Proposal for the Use of Pervious Pavement for Repaving the Belmont High School Parking Lot

PREPARED BY:

Roger D. Colton
Town Meeting Member, Precinct 6

ON BEHALF OF:

Sustainable Belmont
John Kolterman, Chair

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Synopsis

Sustainable Belmont requests that the Belmont Public Schools (BPS) consider the use of pervious pavement in the resurfacing of the Belmont High School (BHS) parking lot. Pervious pavement has the potential to be an effective stormwater Best Management Practice (BMP). Permeable pavement transforms areas that were a source of stormwater runoff into a treatment system and can effectively reduce or eliminate runoff that would have been generated from an impervious paved area. Permeable pavement addresses not merely the flooding issues involved with stormwater runoff, but water pollution issues as well.

There is no question but that the installation of pervious pavement is more expensive on the front-end than non-permeable alternatives, all other things equal. There is, however, also no question but that all other things are not equal. Universally, studies report that permeable pavement may well be cost-effective both on a life-cycle basis and when considering the offsetting costs of avoiding other design needs. Aside from the design cost savings, pervious asphalt has been found to have a lifespan of twice (or more) of traditional asphalt.

While pervious asphalt has some limitations, these limitations should not be over-stated. The limitation perhaps most often discussed is the propensity of pervious asphalt to "clog" over time. Even while accurate, this observation fails to acknowledge the continuing viability of pervious asphalt as a stormwater runoff management strategy even given expected clogging. Even given long-term clogging, surface infiltration rates usually well exceed 1 inch per hour, which is sufficient in most circumstances for the surface to effectively manage intense stormwater events. Clogging can be minimized by engaging in periodic routine, inexpensive maintenance activities such as vacuum sweeping.

The Belmont Public Schools should give serious consideration to the availability of Best Management Practices (BMPs) for stormwater runoff control. In addition to reducing stormwater runoff and its impact on flooding, the use of a pervious surface at BHS would also reduce the non-point pollution discharges flowing out of the Town of Belmont. Even setting aside these environmental concerns, while the use of traditional asphalt may be

cheaper at the front-end, substantial research reports that when all costs are considered, including long-term maintenance, repair and replacement costs, pervious pavement may offer a financial advantage to the Town.

Obviously Belmont will not "solve" its flooding, or its nonpoint pollution runoff problems, with what it does at Belmont High School. Even more obviously, Belmont will never even begin to address these problems unless it begins to take the necessary steps, both large and small, when and where it can. Using pervious asphalt at Belmont High is a beginning step toward a responsible environmental and financial stewardship for the Town.

Sustainable Belmont asks that the Belmont Public Schools consider the use of permeable asphalt as a pavement for BHS and report back to the community whether site conditions are conducive to such use.

Sustainable Belmont requests the Belmont Public Schools ("BPS") to consider the use of pervious pavement[1] in the resurfacing of the Belmont High School ("BHS") parking lot. According to the Federal Highway Administration ("FHWA"):

> Porous pavements have the potential to be an effective ultra-urban [stormwater Best Management Practice] BMP. While conventional pavement results in increased rates and volumes of surface runoff, porous pavements allow some of the stormwater to percolate through the pavement and enter the soil below.
>
> The types of porous pavements used include porous asphalt and concrete surfaces, as well as several types of lattice pavers, which are hollow concrete blocks or stones. . . Porous pavements work by allowing streets, parking lots, sidewalks and other impervious covers to retain their natural infiltration capacity while maintaining the structural and functional features of the materials they replace.[2]

Advantages of Pervious Pavement

The use of pervious pavement at BHS could eliminate, or substantially reduce, stormwater runoff from the BHS parking lot, thus turning the lot into a flood control asset. According to EPA:

> Permeable pavement transforms areas that were a source of stormwater into a treatment system and can effectively reduce or eliminate runoff that would have been generated from an impervious paved area. . .The infiltration rate of properly

[1] The distinctions between porous concrete and porous asphalt will be made where appropriate. Much of the discussion, however, will reference "permeable pavement" (or other similar terms) generically. "Permeable" and "pervious" are preferred over "porous."

[2] Federal Highway Administration, Stormwater Best Management Practices in an Ultra-Urban Setting: Selection and Monitoring, Fact Sheet: Porous Pavements.

> constructed pervious concrete and base generally exceeds the design storm peak rainfall rate.[3]

The use of pervious pavement is a long-term measure to help control stormwater runoff in Belmont. A January 2012 "Transportation Synthesis Report" by the Wisconsin Department of Transportation (WisDOT) states: "infiltration rates are generally hundreds of inches per hour. Even as pavements clog with time, infiltration rates remain above 1 inch per hour, sufficient for most stormwater events. (Regular maintenance will keep permeability even higher.)"[4] EPA agrees, reporting that "infiltration rates are hundreds of inches per hour initially, but over time become as low as 5 inches per hour because of clogging."[5] Similarly, according to the University of New Hampshire Stormwater Center, "permeably paved areas are typically designed to infiltrate runoff from at least a two-year storm; therefore, runoff will be reduced by 100 percent for most rainstorms. Permeably paved areas generally infiltrate 70 percent to 80 percent of annual rainfall."[6]

One 2012 examination of the use of porous asphalt[7] in cold climates reports:

> With the implementation of the Phase II rules under the Clean Water Act and the need for innovative storm-water management, storm-water practitioners are looking for designs that provide a high level of water-quality treatment performance and include infiltration of storm-water runoff, for which soils are useful, particularly for source control. The use of porous pavements for parking lots for new and redevelopment projects are one watershed-based strategy that can meet these requirements. Porous pavements can both mitigate impacts from new development and reverse impacts in areas with redevelopment because of the ability to cleanse and cool runoff and reduce runoff volumes. Adoption of porous pavement usage is hampered by widespread concern with regard to cost, winter performance, clogging and maintenance, and risk to groundwater quality. These concerns can be addressed effectively with appropriate designs, proper

[3] U.S. Environmental Protection Agency (EPA) (September 2009). National Pollutant Discharge Elimination System (NPDES), Pervious Concrete Pavement.
[4] WisDOT Research and Library Unit (January 2012). "Comparison of Permeable Pavement Types: Hydrology, Design, Installation, Maintenance and Cost." This research paper is attached as Appendix A.
[5] U.S. Environmental Protection Agency (September 2009). National Pollutant Discharge Elimination System (NPDES), Pervious Concrete Pavement.
[6] University of New Hampshire Stormwater Center (2008). Permeable Pavement Fact Sheet.
[7] When reference is made to "porous asphalt," care must be taken to not confuse it with older technology. According to Roseen, et. al (see, note 8 below), "[t]he pavement technology for porous asphalts has been in use for decades and is known as open-graded friction course (OGFC), a pavement mix with a void content commonly in the 18–20% range, also known as permeable friction coarse (PFC). Although the two items are similar in many respects, OGFC is not equivalent to porous asphalt (PA), and *many of the misconceptions about PA are with respect to OGFC (i.e., low durability, high maintenance, reduced cold-climate functionality).*" (emphasis added).

installation, long-term maintenance commitment, and quality controls for materials production.[8]

Permeable pavement addresses not merely the flooding issues involved with stormwater runoff, but the water pollution issues as well. The Federal Highway Administration (FHWA) reports that pervious pavements are as effective at removing pollutants from stormwater as other infiltration devices.[9]

The use of permeable paving offers particular cold weather benefits:

- Snow-covered pervious pavement clears more quickly than other pavements since it allows for more rapid thawing;

- Pervious surfaces do not generate ice covers, including black ice, since the moisture drains through the concrete.

According to Roseen (cited previously), the advantages of permeable asphalt include the following:

> Winter Maintenance
>
> Most experience with winter performance and maintenance of PA has been positive, especially compared to standard pavements and in contrast to OGFC. Cahill et al. (2003) reported that PA parking lots require less plowing and that snow and ice melt faster than regular parking lots. The open pore spaces in PA permit water to freely drain through to the bed, providing rapid drainage of any snowmelt. Cahill et al. (2003), Jackson (2003), and Ferguson (2005) proposed several general guidelines for winter maintenance of PA. Ultimately, if reduced winter deicing practices are needed (UNHSC 2009b), porous asphalt could have a winter maintenance cost benefit.[10]

Relative Costs of Pervious Pavement

There is no question but that the installation of pervious pavement[11] is more expensive on the front-end than non-permeable alternatives, all other things equal.[12] There is, however, *also* no

[8] Roseen, et al. (January 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* (ASCE). A complete copy of the Roseen article is attached to this proposal as Appendix B.
[9] EPA (September 2009). Stormwater Best Management Practices in an Ultra-Urban Setting: Selection and Monitoring: Fact Sheet: Porous Pavements, Washington D.C.
[10] Roseen, *Porous Asphalt Pavement in a Cold Climate*, note 8, supra.
[11] Annual maintenance for permeable paving should be budgeted at one percent to two percent of construction costs, just as with any other pavement. Permeable Paving: Massachusetts Nonpoint Source Pollution Management, Metropolitan Area Planning Council (MAPC): Boston (MA).

question but that all other things are *not* equal. Universally, studies report that permeable pavement may well be cost-effective both on a life-cycle basis and when considering the offsetting costs of avoiding other design needs.[13]

- According to the California Stormwater Quality Association,[14] permeable pavements are 25% cheaper when the lack of drainage costs is taken into account.[15]

- A report by the University of New Hampshire Stormwater Center states that costs are generally 10 percent to 20 percent more ($2.80 per square foot for porous asphalt) but are often offset by eliminating stormwater infrastructure installation.[16]

- One case study (Lake County Forest Preserves, Illinois) found that the 25-year life-cycle cost of permeable concrete pavers, including installation, maintenance and repairs, was $190,700 for a 40,000 square foot parking lot, compared to $275,875 for conventional asphalt.[17]

Moreover, the use of permeable surfaces provides other substantial cost savings due to design advantages. According to the Pennsylvania Stormwater Management Manual:

> The added cost of a pervious pavement/infiltration system lies in the underlying stone bed, which is generally deeper than a conventional sub-base and wrapped in geotextile. However, this additional cost is often offset by the significant reduction in the required number of inlets and pipes. . .Furthermore, pervious pavement areas with subsurface infiltration beds often eliminate the need (and associated costs, space, etc.) for detention basins. When all of these factors are considered, pervious pavement with infiltration has proven itself less expensive than the impervious pavement with associated stormwater management. Recent

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[12] The University of New Hampshire's Stormwater Center published a set of specifications for the use of pervious asphalt. That UNH publication can be provided as a separate attachment upon request.

[13] According to Roseen (note 8, supra), "Specifications can be found in a variety of places including storm-water manuals [Pennsylvania Department of Environmental Protection (PADEP) 2006], industry associations [National Asphalt Pavement Association (NAPA) 2002, 2003)], most state transportation departments, and watershed assistance groups [University of New Hampshire Stormwater Center (UNHSC) 2009a]. PA is typically recommended for parking areas and low-volume, low-use roadways."

[14] Formed in 1989 as the California Stormwater Quality Task Force, the SWQTF was a quasi-governmental organization, which advised the California State Water Resources Control Board on matters related to developing stormwater regulations. More specifically, it was intended to help California comply with the municipal and industrial National Pollutant Discharge Elimination System (NPDES) stormwater mandates of the federal Clean Water Act. The Task Force officially became CASQA in September 2002.

[15] California Stormwater BMP Handbook (January 2003). , California Stormwater Quality Association: Menlo Park (CA).

[16] Robert Rosen (March 2010). Porous Asphalt for Stormwater Management, University of New Hampshire Stormwater Center: Durham (NH).

[17] Permeable Paver Research Summary (Feb. 2003). Lake Forest County Preserves (IL).

> (2005) installations have averaged between $2000 and $2500 per parking space, for the pavement and stormwater management.[18]

The UNH Stormwater Center agrees, stating that the "materials cost" of porous asphalt is approximately 20 to 25% more expensive than "traditional asphalt."[19] UNH continues, however, to state that the "*total project cost* is comparable for porous asphalt with reduced stormwater infrastructure vs. standard pavement applications where stormwater infrastructure is required." (emphasis added). This is consistent with the findings of the FHWA, which reports that "[t]he higher costs of installation of porous pavements can be offset to some extent by the elimination of curbs, gutters, and storm drains. In some cases, this may lower the overall cost for a project."[20] One report prepared for the EPA concluded:

> Porous pavement cost comparisons, particularly for parking lots, emphasize that the higher project unit costs (for the surface layer and for underlying and adjacent works) are offset by savings in other drainage features such as culvert pipes. Thus, the project overall may be cost effective, even if the pavement component is somewhat higher than a conventional pavement.[21]

Aside from the design cost savings, pervious asphalt has been found to have a lifespan of twice (or more) of traditional asphalt. This increased life is due to the very nature of the materials. EPA explains:

> Due to the well draining stone bed and deep structural support of porous asphalt pavements, they tend to develop fewer cracks and potholes than conventional asphalt pavement. When cracking and potholes do occur, a conventional patching mix can be used. Freeze/thaw cycling is a major cause of pavement breakdown, especially for parking lots in northern climates. The lifespan of a northern parking lot is typically 15 years for conventional pavements; porous asphalt parking lots can have a lifespan of more than 30 years because of the reduced freeze/thaw stress (Gunderson, 2008).[22]

In addition to these potential cost savings that might be generated by a move to pervious pavement, federal monies are available to help local governments implement projects involving pervious pavement. For example, Belmont might seek funding through the EPA's Section 319 funds administered by the Massachusetts Department of Environmental Protection (DEP).

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[18] Pennsylvania Department of Environmental Protection, Bureau of Watershed Management (December 2006). Pennsylvania Stormwater Management Manual, Section 6: Comprehensive Stormwater Management: Structural BMPs, at 6-20

[19] UNH Stormwater Center, Porous Asphalt Pavement for Stormwater Management.

[20] Best Management Practices in Ultra-Urban Settings, supra.

[21] Cambridge Systematics (June 2005). Cool Pavement Report: EPA Cool Pavements Study – Task 5, prepared for Heat Island Reduction Initiative, U.S. Environmental Protection Agency: Washington D.C.

[22] Environmental Protection Agency (2009). National Pollutant Discharge Elimination System (NPDES), Porous Asphalt Pavement. This EPA publication is attached as Appendix C.

Limitations on Pervious Asphalt

While pervious asphalt has some limitations,[23] these limitations should not be over-stated. While they deserve consideration in Belmont, they do not appear to be show-stoppers for the use of pervious asphalt for the BHS parking lot.

One limitation often discussed is the propensity of pervious asphalt to "clog" over time. Even while accurate, this observation fails to acknowledge the continuing viability of pervious asphalt as a stormwater runoff management strategy even given expected clogging. As EPA notes:

> The most prevalent maintenance concern is the potential clogging of the porous asphalt pores. Fine particles that can clog the pores are deposited on the surface from vehicles, the atmosphere, and runoff from adjacent land surfaces. Clogging will increase with age and use. While more particles become entrained in the pavement surface, it does not become impermeable. Studies of the long-term surface permeability of porous asphalt and other permeable pavements have found high infiltration rates initially, followed by a decrease, and then leveling off with time (Bean, et al., 2007a). With initial infiltration rates of hundreds of inches per hour, the long-term infiltration capacity remains high even with clogging. When clogged, surface infiltration rates usually well exceed 1 inch per hour, which is sufficient in most circumstances for the surface to effectively manage intense stormwater events (ICPI, 2000).[24]

Clogging can be minimized simply by engaging in periodic routine, inexpensive maintenance activities such as vacuum sweeping.

The second limitation is the presence of a clay subsurface soil at Belmont High. EPA notes, however, that "to compensate for the lower structural support capacity of clay soils, additional subbase depth is often required. The increased depth also provides additional storage volume to compensate for the lower infiltration rate of the clay subgrade."[25] The same response to the structural support capacity of clay soils, in other words, provides benefits with respect to the infiltration capacity of clay soils.[26]

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[23] In considering the "limitations" of pervious asphalt, it is important to note the caution expressed in note 7, supra.
[24] NPDES, Porous Asphalt Pavement, supra, attached as Appendix C, internal citations omitted.
[25] NPDES, Porous Asphalt Pavement, supra, attached as Appendix C.
[26] This is not to say that the presence of a clay sub-surface soil at BHS does not merit consideration and attention. It merely indicates that the clay sub-surface soil at BHS does not ipso facto make BHS an inappropriate location for pervious asphalt. Factors to consider are discussed in Hunt and Collins (2008). Permeable Pavement: Research Update and Design Implications, North Carolina State University Cooperative Extension, AGW-588-14, attached to this proposal as Appendix D.

Sustainable Belmont Proposal

Given the substantial concerns expressed by Belmont residents about stormwater flooding, when it comes time to undertake a project where the Town, itself, could implement a long-term practice to help address that very issue, the Belmont Public Schools should give serious consideration to the availability of Best Management Practices (BMPs) for stormwater runoff control.[27] In addition to the advantages of reducing stormwater runoff and its impact on flooding, the use of a pervious surface at BHS would also reduce the non-point pollution discharges flowing out of the Town of Belmont.

Even setting aside these environmental concerns, while the use of traditional asphalt may involve the least planning effort, and may even be cheaper at the front-end, substantial research reports that when all costs are considered, including long-term maintenance, repair and replacement costs, pervious pavement may offer a financial advantage to the Town.

Obviously Belmont will not "solve" its flooding, or its nonpoint pollution runoff problems, with what it does at Belmont High School. Even more obviously, Belmont will never even begin to *address* these problems unless it begins to take the necessary steps, both large and small, when it can. Using pervious asphalt at Belmont High is a beginning step toward a responsible environmental and financial stewardship for the Town. Assuming that site conditions permit,[28] such use should be pursued. Sustainable Belmont asks that the Belmont Public Schools consider the use of permeable asphalt as a pavement for BHS and report back to the community whether site conditions are conducive to such use.

[27] See, the description of Lexington's use of permeable pavement at its Department of Public Works building attached as Appendix E.

[28] Sustainable Belmont believes that pervious pavement should be used if it *can* be used. Clearly, Sustainable Belmont realizes that the BPS professional staff would need to undertake further inquiries about site conditions before committing to such an action. Sustainable Belmont urges that such inquiries be commenced with a report of findings made to the community.

List of Appendices

A. Wisconsin Department of Transportation (WisDOT). (January 2012). Comparison of Permeable Pavement Types: Hydrology, Design, Installation, Maintenance and Cost.

B. Roseen, et al. (January 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* (ASCE).

C. Environmental Protection Agency (2009). National Pollutant Discharge Elimination System (NPDES), Porous Asphalt Pavement.

D. Hunt and Collins (2008). Permeable Pavement: Research Update and Design Implications, North Carolina State University Cooperative Extension, AGW-588-14.

E. Lexington, Massachusetts (2012). Features of the Samuel Hadley Public Services Building, Pervious Pavement.

Appendix A

Transportation Synthesis Report
RESEARCH & LIBRARY SERVICES
research@dot.wi.gov

Comparison of Permeable Pavement Types: Hydrology, Design, Installation, Maintenance and Cost

Prepared for
WisDOT Southeast Region

Prepared by
CTC & Associates LLC
WisDOT Research & Library Unit
January 13, 2012

Transportation Synthesis Reports are brief summaries of currently available information on topics of interest to WisDOT staff throughout the department. Online and print sources for TSRs include NCHRP and other TRB programs, AASHTO, the research and practices of other transportation agencies, and related academic and industry research. Internet hyperlinks in TSRs are active at the time of publication, but changes on the host server can make them obsolete. To request a TSR, e-mail research@dot.wi.gov or call (608) 267-6977.

Request for Report

WisDOT's regional storm water engineer for the Southeast Region is interested in developing a park-and-ride with porous pavement, possibly with the PaveDrain brand of permeable block. Research was needed to determine how well permeable pavements, including porous asphalt, pervious concrete and paver blocks, remove total suspended solids and other nutrients from runoff. Information was also requested on life-cycle costs, maintenance requirements, infiltration rates, installation and design (including aggregate base requirements).

Summary

Many research studies, manuals, fact sheets and other resources compare the hydrology, design, installation, maintenance and cost of permeable pavement types. We provide a selection of these resources, which generally provide similar conclusions, organized in five topic areas:

- General Comparisons of Permeable Pavement Types: Hydrology, Design, Installation, Maintenance and Cost
- Cost Comparisons of Permeable Pavements
- Porous Asphalt
- Pervious Concrete
- Paver Blocks and Permeable Interlocking Concrete

Hydrology

Our research shows that all permeable pavement types do similarly excellent jobs of preventing stormwater runoff and removing pollutants. To quote guidance from the Environmental Protection Agency included in this report:

> Porous asphalt, pervious concrete, and permeable pavers all have the same underlying stormwater storage and support structure. The only difference is the permeable surface treatment. The choice of permeable surface is relevant to user needs, cost, material availability, constructability, and maintenance, but it has minimal impact on the overall stormwater retention, detention, and treatment of the system.

Infiltration rates are generally hundreds of inches per hour. Even as pavements clog with time, infiltration rates remain above 1 inch per hour, sufficient for most stormwater events. (Regular maintenance will keep permeability

even higher.) We found one study on PaveDrain specifically showing that there was no runoff for a one-hour event simulating 4.6 inches of rainfall over a sandy subgrade, and no runoff for a one-hour event simulating 5.1 inches of rainfall over a clayey subgrade. (Note: This study was commissioned by the manufacturer of PaveDrain.)

For all systems, pollutant removals are:

- Total suspended solids: 85 percent to 95 percent
- Total phosphorus: 65 percent to 85 percent
- Total nitrogen: 80 percent to 85 percent
- Nitrate (as N): 30 percent
- Metals: 98 percent

Design, Installation, Maintenance and Cost

Material costs (2005 figures) are 50 cents to $1 per square foot for porous asphalt, $2 to $7 per square foot for pervious concrete and $5 to $10 per square foot for concrete pavers. While these costs are higher (generally by 10 percent to 20 percent) than costs for nonpermeable materials, they are said to be offset by the elimination of the need for detention basins and other stormwater infrastructure. Each pavement type will have a similar base with costs depending on site requirements. (Excavation is $8 to $10 per cubic yard; aggregate is $30 to $35 per cubic yard with base depth dependent on soil type; and geotextile fabric is 70 cents to $1 per square foot.) Other costs vary with materials availability, site conditions, project size, stormwater management requirements and subgrade; for example, clay soils require more base material.

This report includes a number of manuals and specifications detailing the design and installation of permeable pavements, including base aggregate requirements. (For base layer specifications, see page 15 of *Permeable Pavement: Stormwater Design Specification No. 7* in the **Manuals, Specifications and Books** section of **General Comparisons of Permeable Pavement Types: Hydrology, Design, Installation, Maintenance and Cost**.)

Maintenance costs are $400 to $500 per year for vacuum sweeping a half-acre parking lot three to four times annually. One analysis suggests that the 25-year life-cycle cost of a 40,000-square-foot parking lot constructed with one brand of block paver (including installation, biannual vacuum sweeping and other maintenance) is $190,200 compared to $275,875 for impervious asphalt. (See *Permeable Paver Research Summary* in the **Cost** section of **Paver Blocks and Permeable Interlocking Concrete**.) Longevity is assumed to be 20 to 30 years for pervious concrete and block pavements, and 15 to 20 years for porous asphalt.

General Comparisons of Permeable Pavement Types: Hydrology, Design, Installation, Maintenance and Cost

Below we highlight several websites, publications and presentations that include design, maintenance and cost information related to porous asphalt, pervious concrete and permeable paving blocks. A 2011 article summarizes several case studies that incorporate permeable pavement solutions.

EPA Guidance

Porous Asphalt Pavement, National Pollutant Discharge Elimination System, U.S. Environmental Protection Agency, September 2009.
http://cfpub.epa.gov/npdes/stormwater/menuofbmps/index.cfm?action=browse&Rbutton=detail&bmp=135&minmeasure=5
This Web page gives an overview of design criteria, maintenance, stormwater management and pollutant removal efficiencies, and costs for porous asphalt. The base/subbase depth is 18 to 36 inches, with greater width required when installed over less permeable clay soils. The base is typically 3 to 4 inches thick and consists of crushed stones typically 3/4 to 3/16 inch. Subbase stone sizes are larger than the base, typically 3/4 to 2½ inches. Porous asphalt has reduced strength compared to conventional asphalt and will not be appropriate for applications with high volumes and extreme loads. However, these pavements have less freeze-thaw stress than conventional pavements, and in northern climates the service life of a porous parking lot may be doubled to 30 years from the usual 15. Infiltration rates are very high initially—in the hundreds of inches per hour—but are reduced as pavement pores are gradually clogged. (Cold weather does not affect infiltration rates.) However, even when pavement surfaces become clogged,

infiltration rates usually will exceed 1 inch per hour, which is sufficient for most stormwater events. Regular vacuum sweeping will help maintain permeability. Sand should not be used in winter on these pavements, and salt and deicing chemicals must be used in moderation. This page also compares pervious concrete, porous asphalt and permeable pavers (blocks): "Porous asphalt, pervious concrete, and permeable pavers all have the same underlying stormwater storage and support structure. The only difference is the permeable surface treatment. The choice of permeable surface is relevant to user needs, cost, material availability, constructability, and maintenance, but it has minimal impact on the overall stormwater retention, detention, and treatment of the system." The page includes charts comparing volume retention and pollutant reduction for different case studies involving the three types of permeable pavement. Porous asphalt has been recorded to retain 25 percent to 100 percent of stormwater volume; permeable pavers, 34 percent to 100 percent; and pervious concrete, 99 percent to 100 percent. Pollutant removal rates are detailed in Table 3 and comparable for each system. The cost of the porous asphalt material ranges from 50 cents to $1 per square foot (2005 figures); other costs will vary with contractor rates, materials availability, site conditions, project size, stormwater management requirements and subgrade (such as clay soils, which require more base material).

Pervious Concrete Pavement, National Pollutant Discharge Elimination System, U.S. Environmental Protection Agency, September 2009.
http://cfpub.epa.gov/npdes/stormwater/menuofbmps/index.cfm?action=browse&Rbutton=detail&bmp=137&minmeasure=5
This Web page provides an overview of design criteria, maintenance, stormwater management and pollutant removal efficiencies, and costs for pervious concrete. Base and subbase requirements are the same as for porous asphalt (above). Like porous asphalt, pervious concrete has less strength than conventional materials. Unless properly designed, it is more susceptible to freeze-thaw damage than porous asphalt. Infiltration rates are hundreds of inches per hour initially but over time become as low as 5 inches per hour because of clogging. As with porous asphalt, vacuum sweeping helps maintain permeability. Sand should not be used for snow and ice conditions, but salt and deicing chemicals can be used in moderation. The cost of the pervious concrete material ranges from $2 to $7 per square foot (2005 figures); other costs will vary with contractor rates, materials availability, site conditions, project size, stormwater management requirements and subgrade (such as clay soils, which require more base material).

Permeable Interlocking Concrete Pavement, National Pollutant Discharge Elimination System, U.S. Environmental Protection Agency, September 2009.
http://cfpub.epa.gov/npdes/stormwater/menuofbmps/index.cfm?action=browse&Rbutton=detail&bmp=136&minmeasure=5
This Web page gives an overview of design criteria, maintenance, stormwater management and pollutant removal efficiencies, and costs for permeable paving blocks. Base and subbase requirements are similar to porous asphalt and pervious concrete. As with porous asphalt and pervious concrete, infiltration rates are in the hundreds of inches per hour immediately after construction and become lower over time with clogging. However, even clogged pavements have infiltration rates well above 1 inch per hour, and permeability can be maintained with vacuum sweeping. Sand is not used and deicing salts can be used in moderation. Stormwater volume retention and pollutant removal are similar to those of porous asphalt and pervious concrete. The cost of these systems ranges from $2 to $8 per square foot; other costs will vary with contractor rates, materials availability, site conditions, project size, stormwater management requirements and subgrade, such as clay soils, which require more base material.

Manuals, Specifications and Books

Permeable Pavement: Stormwater Design Specification No. 7, Version 1.7, Virginia Department of Conservation and Recreation, March 2010.
http://www.cwp.org/cbstp/Resources/d2s6a-dcr-bmp-permeable.pdf
This specification addresses pervious concrete, porous asphalt and interlocking concrete pavers. Table 7.2 (page 3 of the PDF) compares design, performance and cost, including thickness and gradation of pavement layers:

- Permeability: 10 feet per day for porous concrete, 6 feet for porous asphalt and 2 feet for interlocking pavers
- Construction cost: $2 to $6.50 per square foot for porous concrete, 50 cents to $1 for porous asphalt and $5 to $10 for interlocking pavers

- Longevity: 20 to 30 years for porous concrete, 15 to 20 years for porous asphalt and 20 to 30 years for interlocking pavers.

Pages 4-15 of the PDF provide detailed information about design, with Tables 7.5 and 7.6 (page 15) comparing base layer and pavement layer specifications for each. Pages 17 to 21 of the PDF provide step-by-step construction instructions for each type; and pages 22 to 24 address maintenance.

Related Resources:

Chapter 9.7, Standard for Pervious Paving Systems, New Jersey Stormwater Best Management Practices Manual, New Jersey Department of Environmental Protection, February 2004.
http://www.nj.gov/dep/stormwater/bmp_manual/NJ_SWBMP_9.7.pdf

Chapter 3.3.7, Porous Concrete, Georgia Stormwater Management Manual, Volume 2 (Technical Handbook), Atlanta Regional Commission, Georgia Department of Natural Resources–Environmental Protection Division, August 2001.
http://www.georgiastormwater.com/vol2/3-3-7.pdf

Iowa Stormwater Management Manual, Iowa State University, 2009.
http://www.intrans.iastate.edu/pubs/stormwater/index.cfm

Chapter 4.2, Permeable Pavement Systems, Green Infrastructure Supplemental Stormwater Document (draft), Stormwater Design and Specification Manual, Indianapolis Department of Public Works, 2009.
http://www.indy.gov/eGov/City/DPW/SustainIndy/WaterLand/Documents/4.2%20Permeable%20Pavement%20Systems.pdf

Stormwater Management Manual for Western Washington, Washington State Department of Ecology, 2005.
http://www.ecy.wa.gov/programs/wq/stormwater/manual.html

Low Impact Development (LID) Guidance Manual for Kitsap County, **Washington**, Washington State Department of Ecology, 2009.
http://www.kitsapgov.com/dcd/dev_eng/sw_design_manual/Cookbook061009Print3.pdf

Section 6, Comprehensive Stormwater Management: Structural BMPs, Pennsylvania Stormwater Best Management Practices Manual, Pennsylvania Department of Environmental Protection, January 2005.
http://www.lowimpactdevelopment.org/raingarden_design/downloads/PASWManualStrucBMPsSec6.pdf
A discussion of porous pavement design, maintenance and costs, including for asphalt, concrete and paver blocks, begins on page 203 of the report. Porous asphalt is 10 percent to 20 percent more expensive than standard asphalt, and pervious concrete or blocks are more expensive than asphalt. However, these costs are offset by the elimination of the need for detention basins, which cost $2,000 to $2,500 per parking space. See pages 219-224 of the report for detailed specifications and installation guidance.

Porous Pavements, Integrative Studies in Water Management and Land Development, Bruce K. Ferguson, Taylor & Francis Group, 2005.
Available for purchase at http://www.amazon.com/Porous-Pavements-Integrative-Studies-Management/dp/0849326702
Overview: http://www.rmc-foundation.org/images/PCRC%20Files/Applications%20&%20Case%20Studies/Porous%20Pavements%20-%20The%20Overview.pdf
This book provides extensive information on the design of pervious concrete, porous asphalt and pervious concrete blocks. See especially chapters on dimensions (Chapter 2, page 35); structure (Chapter 3, page 69); hydrology (Chapter 4, page 119); aggregate (Chapter 6, page 199); blocks (Chapter 9, page 323); concrete (Chapter 11, page 417); and asphalt (Chapter 12, page 457). The manual gives infiltration rates for various surfaces (page 124), including aggregates of various sizes (1,300 to 50,000 inches per hour); blocks (9.2 initially and 4.1 after six years); porous concrete (670 to 900); porous asphalt (initially 170 to 500+ but 15 to 39 after four years and 1.4 after four

years of winter sanding); dense concrete (less than 0.00002); and dense asphalt (0.00006 to 6). It likewise gives runoff coefficients (page 126) and other hydrology information (Chapter 4), and aggregate gradation information for walking/parking surfaces (page 216). Many chapters provide cases studies, and the chapter on blocks compares several vendors.

Brochures, Presentations, Fact Sheets and Websites

Pervious Concrete Applications and Stormwater Management, John Kevern, Louisiana Transportation Conference, January 2011.
http://www.ltrc.lsu.edu/ltc_11/pdf/Pervious%20Concrete%20Applications%20and%20Stormwater%20Management.pdf
This presentation compares pervious concrete and interlocking block pavers, and includes several pictures of construction, including excavation and placement. It also provides a chart of permeability in inches per hour as related to the number of maintenance passes, including sweeping and vacuum, wet sweeping, vacuum only, and wash and vacuum. It concludes with several case studies.

Pervious Pavement, LakeSuperiorStreams: Community Partnerships for Understanding Water Quality and Stormwater Impacts at the Head of the Great Lakes, 2011.
http://www.lakesuperiorstreams.org/stormwater/toolkit/paving.html
This Web page includes information for permeable paving systems, including cost comparisons:

- Porous asphalt is 10 percent to 15 percent higher than regular asphalt.
- Porous concrete is approximately 25 percent greater than regular concrete.
- Pavers can be as much as four times the expense of either regular concrete or asphalt.

For all systems, pollutant removals are:

- 82 percent to 95 percent of sediments
- 65 percent total phosphorous
- 80 percent to 85 percent total nitrogen
- High removal rates reported for zinc, lead and chemical oxygen demand

Maintenance contracts stipulating quarterly vacuuming and/or power washing are recommended. If equipment and resources are not available for maintenance, pervious pavement is not recommended.

Permeable Pavement Fact Sheet, University of New Hampshire Stormwater Center, 2008.
http://www.crwa.org/projects/bmpfactsheets/crwa_permeable_pavement.pdf
This fact sheet includes information for both porous asphalt and pervious concrete. Permeably paved areas are typically designed to infiltrate runoff from at least a two-year storm; therefore runoff will be reduced by 100 percent for most rainstorms. Permeably paved areas generally infiltrate 70 percent to 80 percent of annual rainfall.

Pollutant efficiencies:

- Total suspended solids: 85 percent to 95 percent
- Total phosphorus: 65 percent to 85 percent
- Total nitrogen: 80 percent to 85 percent
- Nitrate (as N): 30 percent
- Metals: 98 percent

Installation costs are estimated to be between $7 and $15 per square foot, and maintenance costs are $400 to $500 per year for vacuum sweeping of a half-acre parking lot. Repaving will be required every 15 to 25 years in cold climates.

Permeable Interlocking Concrete Pavement: A Comparison Guide to Porous Asphalt and Pervious Concrete, Interlocking Concrete Pavement Institute, February 2008.
Available for purchase at http://www.icpi.org/node/1234
Brochure and overview: http://www.icpi.org/sites/default/files/pdfs/PICP_Comparison_Brochure.pdf
This brochure advertises the advantages of permeable interlocking concrete pavement over porous asphalt and pervious concrete, including high resistance to freeze-thaw and deicing salt; deicing chemicals are not recommended on pervious concrete (but are on porous asphalt). While permeable interlocking concrete pavement is more expensive than porous asphalt and pervious concrete, this brochure claims reduced life-cycle costs. Other advantages include consistent quality, availability in a wide range of textures and colors as well as mechanical installation (which can be done in freezing temperatures).

Case Studies

Runoff Remedy, Bob Drake, *Civil Engineering News*, August 2011.
http://www.cenews.com/magazine-article-cenews.com-8-2011-runoff_remedy-8423.html
This article summarizes recent projects incorporating permeable pavement solutions, including the:

- **Thorndike Park** parking lot in Arlington, Mass., using BodPave85, which unlike some paving systems does not require vacuuming or sediment removal:
  - "The project called for a cost-effective porous paving solution that required very little maintenance, was highly porous to absorb runoff from adjacent asphalt pavement, would provide a unique aesthetic, and be durable to withstand the wear associated with regular vehicular traffic and the Massachusetts climate."
  - "The highly porous reinforced gravel profile also provides storage capacity during rainfall events; the 4-inch clean gravel profile will accommodate an additional 0.75 inch to 1 inch of rainfall over its relative area, reducing the depth of engineered sub-base storage needed to accommodate the designed storm event."
  - "After its first year of use, the project is 100 percent functional, shows no signs of wear, and has required no maintenance."
- **The Preserve and Clam Farm** in Charleston, S.C., which used the Gravelpave2 permeable paving system for the entrance road, driveways and on-site parking. The system has held up well under traffic, but requires regular maintenance and annual brooming.
- **Porous pavement demonstration** in Timonium, Md., which used 4 inches of porous asphalt over a 3/8-inch aggregate base, 48-inch stone reservoir and clay subgrade.

Cost Comparisons of Permeable Pavements

Below we highlight a 2005 report that provides high-volume retailers with strategies for integrating low-impact development stormwater management techniques and a 2003 handbook that examines installation and maintenance costs.

Low Impact Development for Big Box Retailers, The Low Impact Development Center, November 2005.
http://www.lowimpactdevelopment.org/bigbox/lid%20articles/bigbox_final_doc.pdf
Installation and maintenance cost estimates for permeable pavements can be found on page 62. Costs for installation are (2005 dollars):

- Excavation: $8 to $10 per cubic yard
- Porous asphalt: 50 cents to $1 per square foot
- Porous concrete: $2 to $6.50 per square foot
- Concrete paving blocks: $5 to $10 per square foot
- Aggregate: $30 to $35 per cubic yard
- Geotextile fabric: 70 cents to $1 per square foot

Maintenance costs are estimated at $500 per year for vacuuming sediment three to four times annually.

Pervious Pavements, California Stormwater BMP Handbook, California Stormwater Quality Association, January 2003.
http://www.cabmphandbooks.com/Documents/Development/SD-20.pdf
According to this handbook, permeable pavements are 25 percent cheaper when lack of drainage costs are taken into account. See page 5 for recommended maintenance regimes and page 7 for a detailed breakdown of installation and maintenance costs.

Porous Asphalt

Below we highlight several publications and a 2010 presentation that provide guidelines for porous asphalt pavement design and maintenance.

General

Porous Asphalt Pavements in Minnesota, Jill Thomas, *Hot Mix Asphalt Technology*, November/December 2010.
http://www.asphaltisbest.com/PDFs/Porous%20Pavement%20Article%20HMAT%20Nov-Dec%202010.pdf
This article discusses the use of porous asphalt for several permeable pavements in Minnesota, including use of porous asphalt for the Ramsey-Washington Metro Watershed District Building. Water depth monitoring shows that there has never been discharge into the storm sewer; the greatest water depth was 3 inches after a 5-inch rainfall. The project cost $60,000; maintenance involves two vacuum sweepings a year. After two years, there are signs of clogging, but this has not affected infiltration rates, and there has never been runoff from the parking lot.

Porous Asphalt for Stormwater Management, Robert Roseen, University of New Hampshire Stormwater Center, March 2010.
http://www.unh.edu/unhsc/sites/unh.edu.unhsc/files/presentations/Porous%20Asphalt%20for%20Stormwater%20Management%20From%20the%20Rooftop%20to%20the%20Bay.pdf
This presentation includes information about the hydrology, pollutant removal, design and costs of permeable pavements. Costs are generally 10 percent to 20 percent more ($2.80 per square foot for porous asphalt, $4 to $5 for pervious concrete) but are offset by eliminating stormwater infrastructure installation.

Porous Asphalt Pavements for Stormwater Management: Design, Construction and Maintenance Guide, Information Series 131, National Asphalt Pavement Association, November 2008.
Available for purchase at http://store.asphaltpavement.org/index.php?productID=179
Topics covered include water quality, structural design, soil investigation, hydrologic design, materials, construction, cost and maintenance. A fact sheet based on this book (available at http://www.paiky.org/downloads/PorousBrochureWeb%5B1%5D.pdf) includes a table of pollution removal efficiencies and construction and maintenance guidelines.

Maryland Pervious Asphalt Design Guidelines, Maryland Department of Land and Natural Resources, December 1992.
http://www.smscland.org/pdf/MarylandPerviousAsphalt.pdf
This document includes guidelines for pervious asphalt pavement design; generally the surface course is 2 to 4 inches thick and is placed over a 1- to 2-inch-thick filter course of 0.5-inch crushed stone aggregate and 1.5- to 3-inch reservoir course. (See page 6 for a schematic of road layers.) Maintenance includes regular inspections for surface ponding (an indication of clogging) and vacuum sweeping followed by jet hosing four times per year.

Maintenance

Winter Maintenance Guidelines for Porous Asphalt, University of New Hampshire Stormwater Center, January 2011.
http://www.unh.edu/unhsc/sites/unh.edu.unhsc/files/docs/UNHSC%20porous%20winter%20maintenance%20fact%20sheet_1_11.pdf
This fact sheet includes guidance about maintenance before, during and after winter events.

Pervious Concrete

Below we highlight three publications that address design and maintenance considerations for pervious concrete pavement. A 2010 study evaluates the mechanical and hydraulic properties of several pervious concrete pavement mix designs.

General

Stormwater Management with Pervious Concrete Pavement, American Concrete Pavement Association, 2006.
http://www.smscland.org/pdf/StormwaterManagement.pdf
This brief gives an overview of the use of pervious concrete for stormwater management. It includes design and maintenance considerations, and suggests that pervious concrete reduces runoff by 70 percent to 80 percent and pollutants by 80 percent.

Maintenance

Pervious Concrete Pavement Maintenance Guidelines, National Ready Mixed Concrete Association, 2007.
http://www.chaneyenterprises.com/files/productdocs/Pervious-Concrete-Maintenance-Guidelines.pdf
This document includes guidelines on cleaning, pavement section replacement and cold weather maintenance of pervious concrete.

Porous Pavement Operation and Maintenance Protocol, San Diego County Facilities, 2007.
http://www.sdcounty.ca.gov/reusable_components/images/dgs/Documents/Grants_Prop40_AppendIII_.pdf
This document includes detailed maintenance instructions for porous pavements.

Hydrology

An Investigation into Porous Concrete Pavements for Northern Communities, Report No. 2010-6, Vermont Agency of Transportation, July 2010.
http://www.aot.state.vt.us/matres/Documents/ACROBAT.pdf/R&DDox/McCain-Dewoolkar-PorousConcrete-FinalReport-06-23-10.pdf
Among the properties examined by this study is hydraulic conductivity, which was 225 to 1,729 inches per hour for various pervious concrete mixes. This project also finds that a Burlington, Vt., facility built using pervious concrete has a surface infiltration capacity of 3,500 to 10,600 inches per hour. (A representative 10-year/24-hour design storm for Vermont is about 4 inches per hour.) The study notes that porous pavements have been shown to be effective in pollutant removal, capable of eliminating up to 95 percent of the total suspended solids, 65 percent of the total phosphorous, 85 percent of the total nitrogen and 99 percent of the metals from stormwater runoff.

Paver Blocks and Permeable Interlocking Concrete

Below we highlight several studies that examine structural design as well as cost, performance and infiltration rates of permeable pavement systems.

General

Permeable Interlocking Concrete Pavements Manual: Design, Specification, Construction and Maintenance, David R. Smith, 4th edition, Interlocking Concrete Pavement Institute, 2010.
Available for purchase: http://www.icpi.org/node/2962
From the abstract: This updated edition draws from a wealth of current permeable pavement research on stormwater management, structural design, and performance. The manual is a key resource for design professionals, plus stormwater and transportation government agency staff who support low impact development and green streets/infrastructure using permeable pavement. Since its first publication in 2000, the book remains the industry consensus on [permeable interlocking concrete pavements] and a valuable resource for this rapidly growing pavement system."

Cost

Permeable Paver Research Summary, Lake County Forest Preserves, February 2003.
http://atfiles.org/files/pdf/PermPavers.PDF
This document compares life-cycle costs for Uni-Lock permeable concrete pavers and asphalt (page 3). For a 40,000-square-foot parking lot over 25 years, the cost for installation, biannual vacuum sweeping and other maintenance for pavers is $190,200; for an asphalt parking lot of the same size over 25 years, the cost is $275,875 for installation, crack sealing, seal coat, striping, patching and surface replacement. The document includes numerous case studies.

Hydrology

PaveDrain Permeable Articulating Concrete Block/Mat Under Simulated Rainfall, American Excelsior Company, June 2011.
http://www.pavedrain.com/pdf/PaveDrain-Infiltration-Report.pdf
This study quantified PaveDrain's infiltration capabilities for two test plots with different underlying materials, showing that there was no runoff for a one-hour event simulating 4.6 inches of rainfall over a sandy subgrade, and no runoff for a one-hour event simulating 5.1 inches of rainfall over a clayey subgrade. (Note that this study was commissioned by the manufacturer of PaveDrain.)

Study on the Surface Infiltration Rate of Permeable Pavements, Eban Z. Bean, William F. Hunt, David A. Bidelspach, Jonathan T. Smith, Biological and Agricultural Engineering Department, North Carolina State University, May 2004.
http://www.bae.ncsu.edu/info/permeable-pavement/icpi.pdf
This study tested the surface infiltration rate of 25 permeable pavement sites in North Carolina, Maryland and Delaware using variations of the double ring infiltrometer test. Researchers found high infiltration rates for all sites, with a mean of 2.1 inches per hour for concrete grid pavers. Maintenance generally improved infiltration to a mean of 3.5 inches per hour. Permeable interlocking concrete pavements had a mean of 1.7 inches per hour if near loose fine particles and 900 inches per hour if not.

Long-Term Stormwater Quantity and Quality Performance of Permeable Pavement Systems, Benjamin Brattebo, Derek Booth, Center for Water and Watershed Studies, University of Washington, July 2003.
http://water.washington.edu/research/Reports/permeableparking.pdf
This study examined the long-term effectiveness of permeable pavement as an alternative to traditional impervious asphalt pavement in a parking area. Four commercially available permeable pavement systems were evaluated against a regular asphalt pavement over six years of daily parking usage for structural durability, ability to infiltrate precipitation and impacts on infiltrate water quality:

- Grasspave^2, a flexible plastic grid system with virtually no impervious area, filled with sand and planted with grass
- Gravelpave^2, an equivalent plastic grid, filled with gravel
- Turfstone, a concrete block lattice with about 60 percent impervious coverage, filled with soil and planted with grass
- UNI Eco-Stone, small concrete blocks with about 90 percent impervious coverage, with spaces between blocks filled with gravel

All four permeable pavement systems showed no major signs of wear. Virtually all rainwater infiltrated through the permeable pavements, with almost no surface runoff. (During the period of measurement, rainfall at the site totaled 570 mm.) The infiltrated water had significantly lower levels of copper and zinc than the direct surface runoff from the asphalt area. Motor oil was detected in 89 percent of samples from the asphalt runoff but not in any water sample infiltrated through the permeable pavement. Neither lead nor diesel fuel were detected in any sample. Infiltrate measured five years earlier displayed significantly higher concentrations of zinc and significantly lower concentrations of copper and lead.

Appendix B

Water Quality and Hydrologic Performance of a Porous Asphalt Pavement as a Storm-Water Treatment Strategy in a Cold Climate

Robert M. Roseen, Ph.D., P.E., D.WRE, M.ASCE[1]; Thomas P. Ballestero, Ph.D., P.E., M.ASCE[2]; James J. Houle[3]; Joshua F. Briggs[4]; and Kristopher M. Houle[5]

Abstract: This study examined the functionality of a porous pavement storm-water management system in coastal New Hampshire where 6 months of subfreezing temperatures typically occur. The usage of porous pavements for storm-water management in northern climates has many challenges, most of which relate to the extreme cold and significant frost penetration into the porous media. The porous pavement system was monitored for hydraulic and water-quality performance from 2004 to 2008. The use of porous pavements for parking lots for new and redevelopment projects are one watershed-based strategy that can both mitigate impacts for new development and reverse impacts in areas with redevelopment. Surface infiltration capacity and frost penetration were measured monthly to assess winter performance. Because of the well-drained nature of the porous pavement and reservoir base, issues related to frozen media were minimized. Significant frost penetration was observed up to depths of 71 cm without declines in hydrologic performance or observable frost heave. No consistent statistical difference was observed for seasonal hydrologic performance with mean infiltration capacity ranging from 1,490 to 2,690 cm/h. Adverse freeze-thaw effects, such as heaving, were not observed, and for that reason, the life span is expected to exceed that of typical pavement applications in northern climates. Observed hydrologic response resembled shallow depth groundwater drainage, as is the goal for low-impact development designs. Peak flows were reduced by 90% to $0.58\ \mathrm{m^3/s/km^2} \pm 0.74$ in comparison with standard impervious cover $= 5.5\ \mathrm{m^3/s/km^2} \pm 7.7$. There was exceptional water-quality treatment performance for petroleum hydrocarbons, zinc, and total suspended solids with nearly every value below detection limits. Only moderate removal was observed for phosphorous, and treatment for nitrate (NO3) was negative. **DOI: 10.1061/(ASCE)EE.1943-7870.0000459.** *© 2012 American Society of Civil Engineers.*

CE Database subject headings: Stormwater management; Runoff; Porous media; Pavements; Cold regions; Best Management Practice; Water quality; Water treatment.

Author keywords: Storm-water management; Runoff; Porous pavements; Cold climate; Best management practice.

Introduction

With the implementation of the Phase II rules under the Clean Water Act and the need for innovative storm-water management, storm-water practitioners are looking for designs that provide a high level of water-quality treatment performance and include infiltration of storm-water runoff, for which soils are useful, particularly for source control. The use of porous pavements for parking lots for new and redevelopment projects are one watershed-based strategy that can meet these requirements. Porous pavements can both mitigate impacts from new development and reverse impacts in areas with redevelopment because of the ability to cleanse and cool runoff and reduce runoff volumes. Adoption of porous pavement usage is hampered by widespread concern with regard to cost, winter performance, clogging and maintenance, and risk to groundwater quality. These concerns can be addressed effectively with appropriate designs, proper installation, long-term maintenance commitment, and quality controls for materials production. Although uncertainty exists owing to a lack of long-term performance data for porous pavements, it is obvious that conventional storm-water management is having detrimental impacts on surface waters and that future regulations require the use of innovative storm-water management.

Increased contaminant loading from various land uses with elevated levels of imperviousness is clear [USEPA 1983; Pitt et al. 2004; National Cooperative Highway Research Program (NCHRP) 2006], and conventional storm-water management is doing only a modest job at removing runoff contaminants (Roseen et al. 2006). Accumulation of heavy metals, organics, and inorganic compounds can be acute in urban snow runoff (Sansalone et al. 1996, 2002; Sansalone and Glenn 2002), leaving the need for effective winter storm-water management in northern climates. Low-impact development storm-water designs have been shown to be extremely

[1]Director, The UNH Stormwater Center; and Assistant Research Professor, Dept. of Civil Engineering, 35 Colovos Rd., Univ. of New Hampshire, Durham, NH 03824 (corresponding author). E-mail: robert.roseen@unh.edu

[2]Associate Professor, Dept. of Civil Engineering; and Principal Investigator, The UNH Stormwater Center, 35 Colovos Rd., Univ. of New Hampshire, Durham, NH 03824. E-mail: tom.ballestero@unh.edu

[3]Program Manager, The UNH Stormwater Center, 35 Colovos Rd., Univ. of New Hampshire, Durham, NH 03824. E-mail: James.Houle@unh.edu

[4]Project Engineer, Geosyntec, Acton, MA 01720. E-mail: jbriggs@geosyntec.com

[5]Project Engineer, Horsley Witten Group, Sandwich, MA 02563. E-mail: khoule@horsleywitten.com

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effective at reducing contaminant loads from impervious surfaces (Dietz and Clausen 2008; Dietz 2007), in northern climates (Oberts 2003; Roseen et al. 2009), and for reducing peak flow, lag time, and runoff volume (Hood and Clausen 2007). Porous pavement usage in cold climates has been found to be more resistant to freezing than standard pavements largely because of its disconnection to subsurface moisture and because it thaws more rapidly as a result of the rapid infiltration of meltwater (Backstrom 2000).

Background

The pavement technology for porous asphalts has been in use for decades and is known as open-graded friction course (OGFC), a pavement mix with a void content commonly in the 18–20% range, also known as permeable friction coarse (PFC). Although the two items are similar in many respects, OGFC is not equivalent to porous asphalt (PA), and many of the misconceptions about PA are with respect to OGFC (i.e., low durability, high maintenance, reduced cold-climate functionality). Porous asphalt is a full-depth pavement (typically 6.5–10 cm thick) designed to drain to the subbase. The safety and environmental benefits with porous pavements that result from the rapid infiltration of surface water during storm events include (1) improved wet pavement frictional resistance, (2) reduced hydroplaning, (3) reduced splash and spray, (4) reduced nighttime glare, (5) improved nighttime pavement marking visibility, and (6) reduced pavement noise.

Despite the current success of porous pavements in the United States and Europe, there has been a mixed history of performance associated with porous pavements in asphalt mix design, production and construction, and maintenance. These problems have been solved, in large part, because of the use of modified asphalt binders with polymers and fibers, open aggregate gradations, and quality control assurances (Kandhal and Mallick 1999). In the United States, Oregon, Washington, California, Nevada, Arizona, Florida, Vermont, and Georgia have used OGFC extensively. In Europe, it has been widely implemented since the 1980s in Germany, Netherlands, France, Italy, United Kingdom, Belgium, Spain, ASTMSwitzerland, and Austria.

Specifications can be found in a variety of places including storm-water manuals [Pennsylvania Department of Environmental Protection (PADEP) 2006], industry associations [National Asphalt Pavement Association (NAPA) 2002, 2003)], most state transportation departments, and watershed assistance groups [University of New Hampshire Stormwater Center (UNHSC) 2009a]. PA is typically recommended for parking areas and low-volume, low-use roadways. This is contrary to OGFC usage that has typically been used on large highways in the United States and Europe. Huber (2000) reported that OGFC is best used for high-volume, high-speed roadways. High traffic-intensity roads tend to maintain surface infiltration capacity (IC) of the OGFC because of the suction action of tires that removes detritus.

Structural durability and life cycle are major concerns when selecting pavement type. PA and OGFC have had a mixed record over the past 30 years. The principal cause of parking lot pavement breakdown in northern climates is freeze-thaw cycling with a typical life span of around 15 years. Potential structural durability problems for PA include rutting and distortion under heavy loads, stripping because of prolonged contact with water, and cracking and raveling because of increased photooxidative degradation. Successful examples of long-lasting pavements have accounted properly for asphalt mix design, construction practices, traffic, cold climate issues, and binder draindown and have been demonstrated to be cost-effective. By design, an open-graded, well-drained, significant depth, porous pavement system will have a longer life cycle from reduced freeze-thaw susceptibility and a greater load bearing capacity than conventional parking lot pavement.

Winter Maintenance

Most experience with winter performance and maintenance of PA has been positive, especially compared to standard pavements and in contrast to OGFC. Cahill et al. (2003) reported that PA parking lots require less plowing and that snow and ice melt faster than regular parking lots. The open pore spaces in PA permit water to freely drain through to the bed, providing rapid drainage of any snowmelt. Cahill et al. (2003), Jackson (2003), and Ferguson (2005) proposed several general guidelines for winter maintenance of PA. Ultimately, if reduced winter deicing practices are needed (UNHSC 2009b), porous asphalt could have a winter maintenance cost benefit.

Hydrologic Performance

The hydrologic benefits of the use of porous pavements have been well-documented for volume and peak flow reduction, the degree to which will be dependent on storage within the subbase and the underlying soil type (Abbott and Comino-Mateos 2003). Annual runoff volume reductions of 50–81% have been observed from infiltration in Sweden (Stenmark 1995), 97% volume reduction in Reze, France (Legret and Colandini 1999), and 100% volume reduction over 2 years of study at Pennsylvania State University (Dempsey and Swisher 2003).

Water-Quality Treatment

Several studies have examined water-quality treatment performance and pollutant retention of porous pavements. Most studies concur with the general conclusion that there exists good treatment of hydrocarbons, metals, and suspended solids. Treatment of nutrients and chloride did not appear to be significant in most examples cited. The pavement layer was critical in retention of suspended solids and metals in many studies cited. Physical, chemical, and biological mechanisms served to degrade or at least retain pollutants to a smaller extent in the porous media reservoir and at the geotextile filter (if present) and subgrade soils (if unlined). Hogland et al. (1987) reported on the first year water-quality treatment performance of snowmelt at several PA sites and found a 95% reduction in suspended solids, a 17% reduction in zinc (Zn), a 1,003% increase in nitrate (NO3) (from 0.37 to 4.3 mg/L), and a 650% increase in chloride (from 8 mg/L to 60 mg/L). Nitrate increases were attributed to the presence of residual fertilizers, decomposition of organic materials, and to nutrient leaching from the asphalt itself. Chloride increased, presumably because of winter deicing operations. Legret et al. (1994) published results of a study on the fate of heavy metals in PA from work at a site in Bègles, France. They found that the PA pavement filters out the suspended sediments, which are strongly associated with the heavy metals, lead (Pb), copper (Cu), cadmium (Cd), and zinc. They found no increase in heavy metal pollution in the subgrade soils above background conditions. Legret et al. (1996) reported results from Rezé, France from 30 rainfall events that showed a reduction of suspended solids by 64% and lead by 79%. Subgrade soil samples were not significantly contaminated after 4 years. Soil metal concentrations were close to control sample concentrations and below French regulations for agricultural soil quality standards. Legret and Colandini (1999) explained the water-quality improvement observed in the 1996 study by demonstrating retention of pollutants in the PA structure. Copper, cadmium, and zinc had a 57–85% reduction of the influent concentrations in the underlying porous media. Lead was found to be well-retained in the suspended solids of the filtered material. Dempsey and Swisher (2003) calculated soil loading rates for lead, copper, and zinc; all were well below

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state standards for biosolid (sludge) land application. Baladès et al. (1995) reported from two sites in Bordeaux, France that chemical oxygen demand and lead reduction ranged from 80 to 90% and 90 to 95%, respectively, and total suspended solids (TSS) reductions ranged up to 80%.

Legret et al. (1999) simulated infiltration of dissolved and particulate heavy metal polluted runoff through porous pavement in a laboratory and by computer modeling . Laboratory results confirmed retention of the metals lead, copper, cadmium, and zinc. A 50-year simulation showed slight increases in subbase soil concentrations of lead, copper, and zinc. Infiltrated water showed pollutant migration for cadmium down to 30 cm. Overall groundwater risk appeared low. A study by Brattebo and Booth (2003) in Washington showed that effluent concentrations of four permeable pavements had nondetectable concentrations for motor oil, lead, and diesel fuel for vertical flow paths of only 10 cm. Dreelin et al. (2006) reported reductions for zinc and total phosphorus (TP) of 17 and 80% and increases in total nitrogen (TN) of 43%.

Study Area

The study site is located at the UNHSC porous asphalt test facility. The PA site is located along the eastern perimeter of a 3.6 ha (9 acre) commuter parking lot (West Edge Lot). The PA lot is hydrologically isolated with an area of 465 m^2 and a surface slope of 1%. The area is frequented by passenger vehicles and is subject to frequent plowing, salting, and sanding during the winter months (typically November through April). For the period from January through March, the winter climate in Durham, New Hampshire, generally consists of average temperatures near −2.4°C, with maximum and minimum temperatures of 3.1°C and −8.2°C, respectively. Total precipitation during this time period is approximately 42 cm, and snowfall is around 160 cm. In New Hampshire, the typical maximum depth of frost ranges between 122 and 140 cm from coast to inland, respectively. For porous pavements, greater depth of frost is not the concern but rather the increase in the rate of cycling between freeze and thaw. This rate is highest near the coast (Zielinski and Keim 2005).

Methodology

Porous Asphalt Site Design

Specifications for the porous asphalt were based on guidance from the National Asphalt Pavement Association (Jackson 2003), Cahill et al. (2004), and from the Federal Aviation Administration (FAA) for the subbase design (Ferguson 2005). The PA mix design and construction details are available online [UNHSC 2004]. Pavement and subbase thickness are based on FAA guidance for runways (i.e., $\geq 0.65 \times$ design frost depth; Ferguson 2005). The porous asphalt mix was a PG64-28 with no polymer modifiers or other additives. The mix design was for 18% void space and 5.8% asphalt content. From top to bottom the PA system is a 10-cm layer of porous asphalt, 10-cm choker course of 19 mm of crushed stone, a 61-cm layer of filter course of poorly graded sand/gravel (a.k.a., bank-run gravel), and a 10-cm reservoir course of crushed stone. The fine gradation of the filter course is for enhanced filtration and water-quality improvement and delayed water release. The high air void content of the uniformly graded crushed stone reservoir course maximizes storage of infiltrated water and creates a capillary barrier to the vertical transport of water, thereby inhibiting winter freeze-thaw action. The 15-cm underdrain in the reservoir course is for hydraulic relief and raised 30 cm off the bottom of the stone layer to enhance groundwater recharge during and in between storms. Nonwoven geotextile filter fabric was used along the bottom and sides of the system. However, this is no longer recommended on the bottom unless needed, for structural reasons, upon poor load bearing soils. Fabrics are not recommended along the bottom for porous pavements because clogging has been reported (Boving et al. 2004) and when used as a design component for storm-water filtration (Roseen et al. 2009). Underlying soils were a combination of infill and hydrologic soil group type C soils. The seasonal high groundwater table was unclear because of infill soils. Groundwater wells were installed to monitor elevation and quality.

Monitoring Data, Sampling, and Analysis

Water-quality monitoring reported in this paper occurred from April 2005 to June 2006; however, monitoring continues to the present. Rainfall was measured at 5-min intervals with an ISCO 674 rain gauge. The rain gauge was heated during winter months. Because there exists no surface runoff from porous asphalt, the adjacent impervious watershed was monitored for influent water quality. The PA parking lot of 465 m^2 is a small fraction of the watershed monitored for influent water quality (approximately 3.6 ha). The influent hydrograph was divided proportionally by the ratio of watershed areas. Water-quality concentrations between the influent watershed and the PA effluent were compared directly. Flow-weighting of these concentrations by calculating event mean concentrations (EMC) allowed for meaningful comparisons of influent and effluent water-quality parameters. Monitoring points were located at the downstream end of subsurface collection pipes. In the 15-cm-diameter high density polyethylene (HDPE) pipe at the PA outfall, a Thel-Mar weir was placed at the outlet to measure flow. Real-time water quality parameters were measured with the YSI 6000-XL sonde for temperature, pH, specific conductivity, and dissolved oxygen, which were logged every 5 min. Samples were taken by using ISCO 6712FR automatic samplers. The sample programs consisted of two parts: Part A consisted of four samples that were typically collected at shorter time intervals to represent the first flush of contaminants; and Part B consisted of 20 samples collected at a single time step and was intended to represent the falling limb of the hydrograph. Up to 24 samples were collected in 1-L sample bags (Pro-Pak). After a storm event occurred, samples were transported to the main site, where they were heat-sealed, barcode-labeled, and placed in coolers for same-day transport for analysis. Of the maximum 24 samples collected per storm event, typically eight were sent to a local state-certified laboratory for analysis. Analyses conducted were for nitrate as nitrogen (NO_3-N) by the U.S. EPA Analytical Method E300.0A, total phosphorus as phosphorus by Method E365.3, total petroleum hydrocarbons as diesel (TPH-D) by Method 8015B, total suspended solids by Method E160.2, and zinc by Method 6010B (2011).

For all parameters, paired influent and effluent contrasts were conducted by using either the Student's t-test for normal distributions, or a nonparametric test, Wilcoxon rank sum, for nonnormal distributions (significance level of 95%).

Surface Infiltration Capacity

As a measure of PA hydrologic performance, the surface infiltration capacity was measured near-monthly since installation, from 2004 to 2008, to evaluate seasonal variations associated with temperature. The test performed was similar to that used by Bean (2005), a modification of an ASTM Standard D3385-03 (ASTM 1988). A falling head surface inundation (SI) test was used that involved placing a cylinder of known diameter onto the pavement surface, which was then sealed to the pavement surface (Briggs 2006). The cylinder was situated within a platform base and lined with pliable

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foam to achieve a seal when weighted. Water was poured into the cylinder up to a predetermined depth and volume, and the time required for all the water to infiltrate into the pavement was recorded. Before January 7, 2008, the SI device used was a 30.5-cm aluminum cylinder, and 18.9 L of water were infiltrated during the test. After this date, the device was modified to a 10.2-cm acrylic cylinder to reduce the amount of water used. The volume of water needed for the modified test to remain equivalent to the original SI test was 2.1 L (0.56 gal.).

Three locations (A, B, and C) within the 465 m^2 PA surface were tested beginning in November 2004. Point A is a fast-infiltrating location in the south corner of the lot. Point B is a medium- to high-infiltrating location in a drive lane. Point C is a low-infiltrating location relative to Points A and B and is situated at the exit from the parking lot. Location C near the entrance of the site exhibited an infiltration rate that was too slow to be accurately represented by the SI test as a result of leakage during the test. In response to this problem, a modified double-ring infiltrometer (DRI) test was used for this location (Briggs 2006). The DRI test is a constant-head test that is typically used for measuring infiltration rates of soils. It can provide more representative results than the SI test because of dual columns of infiltrating water. Constant temperature water was used for IC testing. Seasonal temperature-related viscosity effects were not examined; however, if water at the freezing point was used, then the IC value could be expected to be smaller by a factor of 1.82 (Mays 2001).

Frost Depth

Frost depth is defined as the depth below the pavement surface to which subfreezing temperatures exist. This was quantified in the PA pavement by using a frost gauge (Ricard et al. 1976). The frost gauge assembly was placed in a groundwater monitoring well, a 2.5-cm-diameter PVC pipe, fully screened and approximately 1.22 m deep. The well casing was stubbed into a road box and capped. Frost depth measurements for 2005 and 2006 were conducted routinely throughout the winter and on occasion before and after winter rain events. Outside air temperature and air pressure were recorded at a nearby outdoor location.

Water Balance Analysis

A water balance analysis was conducted for the study by measurement of precipitation depth in contrast to effluent flow volume from the subdrains. The total watershed area includes some fringe landscaping (520 m^2). The water balance analysis was performed for an 18-month period from April 1, 2005, to September 30, 2006. Precipitation and effluent were summed monthly, and their cumulative volumes were compared over time. A monthly ratio of precipitation to effluent volume was also computed.

Hydrologic Efficiency Analysis

Hydrologic performance was evaluated by examining hydrograph transformations as measured by the peak flow reduction coefficient (k_p), lag time, and lag coefficient (k_L) (Hood and Clausen 2007). The peak flow reduction coefficient is defined as the ratio of peak flow for the effluent to the maximum event precipitation intensity (weighted for the watershed area). Lag time was calculated as the difference between time at the effluent volume centroid and time at rainfall volume centroid. Lag coefficient is calculated as the ratio of effluent volume centroid to precipitation volume centroid.

Results and Discussion

Surface Infiltration Capacity

Observation of trends in IC for the three locations over 3 years indicates no consistent statistical difference for seasonal hydrologic performance (Fig. 1, Table 1). For two representative locations (Locations A and B in Fig. 2), the mean IC was 3,074 and 1,725 cm/h. For Year 1, at both locations a decline was observed in the first season where winter IC was significantly greater than the first summer, not the reverse, as might be expected. Although there exists a slight trend of declining IC for B and C, there was no observable drop for each winter. An overall downward trend in IC was observed for all three locations corresponding to no pavement maintenance or cleaning until September 22, 2007.

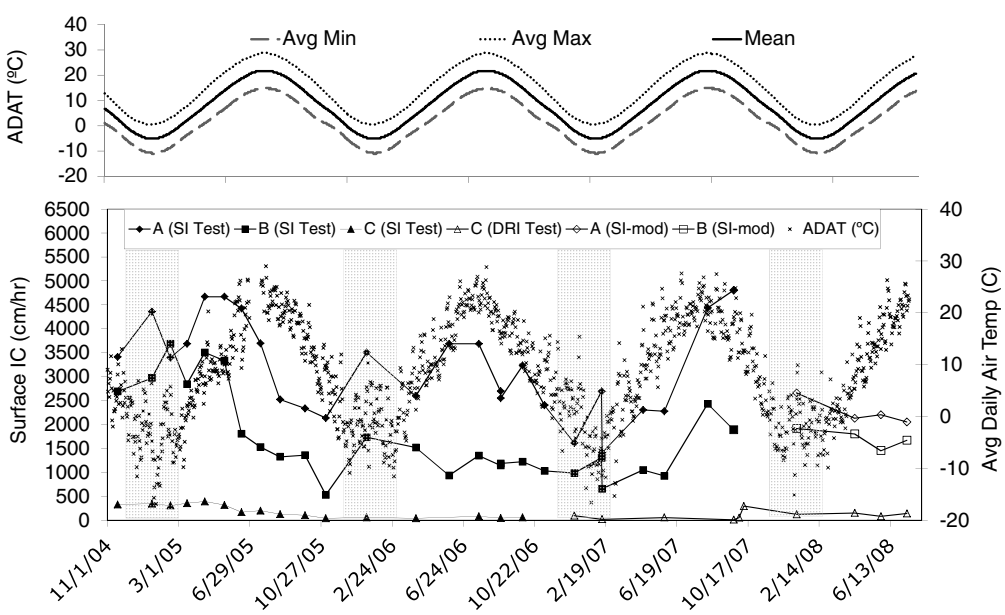

Fig. 1. Time-series plots of porous asphalt surface infiltration capacity (vertical lines indicate winter months) and average daily air temperatures historically and for the monitoring period (2004–2008); SI = surface inundation; DRI = double-ring infiltrometer; ADAT = avg. daily air temp. (pavement cleaning before Sep. 23, 2007, IC measurements)

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Table 1. Seasonal Statistical Comparison of Porous Asphalt Surface Infiltration Capacity (in./h) Using Student's t-test

Period		11/04–10/05		11/05–10/06		11/06–10/07		11/07–7/08	
Season		W	S	W	S	W	S	W	S
Location A	n	5	5	3	5	5	3	2	2
	$\bar{x} \pm \sigma$	$1{,}537 \pm 228$	$1{,}390 \pm 421$	$1{,}080 \pm 274$	$1{,}248 \pm 211$	820 ± 215	$1{,}511 \pm 538$	943 ± 148	838 ± 42
	COV	0.15	0.30	0.25	0.17	0.26	0.36	0.16	0.05
	Significance	No. $P = 0.451$;		No. $P = 0.457$		$P < 0.05$; $S \gg W$		No. $P = 0.733$	
Location B	n	5	5	3	5	5	3	2	2
	$x \pm \sigma$	1235 ± 171	736 ± 331	496 ± 253	459 ± 59	396 ± 91	688 ± 300	732 ± 33	614 ± 59
	COV	0.14	0.45	0.51	0.13	0.23	0.44	0.04	0.10
	Significance	$P < 0.05$; $W \gg S$		No. $P = 0.808$		No. $P = 0.063$		No. $P = 0.569$	
Location C	n	5	5	3	3	2	4	2	2
	$x \pm \sigma$	345 ± 32	183 ± 83	45 ± 11	60 ± 19	23 ± 21	41 ± 51	54 ± 8	44 ± 18
	COV	0.09	0.46	0.23	0.31	0.91	1.24	0.15	0.40
	Significance	$P < 0.05$; $W \gg S$		No. $P = 0.713$		No. $P = 0.666$		No. $P = 0.829$	

Note: W = November–April; S = May–October. In all time periods, measurements were made using surface inundation tests. Exceptions were for Locations A and B for November 2007–July 2008, where a modified surface inundation test was used, and for Location C for November 2006 and later, where a double-ring infiltrometer (DRI) was used.

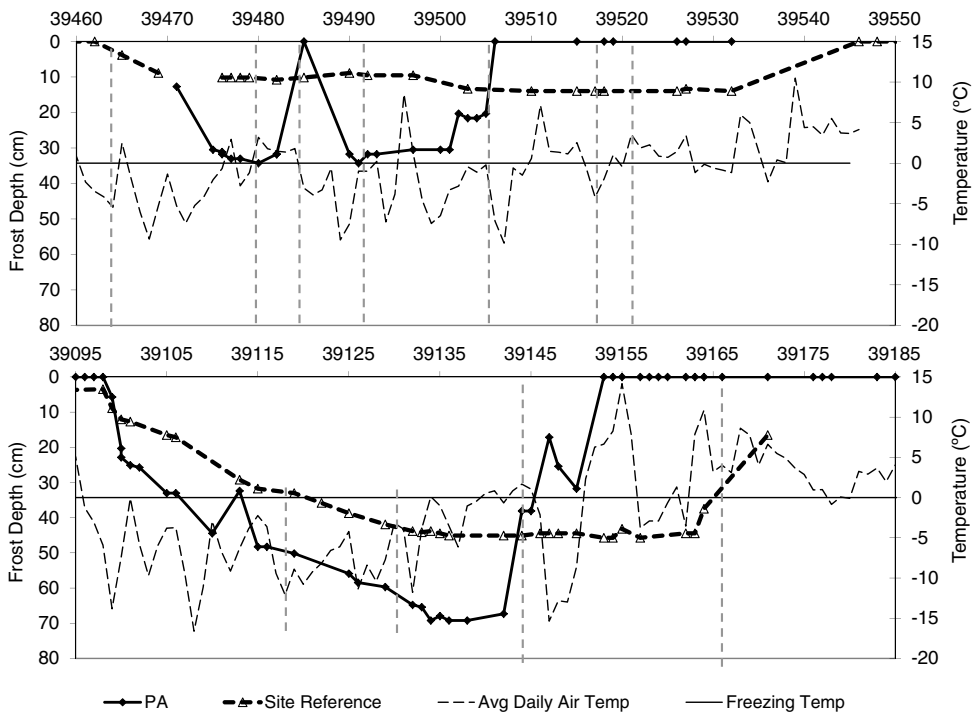

Fig. 2. Frost depth for Winter 2006–2007 (bottom) and 2007–2008 (top); rain events = vertical dashes

The initial decline of IC the summer following installation is supported by Ferguson (2005), who hypothesized that reduction is because of asphalt binder draindown during hot summer months. The PA installation for this location did not include fibers or polymer modifiers, both of which are used to minimize draindown to less than 0.3% (NAPA 2003). Analysis of draindown within the asphalt cores taken at the three locations ranged from 0.3 to 0.45%. Mean in-place draindown was determined by measurement of the asphalt content in the top and bottom halves of the cores to be 4.7 and 5.1%, respectively ($n = 18$). The draindown was apparently limited to the first summer because no equivalent decline in IC was observed for the 2 years following. The initial substantial reduction in summer IC rebounded with the onset of cooler weather. In fact, periods thereafter begin to reflect changes in IC that mirror changes correlated with the cyclical trend of average daily air temperature (ADAT) to some degree.

Several laboratory studies have suggested that the IC of porous asphalt may decline by approximately 50% in below-freezing temperatures but will remain sufficient as long as the pavement is not completely covered with ice or clogged by sand (Stenmark 1995; Backstrom and Bergstrom 2000). Declining infiltration rates from measurements on February 12–13, 2007, demonstrate the effect of air temperature on IC. During this time, the ADAT decreased from −4.4°C to −11.7°C, and the average IC of Locations A and B

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Table 2. Hydraulic Performance Summary for 17 Storm Events

		Precipitation					Peak flow reduction				Effluent delay		
Event no.	Date	Storm duration (min)	Prior rainfall[a] (day)	Storm depth (cm)	Peak intensity (cm/5 min)	Storm volume (L)	Peak precip. (cmskm)	Peak Eff Flow (cmskm)	k_p	Precip. centroid (min)	Effluent centroid (min)	Lag time (min)	k_L
1	4/20/05	480	5.9	1.47	0.10	7,665	3.1	0.1	0.04	220	2,690	2,470	12.2
2	5/7/05	965	4.0	1.60	0.03	8,323	0.8	0.2	0.20	410	1,855	1,445	4.5
3	5/21/05	1150	3.0	2.31	0.05	12,025	1.6	0.2	0.15	460	1,780	1,320	3.9
4	8/13/05	765	10.0	1.30	0.20	6,737	6.3	0.0	0.01	360	2,985	2,625	8.3
5	9/15/05	630	10.0	2.26	0.46	11,760	14.2	0.0	0.00	545	1,500	955	2.8
6	10/8/05	1865	8.0	12.7	0.25	66,060	7.9	2.8	0.36	965	1,480	515	1.5
7	11/30/05	805	5.0	1.75	0.08	9,118	2.4	0.3	0.14	535	1,100	565	2.1
8	12/16/05	625	5.5	3.51	0.15	18,232	4.7	0.5	0.11	425	915	490	2.2
9	1/12/06	300	5.8	1.17	0.10	6,079	3.9	0.2	0.06	185	1,700	1,515	9.2
10	3/13/06	1415	2.5	2.34	0.10	12,154	3.2	0.5	0.16	660	1,855	1,195	2.8
11	5/2/06	2130	7.0	7.59	0.15	39,504	4.7	0.5	0.11	1,005	1,915	910	1.9
12	6/1/06	1035	10.7	6.25	1.04	32,502	32.3	1.7	0.05	320	1,100	1,195	3.4
13	11/8/06	465	5.0	0.79	0.05	4,096	1.6	1.4	0.89	190	1,270	1,080	6.7
14	12/23/06	1020	7.5	3.07	0.08	15,987	2.4	0.5	0.23	625	1,935	1,310	3.1
15	1/6/07	760	2.5	1.27	0.08	6,606	2.4	0.3	0.11	645	1,290	645	2.0
16	3/11/07	430	7.0	0.71	0.03	3,699	0.8	0.2	0.20	215	2,715	2,500	12.6
17	4/12/07	590	6.0	0.94	0.03	4,889	0.8	0.3	0.32	235	1,175	940	5.0
Minimum		300	2.5	0.71	0.03	3,699	0.8	0.02	0.002	185	915	490	1.5
25th quartile		590	5.0	1.27	0.05	6,606	1.6	0.2	0.1	235	1,270	910	2.2
Median		765	5.9	1.75	0.10	9,118	3.1	0.3	0.1	425	1,700	1,195	3.4
75th quartile		1,035	7.5	3.07	0.15	15,987	4.7	0.5	0.2	625	1,915	1,445	6.7
Maximum		2,130	10.7	12.7	1.04	66,060	32.3	2.8	0.9	1,005	2,985	2,625	12.6
Average		908	6.2	3.00	0.17	15,614	5.5	0.58	0.2	471	1,721	1,275	5.0
St. dev.		503	2.5	3.13	0.25	16,291	7.7	0.74	0.2	252	605	677	3.6

Note: k_p = peak reduction coefficient, the ratio of peak effluent flow to peak rate of precipitation integrated over watershed area; k_L = lag coefficient, the ratio of the effluent centroid to the precipitation centroid; cmskm $= \mathrm{m^3/s/km^2}$.

[a]Prior rainfall calculated as the time in days of antecedent dryness since a minimum 0.1-in. storm event, using the UNH Weather Station gauge. All precipitation falling within 6 h counts as the same storm event.

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decreased from 2,000 to 1,030 cm/h in 24 h. The apparent correlation of IC with air temperature continued until April 2008, when the IC rates at Locations A and B stabilized around 2,160 and 1,650 cm/h, respectively. This final trend change is partly because of the modification of the SI testing device (SI-mod). The low-infiltrating area at Location C had low IC since installation because of quality control production problems resulting in a lower percentage void space.

Vacuum maintenance of this PA parking lot occurred only once, on September 22, 2007, and was completed with a combination of an Elgin Whirlwind MV vacuum sweeper and pressure-washing. Pressure-washing was limited to substantially clogged areas with a low-pressure hand wand (3,550 kPa) directed at a low angle to the pavement surface. The lot was routinely plowed and deiced with a sand and salt mixture (~10% sand).

Frost Depth

Depth of frost penetration was observed for the winter seasons of 2006–2007 and 2007–2008 (Fig. 2). Frost depth within the systems is plotted against average daily air temperature and frost depth at a reference location in adjacent soil. Rain events, as occurrences, are plotted as vertical dashed lines. Reliable patterns of freeze and thaw were observed for the two winters and generally reflected a more rapid response to changes in ambient air temperature, in comparison to the reference site located in an adjacent unpaved surface. The same response is not observed in the reference location, likely because of a lack of infiltration of meltwater. The degree of response has not been examined with respect to rain depth or other important factors. Rain events occur throughout the winter and are commonly mixed with snow and ice. The depth of frost penetration was much greater, and the timing of the spring thaw occurred sooner than at the reference location. The frequency and rate of thaw was also greater than the reference site. The porous asphalt thawed completely and refroze repeatedly throughout the winters. The midwinter thaws occurred during episodes of warming and rainfall events in which the infiltration of rainfall and meltwater thawed the frozen filter media. This phenomenon was observed on four occasions during 2008 and one occasion during 2007. The porous pavement thawed completely nearly 30 days earlier than the reference site for both winters. Frost depth trends lagged behind air temperature by a few days, and commonly, the combination effects of ambient air temperature warming followed by rainfall could be observed to thaw the pavement. An example of a rainfall and ambient temperature thaw occurred beginning on March 1, 2007, with warming and rainfall with a frost depth of 69 cm, followed by a number of very cold days and increased frost depth, followed by additional warming and a complete thaw over only 11 days. In contrast, the reference site showed almost no variation at half the depth and remained frozen for almost another 30 days.

Hydrologic Performance and Water Balance

Rainfall and hydrologic performance characteristics of the pavement are presented in Table 2. The water balance was determined for 14 months from April 2005 to June 2006. Peak monthly precipitation volumes were observed in October 2005 (152 m^3) and May 2006 (208 m^3). Minimum monthly precipitation was observed in March 2006 (13.3 m^3). From a storm-water management perspective, it is desirable to have a reduced peak-flow reduction coefficient (k_p), increased lag time, and increased lag coefficient (k_L) relative to unattenuated runoff from impervious surfaces. The PA effluent met these criteria for all storm events considered in this analysis, similar to what might be expected from a shallow flow groundwater signal in small streams. Ideally, storm-water management technologies minimize changes to the hydrologic predevelopment conditions. Fig. 3 depicts rainfall and actual effluent flow in comparison with a rationally derived synthetic flow for a 6.25-cm rainfall event. Fig. 4 illustrates peak-flow performance normalized by the site footprint. Peak flow was reduced significantly in all storm events ($p = 0.009$, at 95% confidence, $n = 17$) with standard pavement flows $\bar{x} = 502\ m^3/s/km^2 \pm 704$ versus flows from the PA lot $\bar{x} = 0.58\ m^3/s/km^2 \pm 0.74$. Even during very large storm events exceeding the 2-year storm (6.35 cm in 24 h), substantial lag time and peak flow reduction were observed. The lag time was increased substantially for all events with an average of 1,275 min.

For the 18-month period (April 1, 2005, to September 30, 2006) that the water balance was determined, a net cumulative recharge was observed for a site located on a hydrologic soil group type C soil. Water balance monitoring began 6 months after site installation. No surface runoff occurred for any storm event, including a 12.7-cm rainfall event. All effluent occurred through subdrains located within the pavement system. Cumulative precipitation increased at a rate greater than cumulative effluent for most of the study period. Cumulative recharge was negative for the first 3 months of the study period, ending in late July 2005. Groundwater was not believed to be a factor in the water balance because water levels in groundwater wells never reached the base elevation of the PA subbase reservoir. By August 2005, the system had a net recharge. By September 30, 2006, precipitation volume totaled 1,220 m^3 and effluent volume totaled 920 m^3, resulting in a net cumulative recharge volume of 299 m^3 (representing a depth of 57.9 cm), which accounted for 25% of cumulative precipitation for the entire study period. Evaporation of groundwater upward through the pavement is unlikely to be significant because of the installation of a capillary barrier (Mays 2001). During months with the greatest precipitation (October 2005, May 2005, and June 2006), precipitation exceeded the effluent volume. Potential sources of error for the water balance include snowmelt onto the pavement footprint and snowplowing outside of the footprint.

Examination of Water Quality

Real-time water quality for specific conductivity (SC), dissolved oxygen (DO), pH, and temperature was analyzed for the 17 storm events. SC was significantly higher in the effluent ($\bar{x} = 1{,}180$ uS/cm) than the influent ($\bar{x} = 415$ uS/cm) (paired t-test $p = 0.0358$, $n = 17$). During storm events, there were predictable patterns observed; influent SC dropped once flow began and then gradually increased back to the prestorm level as flows dissipated. Conversely, effluent specific conductivity increased rapidly once flow began and then gradually decreased to prestorm

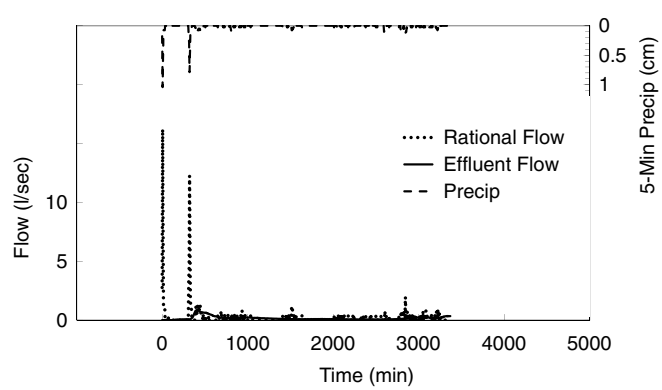

Fig. 3. Hydrologic performance contrasting synthetic rational runoff with effluent flow for 6.25-cm rain event on Jun. 1, 2006

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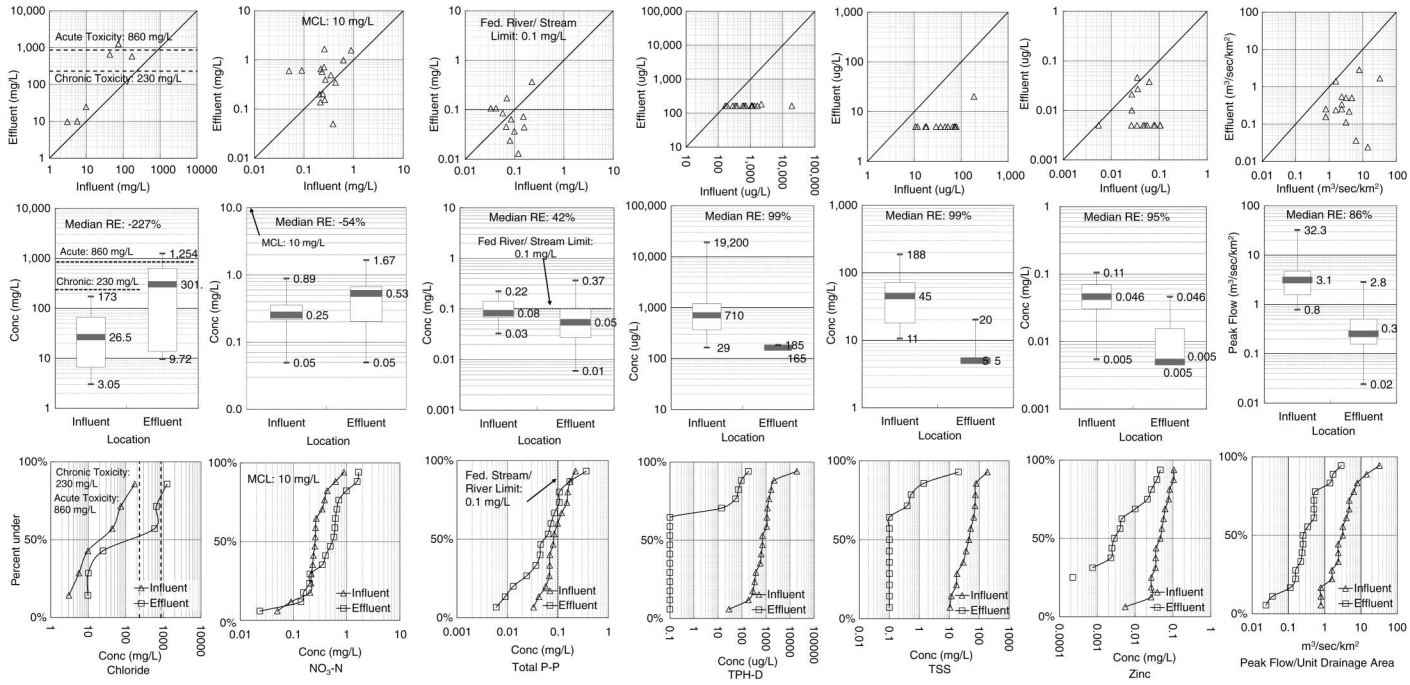

Fig. 4. System performance interquartile distribution and effluent probability plots

levels as flow decreased. DO was not significantly different between influent and effluent ($p = 0.1152$, $n = 17$). Effluent DO was usually slightly lower than influent DO. Effluent pH was significantly greater than influent with a notable buffering effect with a median = 7.1 and 6.1, respectively ($p < 0.0001$). There was no significant difference in median temperatures observed for the influent and effluent, 10.4°C and 9.8°C, respectively ($p = 0.7038$, $n = 17$).

Many EMC values were found to be below detection limits. Values below detection limits are reported and analyzed here as half the detection limit. Fig. 4 presents EMCs interquartile ranges with box and whiskers diagrams and cumulative probability distributions. Treatment for nitrate was significantly poor ($p = 0.0032$, at 95% confidence, $n = 16$) because effluent nitrate ($\bar{x}_{NO3} = 0.31$ mg/L ± 0.20) was greater than influent ($\bar{x}_{NO3} = 0.58$ mg/L ± 0.48) for all but two storm events (November 30, 2005, and December 16, 2005), in which little to no treatment was observed. This is to be expected because removal of nitrate typically only occurs with vegetated filtration (Roseen et al. 2006). Additionally, total phosphorous EMC reduction was not significant ($p = 0.649$, at 95% confidence, $n = 14$) with influent $\bar{x}_{TP} = 0.10$ mg/L ± 0.06 and effluent $\bar{x}_{TP} = 0.08$ mg/L ± 0.09. Total petroleum hydrocarbons (TPH-D) reduction was significant ($p = 0.069$, at 90% confidence, $n = 16$), with all but one effluent EMC below detection limits (320 ug/L). TPH-D treatment performance during the June 1, 2006 storm event was exceptional with the influent EMC = 19,204 ug/L, and the effluent was not detected. Influent $\bar{x}_{TPH-D} = 1970$ ug/L ± 4630, and effluent $\bar{x}_{TPH-D} = 166$ ug/L ± 5.

Treatment reduction for TSS was very significant ($p = 0.002$, at 95% confidence, $n = 13$) with only one effluent event above detection limits (10 mg/L). Influent $\bar{x}_{TSS} = 54$ mg/L ± 47, and effluent $\bar{x}_{TSS} = 6$ mg/L ± 4. The October 8, 2005, storm event was exceptionally intense, and storm depth was greater than 12.7 cm over several days. The June 1, 2006, storm event was the most intense storm witnessed to date at the UNHSC, resulting in high mobilization of TSS at the influent (EMC = 188 mg/L) and resulted in an effluent EMC = 20.3 mg/L. The source of TSS during this storm was most likely fine subgrade materials (clays) that passed through the geotextile filter fabric. Turbidity was also observed during an intense 7.6-cm storm on October 11, 2006 (maximum intensity of 2.54 cm/h per 5-min interval). Turbidity in the effluent was not observed at other times. Zinc reduction was also significant ($p = 0.001$, at 95% confidence, $n = 15$). Zinc effluent concentrations were below detection limits 66% of the time (0.01 mg/L). Influent $\bar{x}_{Zn} = 0.052$ mg/L ± 0.030, and effluent $\bar{x}_{Zn} = 0.013$ mg/L ± 0.014.

Summary and Conclusions

The porous asphalt pavement system performed impressively as a storm-water management strategy despite cold-climate challenges. The pavement system function remained strong for hydraulics and water quality during the coldest periods of the year. Dissolved anionic contaminants, such as nitrate and chloride, showed no removal, as is typical for nitrate for nonvegetated filtration systems and dissolved chlorides. Phosphorous removal, which is always challenging, was only partial (42% removal efficiency). Cationic and undissolved contaminant removal was nearly complete for TPH, zinc, and TSS. Surface infiltration capacity remained high year-round (2,030 cm/h) despite substantial observed frost penetration (maximum 71 cm). The persistence of infiltration capacity during periods of prolonged frost penetration indicates that the coarse open-graded materials retain significant porosity and remain well-drained throughout the year.

Acknowledgments

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Appendix C

U.S. ENVIRONMENTAL PROTECTION AGENCY

National Pollutant Discharge Elimination System (NPDES)

Menu of BMPs Home

BMP Background

Public Education & Outreach on Stormwater Impacts

Public Involvement/ Participation

Illicit Discharge Detection & Elimination

Construction Site Stormwater Runoff Control

Post-Construction Stormwater Management in New Development & Redevelopment

Pollution Prevention/Good Housekeeping for Municipal Operations

Stormwater Home

Porous Asphalt Pavement

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Minimum Measure: Post-Construction Stormwater Management in New Development and Redevelopment

Subcategory: Infiltration

Description

Figure 1. Porous asphalt allows water to flow through it. *Photo courtesy of the National Asphalt Paving Association*

Porous asphalt, also known as pervious, permeable, "popcorn," or open-graded asphalt, is standard hot-mix asphalt with reduced sand or fines and allows water to drain through it. Porous asphalt over an aggregate storage bed will reduce stormwater runoff volume, rate, and pollutants. The reduced fines leave stable air pockets in the asphalt. The interconnected void space allows stormwater to flow through the asphalt as shown in Figure 1, and enter a crushed stone aggregate bedding layer and base that supports the asphalt while providing storage and runoff treatment. When properly constructed, porous asphalt is a durable and cost competitive alternative to conventional asphalt.

Applicability

Porous asphalt can be used for municipal stormwater management programs and private development applications. The runoff volume and rate control, plus pollutant reductions, allow municipalities to improve the quality of stormwater discharges. Municipal initiatives, such as Portland's Green Streets program (Figure 2), use porous asphalt to reduce combined sewer overflows by infiltrating and treating stormwater on site. Private development projects use porous asphalt to meet post-construction stormwater quantity and quality requirements. The use of porous asphalt can potentially reduce additional expenditures and land consumption for conventional collection, conveyance, and detention stormwater infrastructure.

Figure 2. A curb to curb installation of porous asphalt (left) and an installation of porous asphalt in the parking lanes and conventional asphalt in the drive lanes (right), Portland, OR. *Photo courtesy of the Portland Bureau of Environmental Services*

Porous asphalt can replace traditional impervious pavement for most pedestrian and vehicular applications. Open-graded asphalt has been used for decades as a friction course over impervious asphalt on highways to reduce noise, spray, and skidding. Highway applications with all porous asphalt surfacing have been used successfully for highway pilot projects in the United States, but, generally, porous asphalt is recommended for low volume and low speed applications (Hossain et al., 1992). Porous asphalt performs well in pedestrian walkways, sidewalks, driveways, parking lots, and low-volume roadways. The environmental benefits from porous asphalt allow it to be incorporated into municipal green infrastructure and low impact development programs. The appearance of porous asphalt and conventional asphalt is very similar. The surface texture of porous asphalt is slightly rougher, providing more traction to vehicles and pedestrians.

Siting and Design Criteria

Porous asphalt should be designed and sited to intercept, contain, filter, and infiltrate stormwater on site. Several design possibilities can achieve these objectives. For example, porous asphalt can be installed across an entire street width or an entire parking area. The pavement can also be installed in combination with impermeable pavements or roofs to infiltrate runoff. Several applications use porous asphalt in parking lot lanes or parking stalls to treat runoff from adjacent impermeable pavements and roofs. This design economizes porous asphalt installation costs while providing sufficient treatment area for the runoff generated from impervious surfaces. Inlets can be placed in the porous asphalt to accommodate overflows from extreme storms. The stormwater volume to be captured, stored, infiltrated, or harvested determines the scale of permeable pavement required.

Table 1. Asphalt Mix (Adams, 2003)

Sieve Size	% Passing
1/2 in	100
3/8 in	95
#4	35
#8	15
#16	10
#30	2
Percent bituminous asphalt 5.75-6.0% by weight	

Porous asphalt comprises the surface layer of the permeable pavement structure and consists of open-graded coarse aggregate, bonded together by bituminous asphalt. A typical reduced fines asphalt mix is shown in Table 1. Polymers can also be added to the mix to increase strength for heavy load applications. The thickness of porous asphalt ranges from 2 to 4 inches depending on the expected traffic loads. For adequate permeability, the porous asphalt should have a minimum of 16% air voids. Additional subsurface components of this treatment practice are illustrated in Figure 3 and include the following (NAPA, 2008):

- *Choke course* - This permeable layer is typically 1 - 2 inches thick and provides a level and stabilized bed surface for the porous asphalt. It consists of small-sized, open-graded aggregate.
- *Open-graded base reservoir* - This aggregate layer is immediately beneath the choke layer. The base is typically 3 - 4 inches thick and consists of crushed stones typically 3/4 to 3/16 inch. Besides storing water, this high infiltration rate layer provides a transition between the bedding and subbase layers.
- *Open-graded subbase reservoir* - The stone sizes are larger than the base, typically ¾ to 2 ½ inch stone. Like the base layer, water is stored in the spaces among the stones. The subbase layer thickness depends on water storage requirements and traffic loads. A subbase layer may not be required in pedestrian or residential driveway applications. In such instances, the base layer is increased to provide water storage and support.

- *Underdrain (optional)* - In instances where porous asphalt is installed over low-infiltration rate soils, an underdrain facilitates water removal from the base and subbase. The underdrain is perforated pipe that ties into an outlet structure. Supplemental storage can be achieved by using a system of pipes in the aggregate layers. The pipes are typically perforated and provide additional storage volume beyond the stone base.
- *Geotextile (optional)* - This can be used to separate the subbase from the subgrade and prevent the migration of soil into the aggregate subbase or base.
- *Subgrade* - The layer of soil immediately beneath the aggregate base or subbase. The infiltration capacity of the subgrade determines how much water can exfiltrate from the aggregate into the surrounding soils. The subgrade soil is generally not compacted.

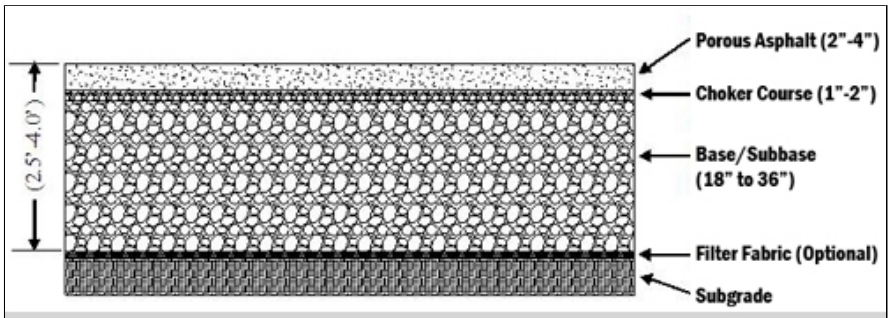

Figure 3. Typical Porous Asphalt Pavement Section *(diagram adapted from US EPA)*

The same equipment can be used for mixing and laying permeable asphalt as conventional asphalt. The method for laying the asphalt will also be similar. During compaction of the asphalt, minimal pressure should be used to avoid closing pore space. Vehicular traffic should be avoided for 24 to 48 hours after pavement is installed.

Figure 4. Porous asphalt installation for a Villanova parking lot. *Photo courtesy of the Villanova Urban Stormwater Partnership*

Specific Design Considerations and Limitations

The load-bearing and infiltration capacities of the subgrade soil, the infiltration capacity of the porous asphalt, and the storage capacity of the stone base/subbase are the key stormwater design parameters. To compensate for the lower structural support capacity of clay soils, additional subbase depth is often required. The increased depth also provides additional storage volume to compensate for the lower infiltration rate of the clay subgrade. Underdrains are often used when permeable pavements are installed over clay. In addition, an impermeable liner may be installed between the subbase and the subgrade to limit water infiltration when clay soils have a high shrink-swell potential, or if there is a high depth to bedrock or water table (Hunt and Collins, 2008).

Measures should be taken to protect permeable pavement from high sediment loads, particularly fine sediment. Appropriate pretreatment BMPs for run-on to permeable pavement include filter strips and swales. Preventing sediment from entering the base of permeable pavement during construction is critical. Runoff from disturbed areas should be diverted away from the permeable pavement until they are stabilized.

Several factors may limit permeable pavement use. Porous asphalt has reduced strength compared to conventional asphalt and will not be appropriate for applications with high volumes and extreme loads. It is not appropriate for stormwater hotspots where hazardous materials are loaded, unloaded, stored, or where there is a potential for spills and fuel leakage. For slopes greater than 2 percent, terracing of the soil subgrade base may likely be needed to slow runoff from flowing through the pavement structure.

Maintenance

The most prevalent maintenance concern is the potential clogging of the porous asphalt pores. Fine particles that can clog the pores are deposited on the surface from vehicles, the atmosphere, and

Key Siting and Maintenance Issues:

runoff from adjacent land surfaces. Clogging will increase with age and use. While more particles become entrained in the pavement surface, it does not become impermeable. Studies of the long-term surface permeability of porous asphalt and other permeable pavements have found high infiltration rates initially, followed by a decrease, and then leveling off with time (Bean, et al., 2007a). With initial infiltration rates of hundreds of inches per hour, the long-term infiltration capacity remains high even with clogging. When clogged, surface infiltration rates usually well exceed 1 inch per hour, which is sufficient in most circumstances for the surface to effectively manage intense stormwater events (ICPI, 2000). Permeability can be increased with vacuum sweeping. In areas where extreme clogging has occurred, half inch holes can be drilled through the pavement surface every few feet or so to allow stormwater to drain to the aggregate base. A stone apron around the pavement connected hydraulically to the aggregate base and subbase can be used as a backup to surface clogging or pavement sealing.

- Do not install in areas where hazardous materials are loaded, unloaded, or stored.
- Avoid high sediment loading areas.
- Divert runoff from disturbed areas until stabilized.
- Do not use sand for snow or ice treatment.
- Periodic maintenance to remove fine sediments from paver surface will optimize permeability.

Due to the well draining stone bed and deep structural support of porous asphalt pavements, they tend to develop fewer cracks and potholes than conventional asphalt pavement. When cracking and potholes do occur, a conventional patching mix can be used. Freeze/thaw cycling is a major cause of pavement breakdown, especially for parking lots in northern climates. The lifespan of a northern parking lot is typically 15 years for conventional pavements; porous asphalt parking lots can have a lifespan of more than 30 years because of the reduced freeze/thaw stress (Gunderson, 2008).

In cold climates, sand should not be applied for snow or ice conditions. However, snow plowing can proceed as with other pavements and salt can be used in moderation. Porous asphalt has been found to work well in cold climates as the rapid drainage of the surface reduces the occurrence of freezing puddles and black ice. Melting snow and ice infiltrates directly into the pavement facilitating faster melting (Gunderson, 2008).

Figure 5. Porous asphalt parking lot one hour after being plowed. *Photo courtesy of the University of New Hampshire Stormwater Center*

Cold weather and frost penetration do not negatively impact surface infiltration rates. Porous asphalt freezes as a porous medium rather than a solid block because permeable pavement systems are designed to be well-drained; infiltration capacity is preserved because of the open void spaces (Gunderson, 2008). However, plowed snow piles should not be left to melt over the porous asphalt as they can receive high sediment concentrations that can clog them more quickly.

Permeable pavements do not treat chlorides from road salts but also require less applied deicers. Deicing treatments are a significant expense and chlorides in stormwater runoff have substantial environmental impacts. Reducing chloride concentrations in runoff is only achieved through reduced application of road salts because removal of chloride with stormwater BMPs is not effective. A porous asphalt lot installed at the University of New Hampshire required 25% of the salt routinely applied to other impervious asphalt lots for equivalent deicing. No salt application was required for the porous pavement to have an equivalent friction factor and traction than normally treated conventional pavements because porous pavement has higher frictional resistance than conventional pavement (UNHSC, 2007).

Effectiveness

All permeable pavements, including pervious asphalt, are on-site stormwater management practices and will have the same or very similar effectiveness with regards to the reduction of the volume and rate of stormwater runoff as well as pollutant concentrations. Porous asphalt, pervious concrete, and permeable pavers all have the same underlying stormwater storage and support structure. The only difference is the permeable surface treatment. The choice of permeable surface is relevant to user needs, cost, material availability, constructability, and maintenance, but it has minimal impact on the overall stormwater retention, detention, and treatment of the system.

Permeable pavement transforms areas that were a source of stormwater to a treatment system and can effectively reduce or eliminate runoff that would have been generated from an impervious paved

area. Because it reduces the effective impervious area of a site, permeable pavement should receive credit for pervious cover in drainage system design. The infiltration rate of properly constructed pervious asphalt and base generally exceeds the design storm peak rainfall rate; the subsoil infiltration rate and base storage capacity are the factors determining stormwater detention potential. Table 2 provides monitored reductions in stormwater volumes via storage and infiltration.

Table 2. Volume Retention of Permeable Pavements

Application	Location	Soil Type	Underdrain	Volume Retention
Porous Asphalt				
Street	France	--	--	96.7%
Parking lot	State College, PA	--	--	Retained the 25 yr - 24 hr storm
Park Lot*	Durham, NH	Clay	Underdrain	25%
Permeable Interlocking Concrete Pavers				
Residential street	Auckland, New Zealand	Clay	Yes	60%
Driveway	Cary, NC	Clay	Yes	66%
Field and laboratory tests	Guelph, Ontario, Canada	--	--	90%
Parking lot	Swansboro, NC	Sandy soil	No	100%
Parking lot	United Kingdom	Impermeable liner installed	Yes	34% - 45%
Parking lot	Renton, WA	---	No	100%
Parking lot	Kinston, NC	Clay	No	55%
Pervious Concrete				
Residential streets and sidewalk	Sultan, WA	--	--	100%
Parking lot	Kingston, NC	Clay	No	99.9%

*System designed to collect infiltrated stormwater in underdrain for monitoring purposes. (Legret, M. & Colandini, 1999)(Cahill et al., 2003)(Roseen and Ballestero, 2008)(Fassman and Blackbourn, 2006)(Bean, et al., 2007a)(Bean et al., 2007b)(Pratt, 1999)(Booth and Leavitt, 1999)(Brattebo and Booth, 2003)(Collins, et al., 2008)(WA Aggregates & Concrete Association, 2006)(Collins, et al., 2008)

Permeable pavement reduces pollutant concentrations through several processes. The aggregate filters the stormwater and slows it sufficiently to allow sedimentation to occur. The subgrade soils are also a major factor in treatment. Sandy soils will infiltrate more stormwater but have less treatment capability. Clay soils have a high cation exchange capacity and will capture more pollutants but will infiltrate less. Also, studies have found that in addition to beneficial treatment bacteria in the soils, beneficial bacteria growth has been found on established aggregate bases. In addition, permeable

pavement can process oil drippings from vehicles (Pratt et al., 1999). Table 3 provides measured pollutant removals from pervious pavement structures.

Table 3. Monitored Pollutant Removals of Permeable Pavement

Application	Location	TSS	Metals	Nutrients
Porous Asphalt				
Highway (friction course only)	Austin, TX	94%	76-93%	43%
Parking lot	Durham, NH	99%	Zn: 97%	TP: 42%
Permeable Interlocking Concrete Pavers				
Driveways	Jordan Cove, CT	67%	Cu: 67% Pb: 67% Zn:71%	TP: 34% NO_3-N: 67% NH_3-N: 72%
Parking lot	Goldsboro, NC	71%	Zn: 88%	TP: 65% TN: 35%
Parking lot	Renton, WA	---	Cu: 79% Zn: 83%	--
Parking lot	King College, ON	81%	Cu: 13% Zn: 72%	TP: 53% TKN: 53%
Pervious Concrete				
Parking lot	Tampa, FL	91%	75-92%	--

(Barrett et al., 2006)(UNHSC, 2007)(Bean, et al., 2007b)(Clausen and Gilbert, 2006)(Van Seters/TRCA 2007)(Rushton, 2001)

Permeable pavement water quantity and pollutant reduction characteristics such as 80 percent total suspended solids reductions can qualify it to earn credits under green or sustainable building evaluation systems such as Leadership in Energy and Environmental Design (LEED®) and Green Globes. Credits also can be earned for water conservation and conservation of materials by utilizing some recycled materials and regional manufacturing and resource use.

Cost

Several factors influence the overall cost of porous asphalt:

- Material availability and transport - The ease of obtaining construction materials and the time and distance for delivery.
- Site conditions - Accessibility by construction equipment, slope, and existing buildings and uses.
- Subgrade - Subgrade soils such as clay may result in additional base material needed for structural support or added stormwater storage volume.
- Stormwater management requirements - The level of control required for the volume, rate, or quality of stormwater discharges will impact the volume of treatment needed.
- Project size - Larger porous asphalt areas tend to have lower per square foot costs due to construction efficiencies.

  Costs vary with site activities and access, porous asphalt depth, drainage, curbing and underdrains (if used), labor rates, contractor expertise, and competition. The cost of the porous asphalt material ranges from $0.50 to $1 per square foot (NCHRP, 2005).

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Appendix D

URBAN Waterways

Permeable Pavement: Research Update and Design Implications

As the use of permeable pavement increases in North Carolina, practitioners can look to research findings for design guidance.

In 2006 and 2007, the Division of Water Quality, North Carolina Department of Environment and Natural Resources (NCDENR), implemented design guidance and a design requirement that will dramatically increase the use of permeable pavement. In July 2006, NCDENR began to credit permeable pavement with runoff reduction. It did this by allowing certain designs of permeable pavement to be treated as if they were 60 percent permeable, such as an urban lawn in a sandy-loam soil. In 2007, the N.C. Legislature enacted a law (Bill H1473) that required 20 percent of a parking lot to be made of permeable pavement or a suitable, environmentally-friendly, alternative stormwater management practice.

Much research has been conducted across North Carolina, the United States, and in other countries on permeable pavement. It has generally focused on four areas: permeable pavement runoff reduction, clogging, long-term hydrology, and water quality. In this update for practitioners, we provide a brief overview of permeable pavements, highlight research findings, provide direct links to the research, and discuss its design implications. This update serves as a companion to an earlier Urban Waterways publication: *Low Impact Development Technologies: Permeable Pavements, Green Roofs, and Water Harvesting* (AG-588-6).

IS IT PERMEABLE, PERVIOUS, OR POROUS PAVEMENT?

All three of these terms are used interchangeably to describe pavement that allows water to flow through it rather than shedding water. Only two of these words, however, are synonymous: *permeable* and *pervious*. Both mean that water can flow through the material via a series of connected holes or pores.

The term *porous* simply means that there are holes in the substance, but does not necessarily mean that these holes are connected. For example, pumice is a porous rock, yet it is not permeable because many of its holes do not connect.

The more technically specific terms are, therefore, *permeable* and *pervious*. However, much of the pavement and design industry uses *porous* instead. According to NCDENR, *permeable* is the preferred term.

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OVERVIEW OF PERMEABLE PAVEMENT

Typical Cross-section

Nearly all permeable pavement types have the same general structure (see Figure 1).

Surface Layer (Cover). This is the top layer that drivers and users see. It is identified by the type of pavement used, such as permeable concrete, permeable interlocking concrete pavers filled with gravel, or segmental plastic pavers to be filled with grass. More on pavement type follows in this section.

Gravel Base. Most pavement types, with the notable exception of permeable concrete, need a gravel (or aggregate) support layer to bear vehicles. The base is immediately below the surface layer (cover). It also stores water during and immediately after a storm event. Despite the fact that permeable concrete does not need an aggregate base layer for structural support, such a layer is often included in permeable concrete designs so that additional water can be stored.

Sub-base. This is the layer of soil immediately below the base layer. The sub-base is necessarily compacted during construction of the permeable lot. It is also referred to as *in situ soil* or *underlying soil*.

Underdrains. These drains are typically small plastic pipes, 4 to 8 inches in diameter. These drainage lines are located at or near the bottom of the sub-base to collect water and convey it to the storm sewer network. Underdrains are most often used when permeable pavements are located in soils that contain clay.

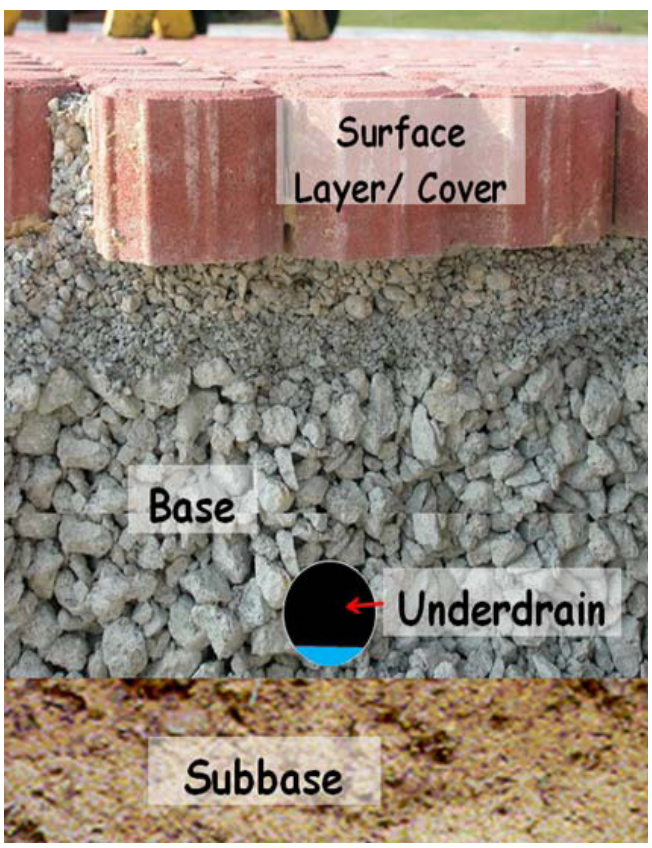

Figure 1. Cross-section of permeable pavement, including the surface layer (cover), a gravel base, the soil sub-base, and the underdrain.

Types of Permeable Pavements

There are five types of permeable pavements: permeable asphalt (PA), permeable concrete (PC), permeable interlocking concrete pavers (PICP), concrete grid pavers (CGP), and plastic grid pavers (PG). The pictures in Figure 2 (page 3) illustrate the five types and a variation of fill for plastic grid pavers. General structural design considerations are discussed for each of the pavements below. For further information about pavement design, see the references to research provided throughout this update.

(PC) Permeable concrete is a mixture of Portland cement, fly ash, washed gravel, and water. The water to cementitious material ratio is typically 0.35 – 0.45 to 1 (**NRMCA, 2004**). Unlike traditional installations of concrete, permeable concrete usually contains a void content of 15 to 25 percent, which allows water to infiltrate directly through the pavement surface to the subsurface. A fine, washed gravel, less than 13 mm in size (No. 8 or 89 stone), is added to the concrete mixture to increase the void space (**GCPA, 2006**). An admixture improves the bonding and strength of the pavements. These pavements are typically laid with a 10 to 20 cm (4 – 8 in) thickness and may contain a gravel base course for additional storage or infiltration. Compressive strength can range from 2.8 to 28 MPa (400 to 4,000 psi) **(NRMCA, 2004)**.

(PA) Permeable asphalt consists of fine and course aggregate stone bound by a bituminous-based binder. The amount of fine aggregate is reduced to allow for a larger void space of typically 15 to 20 percent. Thickness of the asphalt depends on the traffic load, but usually ranges from 7.5 to 18 cm (3 – 7 in). A required underlying base course increases storage and adds strength (**Ferguson, 2005**). Minimal amounts of permeable asphalt have been used in North Carolina.

(PICP) Permeable interlocking concrete pavements are available in many different shapes and sizes. When lain, the blocks form patterns that create openings through which rainfall can infiltrate. These openings, generally 8 to 20 percent of the surface area, are typically filled with pea gravel aggregate, but can also contain top soil and grass. **ASTM C936** specifications (**200 1b**) state that the

Figure 2. Types of permeable pavement

pavers be at least 60 mm (2.36 in) thick with a compressive strength of 55 MPa (8,000 psi) or greater. Typical installations consist of the pavers and gravel fill, a 38 to 76 mm (1.5 – 3.0 in) fine gravel bedding layer, and a gravel base-course storage layer (**ICPI, 2004**).

(CGP) Concrete pavers conform to ASTM C 1319, *Standard Specification for Concrete Grid Paving Units* (2001a), which describes paver properties and specifications. CGP are typically 90 mm (3.5 in) thick with a maximum 60 × 60 cm (24 × 24 in) dimension. The percentage of open area ranges from 20 to 50 percent and can contain topsoil and grass, sand, or aggregate in the void space. The minimum average compressive strength of CGP can be no less than 35 MPa (5,000 psi). A typical installation consists of grid pavers with fill media, 25 to 38 mm (1 – 1.5 in) of bedding sand, gravel base course, and a compacted soil subgrade (**ICPI, 2004**).

(PG) Plastic reinforcement grid pavers, also called geocells, consist of flexible plastic interlocking units that allow for infiltration through large gaps filled with gravel or topsoil planted with turfgrass. A sand bedding layer and gravel base-course are often added to increase infiltration and storage. The empty grids are typically 90 to 98 percent open space, so void space depends on the fill media (**Ferguson, 2005**). To date, no uniform standards exist; however, one product specification defines the typical load-bearing capacity of empty grids at approximately 13.8 MPa (2,000 psi). This value increases up to 38 MPa (5,500 psi) when filled with various materials (**Invisible Structures, 2001**).

Designing Permeable Pavement in Sandy Versus Clayey Sub-bases

There are a few more factors to consider when designing and installing permeable pavement in clayey soils than when placing them in sandy soils. (Further details are provided in the "Review of Permeable Pavement Research" section of this update.)

Clay soils do not provide as much structural support as sandy soils, on average. This means the gravel layer underlying nearly all pavement types will need to be deeper in clay soils than in sandy soils to provide additional strength to the pavement system. The lone exception is permeable concrete, which does not need a gravel layer for structural strength.

Clay soils will not provide as much infiltration as sandy soils, on average. As is discussed in the following sections, necessary compaction can severely limit infiltration to the sub-base. This will probably lead to underdrains being used to slowly drain the base layer of the permeable pavement. Sometimes an impermeable liner will be needed to separate the base from the sub-base, if the underlying clay has a high shrink-swell potential.

Other differences in design are discussed in the "Review of Permeable Pavement Research" section. North Carolina stormwater regulations make it substantially easier to have

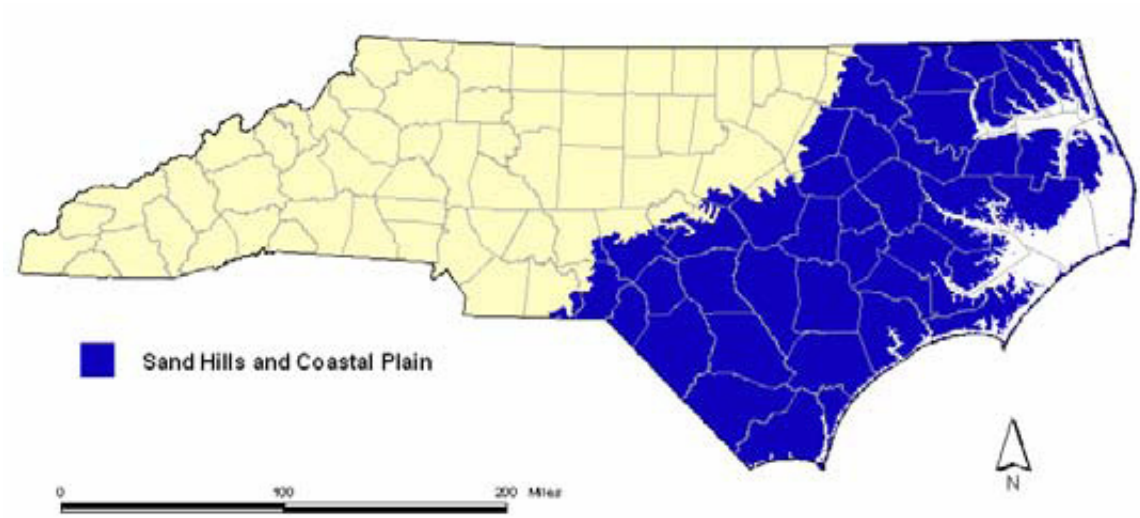

Figure 3. Sandier soil regions of North Carolina, where permeable pavement use is more easily permitted by NCDENR. *(Image courtesy of NCDENR – Division of Water Quality)*

a permeable pavement application approved in sandier soils than clayey soil regions of the state. See Figure 3 for state-delineated sandier soil regions.

Hydrologic Terminology

Terminology for pavement hydrologic terms is presented below. Please refer to Figure 4.

Runoff. Amount of water leaving (or shedding) the surface of the pavement. This water enters the storm sewer network.

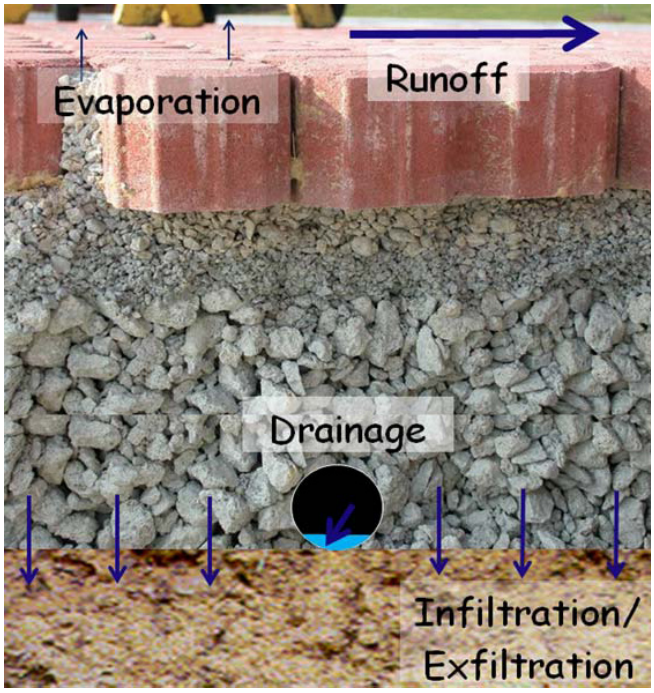

Figure 4. Common hydrologic pathways for permeable pavement include runoff, drainage, infiltration, and evaporation. Note that runoff + drainage = outflow.

Drainage. Water that has passed through the surface of the permeable pavement may still be recollected in underdrain pipes. This water is also discharged to the storm sewer network.

Outflow. The total water leaving a pavement application and entering the storm sewer network. With permeable pavement, outflow is the sum of runoff and drainage. An impermeable pavement's outflow is simply equal to runoff.

Exfiltration/Infiltration. Water that leaves the bottom or sides of the permeable pavement and enters the soil. Water *exfiltrates from* the pavement base layer. It *infiltrates* the surrounding soil.

Evaporation/Evapotranspiration. Water stored in puddles on an impermeable surface or temporarily trapped near the surface of permeable pavement will eventually evaporate to the atmosphere. If plants aid in the release of water to the atmosphere, as some permeable pavements are designed to be vegetated, this process is termed *evapotranspiration*.

REVIEW OF PERMEABLE PAVEMENT RESEARCH

The remaining portions of this update summarize research findings that apply to permeable pavement runoff reduction, clogging, long-term hydrology and water quality, and their implications for permeable pavement design. Major findings are numbered. Citations of work that support these findings are also given, and a complete reference list is provided at the end of this update.

Runoff Reduction

1. Do permeable pavements have a positive hydrologic impact? Yes. Permeable pavements have been regarded as

an effective tool in reducing stormwater runoff. Because of their high surface infiltration rates, permeable pavements can reduce runoff quantity and peak runoff rates, and delay peak flows (**Pratt et al., 1989; Hunt et al., 2002; Brattebo & Booth, 2003; Bean et al., 2007b, Kwiatkowski et al., 2007; Collins et al., 2008a**). This finding has been verified worldwide.

2. Can permeable pavements reduce runoff volumes? If so, by how much? Yes. Permeable pavements substantially reduce surface runoff quantities (**Day et al., 1981; Hunt et al., 2002; Brattebo & Booth, 2003; James & Shahin, 1998**). The most commonly used measure of runoff quantity is the Natural Resources Conservation Service's (NRCS) curve number. The curve number indicates how much runoff will occur from a given land use for a given storm event. The higher the curve number, the more runoff will be generated by a storm event. Studies in North Carolina have shown the average curve number of permeable pavements to range from a low of 45 to a high of 89 (**Bean et al., 2007b**). The curve number for standard impermeable pavement is 98. The variation in the North Carolina study was due to two factors: base (or storage) depth and underlying soil composition. The less the water storage and the more clayey the underlying soil, the higher the curve number.

3. What causes runoff? Does the permeable system fill with water, or does it rain too intensely for water to infiltrate the pavement surface? The amount of surface runoff generated from permeable surfaces is more dependent on rainfall intensity than rainfall depth (**Day et al., 1981; Hunt et al., 2002; Valavala et al., 2006; Collins et al., 2008a**). Therefore, storms of low intensity that have a long duration (and therefore produce a lot of rainfall), are much less likely to produce runoff than very intense, quick duration storms that might have a lower rainfall total. This means that the vast majority of storms do not "fill up" permeable pavements and that when runoff was observed, it was most often due to the rainfall intensity overwhelming the surface infiltration ability of the pavement. The majority of surface infiltration rates examined in one study (**Bean et al., 2007a**) exceeded 2 in/hr. This means that a rainfall event would need to have an intensity of greater than 2 in/hr to produce any runoff.

4. Do different types of permeable pavement types reduce runoff better than others? Not really. In a North Carolina comparison study of PC, two types of PICP, and CGP (**Collins et al., 2008a**), no substantial difference was detected in the amount of runoff from each type (See Table 1). The one pavement type studied that produced *slightly* more runoff was CGP filled with sand. A study in Washington state (**Brattebo and Booth, 2003**) examined PICP, CGP, and two types of PG, found very similar results: only subtle differences in runoff reduction could be detected among the permeable pavement types. *The important implication of these two studies is that different types of permeable pavement systems should probably be treated the same when assigning runoff reduction credit.*

5. Is there a difference between outflow and runoff? If so, do permeable pavements exhibit outflow? Yes, there is a difference (refer to the "Hydrologic Terminology" section). Runoff is part of total outflow (Runoff + Drainage = Outflow). Drained permeable pavement systems do have more outflow. Moreover, the outflow rates and volumes can be dramatically higher than permeable pavement runoff rates and volumes (Collins et al., 2008a). (See Figure 5.)

Table 1. Percent Reduction of Runoff Volume Relative to Rainfall Volumes in Kinston, N.C. Number of storms exceeds 40 in all cases. Data collected in 2006 and 2007.

Pavement Type	Mean (%)	Medium (%)	Minimum (%)
Standard Asphalt	34.6	29.4	0
Pervious Concrete	99.9	99.9	99.0
PICP – Type 1	99.3	99.4	97.8
PICP – Type 2	99.5	99.7	96.9
Concrete Grid Pavement (Sand)	98.2	98.7	91.1

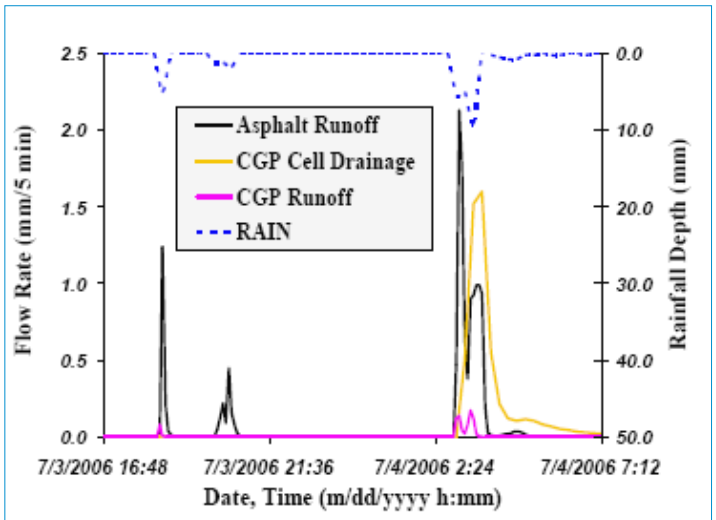

Figure 5. Substantially more water drains from a permeable pavement cell than runs off as is shown for a 1.25-in event that fell on CGP filled with sand.

This study showed that in some cases, drainage + runoff volumes from permeable pavements were essentially equal to the runoff volume associated with an adjoining standard asphalt lot. The study site had underdrains, in part, because the underlying soil (sub-base) was clayey.

6. Can anything be done to reduce outflow from drained permeable pavements? Yes. Research indicates (**Collins et al., 2008a**) that an upturned underdrain—one that creates a storage zone in the bottom of the pavement base layer—can reduce outflow volumes. See Figure 6. A specific study, however, has yet to be conducted on this design feature. Water that initially pools internally in the pavement (1) does not drain and (2) can slowly infiltrate the sub-base, increasing times to peak, reducing runoff volumes, and lowering peak outflow rates. This is not an option when permeable pavement is located in highly plastic soils. Another option with the underdrains is to size them so that they have limited outflow rates. That is, use underdrains with a small diameter. Another option is to cap the underdrains with a restrictive orifice or hole. While this might not substantially reduce outflow volumes, it would dramatically reduce peak flows and increase times to peak for a given storm event. Doing this is akin to using a small orifice to dewater a pond or wetland over a two- to three-day period.

Clogging

Clogging is a very important concern when considering the long-term function of permeable pavements.

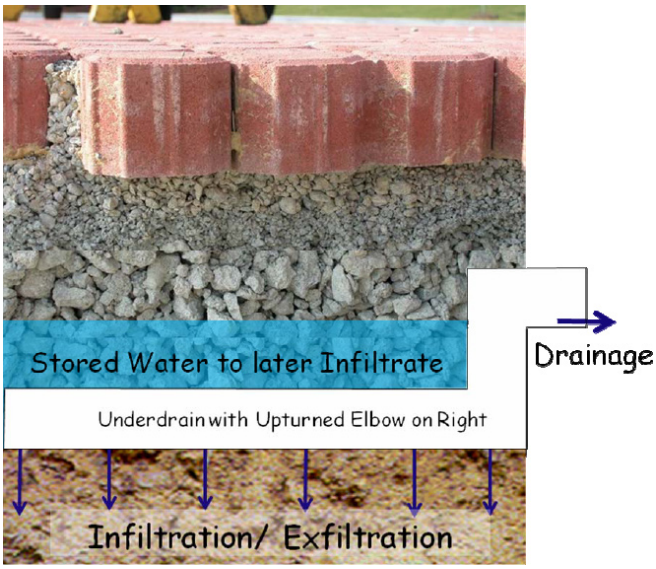

Figure 6. An upturned underdrain elbow creates an internal storage zone for water. This adds to the pavement's ability to infiltrate.

Figure 7. Permeable pavement with gaps clogged with silty-clay soil.

1. Do permeable pavements clog? Yes, but clogging does not always mean sealing. Fine particles will be deposited on the surfaces of permeable pavements. This is typically a result of passing cars, wear of the pavement surface, or transport via wind and runoff from nearby disturbed soils (**Balades et al., 1995**; **Bean et al., 2007a**). See Figure 7.

2. Have factors been found to "predict" the amount of clogging that may have occurred? Yes, there are several. As pavements age and with increasing traffic usage, clogging of pavement increases (**Kresin et al., 1996**; **James & Gerrits, 2003**). Close proximity to sediment can also accelerate clogging (**Bean et al., 2007a**).

3. To what extent will pavements clog? It is important to note that clogging of pavements does not necessarily mean the "sealing" of permeable pavements. While very few permeable applications will display their initial, and often extremely high, infiltration rates (sometimes exceeding 1,000 in/hr) a few years after installation, this does not mean that these pavements' infiltration rates clog to the point of impermeability (0 in/hr). A study of surface infiltration rates conducted in North Carolina, Virginia, Maryland, and Delaware (**Bean et al., 2007a**) found that the surface infiltration rate of pavements that had clogged was usually higher than 1 in/hr.

4. What makes the extent of clogging better or worse? There are a couple of factors: the frequency of maintenance (discussed in the next section) and surrounding soil type. **Bean et al. (2007a)** observed that the surface infiltration rate of the permeable pavement (or the extent of clogging) mirrored that of the surrounding soil's permeability. In other words, if the pavement was located in a sandy part of the state and it was clogged by sand particles, the permeable pavement's surface infiltration rate was similar to that of sand (3 to 4 in/hr), even 20 years after installation.

Figure 8. Brushes from a standard street sweeper can rip apart the clogged portions at the top of CGP filled with sand.

Conversely, the lowest infiltration rate was observed at a lot that had clogged in Cary, N.C., which was located in the piedmont and more clayey soils (less than 0.4 in/hr). *Mainly because of this research finding, N.C. stormwater regulations limit widespread use of permeable pavement in tighter (or more clayey) soil regions of the state*. (See Figure 3, page 4.)

5. Can't clogging be prevented? Clogging is an ongoing process, but it can be restricted by regularly maintaining permeable pavement and, of course, locating permeable pavements away from areas with soil disturbance. Several researchers (**Balades et al. 1995; Hunt et al. 2002; Bean et al., 2007a**) recommend using a street sweeper or a special vacuum street sweeper to maintain lots. The most proven maintenance technique is for CGP and PG filled with sand. These sand-filled pavements tend to have clogging near the surface (top 1 in) of the sand (**James & Gerrits, 2002**), so that a standard street sweeper can scarify the surface of the pavement and break apart the top clogged layer (Figure 8). By simply doing this, permeable pavement surface infiltration rates were shown to improve by 66 percent (**Bean et al., 2007a**). For all other forms of maintenance, only anecdotal (and in some cases minimal) evidence of their effectiveness is available.

Long-Term Hydrology

Studies also indicate some potential water cycle benefits associated with permeable pavement. This is an important part of Low Impact Development (LID), which is predicated on taking what was once runoff and "converting" a portion of it to either evapotranspiration (ET) or infiltration.

1. Does permeable pavement allow for infiltration? Yes. The base layer of permeable pavements retains a portion of the infiltrated rainfall. Some percentage of this stored water will infiltrate (**Brattebo & Booth, 2003**). One study in eastern North Carolina had 100 percent infiltration over the course of the 10-month monitoring period (**Bean et al. 2007b**).

2. Does permeable pavement allow for evaporation and evapotranspiration? A few types of permeable pavement may have surprisingly high infiltration rates. Others probably do not. A system that captures and stores water near the surface of the pavement, such as CGP and PG filled with sand, have been estimated to temporarily store at least 6 mm of most storms and presumably "release" this water to the atmosphere by evaporation or evapotranspiration (**Collins et al. 2008a**). On an annual basis, up to 33 percent of all precipitation events would be "captured" in this way by these pavements. A similar effect was not found for PC or PICP filled with gravel.

3. What are the important properties of permeable pavement that will enhance water retention? The retention properties, along with the permeability, evaporation rate, and drainage rate of concrete block permeable pavements largely depend on the surface void size and the particle size distribution of the bedding material (**Pratt et al. (1989**); **Andersen et al., 1999; James & Shahin, 1998; Collins et al., 2008a**). Materials with greater surface area (e.g., sand or loamy sand) can retain more water. Incorporating a storage zone (shown in Figure 6) will increase infiltration.

Water Quality

Permeable pavements often improve stormwater runoff quality, but not always. Many states, including North Carolina, do not assign pollutant removal credit to these systems. Research has investigated how well permeable pavements remove metals, sediment, motor oil and nutrients and their impact on pH and temperature.

1. In general, have permeable pavements been shown to remove pollutant concentrations? Yes. As compared to asphalt runoff, permeable pavement drainage has been shown to have decreased concentrations of several stormwater pollutants, including heavy metals, motor oil, sediment, and some nutrients **(Pratt et al., 1989; Pratt et al., 1995; James & Shahin, 1998; Brattebo & Booth, 2003; Bean et al., 2007b).** All but nutrient removal has been repeatedly shown in many research locations. Nutrients are specifically discussed later in this section.

2. How are pollutant loads impacted by permeable pavement? Because most permeable pavements substantially reduce the volume of runoff and outflow, it stands to reason that they will also reduce pollutant loads. Several studies confirm that permeable pavements demonstrate lower total pollution loadings than standard pavements. **(Day et al., 1981; Rushton, 2001; Bean et al., 2007b)**.

CONCENTRATIONS VERSUS LOADS

Pollutant removal is often presented as a reduction in either concentrations or loads. They are not the same thing, but they are related. A *load* is a mass of pollutant determined by multiplying *concentration* by volume of runoff. In stormwater, *concentration units* are nearly always shown as mg/L; *measures of load* are g, Kg, and lb. North Carolina's nutrient removal requirements for nitrogen and phosphorus are established for loads.

3. How about thermal pollution (temperature)? Permeable pavements can cause a reduction of thermal pollution **(Karasawa et al., 2006**) compared to conventional asphalt. The decrease in the cited research was between 10 to 25°F. This is in great part due to the pavement's color. Only results for PICP have been published in a peer-reviewed format, so it is possible that not all permeable pavement types, such as PA, will have such an impact.

4. Do permeable pavements buffer pH? Permeable pavements can buffer acidic rainfall pH **(Pratt et al., 1995; James & Shahin, 1998; Dierkes et al.,2002; Collins et al., 2008b)** likely due to the presence of calcium carbonate and magnesium carbonate in the pavement and aggregate materials. They provide a greater buffering capacity than asphalt due to the greater surface area provided by contours in the pavement geometry and the additional coarse aggregate layer through which water migrates. Of all pavement types, PC provided the most buffering capacity, because PC provided influent water the greatest contact time with cementitious materials (**Collins et al., 2008b**). See Figure 9.

5. North Carolina's stormwater rules target nutrients. How well do permeable pavements remove nutrients? The nutrient removal capabilities of permeable pavements are less understood. Some permeable pavement studies have shown removal of total phosphorus (TP) (**Day et al., 1981, Bean et al., 2007b, Gilbert and Clausen, 2006)**, often attributed to adsorption to the sand and gravel sub-base materials. Similar studies have observed little change in TP concentrations of permeable pavement drainage **(James & Shahin, 1998; Bean, 2005; Collins et al., 2008b)**. A few studies have shown a decrease in concentrations of all measured nitrogen species (NH4-N, TKN, and NO3N) **(Pagotto et al., 2000; Gilbert & Clausen, 2006),** but several studies have also shown certain forms of nitrogen concentrations to increase or be unchanged **(Day et al., 1981, Bean et al., 2005, Collins et al., 2008b).** *In general, as of June 2008, the state of North Carolina does not offer blanket nutrient removal credit to all types of permeable pavement. However, some pavement types may be able to receive "special" consideration*. This is discussed next.

6. What features can be included to improve nutrient removal? Several studies have suggested that aerobic conditions, which result as permeable pavement drains, can result in nitrification of ammonia-nitrogen (NH_4-N) to nitrate-nitrogen (NO_3-N). Compared to asphalt, substantially lower NH_4-N and total Kjeldhal nitrogen (TKN) concentrations, and higher NO_3-N concentrations in permeable pavement drainage have been measured in multiple experiments **(James & Shahin, 1998; Bean et al., 2007b, Collins et al., 2008b).** It also appears that CGP and PG filled with sand are more able to reduce total nitrogen

Figure 9. All permeable pavements were able to buffer acidic rainfall. PC provided the most buffering.

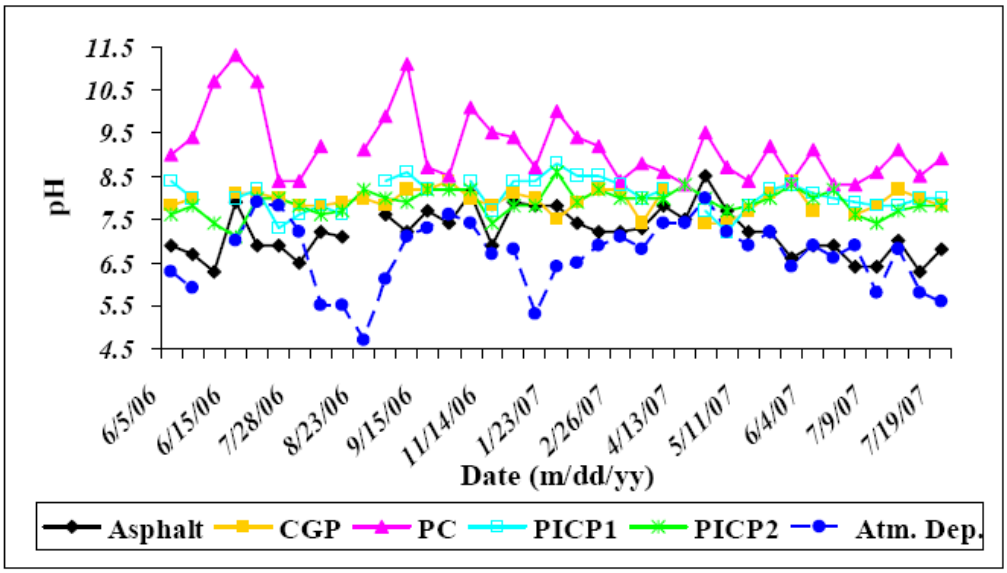

Figure 10. Concrete grid pavers filled with sand (left) employ many of the same removal properties of standard sand filters (right).

(TN). This occurs, because CGP filled with sand very much resembles a low-head, limited-media, depth sand filter (**Collins et al., 2008b**). See Figure 10. Sand filters have repeatedly been shown to improve TN concentrations (**Barrett, 2003**). *This is an important finding, as it means that one type of pavement type (CGP with sand) appears to be "preferable" to other pavement types with respect to nitrogen removal*. Another possibility is to include a sand layer at the bottom of any permeable pavement type. However, this option has not been well tested. More research probably needs to be conducted to verify this finding. If the efficiency of a sand layer is verified, perhaps this type of permeable pavement could receive TN removal allowances.

7. Besides sand, what other factors seem to impact pollutant removal rate? Pollutant removal rates depend upon the material used for the pavers and sub-base material, as well as the surface void space **(Fach and Geiger, 2005; Pratt et al., 1989)**. Fach and Geiger (**2005**) found that installing permeable pavement over a crushed brick base increased the level of metals removal.

8. Where are metals captured in permeable pavements? Most heavy metals are captured in the top layers (1 to 2 in) of material in permeable pavement void space (**Colandini et al., 1995; Dierkes et al., 2002).** For PICP, CGP, and PG that are filled with sand, this implies that *standard street sweeping will probably remove the majority of heavy metals* collected in the pavement fill material. Exact recommendations for disposal have yet to be made.

9. If we are concentrating "all this pollution" in a permeable pavement cell, won't these pollutants impact groundwater? This is possibly the greatest concern regarding long-term pollutant control. Long-term studies and simulations of permeable pavement pollutant distributions have revealed low risks of subsoil pollutant accumulation and groundwater contamination **(Legret et al. 1999; Legret & Colandini, 1999; Dierkes et al., 2002; Kwiatkowski et al., 2007)**. It is important, however, that seasonally high water tables (SHWT) do not encroach the interface of the base and the sub-base, as a high water table would saturate soil that would collect pollutants and eventually leach them into the groundwater. SHWT should be at least 1 foot, and preferably 2 feet from the bottom of the pavement base.

SUMMARY

Permeable pavement use is expected to continue to grow due to recent NCDENR and N.C. Legislative action. As summarized in Table 2 (page 10), several design recommendations can be inferred from research conducted on permeable pavements in North Carolina and elsewhere.

Table 2. Summary of Permeable Pavement Design Guidance		
Design Parameter	**Guidance**	**Rationale**
Optimal pavement types for runoff reduction	All are excellent. PC, PICP, and CGP filled with gravel are best.	Research shows that all types of pavement types reduce runoff substantially. CGP and PG filled with sand have slightly higher runoff rates.
Design surface infiltration rate	1 to 3 in/hr	Studies show that 90% of all study sites had at least 1 in/hr surface infiltration rates, with 2 to 3 in/hr being a median range for partially clogged permeable pavement.
Design base exfiltration rate	0.01 to 1 in/hr. 0.10 in/hr is default for loamy sand.	Even in somewhat sandy soils, exfiltration rates from the base were affected by compaction that occurred during construction.
Curve number	45 to mid 80s, depending upon site. 75 to 80 is recommended.	If the site is free from clogging, extremely low CNs are possible. With moderate clogging, CNs tend to be in the mid-70s. If the pavement is clogged with clay, the CN may exceed 90.
Underdrain flow rate	Release water so that a 2-year event is emptied in 2 – 4 days.	Allows a mimicking of pre-development hydrology stream recharge post event. Mitigates peak flow.
Increasing infiltration to sub-base	Create a sump in base of pavement.	A sump allows water to pool and slowly infiltrate the sub-base. Even at low infiltration rates of 1-2 in/day, many storms are fully captured in the sump. Not recommended in highly plastic sub-base soils.
Optimal pavement types for metal removal	All are excellent. CGP and PG filled with sand are easiest to maintain.	It is easier for street sweepers to remove the *smützdecke* (or clogged layer) from the top of the sand column associated with CGP and PG.
Optimal pavement types for nutrient removal	CGP and PG filled with sand.	These pavements act as if they are low-head, shallow-depth sand filters. More research is needed to confirm this interim finding.
Seasonally high water table (SHWT)	1 foot, preferably 2 feet, from the bottom of the pavement base	SHWT closer to the base will (1) impede exfiltration from the pavement, and (2) lead to pollutant leaching from the pavement.

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Most of these references were published in major peer-reviewed journals and are available to anyone with access to a university library's collection. Nearly all of these articles are available on-line. References for research conducted in North Carolina are in **bold**.

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Related Web Sites

N.C. State University—BAE Permeable Pavement Research Web site: http://www.bae.ncsu.edu/topic/permeable-pavement

N.C. State University—Stormwater Engineering Group Web site: http://www.bae.ncsu.edu/stormwater

Prepared by
William F. Hunt, Assistant Professor and Extension Specialist
Kelly A. Collins, Former Graduate Research Assistant
Department of Biological and Agricultural Engineering
North Carolina State University

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Appendix E

Features of the Samuel Hadley Public Services Building

Pervious Pavement

Pervious pavement is an innovative tool material for storm water management.

Concrete is made by mixing varying amounts of water and other cementitious materials. When very little sand is used, the concrete that forms is pervious. Pervious concrete is used to manage storm water flow by allowing water to soak through the concrete and infiltrate into the ground below. It can also reduce pollutant loads by filtering contaminants as the water is transferred through the pavement. Parking spaces along the public entry to the Public Services Building are made of pervious pavement.

Pervious pavement has many environmental benefits, including:

•Reducing the amount of storm water runoff into nearby water sources, decreasing peak water flow through drainage channels and minimizing flooding

•Reducing the level of pollution contained in any remaining runoff by "treating" pollutants using the chemical and biological principles of soil

•Reducing the need for additional storm water treatment equipment, saving equipment and maintenance costs and promoting more efficient land use