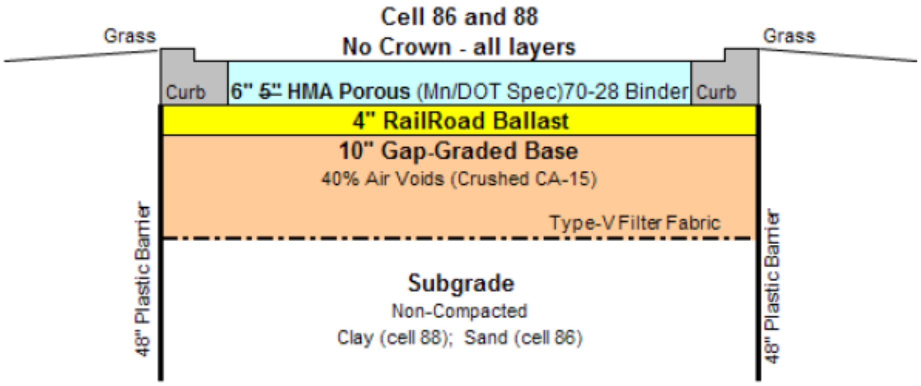
Cells 85 and 89 were seven inch thick, full-depth pervious concrete constructed to industry standards. A cross-section of the pervious concrete pavement test cells is shown in Figure 2a. Beneath the pervious concrete pavement cell consist of, from top to bottom, 4 inches of railroad ballast, 8 inches of gap-graded aggregate, and a geotextile fabric (Type V) on top of the underlying soil. The subgrade layers for both cells 85 and 89 were identical, except for the cell 85 was constructed on natural granular soil and cell 89 was constructed on clayey soil.
A major objective was to evaluate the structural and physical performance of both pervious concrete (PC) and porous asphalt (PA) test cells. Tests were conducted on the PC cells to

evaluate international roughness index (IRI), surface rating, surface texture, friction number, noise, dissipated volumetric rate, clogging characteristics, pavement surface deflection, temperature and moisture. Additional tests, although with less emphasis, were performed to evaluate the surface permeability through water displacement rate.

Two PA test cells (cells 86 and 88) and one conventional, dense-graded asphalt test cell (cell 87) were also constructed and monitored at the MnROAD test facility. A schematic of the cross-section of porous asphalt test cells is shown in Figure 2b. As shown, the PA cross-sections from top to bottom consisted of 6 inches of porous hot mix asphalt, 4 inches of railroad ballast, 10 inches of gap-graded base, a Type-5 filter fabric, and natural sand or clay soil. The two PA test cells were identical except that one was constructed on top of sand (cell 86) and one on top of clay (cell 88). Test loading began in December 2008 and testing and data collection continued until December 2011.



(a) Pervious concrete (Izevbekhai and Akkari, 2011)



(b) Porous asphalt (Lebens and Troyer, 2012)

Figure 3. Cross-section of MnROAD Pervious Concrete and Porous Asphalt Test Cells

The porous asphalt test sections were constructed according to MnDOT (modified) Specification 2360-Porous Asphalt, which is based on the modified National Center for Asphalt Technology (NCAT 2000) Method. The detailed modified specifications for the construction of PA test cells at MnROAD can be obtained in Lebens and Troyer (2012) report.

The testing categories used for evaluating the performance of PC were also applied to the PA test cells. In addition, due to concern about the impact of permeable pavements that may have on groundwater quality, groundwater samples associated with the porous asphalt test cells were analyzed. Results were compared with existing water quality standards in the State of Minnesota. The comparative water quality and the long-term impact on groundwater are planned for further investigation.

3.1.2. Hydrologic Performance

The hydrologic performance of pervious concrete was measured based on the dissipated volumetric rate (DVR), which is similar to the infiltration rate. Values of dissipated volumetric rate were obtained for several locations on each test cell. The values were obtained by using a 90 cm long, about 15 cm diameter cylinder placed vertically and sealed (with a duct seal compound) to the pavement. To conduct the test the cylinder was filled with water and allowed to drain until steady flow developed. Once steady flow was established, the time it took for water to drain from an elevation of 37 cm to 11 cm was recorded and used in equation [1] to determine the dissipated volumetric rate. It should be noted that the dissipated volumetric rate is not a measure of permeability (expressed as unit depth per time (e.g., cm/s)) but rather it is an indicator of pavement infiltration capacity.

$$Dissipated\ Volumetric\ Rate = \frac{(Initial\ Head - Final\ Head) * Cross-sectional\ area}{measured\ flow\ time} \qquad [1]$$

Values of DVR varied greatly from location to location, even on the same test cell. Thus, average values were computed for each cell. The lowest measured flow rate, however, corresponded to an infiltration rate of 0.6 in/sec, a value that would be more than adequate to handle a large rainfall event. In general, the average infiltration flow rate at any test location was generally decreased over time. As may be expected, the average DVR values on test cells constructed over sand were always greater than the average DVR for test cells constructed over clay.

In addition, the quality of water samples taken beneath the porous asphalt pavement test cells were compared to standards for Class 2 waters in Minnesota, which are classified as waters for fishing and swimming. Baseline groundwater sampling for the tested constituents revealed that background concentrations were within the acceptable range of water quality standards and in pavement runoff were typically lower than those in the groundwater. Groundwater samples taken from two test wells below cell 86, however, had higher turbidity, copper, and lead than the baseline water samples. Overall, however, the porous asphalt cells appear to have lower concentrations of copper and zinc. Also, although chloride concentrations were far below the water quality standard, the chloride concentration continually increased over time until 2011 (when no salt was applied during the winter). Since similar water quality monitoring data were not obtained for pervious concrete cells, no comparative water quality performance could be performed.

3.1.3. Structural and Materials Property Performance

Parameters measured to assess the structural and physical performance of pervious concrete cells include: international roughness index (IRI), surface roughness (SR), density, deflection, and temperature. The average IRI in Minnesota is 1.4m/km on interstates and 1.7 m/km on non-interstates. According to FHWA, an IRI less than 1.5 is considered "good condition" and an IRI of less than 2.6 is considered to be "acceptable." The IRI values measured on the pervious concrete test cells were mostly between 3 and 5 with a maximum value of 6.5. These values were above the FHWA limit for an "acceptable" pavement. It was noted that there was no distinct variation in IRI with season but IRI was lowest in the first two tests for all cells. This suggests that raveling and weathering made the pavement rougher over time.

A SR rating of four is considered to be a pavement in perfect condition and a value of less than two is considered to be a pavement in poor condition that is in need of repair. In Minnesota, the average SR value for concrete pavements is 3.3. All SR values measured on the pervious concrete cells were above 3.5. This indicates that the pervious concrete cells have a better than average ride quality. The SR for all cells decreased in September of 2009, suggesting again that raveling and weathering had detrimentally impacted the pavements.

Density measurements on both lanes of both cells (85 and 89) revealed that the lanes have similar densities and, even at a confidence interval of 75%, the densities of the inside and outside lanes cannot be said to be statistically different. Due to the fact that the inside lane is subject to daily truck traffic and the outside lane is not, results indicate that traffic loading does not affect the density of full-depth pervious concrete.

With regards to the falling weight deflectometer (FWD) measurements, the pervious concrete cells experienced more deflection than conventional concrete. In cell 85 the outside lane had higher deflections than the inside lane but in cell 89 the opposite was true. This suggests that deflection is not necessarily dependent on traffic loading. Also, surface deflection was highly variable between seasons, with the minimum deflections typically occurring in the fall and winter.

Temperature sensors within the pervious concrete cells revealed that the pervious concrete had more uniform temperature gradients throughout the pavement structure as compared to conventional concrete pavements. This may be beneficial because large temperature gradients can cause warping and stresses. Also, the data suggests that the pervious concrete cells experienced less freeze-thaw cycles than conventional concrete. Finally, moisture was found to freeze at greater depths in the pervious concrete cells.

The structural and materials property of porous asphalt test cells were also evaluated based on IRI, SR, skid resistance, density, deflection and temperature. Over the course of the study the IRI values for all three asphalt cells changed very little. The porous asphalt cells were consistently rougher than the standard dense-graded asphalt cell and cell 88 (clay) was always slightly rougher than cell 86 (sand). It was thought that roller marks put in the pavement of cell 88 during construction resulted in it being rougher than cell 86.

With regards to skid resistance, both porous asphalt cells had adequate friction numbers (FN) using both smooth and ribbed tires as both pavements had overall average FN's of approximately 50. The conventional dense-graded asphalt cell had FN values less than those of the PA pavements, with the smooth tire FNs being only 50 to 60% of corresponding PA values.

In early 2009, minor surface raveling was observed in patches on the loaded lane of the porous asphalt test cells. Pavement cores revealed that in areas of raveling the pavement was consistent in void content and density from top to bottom and there was no indication of pavement drawdown. Air voids were measured to be 23%, which was higher than the specified content. From observations it was noted that the rate of raveling slowed down after the first few hot days of summer in 2009 and this isolated patches of raveling could be due to localized, insufficient compaction during construction (Lebens and Troyer, 2012).

Rutting was observed on all three porous asphalt cells but the amount of rutting on the standard dense-graded pavement (<0.16 inch) was much less than the porous asphalt pavements (approximately 0.60 inches, on average, for both cells).

Transverse pavement profiles revealed that all three cells experience seasonal vertical distortion. Causes could be the heavy truck loads, movement of base material, and the influence of frost. In 2011, after approximately three years of loading, inspection revealed no longitudinal or transverse cracking. The unloaded lanes showed only minor raveling and scuffs from snow plow blades and the standard hot mix asphalt reference cell had no cracking, raveling, or signs distress.

Density is a strong indicator of void content and has been correlated to structural capacity and lifespan of asphalt pavements. Overall, the densities of the PA pavements were about 120 lb/ft^3 and the dense-graded, hot mix asphalt pavement had a density of about 142 lb/ft^3. Cells 86 and 88 had similar densities over the course of the study with the density of the outside lane of both cells increasing slightly over the testing period. The increase in density in all cases, however, was typically less than 5%. The density of outside lane of the dense-graded, hot mix asphalt cell also increased from about 138 lb/ft^3 to 145 lb/ft^3. Densities of the inside lane of the porous asphalt pavements increased initially but then either dropped or leveled off. In theory, the increase in density could partially be due to pavement consolidation from the heavy traffic loading.

The resilient moduli for the porous asphalt pavements indicated that these pavements were not as stiff as the dense-graded asphalt. The porous pavements, however, were stiff enough to support the heavy truck loading they experienced. This lack of stiffness may also be at least part of the reason for the lack of cracking observed in the porous asphalt pavements.

Temperature monitoring revealed that the porous asphalt internal temperatures rose above freezing several times over the winter months and, in the spring, also rose much faster than the dense-graded, conventional asphalt pavement. In the porous asphalt systems (both cell 86 and 88) the temperature 24 inches below the surface more closely followed the surface temperature as compared to the same measurement in the conventional hot-mix asphalt (HMA) cell. This is most likely due to the fact that porous asphalt pavements experience greater internal heating and provide more heat transfer between the pavement and the subsurface. Moisture sensors installed below the geotextile and in the subgrade below the asphalt test cells were not calibrated and, therefore, did not provide quantitative moisture data.

3.1.4. Clogging and Maintenance Performance

Both pervious concrete and porous asphalt pavements were vacuumed once a year with a Reliakor vacuum truck (with brushes not in use). Porous asphalt pavement was vacuumed three times. The first vacuuming occurred in 2009 when the pavement was approximately one year old and in good condition except for isolated patches of raveling. Inspection of the solids in the vacuum truck after first vacuuming revealed that a small amount of fine aggregate particles were removed from the porous asphalt cells but almost nothing was removed from the dense-graded, conventional asphalt.

The effect of vacuuming on porous asphalt pavements was quantified by comparing flow times of the infiltration tests just prior and after vacuuming. In 2009 after the first vacuuming session, flow times decreased by 30% and 23% in cells 86 and 88, respectively. In 2010, after the second vacuuming, the flow time in the outside lane of cell 88 increased by 15%. It was thought that this latter, unexpected result was due to the fact that the pavement was still relatively new and very clean and it was almost impossible to place the testing unit in the exact same location for both the post-vacuuming and pre-vacuuming tests. In 2011, after the third vacuuming, the flow times decreased and the infiltration capability improved in the loaded lanes. The mechanism related to the decrease or increase in infiltration rate was not understood nor was it explained in the Lebens and Troyer (2012) report, indicating that it may require further investigation.

The impact of vacuuming on pervious concrete on cells 85 and 89 was evaluated twice by measuring the flow time just before and after vacuuming. The first vacuuming was done in November 2009 when the pervious concrete cells were about 1 year old and in good condition. The second vacuuming on pervious concrete cells was done on November 2010. Interpretation of the data for the first and second cleaning do not indicate there is a clear beneficial impact on infiltration capability from vacuuming the surface. Thus, the data does not support the notion that vacuuming can restore infiltration capacity of a pervious concrete surface. Furthermore, the large variation in DVR values, even within one cell, suggests that the pavement mix was highly variable and with uneven consistency within a single cell. Based on these results, Izevbekhai and Akkari (2011) recommended vacuuming pervious concrete pavements twice per year.

Inspection of the pavement and the contents of the vacuum receptacle revealed that the most common clogging compound in the MnROAD test cells were particles from pavement raveling, which were in various stages of fragmentation. There may be additional reasons for this clogging effect. For instance, one common reason for clogging is found to be the transport of silt particles onto the pavement surface by vehicles (FWA et al., 2001). Another possible reason of reduction in void content due to compression is related to heavy traffic loading (Coleri et al., 2013). Both of these causes could be verified by comparing X-ray computed tomography (CT) images of core samples of paved surfaces subject to truck loading and no traffic loading.

3.1.5. Lessons learned from MnROAD Demonstration Project

As presented above, generally the monitoring results related to hydrological, structural and maintenance performance obtained from the MnROAD pervious concrete and porous asphalt test cells revealed a positive picture compared with conventional pavements. Nevertheless, inconclusive results were obtained in certain topics that may require further investigation. The lessons learned from the MnROAD pervious concrete and porous asphalt test cells demonstration project are summarized in Table 6. In addition to these summary results, preliminary sampling and analysis of the infiltrated water quality under porous asphalt pavement cells showed that: (1) full depth porous asphalt generally improved water quality, and (2) groundwater quality was not affected except that chloride concentrations in groundwater below the PA cells continually increased over time, but were below water quality standards for Minnesota Class 2 waters.

3.2. Adapting Permeable Pavement for Highway Shoulders

As presented previously, permeable pavements have been used in many parking lots, commercial and residential areas throughout the United States that receive light and low-speed traffic. Several guidance manuals and publications have been prepared to document their performance. For high-speed pavements, several departments of transportion (DOTs) have used a porous friction course (PFC, also called open graded friction course or OGFC) for noise reduction and increased safety during rain events. PFC is usually comprised of 15 to 25 mm thick hot-mix asphalt (open graded) (HMA-O) constructed as surface overlay over an existing impervious asphalt pavement. With the application of PFC, the surface water penetrates vertically within the open graded friction course (OGFC) and then laterally moves toward the shoulder with little or no volume reduction that needs to be collected or treated.

A more environmentally beneficial and sustainable approach is the use of full depth permeable pavement shoulder design illustrated in Figure 3. Under this proposed design, the entire or majority of runoff water from the highway or major road surface will be retained within the shoulder and there would not be a need for additional treatment. The use of permeable pavement shoulders in highly urbanized areas is especially beneficial since finding sufficient land area to implement infiltration and temporary detention basins is difficult.

Table 6. Summary of Lessons Learned from the MnROAD PC and PA Demonstration Project

Pervious concrete (PC)	Porous asphalt (PA)
IRI values on both pervious concrete test cells were significantly worse than FHWA standards but the cells had excellent surface ratings.	Despite the heavy truck loading, significant PA distress was limited to rutting in the loaded lane and shallow surface raveling
The dissipated volumetric rate varied significantly even within a given cell. This suggests uneven consistency within the pavements.	PG70-28 binder, was selected because it performed better than the NCAT 2000 specified PG63-34 binder in the Lottman (TSR) tests
The dissipated volumetric rate was generally higher in the cell over sand than the cell over clay.	The applied loads and clogging did not appear to cause a significant increase in pavement density.
PC cells had a reduced temperature gradient throughout the pavement, base, and subgrade and experienced less freeze-thaw.	Slight compaction of the base had no significant negative impact on performance.
Vacuuming of pervious concrete pavements more than twice per year was more effective than lighter maintenance schedules.	Pavement volumetric rate decreased with time (even with regular maintenance) but the infiltration was adequate to infiltrate large rainfall events.
Raveling may be caused by freeze-thaw cycling of clogged pavements. Maintaining/vacuuming the pavement can reduce raveling	No cracking or significant distress has been observed in any of the two porous asphalt cells or the reference cell of dense-graded HMA.
PC pavement can be effectively designed with traditional methods such as that in the AASHTO 1993 method or the Mechanistic Empirical design Guide (MEPDG) method	Raveling in the top one inch of pavement had progressed steadily but initial raveling appeared to be due to mixture temperature segregation and the rate of raveling slowed after summer.
Programs such as ISLAB can accurately analyze pervious concrete pavements	Construction requirements led to a higher (140 inch/mile) IRI on the PA cells.
Falling weight deflectometer (FWD) deflections were higher in pervious concrete (as compared to conventional concrete) but its effect on durability was not known.	Average rutting depth on the PA and dense-graded (0.60 and 0.16 inches, respectively) cells were affected by ~1 inch mid-lane settlement and in transverse profile elevation across the loaded lane.
	The RM of the dense-graded HMA pavement was higher than the PA cells. The stiffness of the PA pavements increased in the fall and decreased in the spring.
	The clay subgrade reduced PA stiffness, possibly due to slowing drainage
	Strain in the PA cell over clay were more than the PA cell over sand and the PA strain was up to 2 times higher than the conventional asphalt cell.
	The average PA skid resistance value was about 50 and smooth tire skid resistance was about 50% higher on PA than the conventional asphalt
	The benefits of vacuuming to restore permeability were inconclusive, but cleaning had positive impact on restoring infiltration capability.
	Snow and ice melted more quickly on PA pavements compared to conventional asphalt that required less salt application.

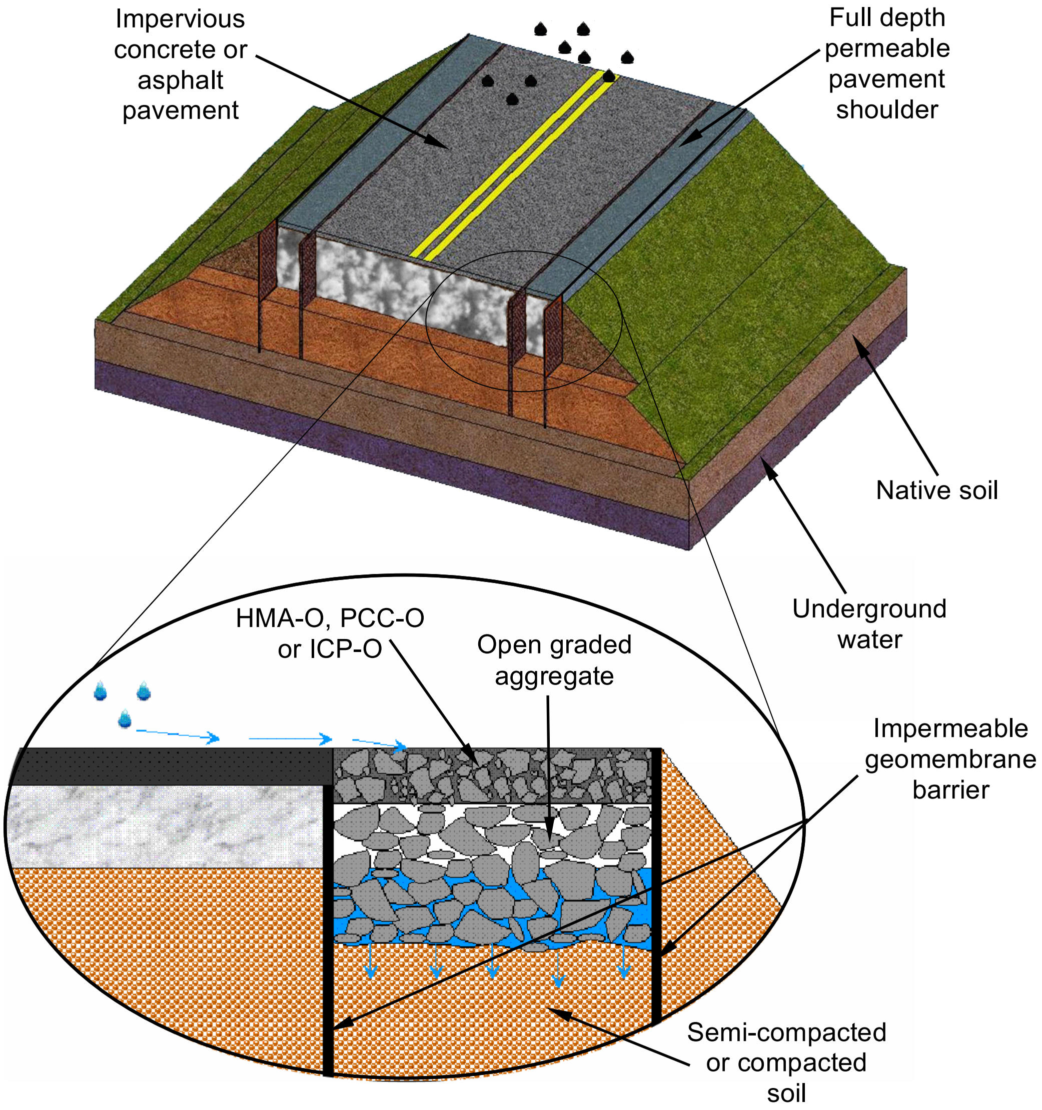


Figure 4. A Conceptual Full Depth Permeable Pavement Shoulder Design for Urban Roads and Highways Runoff Management

Even when space is available, collecting and treating large volumes of polluted runoff in urban areas is often cost prohibitive. A full depth permeable pavement shoulder retrofit in highway or urban roads is an alternative stormwater control measurement solution that can be cost-effective in many cases.

Other than one highway demonstration project previously mentioned, the use of full depth permeable pavement have not been adequately tested for heavy vehicle loads and moderate speed. At present, significant technical barriers exist in applying this effective stormwater measurement control method to heavily used urban roads and highways. To adapt full depth permeable pavement shoulder design, reliable information is needed on structural design and performance specification under traffic exceeding that from parking lots and residential roads.

Toward this goal, two known studies were recently performed in the United States that are described below.

3.2.1 University of California Pavement Research Center (UCPRC) Simulation Study

The UCPRC simulation study was performed for the Caltrans Division of Environmental Analysis. The focus of this study was to measure relevant parameters in the laboratory and use them as input for a computer simulation study to evaluate the structural and hydrologic performance of permeable pavements particularly under medium speed and heavy load (Jones et al. 2010, Li et al. 2012, Chai et al, 2010, Chai et al., 2012). For structural performance evaluation, the mechanistic-empirical (ME) approach was used rather than the R-value design method as assumptions in the latter are not appropriate for fully permeable pavements. Design input variables were subgrade permeability, truck traffic level (i.e. traffic index), climate/region, traffic speed (4 mph or 24 mph), design storm (2, 50, 100 year return period), and the number of adjacent impermeable lanes.

The focus of the hydraulic performance study was to determine the required aggregate depth of highway shoulders in order to provide adequate hydraulic capacity to capture the generated design rainfall volume. The hydraulic performance of permeable pavements was assessed using the commercially available *HYDRUS* software; that is based on unsaturated flow theory and solving Richards' equation. Rainstorms of 2, 50, and 100 year return periods were modeled and simulations were performed for three different climate regions (north with high rainfall, central with medium rainfall, and south with low rainfall) in California. The aggregate permeability was assumed to be constant at 10^{-1} cm/s and the subgrade permeability varied from constant values of 10^{-3} cm/s to 10^{-6} cm/s. Rainfall data, soil data, and other parameters were used to determine the required aggregate depth to capture the entire paved surface runoff volume.

Two recommended design layouts were proposed and, based on that, numerous structural and hydrological simulations were performed. Results from the computer modeling showed that:

- Mechanistic-empirical design equations were an effective way of determining the required thickness of fully permeable pavements so they are strong enough to carry heavy truck traffic.
- All required pavement structures were less than 5 feet in total thickness and most concrete slabs were less than 1.5 feet for the heaviest traffic.
- For most average storm designs an aggregate thickness of about 1 meter was sufficient to capture the entire runoff generated from average rainfall in California. The highest aggregate depth under high rainfall was found to be about 3 meter.
- Required aggregate thickness was influenced by climate, storm recurrence interval, subgrade soil saturated hydraulic conductivity, aggregate void ratio, number of traffic lanes, and boundary conditions. Higher rainfall amounts (and longer recurrence intervals) required larger aggregate thickness depths but the difference in required aggregate thickness for the 50 and 100 year storms was not significant.

- Native subgrade soil saturated hydraulic conductivity (soil permeability) was the factor that had the greatest impact on calculating the subgrade aggregate thickness. Highway surface area and number of traffic lanes also impacted the required aggregate thickness. Increasing traffic lanes from 2 to 4, increased the required aggregate thickness by 100%.

In addition, a Life-Cycle Cost Analysis (LCCA) was performed to evaluate the net present value (NPV) economic costs of full depth permeable pavement compared with the conventional stormwater management alternatives (Jones et al., 2010). When performing the LCCA it was assumed that the fully permeable pavements carried out the same function with regards to stormwater treatment (both runoff volume and water quality) as other alternative BMPs. The full depth permeable pavements shoulder retrofit was considered for a high and low speed highways. The LCCA determined the NPV of the basic elements and included the analysis period, discount rate, costs, and salvage value. Most of material and construction cost related to permeable pavement shoulder retrofits was obtained from local pavement construction companies. All costs were converted to the NPV and compared to other currently available stormwater management practices. The cost of permeable pavement shoulder retrofits was compared with the cost of conventional stormwater BMPs that were obtained from Caltrans pilot BMP retrofit study (Caltrans 2003). Results show that fully permeable pavements for the shoulder retrofits are cost-effective compared with the currently practiced BMPs in most scenarios.

Attempts were also made to perform a Life-Cycle Assessment (LCA) analysis. Performing the LCA analysis require elements of life-cycle inventory (e.g. energy consumption, greenhouse gas emissions, material flows, air and water pollutants, etc.), impact assessment (assessment of inventory results, e.g. climate change), and interpretation. Most of the required environmental evaluation data is not available and hence a true LCA could not be performed and need to be considered in future investigation.

3.2.2 The National Cooperative Highway Research Program (NCHRP) Project

The objective of the NCHRP project was to evaluate the suitability of using permeable pavement shoulder as an alternative method for the management of stormwater runoff volume compared to the traditional stormwater BMPs used in the United States (Hein et al. 2013a). The final NCHRP report evaluated the existing literature and, based on available information, identified some of the key design, construction, implementation and maintenance features of permeable pavement shoulder design. In addition, the NCHRP report also developed a decision matrix tool that could be used for proper selection of suitable sites for the construction of permeable pavement shoulder design.

The information presented in the NCHRP report concluded that permeable pavement shoulder application for highways is technically feasible. The report also suggested two conceptual construction design layers. None of the recommended design, construction and maintenance features were implemented in the field and, hence their potential use and performance were not validated.

4. Research Progress Documented in the Literature

Relatively speaking, compared with conventional pavements, the design and installation of permeable pavements is fairly new. Nevertheless, research performed and corresponding progress have significantly advanced permeable pavement technology during the past two decades. This section is devoted to research involving: (1) mix design, materials property and structural analysis, (2) hydrologic performance evaluation, (3) water quality evaluation, and (3) maintenance, and clogging evaluation. When reviewing the literature, additional emphasis was devoted to Section 5 of this paper, which identifies knowledge gaps and unresolved issues.

4.1. Mixed Design, Materials Property, and Structural Strength

Many researchers have investigated a wide range of issues related to mix design, materials property and structural strength of permeable pavements. The findings of these studies relevant to these topics are summarized below. For instance, a study by Partl et al. (2003) focused on aggregate used in porous asphalt and found that by optimizing the gap in aggregate, a void ratio greater than 25% and an infiltration rate of at least 7 cm/s can be obtained. Reports reviewed in NAPA (2008) indicated that untreated free-draining aggregate base properties are appropriate to use for porous asphalt stone recharge bed properties. NAPA (2008) acknowledged that it is not uncommon to recommend that the bottom of the recharge subbase be placed below the depth of winter frost penetration but that this practice has come into question recently due to successful installations that did not follow this practice. A University of New Hampshire publication recommended the recharge depth be placed 65% of the frost depth (UNHSC 2009).

Several researchers investigated issues related to curing and joint spacing of pervious concrete pavements. Curing should involve misting the surface of the pervious concrete and covering with plastic for at least seven days. Curing should be started no more than 20 minutes after compaction and/or jointing. For pavements in which the concrete had not cured properly, Offenberg (2005) stated there are no sufficient remedies other than discarding the concrete and replacing it. For joints to prevent random cracking, Tennis et al. (2004) recommended joints with one-fourth of the slab thickness and joint spacing of 20 feet or more. Joint installation with a rolling joint tool was recommended soon after construction. Saw cutting joints was not recommended because slurry from sawing can plug voids and raveling of cut joints can be a problem. If random cracking is acceptable, pervious concrete can have no joints as cracking will not affect the strength of the pavement. Although joints can be either cut or formed, Kevern et al. (2006) suggested formed joints (e.g. via a joint roller) as the preferred method. If desired, the Colorado Ready Mixed Concrete Association (2009) recommends the joints be constructed by rolling or forming. For rolled joints, a "pizza cutter" roller was recommended. Joint material must be 0.25 or 0.50 inch flexible foam joint material with a relative density of 1.7 or higher that meets listed American Standard and Testing Methods (ASTM) specifications. Although joints can be omitted if random cracking is preferred, Colorado Ready Mixed Concrete Association (CRMCA, (2009) specified that if joints are installed they should be at regular intervals spaced at 20 feet or less. Kevern et al. (2006) recommended shorter joint spacing of 15 feet. CRMCA (2009) recommended that pervious concrete should only be placed in cold regions between April 1 and November 1 and should not be placed if the temperature is expected to be 40°F or lower or 90°F or higher in the seven days following placement. Pervious concrete should also not be placed on frozen subgrade. During curing, the concrete should be covered with polyethylene sheeting with minimum thickness of 6 millimeters.

Some researchers paid special attention on the freeze-thaw durability when evaluating the overall performance of permeable pavements. In one study Schaefer et al. (2006) investigated various mix designs in order to develop a pervious concrete mix with sufficient infiltration capacity, strength, and freeze-thaw durability. Various concrete mixes with different sizes and types of aggregate, binder content, and admixtures were investigated and evaluated. Aggregates of river gravel and crushed limestone were also investigated. River gravel sizes were 0.5 inch, 0.375 inch, and no. 4 size (100% passing the 0.375 inch sieve and 100% retained on the no. 4 sieve). Crushed limestone (0.375 inch) and pea gravel were also included in the research. Schaefer et al. (2006) concluded the following:

- Mixes with only a single size aggregate have high permeability but insufficient strength.
- Addition of a small fraction of sand to the mix increased strength and freeze-thaw resistance but lowered permeability.
- Mixes with a small percentage of sand showed 2% mass loss after 300 freeze-thaw cycles.
- Low compaction reduced compressive strength, split strength, and unit weight but increased permeability.
- A binder to aggregate ratio of 0.21 and a water to cement ratio of 0.27 was determined to be the optimum in terms of strength, permeability, and void ratio.
- In terms of seven-day strength, the optimum latex content was determined to be 10%.
- Aggregate with higher abrasion resistance resulted in high strength concrete.
- The compressive strength and unit weight decreased linearly as the void ratio increased.
- Permeability increased exponentially as the void ratio increased greater than 25%.
- At regular compaction energy, mixes with void ratios between 15% and 19% had seven-day compressive strengths ranging from 3,300 to 2,900 psi, permeabilities ranging from 135 to 240 in/hr, and unit weights from 127 to 132 pcf. The split strength was about 12% of the compressive strength.

Yang et al. (2006) expanded slightly on the durability study conducted by Schaefer et al. (2006) to examine the influence of moisture conditions on freeze-thaw durability; this study found a positive correlation between saturation levels during curing and freeze-thaw durability. In a laboratory study simulating field conditions on pervious concrete specimens, the voids in pervious concrete can provide freeze-thaw resistance if these voids drain before freezing. Air entrained in the paste can also improve freeze-thaw resistance and placing the pervious concrete over at least 6 inches of drainable rock base is recommended in freeze-thaw environments (Tennis et al. 2004). In another study Kevern et al. (2009) measured the thermal profile of pervious concrete pavements and have found that pervious pavements can demonstrate a more rapid heating and cooling cycle as compared to traditional concrete pavements. In areas subject to freeze-thaw cycles, the American Concrete Institute (ACI) recommended the use of a gravel base (ACI 2010). If a rock base for stormwater storage is to be used, a geotextile fabric should be placed between the rock and the subgrade. Yang (2011) found that the inclusion of polypropylene fibers increased freeze-thaw durability and that the application of salt to specimens decreased durability.

Several studies have focused on material strength. For example, a study by Meininger (1988) showed a drop in compressive strength from over 5000 psi at an air content between 5% and 10% to just over 1000 psi at an air content between 25% and 30%. Toughness, as measured by ASTM C1399, can be improved by adding synthetic fibers. One study (SI Concrete Systems 2002) found that fibers 1.5 to 2.0 inches in length were most effective in increasing toughness. Shrinkage, which is typically around 200×10^{-6}, is about one-half of what typically occurs in conventional concrete (Tennis et al. 2004). For quality control, Tennis et al. (2004) recommend using unit weight or bulk density because other properties, such as slump and cylinder strength tests, don't have much meaning for pervious concrete. Strengths are a function of void content and placement methods and it's difficult to accurately represent field placement in a cylinder test. In another study Mulligan (2005) showed that compressive strength increased with unit weight. It has been reported that a porosity of at 15% is required to achieve a permeability of 1 cm/s (Meininger 1988).

The pore size in pervious concrete is another important parameter as it affects properties such as permeability and sound adsorption. Low et al. (2008) used a statistical method to determine that aggregate size, aggregate to cement ratio, and water-cement ratio greatly impacted pore structure. In addition, percolation rate (or permeability) is directly related to the porosity and the pore size of pervious concrete. Laboratory tests were performed by Wanielista and Chopra (2007a) who investigated the effect of varying components of pervious concrete on its strength; and determined the traffic loads and volumes that pervious concrete can withstand. Wanielista and Chopra (2007a) used aggregate with a specific gravity of 2.36 and a unit weight of 147.5 lb/ft^3. Concrete cylinders with different properties and different permeability were constructed. Water to cement ratios were varied from 0.32 to 0.52 by weight; and aggregate to cement ratios varied from 4 to 7 by volume. Resulting permeability values ranged from zero to 2688 in/hr and specific gravity values ranged from 1.95 to 2.36. Wanielista and Chopra (2007a) also investigated existing pervious concrete systems to gather information regarding long-term performance and vitality and reached the following conclusions:

- An aggregate to cement (A/C) ratio less than 5 in combination with a water to cement ratio from 0.35 to 0.39 resulted in the highest compressive strength without jeopardizing permeability.
- Higher A/C ratios did not have enough cement.
- Higher water to cement ratios eliminated void spaces.
- The energy applied to the pervious concrete was 1,544 kN-m/m^3 (modified Proctor). Higher compaction energy did not reduce permeability but it increased compressive strength.

- The compressive strengths obtained would support traffic loads up to 40 tons.

ACI (2010) reported that void content is highly dependent on aggregate gradation, cementitious material content, water to cement ratio, and compactive effort. It is also stated that a range of porosities can be achieved by blending two different size aggregates. If this is done, however, the larger aggregate should be less than ~2.5 times the size of the smaller aggregate or else the smaller aggregate may fill in the voids and reduce permeability. However, if the aggregate size ratio is large, it is expected that the mechanical properties of pervious pavement be enhanced. A recent laboratory test conducted by UCPRC (Jones et al. 2010, Li et al. 2012) found a clear relationship between aggregate grading, cement content, water to cement ratio, and strength and permeability. All specimens tested exceeded permeability requirements, suggesting that adjustments can be made to optimize mixes while still maintaining adequate permeability. In addition, results specific to porous asphalt concluded that

- Particle size distribution and the binder type are the two most important factors for selecting an appropriate mix,
- Most hot-mix asphalts tested had sufficient permeability,
- Rutting of the surface appeared to be a problem for a mix with conventional binder and one with a rubberized binder. Most of the mixes tested had sufficient resistance to raveling as compared to a dense-graded control.

The Colorado Ready Mixed Concrete Association (CRMCA 2009) recommended that additional sand increases resistance to freeze-thaw cycles, durability, and strength while maintaining enough infiltration capacity; this result is supported by observations made in Henderson and Tighe (2012). Furthermore, CRMCA recommended that the mixture have a density of 105 lb/ft3 to 130 lb/ft^3 and should conform to ASTM C29. The void content should be from 15% to 25%, the water to cement ratio shall be 0.26 to 0.35, and the cementitious content shall be from 450 lb/yd^3 to 550 lb/yd^3. With regards to concrete strength, Sonbei and Bassuoni (2013) used statistical modeling to estimate the impact of design variables on resulting density, void ratio, infiltration rate, and compressive strength.

To increase the structural strength of permeable pavement, Offenberg (2005) suggested that compaction of subgrade be performed to 92% to 96% of the modified Proctor maximum density for sandy subgrades. ACI (2010) stated a typical subgrade compaction of 90% of the Standard Proctor Maximum Dry Density in order to maintain infiltration capacity. However, the subgrade soil type should be considered when compacting because compacting clayey soils to 90% can essentially eliminate infiltration whereas compacting some sandy soils to 100% has no impact on infiltration. Regardless of the extent of compaction specified, it is important to field test the base and subgrade after compaction to ensure that it meets the desired objectives with respect to infiltration and structural integrity. In addition, to develop preliminary specifications for pervious concrete, the Maryland Department of Transportation conducted investigations to enhance the structural performance and durability of pervious concrete (Amde and Rogge 2013). This was accomplished through testing different admixtures (e.g., cellulose fibers, a delayed set modifier, and a viscosity modifier). The cellulose fiber admixture had the greatest impact on concrete durability due to the fibers ability to help hold the aggregate/paste mix together. Both abrasion resistance and freeze-thaw durability increased with the addition of cellulose fibers, although the result regarding abrasion is contradicted by Wu et al. (2011) and should thus be considered with caution. The delayed set modifier reduced permeability because more concrete paste settled to the bottom and developed a less pervious layer. The viscosity modifier resulted in a mix that was easier to handle but had little other impact.

It should be noted that there have been more innovative approaches to pervious concrete mix designs that featured the use of supplementary cementitious materials and recycled aggregates. This work included studies by Ravindrarajah and Yukari (2010) and Sata et al. (2013). Ravindrarajah and Yukari (2010) examined the use of high-levels of fly ash to replace cement in pervious concrete and recommended that measures be taken to insure that adequate strength levels are preserved if high levels of fly ash (as much as 50%) are used. Likewise, Sata et al. (2013) found that the use of so-called geopolymer concrete as a basis for pervious pavement could be used, but steps should be taken to account for significantly lower strength than would be present using conventional concretes.

4.2. Hydraulic Performance Evaluation

Permeable pavements are often used as a stormwater management practice because of their ability to infiltrate stormwater runoff. In order to do this the surface layer of the pavement must allow water to pass through to the underlying layers of the pavement structure. Of course, if infiltrated runoff is to reach the original existing soil, the underlying layers of the pavement structure such as bedding layers, choker courses, and geotextile fabrics, if used, must also have the ability to pass water. Thus, the ability of permeable pavements to infiltrate water has been the subject of many studies. These studies are organized and summarized based on the surface infiltration capacity, impact of geotextile fabric on infiltration rate, and winter hydraulic performance.

4.2.1 Surface Infiltration Capacity

Almost all studies have concluded that permeable pavements, when constructed well and when they have received regular maintenance, will have the ability to reduce peak runoff flow rates and infiltrate a significant fraction of runoff volume. For example, Huang et al. (2012) found that PICPs reduced peak flows by 21%. Bean et al. (2004) suggested permeable pavements can reduce runoff volume if the following conditions are met, (1) the underlying soil is sandy or loamy sand, (2) there is no high water table, (3) the pavement receives regular maintenance, (4) the pavement is properly constructed, (5) the pavement surface is flat, and (6) there are no over burdening loads. Drake (2013), however, showed that volume and peak flow reduction is possible even if the underlying soil is not sandy or loamy sand. In Drake (2013), permeable pavement systems constructed with underdrains that had valves for restricting outflow reduced peak flows by over 90% and reduced runoff volumes by 43% even though they were constructed over clayey soils. Also, contrary to Bean et al. (2004), Gonzalez and Angullo (2008) found that PICP on a 2% slope that were clogged with construction debris still infiltrated 81% of a 50 mm/hr rainfall and 90% of a 25 mm/hr rainfall. The variability in results can be attributed to differences in permeable pavements, construction methods, clogging, rainfall patterns, and other variables.

Brattebo and Booth (2003) investigated PICPs that had been in service for over six years and found that almost all rainwater reaching the pavers still infiltrated. No mention was made of maintenance history and the investigation took place in the Pacific Northwest where rainfall intensities are typically low. Li et al. (2013a) investigated infiltration rates of newly constructed PICP, pervious concrete, and pervious asphalt and concluded that PICP had the highest infiltration rates (0.5 cm/s), pervious concrete the second highest (~0.3 cm/s), and porous asphalt the lowest (0.1 cm/s). Results should be expected to vary because infiltration rates depend on materials, mix designs, construction techniques, maintenance received, and other factors. For example, Haselbach et al. (2006) stated that pervious concrete can typically infiltrate at 0.2 cm/s (which still ranks second to the PICP rate found by Li et al. (2013a). Gilbert and Clausen (2006) found that the infiltration rates of PICPs of over 11 cm/hr but that infiltration rates decreased slightly over time, probably due to fine particle clogging. Other factors such as PICP spacing and joint material also affect infiltration rates but, in general, infiltration rates have been found sufficient to eliminate or significantly reduce surface runoff. Also, infiltration capacity can vary significantly even on the surface of a single permeable pavement. For example, Lucke and Beecham (2011) found that although the amount of potentially clogging sediment varied by 56% over 12 test locations, the infiltration rate at those same locations varied by over a factor of 10^4 (from 6 to 13,230 mm/hr). It is possible that even if some area of a permeable pavement is severely clogged and cannot infiltrate runoff, other areas of the pavement may compensate for clogged area so the pavement is still functional.

Wardynski et al. (2013) investigated a PICP parking lot with different underground drainage configurations. The parking lot was divided into three cells with varying aggregate depths (deep, medium, and shallow internal water storage) and drainage configurations. The conventional cell had a 25 cm thick aggregate layer for water storage with an underdrain at the bottom of this layer, the shallow cell was identical except that the drain was located at the top of the aggregate storage layer, and the deep cell had a 56 cm thick aggregate storage layer with an underdrain located 25 cm below the top of the aggregate layer. The shallow and deep cells reduced runoff volumes by 99.6% and 100%, respectively, while the conventional cell achieved only 7% volume reduction.

Haselbach et al. (2006) experimentally determined the infiltration rate of pervious concrete covered with sand (from 1.3 to 5.0 cm thick) to be about 14 cm/hr, which is similar to the 100 year, 30 minute rainstorm intensity in the southeastern United States. Thus, for simulated rainfalls, the pervious concrete generated no runoff for rainfalls corresponding to return periods of up to 100 years if the pavement received only direct rainfall. However, if the pavement received runoff from adjacent areas, then runoff did occur.

Chopra et al. (2010) measured infiltration rates of pervious concrete cores from eight different parking lots ranged from 0.4 to 227 in/hr. The underlying soil at these sites were found to have infiltration rates from zero to 35.5 in/hr. Chopra et al. (2010) concluded that clogging could occur because of particles in the pervious concrete or at the underlying soil.

In a separate study, Tyner et al. (2009) investigated the effectiveness of underlying soil modification techniques on the ability of pervious concrete systems to infiltrate water. Three different techniques were investigate, (1) installing trenches filled with aggregate in the underlying soil, (2) ripping the underlying soil, and (3) drilling boreholes in the underlying soil and backfilling the holes with sand. The trench technique was found to be superior to the other two methods, although all three methods were able to drain the design volume of water within three days.

Other issues may affect the infiltration capacity of permeable pavements. For example, Shu et al. (2011) found that concrete mixes containing limestone aggregate and latex admixtures may be stronger but they also have lower porosity and infiltration capacity. In general, reducing the air voids of a pervious concrete pavement will make it stronger but it will also reduce infiltration capacity. Also, pavement use can affect permeable pavement infiltration capacity. For example, traffic lanes generally have lower infiltration capacity than parking stalls because more sediment typically falls on traffic lanes as compared to parking stalls (Henderson and Tighe 2012). Kayhanian et al. (2012b) found infiltration capacity to vary by up to 1000 times between parking spaces and traffic lanes and determined that the most important factors affecting infiltration capacity were pavement age and the amount of accumulated fine sediment (< 38 microns). In an investigation of porous asphalt pavements, Boving et al. (2008) observed low infiltration rates in high traffic areas and snow storage areas. Most likely the low infiltration rates were caused by particle accumulation, however, porous asphalt can also experience clogging through compression and a reduction of void content (Coleri et al. 2013). Drake et al. (2013) also noted that there is some indication that vegetation (plant growth and leaf litter) may help sustain infiltration (James and Gerrits 2003).

Although infiltration capacity is important and the subject of many studies, Henderson and Tighe (2012) state that infiltration capacity was not the determining factor in the overall performance of the pervious concrete systems. Rather, mix designs and construction methods were more critical as they greatly impacted the durability of the pavement surface.

4.2.2 Impact of Geotextile Fabrics on Infiltration Rate

Geotextile fabrics at the bottom of permeable pavements is an effective means of retaining clayey and silty material passed through the pavement (Mata and Leming (2013). In a literature review paper Drake et al. (2013) noted that the results obtained from field studies (Boving et al. 2008) and lab studies (Yong et al. 2008, Brown et al. 2009) have indicated that incorporating geotextiles in the design of permeable pavements can reduce infiltration rates by accumulating sediment on the geotextile. Also, Yong et al. (2013) noted that a concrete paver clogged at the geotextile layer. Because geotextiles can cause clogging, the University of New Hampshire Stormwater Center recommended eliminating the use of geotextiles or filter fabrics for porous asphalt pavements design (UNHSC 2009). Imran et al. (2013), however, performed a literature review and concluded that geotextile fabric can increase pollutant retention capability, enhance biodegradation, and prevent the transport of fines to lower layers. Scholz (2013) reviewed literature and found such water quality improvement is due to the retention of solid particles (and associated particle-bound pollutants) on the fabric and any contaminants not associated with solids (e.g. chloride) were essentially unaffected.

4.2.3 Winter Hydraulic Performance

Studies that have investigated the winter performance of permeable pavements have generally found that they retain their infiltration capability throughout the winter. Gunderson (2008), in a review of work done at the University of New Hampshire Stormwater Center (UNHSC), stated that freeze-thaw is not an issue impacting permeable pavements or infiltration and that the subbase, if well-drained, remains open in the winter. In fact, Gunderson (2008) stated that infiltration rates of a porous asphalt system were consistently higher in the winter than in the summer. The observed pattern was cyclical and was attributed to binder expansion from summer heat and a corresponding reduction in void content. Houle (2008) reported that frost depths of 27 inches did not decrease infiltration rates. Roseen et al. (2012) monitored a porous asphalt parking lot for over 4 years in a cold winter climate and noticed that frost penetration of up to 71 centimeters was observed and there was no decrease in infiltration capacity or any impact from frost heave. Kevern et al. (2009) found that air in the aggregate layer provided insulation that warms the pavement and underlying soils and that this delays frost formation. Similar findings were reported in Wenck (2014).

4.3. Maintenance Performance Evaluation

Permeable pavements, as with any stormwater control measurement practice, require regular maintenance in order to remain effective. Questions arise, however, with regards to what maintenance activities are most effective, what cleaning methods and frequencies are optimal, and what is the recommended sand and salt application. This section summarizes publications that try to answer the above questions.

4.3.1. Clogging Impact and the Effective Maintenance Requirement

Regular maintenance of permeable pavement must be performed if the long-term ability of the pavement to infiltrate water is to be maintained (Bean et al. 2004, Briggs 2006, Chai et al. 2012, Al-Rubaei et al. 2013). Permeable pavements can become clogged with particles and this can reduce infiltration rates. Because permeable pavements typically have high initial infiltration rates compared to rainfall intensities, clogging would have to be severe for the pavement to lose its functionality (Chai et al. 2012). Also, full restoration to initial infiltration rates is not necessary for a permeable pavement to remain effective. Without regular maintenance, however, clogging may occur and as a result the infiltration rates will be reduced to an unacceptable levels or prevent surface infiltration altogether.

Some researchers have found that particle clogging usually occurs in the upper layer of the pavement (Kayhanian et al. 2012a, Mata and Leming 2012, Yong et al. 2013). Lucke and Beecham (2011), however, found that over 90% of the trapped sediment in a PICP system occurred in the top two layers, which were the pavement and bedding (2-5 mm sized aggregate) layer. The collection of fines in the top two layers may be attributed to PICP, which typically has joint spaces that can pass larger particles than pervious concrete or porous asphalt. Most of the fines (< 33 microns), however, were not retained in the upper two layers but rather migrated past these layers and were retained by the geotextile fabric. Also, Chopra et al. (2010) found that clogging by particles in pervious concrete may be just as likely at the underlying soil or in the pervious concrete itself. Thus, results have varied and this indicates that there is no single location or depth within the pavement where clogging typically occurs. Clogging processes will depend on characteristics of the pavement (e.g. void content, pore size, the presence of a choker or bedding course) and the solids that reach the pavement. Particles that cause clogging may originate from pavement wear due to tire friction (Ferguson 2005), erosion from adjacent areas, vegetation, or the application of sand during the winter months. Even without the application of sand during the winter months, solid particles will reach the surface of permeable pavements via vehicles from other roads that have been sanded (Ferguson 2005). Thus, permeable pavements must be maintained to remove these particles and reduce the impact of clogging.

Another cause of clogging in porous asphalt is drawdown, which can occur on hot days when the asphalt binder becomes less viscous and drains towards the bottom of the pavement (Ferguson 2005). Roseen et al. (2012) suggests that the drop in infiltration capacity of a porous asphalt parking lot observed the first summer after construction was likely due to binder drawdown. A mix design that minimizes binder drawdown can help minimize clogging (Gunderson 2008) and the addition of fibers or polymer additives to the mix can be used to minimize drawdown (NAPA 2003). Gunderson (2008) reported that binder can swell during the hot summer months and that this process will also cause a reduction in infiltration capacity even if drawdown does not occur. This phenomenon has been shown to repeat in a cyclical fashion with infiltration rates increasing in the winter and decreasing in the summer. Decreased infiltration rates will persist as long as temperatures remain high but increase again when temperature drops.

Porous asphalt may also clog due to routing and deformation of the asphalt pavement under heavy loads. This reduces air voids in the pavement and reduces the pavements infiltration capacity (Coleri et al. 2013).

4.2.3 Recommended Cleaning Methods and Frequency

Power washing and/or vacuum sweeping are the two most recommended cleaning activities (Golroo and Tighe 2012b, Drake 2013) along with preventing sediment from adjacent areas from washing onto the pavement (Chai et al. 2012). Several researchers have investigated the effectiveness of pressure washing and/or vacuuming and found that these techniques can often at least partially restore the infiltration capacity of a permeable pavement. For instance, Al-Rubaei et al. (2013) investigated the effectiveness of pressure washing and vacuuming on two older porous asphalt pavements. This combination was found to increase average infiltration rates from 0.50 mm/min to 3.48 mm/min on one of the porous asphalt pavements but it had no effect on the other. The difference was attributed to the fact that the pavement on which it was effective had received regular maintenance (pressure washing, vacuuming, and annual sweeping) over its time in service whereas the other pavement had not. Chopra et al. (2010) found that for pervious concrete that has become clogged, pressure washing was more effective than vacuum sweeping although Mata and Leming (2012) found that vacuum sweeping could partially restore the infiltration capacity of pervious concrete. Drake (2013) found that vacuuming was effective at one pervious concrete site investigated but not at another. Drake (2013) found, however, that vacuuming and pressure washing can at least partially restore infiltration rates. Hein et al. (2013b) reported that pressure washing and vacuuming were both effective initial cleaning methods but that pressure washing followed by vacuuming followed by a second round of pressure washing was significantly more effective at restoring infiltration rates of clogged pervious concrete pavements.

It has also been noted that in some cases vacuuming could not remove the particles causing the clogging (Chopra et al. 2010) and that high pressure washing may push particles further into the pavement (Chopra et al. 2010, Henderson and Tighe 2012). It was also noted that it is extremely difficult to restore infiltration rates (to initial values or larger) of a pavement that had low initial infiltration rates. Low initial infiltration rates are likely due to poor mix design and/or improper construction.

Finally, recommended frequency of maintenance ranges from at least annually (Drake 2013) to two to four times per year (Gunderson 2008).

4.3.3 Recommended Winter Sand and Salt Application

Applications of sand onto permeable pavements are generally not recommended because the sand particles can clog the pavement and reduce infiltration rates (Al-Rubaei et al., 2013). Huang et al. (2012) found that winter sanding reduced the infiltration capacity of PICP from over 7500 mm/hr to less than 500 mm/hr. Henderson and Tighe (2012), however, investigated pervious concrete installations and found that winter maintenance of salt and sand application did not affect the infiltration rate after 22 months of service if the concrete had initially high infiltration rates. No mention was made, however, of the long-term effects of sanding on infiltration rates and generally it is recommended to avoid sand application.

Studies assessing necessary salt application on permeable pavements for winter safety have found that permeable pavements typically require less salt loads for the same level of safety and/or bare roadway as their non-permeable counterparts. Roseen et al. (2014), for example, concluded that 64 to 77% less salt was needed for a porous asphalt parking lot to maintain surface conditions of the same quality or better of a non-porous asphalt lot. Compared to non-permeable pavements, Houle (2008) found that salt application could be reduced by 75% for porous asphalt and that permeable pavements have higher skid resistance values in the winter. Wenck (2014) found that unsalted, porous asphalt sections had a similar amount of bare pavement compared to salted, conventional asphalt sections but also noted that there was a lag from two to several hours in the appearance of bare pavement on the porous asphalt. A lower necessary salt load is attributed to the fact that permeable pavements can retain their infiltration capacity throughout the winter, even in cold climates (Roseen et al. 2014). This allows melt water to infiltrate rather than collect on the surface of the pavement.

4.4. Water Quality Evaluation

Because some permeable pavements may be a source of stormwater pollutants, this section is devoted to the evaluation of leachate quality. Also included is the evaluation of pollutant characteristics of subgrade infiltrated water.

4.4.1 Pollutants Generated from Permeable Pavements

When evaluating the water quality of infiltrated water, particularly with respect to groundwater pollution, one issue that must be addressed is the type and concentration of pollutant generated from permeable pavement materials. To address this issue, controlled laboratory experiments were performed by researchers from the University of California at Davis who evaluated the leachate generated from a range of open- and dense-graded concrete and asphalt pavements (Kayhanian et al., 2010). Each specimen was also artificially aged and the leachate results were compared with fresh specimens. The results showed that the contaminant contributions to leachate were generally extremely low, except for dissolved chromium from a few sources of cement (Signore et al, 2008; Kayhanian et al. 2009a, Kayhanian et al. 2009b). The UC Davis control laboratory study and a recent review article prepared by Kayhanian et al. (2012b) concluded that the major source of pollutants measured from road surface runoff is anthropogenic and mostly associated with vehicles and airborne deposition. For example, poly-aromatic hydrocarbons (PAHs) which, were not detected during the controlled laboratory study but were reported in urban and highway runoff and found to be mostly related to the combustion of transportation fuels (Lau et al. 2005, Kang et al. 2009).

4.4.2. Pollutant Characteristics of Subgrade Infiltrated Water

As previously discussed, most full depth permeable pavement systems are designed and constructed to capture the design storm based on local stormwater management criteria. The captured water is usually stored in a subgrade aggregate base and eventually infiltrates into the subgrade soil. Design drawdown times usually ranges from 48 to 72 hours. Extra water that cannot be retained within the subgrade aggregate base during a storm event will be discharged as effluent. Depending on the subgrade soil infiltration capacity, perforated pipes are sometimes installed within the aggregate reservoir layer (above native subbase soil) to allow the discharge of effluent. Therefore, a majority of water quality characteristics (physical, chemical, and biological) that have been investigated by researchers is based on the sampling and analysis of discharged subgrade effluent water. The findings of these studies are summarized in chronological order below.

A study performed by St. John and Horner (1997) in the State of Washington in which they compared the quality of water produced from conventional asphalt and porous asphalt shoulders on a two-lane roadway with an average daily traffic count of about 9,000 vehicles in each direction. Results showed that: (1) total suspended solids (TSS) event mean concentration (EMC) from the porous asphalt shoulder was 75% lower than the conventional asphalt, (2) the average turbidity from the porous asphalt shoulders was over 50% less than that of the conventional asphalt shoulder, (3) the average chemical oxygen demand (COD) EMC values from the porous asphalt shoulders were 51% lower than the average COD EMC from the conventional asphalt shoulder, (4) COD and biochemical oxygen demand (BOD) loads from porous asphalt shoulders were 94% and 84% lower than the average COD and BOD load from the conventional asphalt shoulder, respectively, (5) total phosphorus (TP) loads from the asphalt shoulders were 6% of the load from the conventional asphalt shoulder, (6) ortho-phosphorus loads were 90% lower in the porous asphalt shoulder runoff as compared to the load from the conventional asphalt shoulder, (7) total zinc and copper loads from the porous asphalt shoulder were all at least 90% lower than the load from the conventional asphalt shoulder, and (8) porous asphalt shoulders were more effective at removing soluble pollutants, especially ortho-phosphorus, as compared to conventional asphalt shoulders.

Pratt et al. (1999) performed a full-scale laboratory study of a permeable pavement system with concrete pavers in a bed of gravel to investigate its ability to retain and treat petroleum-based contaminants. The gravel, which extended 20 mm below the pavers, was placed on top of a geotextile that was placed on top of 600 mm of 20-50 mm diameter crushed granite. The entire unit rested on and was supported by another layer of geotextile and an underlying stainless steel mesh. The test section was subject to long-term, low level hydrocarbon loading at rates that would be typically experienced by urban roads and/or parking lots. Only clean motor oil, which has low poly-aromatic hydrocarbon (PAH) concentrations, was applied. Water quality was monitored over several months to determine the ability of the pavement system to retain and treat the petroleum-based contaminants. Results indicated that a permeable pavement can sustain microbial populations such that the subgrade structure acts as an *in situ* bioreactor with regards to petroleum based contaminants. Petroleum contamination in the effluent was reduced to 2.4% of what was applied (reduced from an influent concentration of 900 g/m^2-year to an effluent concentration of 22 g/m^2-year). A limiting factor in the reduction of petroleum appears to be nutrient supply but a slow-release fertilizer was used to supply nutrients to the pavement structure, which enabled petroleum degradation to be sustained. Clearly, the results obtained in this study are inconclusive and raised several unresolved questions. For instance, the use of clean engine oil is unreal and the application of fertilizer as nutrient source may generate additional problems with respect to nitrogen and other pollution discharge to groundwater or receiving waters.

Brattebo and Booth (2003) investigated the long-term (six years) water quality performance of four commercially available permeable pavers (Grasspave®, Gravelpave®, Turfstone®, UNI Eco-Stone®) used in a parking lot. The study site was located in the Pacific Northwest, which typically has low intensity rainfalls and was not subject to extended periods of below freezing weather. Monitoring results showed that infiltrated runoff had significantly lower levels of copper and zinc than the runoff from the adjacent asphalt parking area. Whereas almost all adjacent asphalt parking lot runoff samples had copper and zinc concentrations above toxic levels. Although motor oil was found in 89% of the runoff samples from the asphalt area, none of the infiltrated water samples contained motor oil.

Gilbert and Clausen (2006) compared the quality of stormwater runoff produced from replicated asphalt, permeable paver, and crushed-stone driveways. Flow-weighted composite samples were analyzed once a week for water quality parameters such as total suspended solids, total Kjeldahl nitrogen, nitrate-nitrogen, ammonia-nitrogen, total phosphorus, copper, lead, and zinc. Compared to the conventional asphalt pavement, the permeable paver runoff contained significantly lower concentrations of all pollutants. The pollutant mass loading from each pavement corresponded to the volume of runoff from each pavement, not the concentrations.

Wanielista and Chopra (2007b) collected water samples from the bottom of the storage reservoir of a pervious concrete pavement and concentrations of nitrate and orthophosphorus were compared with surface runoff concentrations. On average, the concentrations of nitrate and orthophosphate from the pervious concrete pavement were lower.

Boving et al. (2008) investigated the characteristics of infiltrated stormwater pollutants (organic, inorganic, and bacteria) immediately below a porous asphalt parking lot. To investigate the impact on water quality, deep and shallow sampling ports were installed below low and high traffic areas of the porous asphalt and one sampling port was installed just outside the lot. Bacteria and BOD was not detected in any infiltrated water and polycyclic aromatic hydrocarbons (PAH) were found at levels near the detection limit. Nitrate and phosphate from the porous asphalt surface leached into the ground at a rate of 0.45–0.84 g/m^2-year. A multi-species tracer test determined the retention capacity of the porous asphalt system to be 90% for metals and 27% for nutrients. Contaminant concentrations observed in water samples taken below the pavement varied with the season. Higher nitrate and phosphorus concentrations were observed during the spring and fall (periods of fertilizer application) while metal and chloride concentrations were higher in later winter and early spring (periods of high road salt application). In addition, comparing PAH flux through the porous asphalt parking lot system to fluxes observed on conventional roads in the region indicated that the porous pavement structure removed PAH's or at least impedes or retards PAH transport.

Roseen et al. (2009) monitored six different low impact development (LID) designs including porous asphalt at the University of New Hampshire Stormwater Center for two years (and 27 runoff events) to assess winter performance. Influent and effluent samples were analyzed for total suspended solids (TSS), total petroleum hydrocarbons-diesel (TPH-D), dissolved inorganic nitrogen (DIN, comprised of nitrate, nitrite, and ammonia), total phosphorous (TP), and total zinc (TZn). The water quality improvements were measured through pollutant removal efficiency and effective ratio. Results showed that porous asphalt has a high level of performance (except for dissolved nitrogen) during the winter and performance was not reduced by frozen filter media.

Collins et al. (2010) monitored four permeable pavements and a conventional asphalt pavement for seven months to determine the performance of each with respect to stormwater runoff quality. The permeable pavements investigated were pervious concrete, two permeable interlocking concrete pavers (joints filled with small aggregate), and a concrete grid paver filled with sand. Due to poorly draining native soils at the site, all systems included a crushed stone base that contained a perforated drain pipe. Composite, flow-weighted samples of runoff discharged from the permeable pavement systems were analyzed for pH, total nitrogen, nitrite/nitrate nitrogen, ammonium, and organic nitrogen concentrations. Results indicated that the pH of the permeable pavement effluent was higher than runoff from the asphalt pavement with pervious concrete having the highest pH. Ammonium and total Kjeldahl nitrogen concentrations corresponding to the permeable pavements were lower than those corresponding to traditional asphalt. Except for the concrete grid pavers, the nitrite/nitrate concentrations were higher than that of the asphalt pavement. The authors attributed this to nitrification occurring in the permeable pavement system. Collins et al. (2010) concluded that all four permeable pavements performed similarly with respect to nitrogen removal and that the removal efficiency was similar to that of a sand filter treatment.

Thomle (2010) investigated the temporal pH change of stormwater that had come in contact with pervious concrete that aged under various air restrictions. Pervious concrete specimens were prepared in the laboratory and exposed to three different levels of ambient air restriction. The pH of specimens was assessed by either infiltrating tap or deionized water through the specimens or by soaking the specimens in tap or deionized water. The study also investigated the decline in pH of water in contact with pervious concrete exposed to carbonate laden water. Results showed that the pH of water exposed to concrete decreases due to a chemical process called carbonation. In this process the hydroxide anion associated with calcium hydroxide is replaced with a carbonate anion and forms calcium carbonate. More exposure to ambient air caused a significant increase in the rate of pH decline. Tap water, which represented a more typical stormwater for the study, had much lower pH values than deionized water. Minerals in the tap water help lessen the impact of the concrete and, as a result, the pH did not rise as much as in deionized water. It is expected that, for most typical field conditions, the pH values will decline to acceptable values in much less than one year. In the carbonate laden water tests, the pH of water exposed to concrete that had previously been exposed to carbonate laden water decreased more quickly when exposed to ambient air.

Drake et. al (2012) investigated the water quality aspects of three different types of permeable pavements (two permeable interlocking pavers and pervious concrete). The study was conducted at the Toronto and Region Conservation Authority's Living City Campus, about 5 miles north of Toronto, Canada. An existing parking area was replaced so that there were four cells, each about 2500 ft^2 in surface area. Two cells were constructed with permeable interlocking concrete pavers (AquaPave® and Eco-Optiloc®), one cell with pervious concrete, and one with conventional impermeable asphalt. Drake et al. (2012) concluded that all stormwater that infiltrated through any of the porous asphalt pavements had significantly reduced mean and median event mean concentrations (as compared to the traditional asphalt lot) for suspended solids, oil and grease, ammonia, ammonium, nitrite, total Kjeldahl nitrogen, total phosphorus, chloride, calcium, copper, iron, manganese, and zinc. The average pH of effluent from the pervious concrete and PICP lots was 9.2 and 8.3, respectively.
Huang et al. (2012) investigated the impact of a concrete inter-locking paver (UNI Eco-Optic®) on stormwater runoff reduction (peak flows and total volume) and water quality characteristics. The monitoring was performed by analysis of samples artificially generated rainfall-runoff events from a test cell in Calgary, Alberta during the winter. The impact on water quality focused on total suspended solids (TSS), total phosphorus (TP), total nitrogen (TN),

copper (Cu), lead (Pb), and zinc (Zn). Overall, the pavers improved the quality of the runoff with average removal rates (concentration based) of 91%, 78%, 6%, 68%, 65% and 55%, for TSS, TP, TN, Cu, Pb, and Zn, respectively.

Roseen et al. (2012) monitored a porous asphalt test section (with an area of 464 m^2) in a parking lot at the University of New Hampshire Stormwater Center for four years to assess hydraulic performance and impact on water quality. Results of this study showed that peak flows were reduced by 90% and the majority of total suspended solids, petroleum hydrocarbons, and zinc effluent values were below detection limits. Dissolved anions, such as nitrate and chloride, experienced no removal, and the phosphorus removal efficiency was 42%.

Wardynski at al (2013) monitored a PICP parking lot in North Carolina for one year to assess the impact the pavers had on stormwater temperature and thermal load export. The parking lot had an area of 239 m^2 and was divided into three cells with varying aggregate depths (deep, medium and shallow internal water storage) and drainage configurations. The shallow and deep cells had the largest stormwater volume reductions (99.6 and 100%, respectively) while a conventionally drained cell had a volume reduction of 7%. Thermal loads for the deep, shallow and conventionally drained cells were reduced in direct proportion to the corresponding volume reduction. Median effluent temperature from the conventionally drained cell exceeded the critical trout temperature of 21^oC during 8 of the 54 events that were monitored. Effluent temperatures for the two cells with internal water storage never exceeded the critical trout temperature. Temperature profiles indicated that the pavers buffered the impact of high runoff temperatures. During cold winter months the temperature of the subsurface soils never reached freezing. Thus, the authors concluded, frost heave of such pavers should not be expected in similar climates.

In a laboratory study Mbanaso et al. (2013) investigated the effect of adding glyphosate-containing herbicides on hydrocarbon retention and biodegradation within permeable pavements. The glyphosate-containing herbicides appeared to reduce hydrocarbon retention by geotextiles by pushing oils through the pavement systems. Permeable pavement systems with only oil added discharged effluent with a hydrocarbon concentration of up to 24.5 mg/L whereas systems with oil and herbicide added had effluent with hydrocarbon concentrations of up to 73.2 mg/L. The authors note that some of the increase is probably due to the fact that the herbicide itself contains hydrocarbons. The herbicide also reduced the ability of the geotextile to retain metals. When glyphosate-containing hydrocarbons were added, high concentrations of lead, copper, and zinc were found in the effluent from the permeable pavement. The herbicide also stimulated populations of bacteria and fungi and increased their population, thus increasing the number of organic degraders.

Fan et al. (2013) investigated the microbial structure and activity in soil under several permeable pavements. Two soil layers were collected (aggregate and soil bases) under a permeable asphalt, concrete brick, concrete-glass block, and JW pavement. A JW pavement is a newly designed concrete pavement with high load bearing properties and permeability. Each soil layer was evaluated for granulometry, water content, pH, total organic carbon, total nitrogen, enzymatic activities, community-level physiological profiles, and phylogenetic bacterial diversity. The results indicated that the amount and diversity of bacterial communities and the activation and versatility of microbial activities were related to the total organic carbon content of the pavements. JW pavement had microbial compositions and activities much stronger than those under the other pavements (except for fungi and actinobacteria). Bacteria under the JW pavement were also more abundant and diverse and the soil there indicated more activated and versatile microbial metabolism in all substrates and some types of functional guilds. The authors attributed these results to a looser structure and higher water and total organic carbon content within the soil.

Drake et al. (2013) performed a literature review regarding the hydrology, effect on water quality, long-term performance, and maintenance requirements of permeable pavements. The paper focused on studies that monitored and/or tested full-scale parking lots with traffic and natural precipitation. Because results depend on the climate and geography of the area, pavement type, and design of the overall system (e.g. use of geotextiles, underdrains, etc.), a meaningful comparison of results between studies was difficult. Although results have varied, in general, studies have found that permeable pavements can retain 50% to 60% of solids and particle-bound metals (typically lead, zinc, cadmium, copper, iron). Due to a limited number of samples, confidence intervals for individual studies are large but, as a whole, Drake et al. (2013) concluded that porous asphalt, pervious concrete, and permeable interlocking concrete pavers have the ability to remove suspended solids and the particulate metals. Hydrocarbons are also retained in permeable pavement systems. Also, removal of oils and greases often results in concentrations less than detection limits. With regards to nitrogen, it has been reported that permeable pavement systems provide suitable conditions for nitrification (ammonium to nitrate) but it has also been observed that total nitrogen concentrations can be higher in permeable pavement effluent than in conventional asphalt runoff or atmospheric deposition. Also, particulate bound phosphorus can be removed by filtration within the pavement structure. Several studies have observed that most particulate pollutants are retained either at the surface or within the first few centimeters below the surface within the pores. Most studies have also found zero or minimal stormwater pollutants in the soils underlying permeable pavements. This indicates that the transport of pollutant (particularly particle-bound) to groundwater is unlikely. The Drake et al. (2013) review also indicated that porous pavements tend to raise the pH of infiltrated water from acidic to values between 8 and 9.5. Because most metals are less soluble at higher pH's, this may also cause metals to precipitate. Studies have been conducted on the impact that certain design variations have on water quality. Examples include geotextiles (may affect nutrient removal), phosphorus absorbing materials, anaerobic zones (may increase nutrient removal), sand layers (may increase nitrogen removal), and crushed brick, limestone, and basalt (the former two have more metal removal than the latter). Materials within the pavement structure itself can react chemically and/or dissolve thereby increasing the pH, conductivity, alkalinity, hardness, and concentrations of dissolved solids. One three-year long study concluded that the source of all pollutants found in water samples was sand used for joints and beds and not from surface inputs. Salts appear to be the only contaminant with a significant potential for groundwater contamination. Furthermore, salts can cause the leaching of metals through cation exchange.

Imran et al. (2013) reviewed the use of permeable pavements for different purposes while focusing runoff quality and drainage from roads, roofs, driveways, and parking lots. According to this review paper, geotextile fabric between the base layer and bedding layer can increase pollutant retention capability, enhance biodegradation, and prevent the transport of fines to lower layers. The bedding layer is defined as a layer of fine sand, which can also retain pollutants. Some report that a permeable pavement with a geotextile layer is more effective in retaining pollutants than only permeable pavement. Some studies have reported that solids removal may occur at the surface of the pavement, however, while others found that this occurs at the geotextile layer. Imran et al. (2013) also reported that permeable pavements can remove pathogens from infiltrated water. Porous asphalt is summarized as having the ability to significantly retain metals and organic carbon from infiltrated water but not having much ability to retain nitrogen and ammonia.

Scholz (2013) performed a review study by critically assessing the impact of geotextiles on water quality. Pollutants considered when assessing the impact of geotextiles on water quality were organics, nutrients, metals, motor oils, suspended solids, and chloride. From the available literature, Scholz (2013) concluded that any water quality improvement due to the presence of a geotextile is mostly related to the retention of solid particles (and associated particle-bound pollutants) on the fabric. Contaminants that are not associated with solids (e.g. chloride) were essentially unaffected. The information presented was not conclusive and available data was deemed unsuitable for further statistical analysis.

While most previous studies showed positive water quality benefits, a few study showed no or adverse effect of permeable pavements. For instance, the Urban Drainage and Flood Control District (UDFCD, 2011a) in Denver, Colorado monitored the water quality performance of a PICP system at the Denver wastewater treatment plant and the results showed that the concentration of some contaminants were higher in the PICP site compared to the control site. The authors explained that this could be due to the difference in traffic activities at the control site because it was an employee parking lot, which received little vehicular traffic compared to the PICP site. Overall, only 11 of the 29 contaminant concentrations were found to be statistically different between the sites and only 5 of the 11 were found to be lower on the PICP site. Those five were dissolved manganese, total zinc, chemical oxygen demand, total Kjeldahl nitrogen, and total suspended solids. Contaminant concentrations that increased were nitrates/nitrites and total cadmium, although these differences were not statistically significant. In addition, UDFCD (2011b) monitored the water quality characteristics of effluent from the porous asphalt site and compared them to the water quality of runoff from the control site. Dissolved petroleum, chloride, and dissolved phosphorus were significantly lower in the porous asphalt effluent. Nitrate/nitrite, total selenium, and dissolved sodium, however, were higher. Again, these differences may be due to differences in traffic volumes at each location because the control site received much less traffic. Because of the major difference in traffic activities between the control site and the test site (i.e. PICP or porous asphalt) and with limited monitoring data, drawing definitive conclusions regarding the impact of the PICP or porous asphalt on water quality is not justified.

In addition to the pollutant reduction observed from the above full depth permeable pavement study, several researchers also documented water quality benefits from the use of open graded friction course (OGFC) pavements (Barrett et al. 2006; Bean et al. 2007; Roseen et al. 2012). An OGFC pavement is a thin layer of permeable pavement (usually asphalt) that is constructed over an existing conventional asphalt pavement. The exact mechanism of pollutant removal is not known but it has been speculated that the majority of pollutants were removed through vehicular activities and pollutant absorption to body of the cars.

5. Knowledge Gaps, Unresolved Issues and Future Direction

5.1.Knowledge Gaps Identified In the Literature

As noted previously, the amount of literature in the past two decades has increased exponentially providing a wealth of information related to the mixed design, structural analysis, hydrologic performance, maintenance requirement, and various other topics regarding the application of permeable pavements. While tremendous amount of progress has been made with this relatively new pavement technology, at the same time some knowledge gaps still exists and there are numerous issues that are unresolved and need to be further investigated. Table 7 summarizes, by topic, some of the most common unresolved knowledge gaps that are recommended by different researchers for further investigation. From this summary list, the unresolved research topics are further organized and recommended for future consideration based on their immediate, short-term, and long-term impact (see table 8).

5.2. Future Direction

Investigations previously discussed lacked an integrated network approach coupling materials, energy, water and pollutant flows across complex pavement system boundaries. In the future, it is expected that most old urban areas will be retrofitted with green technologies including permeable pavements and the new urban developments may use sustainable and integrated approaches for creating greener environments. This envisioned impermeable-to-permeable ***urban surface evolution*** (see Figure 5) will have broader impacts to a society that can benefit from a cooler, cleaner, quieter, and healthier urban environment. Therefore, use of permeable pavement from the sustainable point of view, especially for urban areas, may be accomplished by using the new generation of permeable pavements with their end use phase impact in mind (see Figure 6). As shown, the successful sustainable implementation of permeable pavement in the future that can provide multiple end benefits may require integrated approach to advance pavement characteristics analyses.

Figure 5. Concept of Urban Surface Evolution

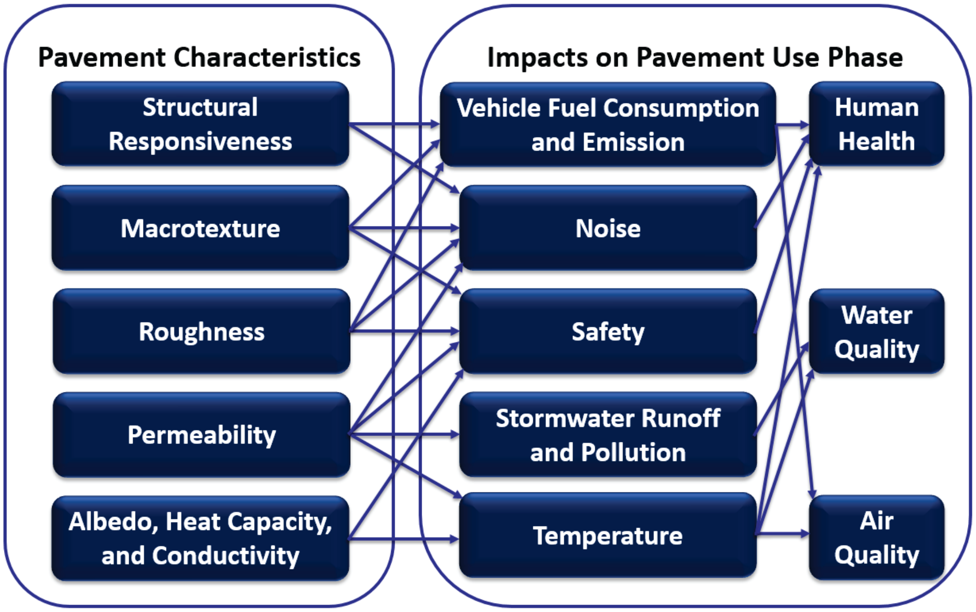


Figure 6. Future Direction of Sustainable Use of Permeable Pavements with End Use Objectives (Source: Van Dam et al., 2015)

For example, as shown in Figure 6, pavement characteristics will influence vehicle fuel consumption, noise, safety, stormwater runoff pollution, and surface temperature and ultimately each of these parameters will impacts the human health and the environment through water and air quality. Some of the challenging integrated unresolved issues that are directly or indirectly related to permeable pavements that are identified for future consideration include: climate change, micrometeorology, stormwater pollution, cool island impact, noise impact, energy impact, and materials recycling impact. The significance, knowledge gaps and future direction related to each of the above topic are summarized in Table 9.

Table 7. Summary of Unresolved Research Topics (by area) Suggested by Different Researchers

Data gap area	Reference	Suggested unresolved research topic(s)
Materials property and structural strength	Lampe et al., 2004	• Aggregate grading and performance under load • Performance of geo-synthetic fabric in PP construction • Specifications for geotextiles (where to install? What type?) to maximize pollutant capture • Structural analysis under load when subgrade soil is wet and saturated
	Kevern et al. (2006)	• Effect of different construction methods and compaction energy on the freeze thaw durability of various mix designs
	Schaefer et al., 2006	• Evaluate how compaction energy affects pervious concrete properties (e.g. strength, void ratio, permeability, freeze-thaw durability) to develop standard construction method
	Wanielista and Chopra, 2007	• Investigate the impact of accurate traffic volumes and loadings to determine how such variables impact the long-term performance of pervious pavement
	Delatte et al, 2007	• Develop in-situ test methods to measure strength, thickness, and void ratio of in place pervious concrete so that cores do not have to be taken
	Kayhanian et al., 2010	• HVS or bus route test sections to evaluate structural performance under heavy load and load speed
	Jones at al., 2010	• Life cycle cost analysis based on pavement type and materials • Standard compaction method for subgrade aggregate. • Design of pervious concrete pavement using lower aggregate size and higher cement content • Use of modified polymer in HMA-O mix to reduce the likely risk of raveling, rutting, and cracking
	ACI, 2010	• Understanding of the pore structure in order to determine material based performance design standards • Development of non-destructive test methods • Standard method to measure fatigue • Freeze-thaw and cold climate applications performance
	Vancura et al., 2010	• Full-scale field testing studies to assess the applicability of the StreetPave model to pervious concrete systems • Monitoring over time to develop a better understanding of the long-term performance of pervious concrete • Effect of lightweight aggregate on pervious concrete performance • Develop and calibrate a fatigue model for pervious concrete
	Drake et al., 2012	• Test methods of evaluating dislodging material from permeable pavement surfaces • Long-term performance evaluation, especially in cold climate • Impact of heavy traffic and loading on permeable pavement

Table 7 (continued)

Data gap area	Reference	Suggested unresolved research topic(s)
Materials property and structural strength (continued)	Amde and Rogge, 2013	• Develop a non-destructive test to determine the uniform level of compaction throughout a pervious concrete sample • Fatigue investigation of pervious concrete under light and medium traffic situations • Impact of recycled aggregate on pervious concrete properties
	Li et al (2012)	• Validate mechanistic design with field demonstration • Perform life-cycle cost and environmental life cycle analysis
	Drake et al (2013)	• Life-cycle cost analysis
	Li et al (2013a)	• Structural performance under traffic loading
	Scholz (2013)	• Long-term testing on the impact of geotextiles with underground testing units to mimic actual field conditions
	Houle (2008)	• Full life-cycle costs analysis to compare permeable pavements amongst themselves and with traditional pavements
	Boyer (2011)	• Perform a life-cycle analysis including environmental, energy, and economic considerations
	Drake (2013)	• Accurate and reliable life-cycle cost analysis of permeable pavements with proven maintenance activities and their costs • Benefit of permeable pavement at watershed-scale
Hydraulic/water quality	St. John and Horner, 1997	• Evaluate aggregate mix design as a source of pollution
	Lampe et al., 2004	• Impact on groundwater quality based on flow rate, pollutant type and load
	Wanielista et al., 2007	• Developing a test method for measuring the infiltration rate of the underlying gravel reservoir • Developing a mass balance model, capable of simulating unsaturated flow within the underlying soil to the water table
	Kayhanian et al., 2010	• Evaluate hydraulic performance under heavy load and low speed under HVS or bus route test sections using real or simulated rainfall • Develop a user-friendly infiltration model to assess the short and long-term impact of possible pollutants on groundwater
	ACI, 2010	• Effect of water with high sulfate concentrations or acidic water on the durability of pervious concrete • Urban heat island effect and thermal properties
	Vancura et al., 2010	• Evaluation of freeze-thaw damage due to the lack of paste hydration or the lack of a standard air void distribution
	Drake et al., 2012	• Use raised pipe or control valves to increase infiltration and reduce effluent volume • Testing on leachate of materials from pervious pavements

Table 7 (continued)

Data gap area	Reference	Suggested unresolved research topic(s)
Hydraulic/ water quality (continued)	Boving et al (2008)	• Pollutant removal within pavement structure (i.e. asphalt, trapped particles in aggregate, etc.) • Long-term water quality monitoring
	Collins et al (2010)	• Isolate the underlying soils to investigate and gain a better understanding of the water quality response within the pavement system
	Drake et al (2013)	• Nitrogen fate and transport in porous pavement • Long-term fate and transport of the phosphorus (i.e., does it become mobile later?) • Impact of design and materials used on water quality • Impact of infiltration on groundwater quality • Impact of permeable pavement at watershed-scale
	Imran et al (2013)	• Investigation of biodegradation process in permeable pavements (e.g., species, dispersal, and colonization rate) • Removal/retention of nutrient within permeable pavements • Optimum environment for biodegradation for various organisms • Study of temperature profiles, biodegradation, and microorganism life cycles • Study of different media mixes to enhance bio-retention • Performance of filter media in sumps at the bottom of permeable pavement structures • Removal and leaching of phosphorus within permeable pavements
	Li et al (2013a)	• Impact of permeable pavement on urban heat island effect
	Scholz (2013)	• Performance evaluation of different or modified geotextile for organic and trace elements removal
	Briggs (2006)	• Improved method of infiltration to minimize leaking • Pavement cores analysis to determine the extent that binder drawdown affected infiltration • Infiltration capacity prior to and after cleaning to determine the impact of maintenance activities • Optimize winter maintenance by minimizing the application of deicers and sand • Impact on groundwater quality • Better record of chloride application rates
	Houle (2008)	• Long-term infiltration rate
	Thomle (2010)	• Quantification of the amount of carbon sequestered in the specimens when exposed to carbonate laden waters
	Drake (2013)	• Water quality evaluation by using load vs. concentration; include data below detection limit and frequency analysis

Table 7 (continued)

Data gap area	Reference	Suggested unresolved research topic(s)
Hydraulic/ water quality (continued)	Boyer (2011)	• Temperature and materials property profile to investigate the urban heat island effect • A model to measure the temperature gain and loss when evaluating the heating and cooling of previous concrete • Perform a study to measure the amount of water retained in the pervious concrete layer after a rainfall event and also the evaporation and cooling effect of this water
Maintenance/clogging	Briggs (2006)	• Improved method of infiltration to minimize leaking when measuring surface permeability • Infiltration capacity (permeability) prior to and after cleaning to determine the impact of maintenance activities
	St. John and Horner, 1997	• Quantitative evaluation of clogging
	Lampe et al., 2004	• Cleaning equipment and maintenance intervals for clogging
	Chopra et al., 2007	• Permeability measurement over time • High volume flushing
	Kayhanian et al., 2010	• Evaluate various cleaning methods to remove clogging
	Drake et al., 2012	• Cleaning frequency • The need for salt application on permeable pavement
	Drake et al (2013)	• Pavement design that optimize pollutant retention and minimize clogging
	Houle (2008)	• Chloride retention and export amount • Non-chloride salts investigation to determine their performance and required loading rates • Measure vertical temperature profiles below the ground surface as well as groundwater elevations to determine if latent heat from the ground and infiltrated water can melt snow and ice in or on the pavement
	Drake (2013)	• Techniques to dislodge particles causing clogging are needed as this would increase the effectiveness of vacuum sweeping and regenerative air sweeping • Performance of permeable pavements in cold weather over long-term time scales

Table 8. Summary of Key Issues that will Require Additional Research and Development Based on their Immediate, Short-term and Long-term Impact

Topic	Immediate impact	Short-term impact	Long term impact
Hydraulic design	• Investigate the impact of effluent control (e.g. through valves) to optimize hydraulic performance • Evaluate hydraulic performance under heavy load and traffic • Develop method to accurately measure the effective saturated and unsaturated hydraulic conductivity (K_{sat} and K_{unsat}) to determine the infiltration capacity	• Develop an in-situ test method to measure the volume reduction capacity of subgrade gravel reservoirs • Evaluate freeze-thaw damage due to the lack of paste hydration or lack of standard air void distribution • Determine the extent that binder drawdown affects infiltration performance	• Determine the hydraulic impact (i.e., impervious vs. pervious) of permeable pavement on a watershed scale • Modify infiltration models to incorporate the hydraulic performance of permeable pavement
Structural design	• Determine bearing capacity of permeable pavements • Shear failure criteria for base, subbase, and subgrade • Shear resistance of surface • Design and construction of base and subbase layers • Strength vs. Permeability vs. Cost • Non-destructive evaluation • Performance-related Specifications	• Develop guidelines for Joint spacing, formation, maintenance and repair • Design and construction of transition elements with adjacent pavements and utilities • Concrete placement and curing • Non-destructive characterization of in-place concrete, rational acceptance criteria, and pay factors • Identification of main modes of fatigue cracking, rutting, and thermal cracking resistance	• Current permeable designs rely on existing procedures for conventional pavements. Develop specific structural design method related to permeable pavement that address modes of failure, pavement behavior with construction practices, and fully validated performance models.
Maintenance	• Determine the impact of sub-surface temperature profiles on maintenance requirements • Investigate potential reduction in salt application with permeable pavements	• Investigate non-chloride deicers to determine their performance and required loading rates • Determine optimum methods and frequency of cleaning	• Investigate long-term permeability performance • Development of a standard method to evaluate clogging and surface cleaning
Water quality	• Quantify the carbon sequestration in the concrete permeable pavement • Quantify surface pollutant load reduction associated with permeable pavement installations • Obtain a better record of chloride application rates and use mass balance approach to determine chloride discharge to surface water	• Investigate fate and transport of nitrogen and phosphorus in permeable pavement system • Evaluate modified binder and aggregate mix design as a source of pollution • Determine impact of permeable pavement on water quality on watershed scale	• Simulate the short and long-term impact of possible pollutants on groundwater • Monitor long-term water quality to calibrate and verify infiltration/water quality models • Investigate the impact of different environments for microorganisms within the PP system for pollutant removal

Table 9. Summary of Significance, Knowledge Gaps and Future Direction Related to the Sustainable Permeable Pavement with Respect to the Proposed Surface Urban Revelution

Topic	Significance	Knowledge gaps and future direction
Climate change	Climate changes will create new normative urban environments for permeable pavement systems. For instance, the anticipated rainfall environment is determined by percentiles of historical rainfall data (Smith et al. 2013), but the amount associated with the same percentiles will be different in the future. Thus, water and heat flux and storage will be different, as will the stress on the system from weather and human activity.	Climate indices and thresholds for permeable pavement systems, their variability in the past, and their expected variability under climate warming.
Micrometeorology	We lack a quantitative understanding of how permeable pavements differ in terms of absorbing, storing, and transmitting both heat and water, under the full range of environmental conditions. We do not know how the pavement system's radiative, thermal, and hydrologic properties combine to partition solar energy between reflection, sensible heat, latent heat, and ground heat.	Effective (apparent) thermal conductivity of pavement, which quantifies heat transfer by both conduction and phase change. Assessment of how pavement and base layer radiative, thermal, and hydrologic properties interact in affecting the urban area under diurnal and longer climatic inputs. A model coupling energy and water flow in a permeable pavement system, allowing numerical evaluation of new materials and designs.
Stormwater pollution	It is unclear if permeable pavement and soil lose their filtration ability over time. At the same time, little is known about the ability of permeable pavements to remove dissolved components, raising the possibility that permeable surfaces could increase discharge of solutes into groundwater or other receiving waters. We need to understand how that change will alter the hydrologic regimes and the transport and fate of urban stormwater pollutants. Additionally, there is need to investigate how actively controlled (i.e., smart) subsurface drainage systems can be developed to optimize the otherwise passive drainage system approaches used today.	Better understanding of water flow, and transport and fate of major urban pollutants, including, nutrients, organics, metals, and pathogens, within and through the vadose zone under permeable pavements, subject to different climatic, soil, and hydrogeological conditions as well as varying pollutant loads. Investigating beneficial microbial activities and their impact on retention and biodegradation of pollutants in infiltrated urban stormwater under permeable pavements. Developing a smart subsurface drainage system with sensors and controls interface for performance monitoring within a geospatial system network.

Table 9 (continued)

Cool island impact	Cooling impact of permeable pavement (particularly pervious concrete) has been documented (Haselbach et al., 2011; Li, 2012). However, the literature is lacking any research or guidance for improving permeable pavement heat storage potential besides albedo. Additionally, the literature is lacking information related to the impacts of clogging and cleaning on heat transfer. Additional research is needed to provide results necessary for accurate thermal modeling and support actively designing urban heat island mitigating permeable pavements.	Understand the influence of porosity and size of interconnected voids in permeable pavement on heat storage behavior across coarse aggregate types. Use photocatalytic surface on concrete pavement to reduce soiling Use cleaning program to maintain high solar reflectance of concrete surfaces Evaluate how pavement materials that either retain or wick moisture will result in enhanced evaporative cooling or stormwater retention.
Energy impact	Permeable pavement characteristics such as roughness, microtexture, and rolling resistance usually are the three parameters that influences the fuel consumptions of vehicles in transportation sectors.	Pavement design process that considers smoothness over time as a key design parameter Optimizing maintenance time and rehabilitation based on IRI trigger value and traffic volume Minimizing pavement roughness due to utility cuts Design pavements with less deflection and less viscoelastic damping, in lanes with high volumes of heavy trucks, slow speeds and hot temperatures Use of open-graded asphalt mixes and exposed aggregate concrete surfaces with high macrotexture.
Noise impact	Quieter pavement will generate less noise and make the nearby highway environment a better place to live for both animal and human	Use durable open-graded or SMA mixes Elimination of transverse tining and use of narrow joints
Materials recycling impact	For sustainability purpose, it is anticipated that large quantities of existing pavements materials be recycled and the recycled crushed stone, gravel, and sand be used for construction of new permeable pavements. The impact of these recycled materials on structural property and water quality is not known.	The physical and chemical properties of recycled materials. Impact of recycled materials on structural integrity and groundwater contamination. Life cycle cost analysis

References

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

ACI (American Concrete Institute). 2010. *Report on Pervious Concrete*. ACI, Farmington Hills, MI, USA. ACI 522R-10.

ACPA (American Concrete Paving Association). 2009. Stormwater management with pervious concrete pavement. ACPA, Skokie, IL, USA.

Akbari, H., L. Rose, and H. Taha. 1999. Characterizing the Fabric of the Urban Environment: A Case Study of Sacramento. CA. LBNL-44688. http://sfrc.ufl.edu/urbanforestry/Resources/PDF%20downloads/Akabari_1999.pdf (Accessed June 16, 2015). Lawrence Berkeley National Laboratory, Berkeley, CA.

Akbari, H., M. Pomerantz, and H. Taha, (2001), Cool surfaces and shade trees to reduce energy use and improve ari quality in urban areas, Solar Energy, 70(3), 295-310.

Akbari, H., Rose, L. S., & Taha, H. (2003). Analyzing the land cover of an urban environment using high- resolution orthophotos. Landscape and Urban Planning, 63,1–14.

Al-Rubaei, A.M, Stenglein, A.L, Viklander, M., Blecken, G.T. (2013). Long-term hydraulic performance of porous asphalt pavements in northern Sweden. Journal of Irrigation and Drainage Engineering, 139(6), 499-505.

Amde, A.M., Rogge, S. (2013). *Development of high quality pervious concrete specifications for Maryland conditions*. State Highway Administration Maryland Department of Transportation, Report number: MD-13-SP009B4F, Baltimore, MD, USA.

Barrett M. E., P. Kearfott, J. F. Malina (2006). Stormwater Quality Benefits of a Porous friction course and its effect on pollutant removal by roadside shoulders, Water Environment Research, 78(11), 2177-2185.

Bean, E.Z., Hunt, W.F., Bidelspach, D.A., Burak, R.J. (2004). Study on the surface infiltration rate of permeable pavements. *Proceedings of the 1st Water and Environment Specialty Conference of the Canadian Society for Civil Engineering*, Saskatoon, Saskatchewan, Canada, June 2-5.

Bean, Z., E. Frederick, W. Hunt, and D.A. Bidelspach (2007). Evaluation of Four Permeable Pavement Sites in Eastern North Carolina for Runoff Reduction and Water Quality Impacts. J. Irrig. Drain Eng., 133(6), 583–592.

Boving, T., Stolt, M., Augenstern, J. & Brosnan, B. (2008). Potential for localized groundwater contamination in a porous pavement parking lot setting in Rhode Island. Environ. Geol., 55 (3), 571–582.

Brattebo, B.O., Booth, D.B. 2003. Long-term stormwater quantity and quality performance of permeable pavement systems. Water Research, 37(18), 4369–4376.

Briggs, J.F. 2006. Performance assessment of porous asphalt for stormwater treatment. M.S. Thesis. University of New Hampshire, Durham, NH, USA.

Brown, C., Chu, A., van Duin, B. & Valeo, C. 2009. Characteristics of sediment removal in two types of permeable pavement. Water Qual. Res. J. Can., 44 (1), 59–70.

Caltrans. (2003). Caltrans retrofit program final report. Caltrans Division of Environmental Analysis, Report No. CTSW - RT - 01 – 050, Sacramento, California, USA.

Campbell, G.S., J.D. Jungbauer, W.R. Bidlake, and R.D. Hungerford (1994), Predicting the effect of temperature on soil thermal conductivity, Soil Sci., 158, 307–313.

Chai, L., M. Kayhanian, B. Givens, J. Harvey and D. Jones (2012). Hydraulic Performance of Fully Permeable Highway Shoulder Retrofit for Stormwater Runoff Management. Journal of Environmental Engineering, 138(7), 711-722.

Chopra, M., Kakuturu, S., Ballock, C., Spence, J., Wanielista, M. (2010). Effect of Rejuvenation Methods on the Infiltration Rates of Pervious Concrete Pavements. Journal of Hydrologic Engineering, 15(6), 426-433.

Coleri, E., M. Kayhanian, J.T. Harvey, K. Yang and J. M. Boone (2013). Clogging Evaluation of Open Graded Friction Course Pavements Tested under Rainfall Simulation and Heavy Vehicle Simulator. Journal Environmental Management, 129(8), 164-172.

Collins, K.A., Hunt, W.F, Hathaway, J.M. (2010). Side-by-side comparison of nitrogen species removal for four types of permeable pavement and standard asphalt in eastern North Carolina, Journal of Hydrologic Engineering, 15(6), 512-521.

Coseo, P. and L. Larsen. (2014). How factors of land use/land cover, building configuration, and adjacent heat sources and sinks explain Urban Heat Islands in Chicago. Landscape and Urban Planning, 125, 117-129.

CRMCA (Colorado Ready Mixed Concrete Association). (2009). *Specifier's guide for pervious concrete pavement design*. CRMCA, Centenial, CO, USA.

Dannenberg, A., H. Frumkin, & R. Jackson, (2011), Making Healthy Places: A Built Environment for Health, Well-Being, and Sustainability, Washington: Island Press.

Dean, J., K. van Doooren, & P. Weinstein, (2011), Does biodiversity improve mental health in urban settings? Medical Hypotheses, 76, 877-880.

Donavan, P. (2006). Comparative Measurements of Tire/Pavement Noise in Europe and the United States – NITE Study. FHWA/CA/MI-2006/09. http://www.dot.ca.gov/hq/env/noise/pub/NITE_Study_FINAL.pdf (Accessed June 16, 2015). California Department of Transportation, Sacramento, CA.

Donovan, G., D. Butry, Y. Michael, J. Prestemon, A. Liebhold, D. Gatziolis, & M. Mao, (2013), American Journal of Preventative Medicine, 44(2), 139-145.

Drake, J. (2013). Performance and operation of partial infiltration permeable pavement systems in the Ontario climate. Ph.D. Thesis, University of Guelph, Guelph, Ontario, Canada, June 2013.

Drake, J., Bradford, A., Marsalek, J. (2013). Review of environmental performance of permeable pavement systems: state of the knowledge. Water Quality Research Journal of Canada, 48(3), 203-222.

Drake, J., Bradford, A., Van Seeters, T., MacMillan, G. (2012). Evaluation of permeable pavements in cold climates. Toronto and Region Conservation Authority, Toronto, Canada.

Ellis, E., Wang, H., Xioa, H., Peng, K., Liu, X., Li, S., Ouyand, H., Cheng, X., Yang, L. (2006). Measuring long-term ecological changes in densely populated landscapes using current and historical high resolution imagery. Remote Sensing of Environment, 100, 457-473.

Fan, L.F., Chen, J.W., Wang, S.F., Chen, T.H., Chen, C.P., Chao, W.L., Hsieh, H.L. (2013). Microbial Community Structure and Activity under Various Pervious Pavements. Journal of Environmental Engineering, Published online, 10.1061/(ASCE)EE.1943-7870.0000798.

Ferguson, B. (2005). Porous Pavements. Taylor & Francis, New York, NY, USA. ISBN-13: 978-0849326707.

Frumkin, H., (2003), Healthy places: Exploring the evidence, American Journal of Public Health, 93 (9).

Fwa, T.F., Tana, S.A., Chuaia, C.T., Guwea, Y.K. (2001). Expedient permeability measurement for pervious pavement surface.” International Journal of Pavement Engineering, 2(4), 259-270.

Gilbert, J.K., Clausen, J.C. (2006). Stormwater runoff quality and quantity from asphalt, paver, and crushed stone driveways in Connecticut. Water Research, 40(4), 826-832.

Golroo, A., Tighe, S.L., (2012b). Pervious concrete pavement performance modeling: an empirical approach in cold climates. Canadian Journal of Civil Engineering, 39(10), 1100-1112.

Grimm, N., S. Faeth, N. Golubiewski, C. Redman, J. Wu, X. Bai, & J. Briggs, (2008), Global change and the ecology of cities, Science, 319, 756-760.

Gulyas, A., J. Unger, A. Matzarakis, (2006), Assessment of the microclimatic an human comfort conditions in a complex urban environment: Modelling and measurements, Building and Environment 41, 1713-1722.

Gunderson, J. (2008). Pervious pavements: New findings about their functionality and performance in cold climates. Stormwater Magazine, September.

Harlan, S., A. Brazel, L. Prashad, W. Stefanov & L. Larsen, (2006), Neighborhood microclimates and exposure to heat stress. Social Science & Medicine 63, 2847-2863.

Haselbach, L., M. Boyer, J.T. Kevern, and V.R. Schaefer (2011), Cyclic heat island impacts on traditional versus pervious concrete pavement systems, Trans. Res. Rec. 2240, 107–115.

Haselbach, L.M., Freeman, R.M. (2006). Vertical porosity distributions in pervious concrete pavement. *ACI Materials Journal*, 103(6), 452.

Hayden, R. E. (1971). “Roadside Noise from the Interaction of a Rolling Tire with Road Surface.” Proceedings of Purdue Noise Conference. West Lafayette, IN. pp. 62–67.

Hein, D., Strecker E., Poresky A., and Roseen R. (2013a). Permeable Shoulders with Stone Reservoirs.” Report prepared from the American Association of State Highway and Transportation Officials (AASHTO), NCHRP Project 25-25, Task 82, Transportation Research Board, Washington D.C. http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP25-25(82)_FR.pdf (Accessed June 16, 2015)

Hein, M.F., Dougherty, M., Hobbs, T., (2013b). Cleaning Methods for Pervious Concrete Pavements. International Journal of Construction Education and Research, 9(2):102-116.

Henderson, V., Tighe, S. (2012). Evaluation of pervious concrete pavement performance in cold weather climates. International Journal of Pavement Engineering, 13(3), 197-208.

Hicks G. (1991), Moisture damage in asphalt concrete. Synthesis of Highway Practice No. 175, National Cooperative Highway Research program (NCHRP), Washington D.C, United States.

Houle, J., Roseen, R., Ballestero, T., Puls, T.,Sherrard, J., Jr. (2013). Comparison of maintenance cost, labor demands, and system performance for LID and conventional stormwater management. J. Environ. Eng., 139(7), 932–938.

Houle, K. (2008). Winter performance assessment of permeable pavements - A comparative study of porous asphalt, pervious concrete, and conventional asphalt in a northern climate. M.S. Thesis. University of New Hampshire, Durham, NH, USA.

Huang, J., Valeo, C., He, J., Chu, A. (2012). Winter performance of inter-locking pavers-stormwater quantity and quality. Water, 4(4), 995-2008.

Imran, H. M., Akib, S., Karim, M.R. (2013). Permeable pavement and stormwater management systems: a review. Environmental Technology, 13(18), 2649-3656.

Izevbekhai, B.I., Akkari, A. (2011). Pervious concrete cells on MnROAD low-volume road. Minnesota Department of Transportation report no. MN/RC 2011-23, St. Paul, MN, USA.

James, W. & Gerrits, C. (2003). Maintenance of infiltration in modular interlocking concrete pavers with external drainage cells. In: Practical Modeling of Urban Stormwater Systems, (W. James, ed.). Computational Hydraulics International, Guelph, (11), 417–4

Jones D., J. Harvey,H.Li,T. Wang, R.Wu and B.Campbell (2010). Laboratory Testing and Modeling for Structural Performance of Fully Permeable Pavements under Heavy Traffic: Final Report. Prepared for the California Department of Transportation Division of Environmental Analysis-Storm Water Program.Sacramento, CA.CTSW-RT-10-249.04/UCPRC-RR-2010-01.

Kang J-H, S. L. Lau, M. Kayhanian, and M.K. Stenstrom (2009). Characteristics of Highway Stormwater Runoff in Los Angeles: Metals and PAHs. Water Environment Research, 81(3), 308-318.

Kayhanian M., C. Stransky, S. Bay, S. L. Lau, and M. K., Stenstrom (2008). Toxicity Evaluation of Urban Highway Runoff with Respect to Storm Duration. Journal of Science of the Total Environment, 389(2-3), 386-406.

Kayhanian M., Chai L., Givens B. (2010). Laboratory testing and simulation for hydraulic performance of fully permeable pavements. Report number CTSW-RT-10-247.03 prepared for California Department of Transportation, Sacramento, California.

Kayhanian M., D. Anderson, J. Harvey, D. Jones and B. Muhunthan (2012). Permeability Measurement and Scanning Images to Investigate Clogging of Pervious Concrete Pavements in Parking Lots. Journal of Environmental Management, 95(1), 114-123.

Kayhanian, M, A. Vichare, P. Green, C. Alaimo, H-M Hwang, J. M. Signore, M. Troxler, D. Jones, Harvey, J. (2009a). Water quality evaluation of leachate produced from pavement specimens under controlled laboratory conditions. Journal of Road Materials and Pavement Design, 11(1), 9-28.

Kayhanian, M., A. Vichare, P. Green, Harvey, J. (2009b). Leachability of dissolved chromium from asphalt and concrete surfacing materials. Journal of Environmental Management, 90(11), 3574-3580.

Kayhanian, M., Anderson, D., Harvey, J.T., Jones, D., Muhunthan, B. (2012a). Permeability measurement and scan imaging to assess clogging of pervious concrete pavements in parking lots. Journal of Environmental Management, 95(1),114-123.

Kayhanian, M., B. Fruchtman, J.S. Gulliver, C. Montanaro and Ezio Raniere (2012). Review of Highway Runoff Characteristics: Comparative Analysis and Universal Implications. Water Research, 46(20), 6609-6624.

Kayhanian, M., C. Suverkropp, A. Ruby, and K. Tsay (2007). Characterization and Prediction of Highway Stormwater Pollutant Event Mean Concentrations. Environmental Management, 85(2) 279- 295.

Kevern, J.T., Schaefer, V.R., Wang, K. (2009). Temperature Behavior of Pervious Concrete Systems. Journal of the Transportation Research Board, 2098, 94-101.

Kevern, J.T., Wang, K., Schaefer, V.R. (2008). Pervious Concrete in Severe Exposures. *Concrete International*, 30(7), 43-49.

LADPW (Los Angeles County Department of Public Works). (2002). Development planning for storm water management. Los Angeles County.

Lau S. L., M. Kayhanian, and M. K. Stenstrom (2005). PAHs and Organic Pollutants in Highway Runoff. Paper 7F5, Proceedings of the IAW-ASPIRE Conference, July 10-15, Singapore.

Lebens, M.A., Troyer, B. (2012). Porous Asphalt Pavement Performance in Cold Regions, Minnesota Department of Transportation (MnDOT), Report number MN/RC 2012-12, St. Paul, MN, USA.

Leming, M.L., Malcom, H.R., Tennis, P.D. (2007). Hydrologic Design of Pervious Concrete, Portland Cement Association (PCA), Skokie, IL, USA.

LI, H., Jones, D., Wu, R. and Harvey, J. (2014). Development and HVS Validation of Design Tables for Permeable Interlocking Concrete Pavement: Final Report. Davis and Berkeley, CA: University of California Pavement Research Center. (RR-2014-04).

Li H., J. Harvey and A. Kendall (2012). Field Measurement of Albedo for Different Land Cover Materials and Effects on Thermal Performance, Journal of Building and Environment, 59(0), 536-46.

Li H., J. Harvey and D. Jones (2012). Developing a Mechanistic-Empirical Design Procedure for Fully Permeable Pavement under Heavy Traffic.Transportation Research Record: Journal of the Transportation Research Board, 2305(0), 83–94.

Li, H., Harvey, J.T., Holland, T.J., Kayhanian, M. (2013a). The use of reflective and permeable pavements as a potential practice for heat island mitigation and stormwater management. Environmental Research Letters, 8, 1-14.

Li, H., Jones, D., Harvey, J. 2012. Development of mechanistic-empirical design procedure for fully permeable pavement under heavy traffic. Transportation Research Record, 2305, 83-94.

Liu Q. 1 and D. Cao (2009). Research on Material Composition and Performance of Porous Asphalt pavements. Journal of Materials in Civil Engineering, 21(4), 135-145.

Low, K.; Harz, D.; and Neithalath, N., (2008). Statistical Characterization of the Pore Structure of Enhanced Porosity Concretes. *Proceedings of the NRMCA Concrete Technology Forum*, Denver, CO.

Lucke, T., Beecham, S. (2011). Field investigation of clogging in a permeable pavement system. Building Research and Information, 39(6), 603-615.

Mallela, J., Larson, G., Wyatt, T., Hall, J. and Barker, W. (2002). User's Guide for, Drainage Requirements In Pavements – Drip 2.0 Microcomputer Program, Report No. FHWA-IF-02-05C, Office of Pavement Technology, Federal Highway Administration, Washington, DC.

Massoudieh A. and M. Kayhanian (2013). A Bayesian Chemical Mass Balance Method for Surface Water Contaminant Source Apportionment. Journal of Environment Engineering, 139(2), 250-260.

Massoudieh, A., Ginn, T. R. (2008). Modeling colloid-enhanced contaminant transport in stormwater infiltration basin BMPs" Vadose Zone Journal, 7(4), 1261-1268.

Mata, L.A., Leming, M.L. (2012). Vertical Distribution of Sediments in Pervious Concrete Pavement Systems. ACI Materials Journal, 109(2), 149-155.

Mayer, H., J. Holst, P. Dostal, F. Imbery, & D. Schindler, (2008), Human thermal comfort in summer within an urban street canyon in Central Europe. Meteorology Z., 17(3), 241-250.

Mbanaso , F.U., Coupe, S.J., Charlesworth, S.M., Nnadi, E.O. (2013). Laboratory-based experiments to investigate the impact of glyphosate-containing herbicide on pollution attenuation and biodegradation in a model pervious paving system. Chemosphere, 90(2), 737-746.

McDaniel, R. S. and W. D. Thorton. (2005). Field Evaluation of a Porous Friction Course for Noise Control. 84th Annual Meeting of the Transportation Research Board. Transportation Research Board, Washington, DC.

Meininger, R.C. (1988). No-fines pervious concrete for paving. *Concrete International*, 10(8), 20-27.

Millstein, D. (2013). Cool Communities: Benefits of Cool Pavements in CA Cities. Presented at the 2013 International Concrete Sustainability Conference. San Francisco, CA. May 7. http://www.nrmcaevents.org/?nav=display&file=409

Mulligan, A., (2005). *Attainable Compressive Strength of Pervious Concrete Paving Systems*. MS Thesis, University of Central Florida, 132 pp.

NAPA (National Asphalt Pavement Association). (2008). Porous asphalt pavements for stormwater management, Design, Construction and maintenance guide. Publication IS-131, NAPA, Lanham, MD, USA.

NRCS (National Resource Conservation Service, U.S. Department of Agriculture). (1986). Urban hydrology for small watersheds, TR 55, Washington D.C.

Offenberg, M. 2005. Producing Pervious Pavements. *Concrete International*. 27(3), 50-54.

Ongel, A., J. T. Harvey, E. Kohler, Q. Lu, and B. D. Steven. (2008). Investigation of Noise, Durability, Permeability, and Friction Performance Trends for Asphaltic Pavement Surface Types: First- and Second-Year Results. UCPRC-RR-2007-03. University of California Pavement Research Center, Davis and Berkeley, CA.

Partl, M.N., Momm, F., Bariani, B. (2003). Study of the aggregate for the pervious asphaltconcrete performance testing and evaluation of bituminous materials. *Proceedings of the6th International RILEM Symposium*, 2003/04/14-2003/04/16. Zurich, Switzerland. pp.237-243.

Pratt, C.J., Newman, A.P., Bond, P.C. (1999). Mineral oil bio-degradations within a permeable pavement: Long term observations. Water Science and Technology, 39(2), 103-109.

Reyes, C. H. and J. Harvey. (2011). A Method for Predicting Sound Intensity Noise Levels Using Laboratory Pavement Cores. INTER-NOISE and NOISE-CON Congress and Conference Proceedings. Portland, OR.

Rose, L., H. Akbari and H. Taha. (2003). Characterizing the Fabric of the Urban Environment: A Case Study of Metropolitan Houston. TX. LBNL-51448. http://escholarship.org/uc/item/3ww7p48f (Accessed July 14, 2013). Lawrence Berkeley National Laboratory, Berkeley, CA.

Roseen, R.M., Ballestero, T.P., Houle, J.J., Avellaneda, P., Briggs, J., Fowler, G., Wildey, R. (2009). Seasonal performance variations for storm-water management systems in cold climate conditions. Journal of Environmental Engineering, 135(3), 128-137.

Roseen, R.M., Ballestero, T.P., Houle, J.J., Avellaneda, P., Briggs, J., Houle, K.M. (2012).Water quality and hydrologic performance of a porous asphalt pavement as a storm-water treatment strategy in a cold climate. Journal of Environmental Engineering, 138(1), 81-89.

Roseen, R.M., Ballestero, T.P., Houle, K.M., Heath, D., Houle, J.J. (2014). Assessment of winter maintenance of porous asphalt and its function for chloride source control, Journal of Transportation Engineering, 140(2), 1-8.

Rowe, A. A., Borst, M., O'Connor, T.P. and Stander, E.K. (2010). Permeable pavement demonstration at the Edison Environmental Center, in Proceedings, Low Impact Development 2010: Redefining Water in the City, 2010 ASCE, Reston, VA.

Schaefer, V.R., Wang, K., Suleiman, M.T., Kevern, J.T. (2006). *Mix Design Development for Pervious Concrete In Cold Weather Climates*, Iowa Department of Transportation, Report number 2006-01, Ames, IA, USA.

Scholz M., P. Grabowiecki (2007). Review of permeable pavement systems. Building and Environment, 42(11), 3830–3836.

Scholz, M. (2013). Water Quality Improvement Performance of Geotextiles Within Permeable Pavement Systems: A Critical Review. Water, 5(2), 462-479.

Schwartz, S.S. (2010). Effective CN and hydrologic design of pervious concrete storm-water systems. Journal of Hydrologic Engineering, 15(6), 465-474.

Shu, X., Huang, B., Wu, H., Dong, Q., Burdette, E.G. (2011). Performance comparison of laboratory and field produced pervious concrete mixtures. Construction and Building Materials, 25(2011), 3187–3192.

SI Concrete Systems. (2002). Fiber-Reinforced Pervious Concrete. Project 2120-36, Chattanooga, TN, Oct. 25.

Signore J., J. Harvey, M. Kayhanian, N. Santero, R. Wu, M. Troxler, F. Farshidi. (2008). Performance evaluation of permeable pavements for water quality under heavy traffic. Final report prepared for the Caltrans Division of Environmental Analysis, Report No. CTSW-RT-07-168-16.2, Sacramento, California, USA.

Smith, David R. (2011). *Permeable Interlocking Concrete Pavements, 4th edition*. Interlocking Concrete Pavement Institute (ICPI), Herndon, VA, USA.

Sonebi, M., Bassuoni, M.T. (2013). Investigating the effect of mixture design parameters on pervious concrete by statistical modeling. *Construction and Building Materials*, 38:147-154.

St. John, M.S., Horner, R.R. (1997). Effect of Road Shoulder Treatments on Highway Runoff Quality and Quantity, Report WA-RD 429.1, Washington State Transportation Center, University of Washington, Seattle, WA.

Standish, R., Hobbs, R., & J. Miller, (2013), Improving city life: Options for ecological restoration in urban landscapes and how these might influence interactions between people and nature, Landscape Ecology 28(6), 1213-1221.

Thomle, J.N. (2010). The Declining pH of Waters Exposed to Pervious Concrete. MS Thesis, Department of Civil and Environmental Engineering, Washington State University, Pullman, WA, USA.

Tyner, J.S., Wright, W.C., Dobbs, P.A. (2009). Increasing exfiltration from pervious concrete and temperature monitoring. Journal of Environmental Management, 90(8), 2636-2641.

UNHSC (University of New Hampshire Stormwater Center). (2009). UNHSC Design specifications for porous asphalt pavement and infiltration beds. University of New Hampshire, Durham, NH, USA.

Urban Drainage and Flood Control District (UDFCD). (2011a). Stormwater Quality Monitoring Report Permeable Interlocking Concrete Pavement (PICP) at Denver Wastewater Management Building Denver, Colorado 2008-2010. UDFCD, Denver, CO, USA.

Urban Drainage and Flood Control District (UDFCD). (2011b). Stormwater Quality Monitoring Report Porous Asphalt at Denver Wastewater Management Building Denver, Colorado 2008-2010. UDFCD, Denver, CO, USA.

USEPA (1983). Results of the Nationwide Urban Runoff Program. PB 84-185552, Washington, DC.

USEPA (2008). Reducing Urban Heat Islands: Compendium of Strategies–Cool Pavements. Draft. http://www.epa.gov/heatislands/resources/pdf/CoolPavesCompendium.pdf (Assessed June 16, 2015). US Environmental Protection Agency, Washington, DC.

USEPA (2010). Post-Construction Stormwater Management in New Development and Redevelopment. http://water.epa.gov/polwaste/npdes/swbmp/PostConstruction-Stormwater-Management-in-New-Development-and-Redevelopment.cfm (Assessed June 16, 2015). U. Environmental Protection Agency, Washington, DC.

USEPA (2014). SUSTAIN System for Urban Stormwater Treatment and Analysis Integration Model." http://www2.epa.gov/water-research/system-urban-stormwater-treatment-and-analysis-integration-sustain. Accessed June 16, 2015.

USEPA. (2012). District-Scale Green Infrastructure Scenarios for the Zidell Development Site, City of Portland". 2012. Green Infrastructure Technical Assistance Program. (EPA 830 R13-002), http://water.epa.gov/infrastructure/greeninfrastructure/upload/Portland_Zidell_Report.pdf

USNRC. (2008). Urban Stormwater Management in the United State. The National Academies Press, Washington, DC.

Van Dam, T., J. Harvey, S. Muench, K. Smith, M. Snyder, I. Al-Qadi, H. Ozer, J. Meijer, P. Ram, J. Roesler, A. Kendall. (2015). Towards Sustainable Pavement Systems: A Reference Document. FHWA-HIF-15-002. Federal Highway Administration, US Department of Transportation. www.fhwa.dot.gov/pavement/sustainability/ref_doc.cfm (Accessed 12 March, 2015)

Van Seters, T. (2007). Performance Evaluation of Permeable Pavement and a Bioretention *Swale, King City, Ontario*, Interim Report #3, Toronto and Region Conservation Authority, Downsview, Ontario.

Wan, W. C., W. N. Hien, T. P. Ping, and A. Z. W. Aloysius. (2009). A Study on the Effectiveness of Heat Mitigating Pavement Coatings in Singapore. 2nd International Conference on Countermeasures to Urban Heat Islands. http://heatisland2009.lbl.gov/docs/211300-ping-doc.pdf (Assessed July 12, 2013). Berkeley, CA.

Wang, T. (2013). Reducing Greenhouse Gas Emissions and Energy Consumption Using Pavement Maintenance and Rehabilitation: Refinement and Application of a Life Cycle Assessment Approach. ProQuest, UMI Dissertations Publishing, US, 2013. ISBN 1303444089/9781303444081.

Wanielista, M., Chopra, M. (2007a). *Performance Assessment of a Pervious Concrete Pavement, Report 3 of 4: Compressive strength of pervious concrete pavements*. Stormwater Management Academy, University of Central Florida, Orlando, FL, USA.

Wanielista, M., Chopra, M. (2007b). *Performance Assessment of a Pervious Concrete Pavement Used as a Shoulder for an Interstate Rest Area Parking Lot*. Stormwater Management Academy, University of Central Florida, Orlando, FL, USA.

Wardynski, B.J., Winston, R.J., Hunt, W.F. (2013). Internal water storage enhances exfiltration and thermal load reduction from permeable pavement in the North Carolina mountains. Journal of Environmental Engineering, 139(2), 187-195.

Weiss, P.T., Kayhanian, M., Khazanovich, L., and J.S. Gulliver, "Permeable Pavements in Cold Climates: State of the Art and Cold Climate Case Studies," Minnesota Department of Transportation, St. Paul, MN. (In Press).

Wenck Associates, Inc. (2014). Porous pavement paired intersection study, prepared for the Shingle Creek Watershed Management Commission, City of Robbinsdale, MN, and the Minnesota Pollution Control Agency, Maple Plain, MN, USA.

World Health Organization (WHO) (2013). Noise and Health. http://www.euro.who.int/en/health-topics/environment-and-health/nois (Accessed June 16, 2015). World Health Organization, Regional Office for Europe. Copenhagen, Denmark.

Wu, H., Huang, B., Shu, X., Dong, Q. (2011). Laboratory evaluation of abrasion resistance of Portland Cement pervious concrete, *Journal of Materials in Civil Engineering*, 23(5), 697-702.

Yang, Z., Brown, H., Cheney, A. (2006). Influence of Moisture Conditions on Freeze and Thaw Durability of Portland Cement Pervious Concrete. *Proceedings of Concrete Technology Forum: Focus on Pervious Concrete*, May 24-25, 2006, Nashville, Tennessee, 15pp.

Yong, C., Deletic, A., Fletcher, T. & Grace, M. (2008). The clogging behaviour and treatment efficiency of a range of porous pavements. Proceedings from the 11th International Conference on Urban Drainage. Edinburgh, pp. 1–10.

Yong, C.F., McCarthy, D.T., Deletic, A. (2013). Predicting physical clogging of porous and permeable pavements. Journal of Hydrology, 481:48-55.