Permeable Shoulders
With Stone Reservoirs

Requested by:

American Association of State Highway
and Transportation Officials (AASHTO)

Standing Committee on the Environment

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Abstract

The objective of this study is to evaluate the suitability of using permeable pavement for roadway shoulder applications. Permeable pavement systems are designed to minimize environmental impacts, stormwater runoff, and flooding and to treat or remove pollutants by allowing stormwater to infiltrate through the pavement in a manner similar to pre-development hydrologic conditions

State Departments of Transportation (DOTs) and other municipal organizations have expressed interest in permeable shoulders to assist in the overall management of stormwater. Water from the surface of the roadway would flow into the permeable shoulder into a stone reservoir to temporarily store and treat runoff before infiltration into the roadway subgrade soils and/or discharge to other stormwater conveyance and treatment systems. The primary benefits of permeable pavements are to reduce stormwater runoff volume, reduce stormwater runoff peak flows, reduce surface ponding, reduce stormwater pollutant load, decrease downstream erosion and increase groundwater recharge.

Careful consideration of design features and construction techniques are necessary to ensure their success. Key design features include a careful assessment of the permeable pavement site and its surrounding land use to ensure that the pavement surface does not become contaminated with sand/dust or vegetative matter. A rational assessment of the traffic to which the pavement will be exposed will permit the designer to ensure that the pavement has sufficient structural capacity for its design life. A hydrological design taking into account rain water landing on the pavement and water shed from the highway lanes can be accommodated into the permeable pavement and then properly treated for water quality improvements and permitted to exit the pavement either through infiltration into the subgrade or controlled through underdrains. Construction processes and techniques should consider the protection of the permeable pavement from contaminants during construction and to ensure that the pavement is able to accommodate both vehicle loading and water infiltration and exfiltration in accordance with the pavement design. Finally, with all pavements, maintenance practices should including occasional vacuum sweeping to ensure the longevity of the permeable surface with repairs completed to address any localized deficiencies.

Table of Contents

List of Tables

List of Figures

List of Appendices

1. Introduction

The objective of this study is to evaluate the suitability of using permeable pavement for roadway shoulder applications. This research is also in direct support of the Moving Ahead for Progress in the 21st Century (MAP-21) Act, in that Section 503 promotes the adoption of permeable, pervious or porous paving materials, practices and systems that are designed to minimize environmental impacts, stormwater runoff, and flooding and to treat or remove pollutants by allowing stormwater to infiltrate through the pavement in a manner similar to pre-development hydrologic conditions [MAP-21 2012].

State Departments of Transportation (DOTs) and other municipal organizations have expressed interest in permeable shoulders to assist in the overall management of stormwater [NCHRP 25-42 interviews, NCHRP 25-25/82 research statement]. Water from the surface of the roadway would flow into the permeable shoulder into a stone reservoir to temporarily store and treat runoff before infiltration into the roadway subgrade soils and/or discharge to other stormwater conveyance and treatment systems. The primary benefits of permeable pavements are to reduce stormwater runoff volume, reduce stormwater runoff peak flows, reduce surface ponding, reduce stormwater pollutant load, decrease downstream erosion and increase groundwater recharge. This would potentially alleviate the conditions shown in Figure 1.1.

Figure 1.1. Ponding on highway shoulder.

Potential challenges for success of permeable shoulders include: reduced structural capacity compared to conventional pavements, possible moisture weakening of adjacent roadway lanes (and shoulders themselves), potential maintenance issues, varying maintenance needs from permeable to impermeable surfaces, durability, perceived safety concerns and overall life-cycle costs, including initial construction and maintenance costs.

2. Scope

This report provides guidance for permeable shoulders with stone reservoirs using various permeable pavement technologies with respect to structural and hydrologic design, construction issues and maintenance standards. Generically, pavements that are specifically designed to infiltrate water are referred to as "permeable pavements;" however, the common naming convention for permeable pavements differs by industry as follows:

- Asphalt industry – Porous Asphalt;
- Concrete industry – Pervious Concrete; and
- Interlocking concrete pavement industry – Permeable Interlocking Concrete Pavement (PICP).

The report assesses the following:

- Ability of porous shoulders to reduce downstream infrastructure requirements (either conveyance and/or water quality treatment;
- Various subgrade conditions likely to be encountered;
- Recommended construction materials;
- Changes to the surface drainage system;
- Safety issues;
- Maintenance needs;
- Potential adverse impacts to the mainline structural section and
- Potential other impacts of water infiltration into the shoulders.

A checklist of considerations for where permeable pavement approaches are appropriate and not based upon the factors identified during the literature review is also provided.

The literature review conducted as part of this research has been provided in Appendix A.

2.1 Structural and Hydrologic Design

Design guidance accommodates various types of structural sections in the adjacent mainline, superelevation and grade, various mainline pavement and shoulder widths (tributary area), recommended applications, and conditions that would and would not support use of the permeable shoulder section. Additional parameters considered include the following:

- Compaction and the use of underdrain systems for poorly drained soils;
- Use of impermeable liners to line the stone reservoir; and
- Type of embankment or natural soils.

The structural and hydrologic design analysis is used to provide guidance to designers and practitioners on the feasibility of utilizing permeable shoulders for roadway pavements. Guidance is also provided with respect to the hydrological considerations necessary to manage stormwater runoff effectively.

2.2 Construction Issues

An important part of the scope of this report is an evaluation of construction techniques and issues related to permeable shoulders. These include elements associated with both new and retrofit/rehabilitation shoulder construction, construction materials, quality assurance guidance, and items related to underground utilities. The report provides general guidance for specifications and construction of permeable shoulders.

2.3 Maintenance Standards

Proper and timely maintenance is considered extremely critical for permeable pavement systems. The surface should be properly monitored and maintained to provide a durable and safe driving surface. Maintenance practices can greatly affect the ability of the permeable pavement system to effectively infiltrate water. Additionally, winter maintenance for permeable and impermeable pavements has important differences that need to be understood [Roseen 2013]. This report will provide guidelines and recommendations for permeable pavement maintenance and restoration.

3. Permeable Pavement Technology

National, state/provincial and municipal legislation regulating stormwater runoff in the United States and Canada has provided increased incentives for using permeable pavements. In addition, regulatory frameworks for implementation of sustainable design have embraced permeable pavement solutions. These regulations are often called low impact development (LID) or sustainable urban drainage systems (SUDS).

Permeable pavements in some form have been around for centuries and in the literature since the early 1970s [Ferguson 2005]. Early turf systems were developed to allow passage of personal vehicles and occasional heavy vehicles to drive and/or park on non-roadways surfaces without permanently disturbing the surface of the ground. In order to prevent damage to the ground, it is “reinforced” using geogrids, cellular structures or block pavers such as those shown in Figure 3.1. These systems permit natural vegetative growth to continue while providing support for vehicular traffic.

Figure 3.1. Turf pavers providing structural support and vegetative growth/permeability.

More recently, permeable pavement systems have been designed to accommodate more frequent and heavier loading than those of turf systems. These have included porous asphalt, pervious concrete, and permeable interlocking concrete paver surfaced pavements. Their application has expanded to include walkways, trails, driveways, large commercial parking areas, alleys and roadways.

This research focuses specifically on the application of permeable pavements for highway shoulder applications. Additionally, while turf and cellular confinement systems may be considered for some shoulder applications, the focus of this research is on conventional hard-surfaced permeable paving surfaces: asphalt, concrete, and pavers.

The following sections provide an overview of permeable pavement systems.

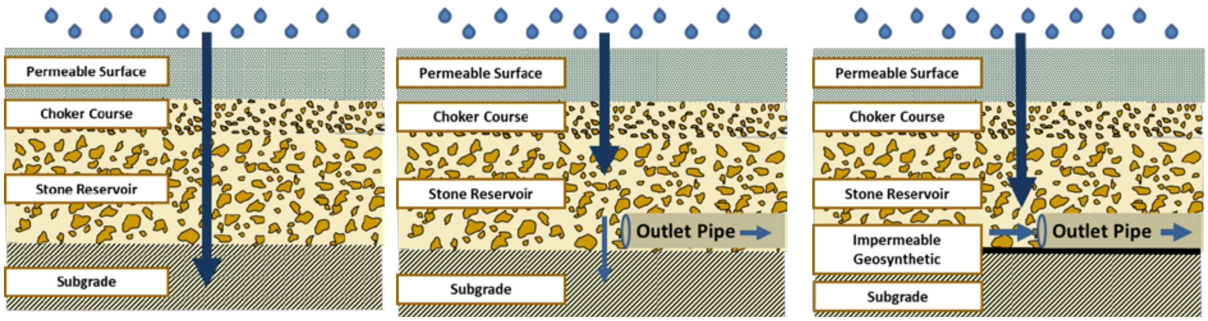
3.1 Permeable Pavement System

Permeable pavement systems consist of a surface with joints and/or openings that will freely allow water to infiltrate to the subgrade. The openings allow water from storm events to flow freely through the surface into a stone reservoir where it is collected and stored before it leaves the pavement structure. For low-infiltration rate soils, perforated drain pipes are often placed in the stone reservoir or subgrade to drain excess water, thereby functioning as a detention facility that provides treatment for removal of stormwater pollutants and allows some infiltration. Infiltration reservoirs in the subsurface are often used to maximize storage and infiltration and can be used to replace end of pipe volume control practices. For sites that do not allow for any infiltration, permeable pavement is designed with an impermeable liner that prevents water from entering the soil subgrade; water is detained, treated, and exits via underdrains. Such sites could be locations where concerns exist for groundwater contamination due high risk pollutant load, shallow depth to groundwater or bedrock, and contaminated soils.

Permeable pavement systems can support vehicular or pedestrian traffic while minimizing stormwater runoff and recharging groundwater supplies. Research on permeable asphalt friction courses over impervious asphalt has demonstrated that permeable pavements are an effective method for reducing stormwater runoff and pollutants from urbanized areas and can function well with minimal maintenance [Eck 2012]. For fully permeable pavement systems, Initial surface infiltration rates in a parking lot installation exceeded 200 cm/hr (80 in/hr) [USEPA 2010], which provides effective passage for rainfall and adjacent runoff into the stone reservoir. Design pollutant removal efficiencies are on the order of 85 percent for total suspended solids (TSS), 35 percent for Total Phosphorus and 30 percent for Total Nitrogen [NCDENR 2012].

Like all permeable pavements, the surface will accept sediment thereby potentially decreasing its infiltration rate with time. The rate of decrease depends on sources of deposited sediment typically from ordinary use and unexpected soil erosion from adjacent surfaces or spilled or applied (i.e. road sanding) materials. Such reductions from normal use still render a surface that can infiltrate most rain events, as Eck et. al indicate. Gradual clogging of the surface layer can have the benefit of capturing some suspended solids that would otherwise be deposited into the stone reservoir and/or discharge from the underdrains. With regular maintenance, the solids that are captured near the surface can be more readily removed than sediment that accumulates in the stone reservoir.

General configurations of permeable pavements based on subgrade infiltration are shown in Figure 3.2. Each of these can be further detailed to achieve the specific goals for an individual installation, including items such as: surface type, curbing and other support features, use of geotextile for layer separation or water filtration, outlet pipe location, downstream water volume and quality treatment, etc.



a. Full Infiltration b. Partial Infiltration c. Low Infiltration

Figure 3.2. Permeable pavement infiltration types.

Figure 3.2a shows a full infiltration design. All stormwater is infiltrated into the subgrade below the pavement. Notably, this system does not require any additional stormwater features such as catchbasins, outlet pipes, stormwater management ponds, etc. This system is typically only used in areas where the subgrade materials have high infiltration rates.

Figure 3.2b, shows a partial infiltration design. Water is encouraged to infiltrate the subgrade; however, excess water from higher intensity storms is removed from the pavement structure using outlet pipes to ensure that that the pavement system does not overflow. The outlet pipe under the permeable pavement is typically placed at the bottom of the stone reservoir layer or in a shallow trench near the top of the subgrade layer to prevent it from being damaged during construction. In a partial infiltration design, the surface discharge elevation can be set by the designer based on how much infiltration is allowable and desired for site conditions. The controlling discharge elevation can also be controlled by an upturned elbow design, weir box, or other outlet structure at the downstream end of the outlet pipe. These designs can be effective even in low conductivity soils and they are especially useful in replacement of end of pipe peak flow control practices such as retention ponds. Water is encouraged to infiltrate the subgrade; however, excess water from higher intensity storms is removed from the pavement structure using outlet pipes to ensure that that the pavement system does not overflow. The outlet pipe under the permeable pavement is typically placed at least 10 cm (4 in.) from the bottom of the stone reservoir layer to maximize infiltration. The depth of the reservoir and location of the underdrain is determined by storage and infiltration needs for the project.

Figure 3.2c, shows a low infiltration design. This type of system may be used for low permeability subgrade and where infiltration is not desirable (i.e. contaminated or moisture sensitive soils). They are also used for applications where infiltration would be undesirable, such as:

- Water harvesting applications where water is stored for subsequent use;
- "Brownfield" sites where it is not desirable to have water flowing through contaminated subgrades;
- Areas where the subgrade is susceptible to frost heaving or swelling due to moisture content variations;
- Areas with underground infrastructure that could be damaged via increased infiltration; or
- Where subgrade exposure to saturated conditions would result in a reduction in subgrade strength requiring a very thick pavement structure to accommodate traffic loading or create slope stability issues.

While water will move laterally in the stone reservoir layer in the absence of underdrains, a perforated underdrain pipe is commonly used in design. The purpose of the underdrain pipe and outlet are to (1) provide a preferred pathway for water flow that has lesser potential to re-suspend settled particles at the bottom of the stone reservoir, and/or (2) provide a means to control the rate and controlling elevation of discharge to provide enhanced infiltration and/or flow control and limit the maximum water depth to protect the surface of the pavement.

The three primary permeable pavement surface types as designated by their industry associations include porous asphalt, pervious concrete and permeable interlocking concrete pavement. These surface layers are typically underlain by open graded aggregate layer(s) (stone reservoir). These aggregate layers provide structural capacity to accommodate the traffic loading and act as a reservoir to store and release stormwater as required by the designer. As a design variation to increase load carrying capacity, the pavement industry in the United Kingdom has published a guide to the design and construction of permeable pavements that includes a layer of asphalt concrete beneath the permeable surface [Interpave 2012]. To maintain permeability, holes are drilled in the asphalt concrete and filled with open graded aggregate. The asphalt concrete layer provides additional strength and stability to the permeable surface while the aggregate filled holes provide positive drainage to the underlying stone reservoir.

3.2 Porous Asphalt

Conventional asphalt concrete is typically designed to accommodate vehicle wheel loading and transmit this load to the underlying pavement layers. It is designed to be as dense as possible to provide maximum strength, prevent water from infiltrating beneath the pavement, and resist deformation under traffic loading. These characteristics result in a pavement surface that is relatively impermeable. In order to increase its permeability for use in permeable pavement systems, the aggregate gradation is modified to increase the air void space resulting in higher permeability.

Historically, open graded asphalt has been used as a surface for conventional dense graded pavements to reduce noise and vehicle water spray during rainfall events. This open graded friction course (OGFC) is placed in a thickness of about 25 mm (1 in.). Water entering the OGFC is not transmitted into the overall pavement structure but rather laterally to the edge of the roadway. Another historic application of porous asphalt is for the construction of an open grade drainage layer which may be placed under the dense graded asphalt or concrete layers to provide lateral drainage for water penetrating the surface. This water is transmitted laterally to subdrains typically placed longitudinally along the edge of the pavement or shoulder. One of the oldest porous pavement installations was constructed in 1977 at the Walden Pond State Reservation in Massachusetts. It currently is in good condition and exhibits little cracking or other distresses, although its permeability has been impacted by the lack of maintenance that most BMPs require [NAPA 2013].

Porous asphalt is now being used as a complete surface for the pavement structure for permeable pavement applications. The porous asphalt provides a stable wearing surface for the pavement while transmitting all of the stormwater through the surface to the underlying stone reservoir. The void space of porous asphalt is at least 16 percent, as opposed to 6 to 8 percent for conventional asphalt. Treated runoff is temporarily stored in the reservoir bed, a highly permeable layer of open graded clean-washed aggregate with about 40 percent void space. Unmodified porous asphalt has lower strength than conventional dense graded asphalt. For example, thin layers of OGFC used for highway surfacing are typically assigned no structural contribution to the pavement. Porous asphalt used in moderate to high traffic applications includes the use of admixtures to increase the strength and durability of the pavement. Porous asphalt used for permeable pavements is assigned a structural contribution between that of a dense graded base and dense graded asphalt concrete.

Mix design procedures for porous asphalt are similar to those used for OGFC mixes. This may include admixtures such as anti-stripping agents to enhance asphalt cement/aggregate adhesion. Mix designs for conventional asphalt concrete typically involve the use of stiffer grade asphalt binders achieved with a styrene butadiene rubber (SBR) or a styrene butadiene styrene (SBS), and/or the addition of fibers, and a dense material to provide strength and rut resistance with sufficient asphalt cement coating to resist thermal cracking [NAPA 2008]. Porous asphalt mix deigns, focus on the provision of an open structure to provide infiltration capacity while being stable and resistant to rutting/deformation under traffic. To improve durability of porous asphalt, a drain down test is completed (which is not typical for dense graded mixes other than stone mastic asphalt) and often there is a minimum asphalt content to assure a thick film. A Cantabro Abrasion test is used to evaluate the mix design durability (ASTM D7064-04). An example porous asphalt pavement is shown in Figure 3.3.

Figure 3.3. Porous asphalt pavement.

For more information regarding porous asphalt:
www.asphaltpavement.org/index.php?option=com_content&view=article&id=359&Itemid=863

3.3 Pervious Concrete

Conventional concrete is designed to be as dense as possible to be strong and relatively impermeable. In order to provide permeability for use in a pavement system, the aggregate gradation is modified to increase the air void space. Similar to asphalt, pervious concrete has also been used as an open graded drainage layer beneath conventional highway surfaces.

The strength of pervious concrete is less than that of conventional concrete and as such needs to be thicker than conventional concrete pavements for the same level of traffic. The structural design for pervious concrete is different than that of asphalt concrete and is discussed in Section 6. Mix design procedures for pervious concrete are similar to that of conventional concrete using compressive strength cylinders and flexural strength beams to assess structural capacity. An example pervious concrete pavement is shown in Figure 3.4.

Figure 3.4. Pervious concrete pavement.

For more information regarding pervious concrete: http://acpa.org/PerviousPave/

3.4 Permeable Interlocking Concrete Pavement

There are several types of permeable interlocking concrete pavements (PICPs). Conventional interlocking concrete pavement (ICP) consists of high strength impermeable concrete blocks laid over a sand bedding course with sand-filled joints to assist in interlocking the blocks together. This type of system is not very permeable. In order to make it permeable, either the concrete block has to be permeable or the blocks must be constructed such that their configuration provides openings to provide permeability. Both the sand bedding and joint filler for PICPs is replaced with a stone chip material that provides both friction to prevent block movement and permeability to allow the infiltration of water. A key advantage of the PICP systems is that the blocks are hard and durable with compressive strengths in the order of 55 MPa (8,000 psi). An example PICP is shown in Figure 3.5.

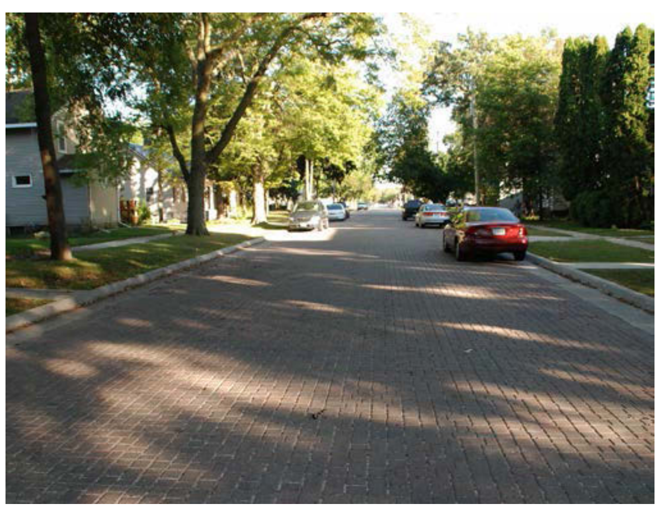


Figure 3.5. Permeable interlocking concrete pavement.

For more information regarding permeable interlocking concrete pavement:
http://www.icpi.org/node/553

4. Permeable Shoulder Feasibility Decision Criteria

The primary purpose of an 'outside', i.e. to the right of the travel lanes, highway shoulder is to provide a safety zone for emergency pull-off from the main highway lanes. The median shoulder (depending on the width), may also provide a safety zone or offset from median barrier systems. Shoulders may be used to carry mainline traffic during rehabilitation and maintenance operations and be used by other modes of transportation including buses, bicycles, etc. Shoulders also provide lateral support to the pavement structure and drainage of surface water away from the travelled portion of the roadway. Shoulder pavements may be constructed as granular surface, partially and/or fully paved hard surface depending on the highway classification and locations, e.g. urban versus rural. Permeable shoulders may provide all of the features above, but also provide the opportunity for stormwater management.

While the use of permeable shoulders may have significant benefits in terms of stormwater management, their application is not be suitable for all situations. In order to be successful, consideration must be given to site specific conditions, design, construction and maintenance details. The following stepwise process is recommended for evaluating the suitability and opportunity for permeable pavement and identifying key factors that may influence design and effectiveness.

Step 1 - Evaluate acceptability. The first step in determining the suitability of a project for permeable pavement shoulders is to determine if they are permitted by national and local regulations for the project location. The advantages of permeable shoulders are such that lack of prohibition should be taken as permissive or demonstrative (allowing a demonstration of the benefits).

Step 2 - Evaluate opportunities and drivers. The next step is to evaluate whether the project provides the opportunity for any of the following general considerations:

- Desire or regulatory requirements to reduce the volume of stormwater runoff, reduce peak runoff flowrates, improve the quality of stormwater runoff, and/or and address other related run-off issues such as effluent temperature;
- Increase safety via reducing splash and/or surface ponding when vehicles are using the shoulder;
- Potential for reduction in future stormwater management costs by modifying pavement design for stormwater management and eliminating end of pipe structures; and
- Incentives (financial, environmental benefits, sustainability achievement, etc.).

Step 3 - Evaluate benefits, risks, and technical design factors. If the analysis in Step 1 and 2 indicates that the use of a permeable shoulder may be suitable for a particular project, additional specific considerations should be analyzed to evaluate the anticipated benefits and risks associated with its use.

To determine the suitability of a project for permeable pavement shoulders, the key factors specific to the project should be considered. Based on their importance in overall decision making, these factors can be divided into primary, secondary, and other considerations which may impact the decision to use permeable shoulders for a particular project. Primary considerations (i.e., fatal flaws or major design challenges) are those that would have an overriding influence on the decision to move forward with the project. Secondary considerations are those that have a lesser influence and usually are taken into account as part of the design process when there are no overriding considerations. These factors may diminish the performance or acceptability of permeable shoulders or may require additional design provisions (and associated costs) to avoid risks. Other considerations may have some influence on the decision to include permeable shoulders for a particular project. The primary considerations should generally be weighted the highest to reflect their importance in moving forward with the project, while secondary and other considerations are useful to prioritize between sites and influence design, but are not generally fatal flaws.

1. Primary Considerations

- Availability of capital funding
- Status of environmental approval
- Regulatory requirement to consider use of permeable shoulders
- Safety
- Significant longitudinal grades (>5 percent)
- Depth of water table
- Geotechnical risks
- Groundwater contamination risk

2. Secondary Considerations

- Stringent receiving water quality standards
- Sand use for winter maintenance
- Run-on from adjacent areas with exposed soils
- Low soil infiltration rates
- Target design volumes and runoff rates
- Complexity of geometric conditions (super elevation, shoulder width available, number of lanes, etc.)
- Risk of flooding
- Mandates for stormwater quality control
- Mandates for drainage and peak flow control
- Maintenance protocols
- Shoulder utilization

3. Other Considerations

- Interest in innovation
- Presence of utilities
- Impact of unknown site conditions
- Risk of accidental chemical spill
- Owner experience and resources

This list of considerations was developed for illustrative purposes. This is not an exhaustive list, but rather reflects typical needs and expectations. Constraints and project-specific considerations should be added or deleted as necessary. The individual weighting of the considerations should be modified to reflect local agency needs and expectations. A description of each of the considerations is summarized in Table 4.1.

Table 4.1. Decision matrix considerations

Importance Level	Description
Primary Considerations	
Availability of capital funding	The initial capital construction cost of permeable pavement is typically higher than for conventional pavement. Overall long term life-cycle costs can be very competitive if consideration is given to stormwater quality and quantity benefits and the costs of constructing and maintaining other stormwater treatment facilities in the right-of-way.
Status of environmental approval	In some jurisdictions, permeable pavement may not be permitted or may require additional environmental approvals. On the other hand, desirability for stormwater quality and quantity management can drive regulatory acceptance of and even advocacy for permeable pavements.
Safety	Ability to accommodate safety features such as rumble strips, vegetative growth, etc.
Significant longitudinal grades	Grades of more than 5 percent may pose significant design challenges. A stone reservoir with a sloped base may be much less effective at promoting infiltration than a flat reservoir because water will seek a level surface and pond. Significant longitudinal grades may require relatively costly design features such as regular cut-off walls or below grade shallow slopes with step-downs to provide needed level of infiltration to achieve design goals.
Depth of water table	Permeable pavements should not be used in areas where the water table is within 0.6 m (2 ft) of the top of the soil subgrade. It must be possible to drain water entering the subgrade. Note, this criteria is not intended to address potential for groundwater contamination as a result of high groundwater table or other soil factors (see “groundwater contamination risk”)
Geotechnical risks	Depending on site-specific conditions, infiltration of water below a road shoulder may pose a range of geotechnical risks, such as reduced subgrade support, slope stability, scouring, etc. In Karst areas, increased below ground infiltration may cause sink holes. Geotechnical risks may introduce added design complexity and may necessitate the use of an underdrain and/or impermeable liner.

Importance Level	Description
Groundwater contamination risk	A variety of factors influence the potential for stormwater sources to contaminate groundwater, including soil characteristics, depth to groundwater, traffic volume, existing soil contamination, and application of salt for deicing. Where there is elevated potential for contamination, design features may be included or required to mitigate this risk, including soil amendment below shoulders, use of an underdrain, and/or a liner.
Secondary Considerations	
Stringent receiving water quality standards	While the presence of and need to protect nearby aquatic resources may provide incentives for the use of permeable pavements in cases, for some protected watersheds, cold water streams, and other receiving waters with stringent water quality standards, the level of treatment provided by permeable pavements (for water discharged from underdrains) may not provide adequate protection from stormwater quality impacts. In cases where infiltration is not feasible, permeable shoulders with underdrains may need to be coupled with an additional treatment system. In such a case, permeable shoulders may not provide sufficient benefit to justify their use.
Sand use for winter maintenance	Winter sand may clog permeable pavement systems resulting in reduced system permeability.
Low soil infiltration rates	Soil infiltration rates influence performance of permeable shoulders for volume and peak flow reduction. Low soil infiltration rates may need to be supplemented with an underdrain to provide adequate drainage, which tends to reduce performance and increase costs compared to conditions where infiltration rates are adequate to support a design without underdrains.
Target design volumes and runoff rates	Due to geometric factors, permeable shoulders may be limited in terms of how much volume they can store and the maximum rate of sheet flow from travel lanes that can be captured in the permeable shoulder. Where target design volumes or intensities are large in comparison to available space, permeable shoulders may have a reduced effectiveness. A site-specific hydrologic analysis based on site rainfall patterns, roadway geometry (i.e., number of lanes vs. shoulder area), stormwater management goals (i.e., long term volume control vs. peak event mitigation) is recommended to evaluate whether permeable shoulders would be suitable for meeting design goals.
Complexity of geometric conditions	Geometric constraints such as horizontal or vertical grades, presence of bridge structures, curbs, retaining walls, guiderails, etc.

Importance Level	Description
Risk of flooding	Permeable shoulders may not be capable of conveying flows from peak storm events. Areas subject to frequent roadway flooding may require supplemental drainage features to ensure that the roadway surface is properly drained; however, it is likely that such drainage features would be required with or without the use of impermeable shoulders.
Mandates for stormwater quality control	Permeable pavements may contribute substantially to water quality improvement. Where regulations are in place requiring stormwater quality management, this may significantly incentivize the use of permeable shoulders.
Mandates for drainage and peak flow control	Permeable pavements provide stormwater management alternatives to more costly or complicated practices to provide drainage and peak flow control.
Maintenance protocols	In order to maintain their effectiveness in some areas, permeable pavement systems require mandatory maintenance practices such as vacuum sweeping, which may influence their applicability and desirability for a project.
Shoulder utilization	Some shoulders are used as driving lanes for specific conditions or circumstances, e.g. evacuation routes, rush hour traffic, pullovers for passing, high occupancy vehicle routes, emergency vehicles, etc. Design of shoulders for moderate to heavy traffic use would require additional considerations and additional costs.
Other Considerations	
Interest in innovation	Utilizing nontraditional surfaces for stormwater management provides opportunities for innovation.
Presence of utilities	The design and construction of permeable shoulders may be problematic or require additional design features, such as cutoff walls, in areas where utilities are present along the roadway shoulders.
Impact of unknown site conditions	Variability of soil conditions, presence of organics, potential for frost heave, etc. may impact shoulder pavement performance.
Risk of accidental chemical spill	While spills are relatively uncommon and tend to occur at low volumes they can typically be retained in the permeable shoulder. Based on typical volume of chemical spill being less than the capacity of water quality facilities, it is likely that spills would be captured by the stone reservoir. This would be a benefit in some respects; however, if conditions are conducive for migration of spilled substances to groundwater, the use of permeable shoulders could increase the potential for major soil/groundwater cleanup efforts, depending on the downstream conditions. Higher weighting may be considered in relation to the groundwater quality risks posed by spills (i.e., soil type, depth to groundwater).
Owner experience and resources	The use of permeable pavements for roadway shoulders is very limited at present.

4.1 Permeable Shoulder Feasibility Decision Matrix

To assist in evaluating the suitability of projects for the use of permeable shoulders, a project suitability matrix (template) was developed (Table 4.2) which could be tailored for individual user needs. The matrix includes the considerations outlined above with appropriate weighting factors for each group. Within each group, the individual consideration items also are given weighting factors. Each factor should be assessed using specific criteria of the owner's needs and expectations for the project. Once the factor is rated, the total scores are summed on a scale of 0 to 100. A suggested total score evaluation metric includes if the score totals less than 65; the project is not considered a good candidate for permeable shoulders. Between 65 and 75, the project can be considered for permeable shoulders. Scores over 75 indicate that the project is well suited for permeable shoulders. This scoring evaluation should be vetted by DOTs and adjusted as necessary for their own conditions.

In the example shown in Table 4.2, the primary considerations have been given a category weighting of 60 points; the secondary considerations are weighted at 30, and other considerations are weighted at 10. When considering the primary factors, there was a preference for selecting projects where funding was available, where there are minimal environmental issues and where there is sufficient depth to the water table to provide adequate drainage. In terms of secondary factors, there is a clear mandate for stormwater quality and quantity improvements with minimal maintenance and operational concerns, favoring the use of permeable pavements. The "other considerations" category provides only a minimal contribution to the decision weighting. These weighting factors can be adjusted by DOTs to better reflect their goals and objectives.

Table 4.2. Permeable shoulder feasibility decision matrix (with example project scores)

1. Primary Considerations

Part 1 Weighting: 60

Consideration	Project Score	Weighting	Weighted Score	Project Scoring Guidelines A Favorable for Permeable Shoulders	B <<====================>>	C Not Favorable for Permeable Shoulders
Availability of Capital Funding	B	20.0	12.0	Project funded; requirement to implement	Need to justify funding	No specific funding available; no requirement to implement
Status of Environmental Approval	B	20.0	12.0	Approved	Approval pending	Application required
Safety	A	10.0	10.0	Minimal safety issues	Safety issues can be addressed	Significant safety issues
Significant Longitudinal Grades	B	10.0	6.0	Grades < 2 percent	Grades of 2 to 5 percent	Grades > 5 percent
Depth of Water Table	B	20.0	12.0	Water table > 1.5 m (5 ft) below subgrade	Water table 0.6-1.5 m (2-5 ft) below subgrade	Water table < 0.6 m (2 ft) below subgrade
Geotechnical Risks	B	10.0	6.0	Low complexity	Medium complexity	High complexity
Groundwater Contamination Risk	A	10.0	10.0	Low risk	Elevated Risk	High risk
Total		**100.0**	**68.0**	See Table 4.1 for guidance on scoring		
	Weighted Total Score:		**40.8**			

2. Secondary Considerations

Part 2 Weighting: 30

Consideration	Project Score	Weighting	Weighted Score	Project Scoring Guidelines A Favorable for Permeable Shoulders	B <<====================>>	C Not Favorable for Permeable Shoulders
Stringent Water Quality Standards	B	10.0	6.0	Regulations in place	Limited restriction	No restrictions
Sand use for Winter Maintenance	B	10.0	6.0	No sand use	Used < 2 times/year	Used > 2 times/year
Low Soil Infiltration Rates	A	10.0	10.0	Infiltration < 12 mm/hr (1/2 in./hr)	Infiltration >12mm/hr (1/2 in./hr) < 40 mm/hr (1.5 in./hr)	Infiltration > 40 mm/hr (1.5 in./hr)
Target Design Volumes and Runoff	A	10.0	10.0	Frequent/non-intense storm	Moderate frequency/intensity	Intense storms
Complexity of Geometric Conditions	A	10.0	10.0	Minimal geometric restrictions	Some geometric challenges	Significant geometric restrictions
Risk of Flooding	A	10.0	10.0	None	Occasional	Frequent
Mandates for Water Quality	B	10.0	6.0	Water quality concerns	Some water quality issues	No concerns
Mandates for Stormwater Management	A	10.0	10.0	Stormwater management concerns	Some stormwater management issues	No concerns
Maintenance Protocols	C	10.0	2.0	Proactive maintenance	Reactive maintenance	Minimal maintenance
Shoulder Utilization	B	10.0	6.0	Use for emergency stopping only	Occasional use for traffic	Regular use by traffic
Total		**100.0**	**76.0**	See Table 4.1 for guidance on scoring		
	Weighted Total Score:		**22.8**			

3. Other Considerations

Part 3 Weighting: 10

Consideration	Project Score	Weighting	Weighted Score	Project Scoring Guidelines A Favorable for Permeable Shoulders	B <<====================>>	C Not Favorable for Permeable Shoulders
Interest in Innovation	B	20.0	12.0	Regular innovation implementation	Innovation encouraged	Minimal interest
Presence of Utilities	B	20.0	12.0	None	Non-critical utilities	Critical utilities
Impact of Unknown Site Conditions	B	20.0	12.0	Site conditions well known	Some site information available	No site specific information available
Risk of Accidental Chemical Spill	A	20.0	20.0	Limited exposure	Elevated risk of spills or elevated risk of gr	Elevated risk of spills and elevated risk of groundwater contamination
Owner Experience and Resources	C	20.0	4.0	Significant owner experience	Limited owner experience	No owner experience
Total		**100.0**	**60.0**	See Table 4.1 for guidance on scoring		
	Weighted Total Score:		**6.0**			

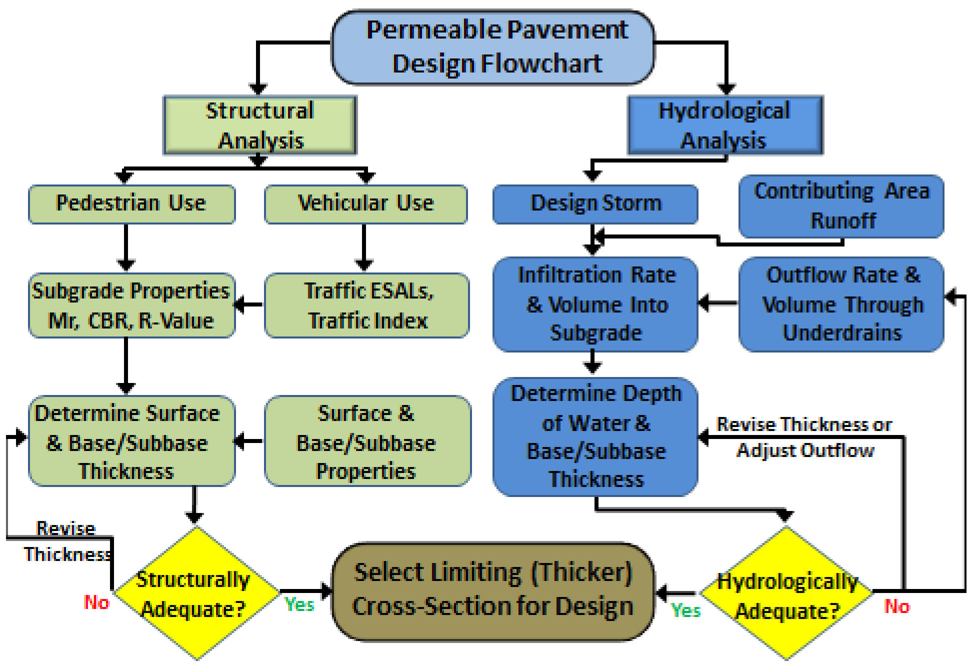
Sub Totals

1. Primary Considerations	60	40.8
2. Secondary Considerations	30	22.8
3. Other Considerations	10	6.0
Grand Total Project Score	**100**	**69.6**
Decision		**Can Consider**

Decision Range		
From	**To**	**Implement Alternative**
0	65	**No**
65	75	**Can Consider**
75	100	**Yes**

5. Structural and Hydrological Design of Permeable Pavements

The design of permeable pavements requires the consideration of both structural and hydrological components as shown in Figure 5.1. The structural design of the pavement is completed to determine the thickness of the various pavement components that are necessary to support the intended design traffic while protecting the subgrade from permanent deformation. The hydrological design determines the key design elements necessary to infiltrate rainwater and surface runoff into the pavement and hold and/or detain and filter the water to achieve the stormwater management objectives. An optimal pavement design is one that is just strong enough to accommodate the design traffic and has the minimum hydrological features to provide water quantity and quality management. For example, if a 230 mm (9 in.) stone reservoir is needed to provide adequate structural integrity and a 230 mm (9 in.) stone reservoir is needed to provide the storage needed to meet hydrologic goals, and then the design would be considered “optimal.” Frequently; however, designs are controlled by structural considerations and therefore may be “over designed” for hydrologic performance.



[Smith 2011]

Figure 5.1. Structural and hydrological design flowchart.

5.1 Design for Pavement Structural Capacity

The most common structural analysis procedure for porous asphalt and permeable interlocking concrete pavement follows the requirements of the American Association of State Highway and Transportation Officials (AASHTO) Guide for the Design of Pavement Structures [AASHTO 1993]. Pervious concrete structural design is based on the StreetPave system as modified by the American Concrete Paving Association (ACPA) [ACPA 2012]. Brief descriptions of the design methods used with these systems is provided in the following sections.

5.1.1 Porous Asphalt and PICP Structural Design

The AASHTO pavement structural design method is summarized using the following equation (U.S. Customary Units) [AASHTO 93]:

$$\text{Log}W = Z_R \times S_0 + 9.36 \times \log(SN+1) - 0.20 + \frac{\log\left[\dfrac{p_i - p_t}{p_i - 1.5}\right]}{0.40 + \dfrac{1094}{(SN+1)^{5.19}}} + 2.32 \times \log(M_R) - 8.07 \quad \text{[EQN 5.1]}$$

where:

W = design traffic load in equivalent single axle loads (ESALs)
Z_R = standard normal deviate for reliability "R"
S_0 = standard deviation
SN = structural number of the pavement
= $\Sigma\, a_i * d_i$
a_i = structural layer coefficient
d_i = layer thickness
p_i = initial serviceability
p_t = terminal serviceability
M_R = subgrade resilient modulus (units must be U.S. Customary).

A brief discussion of the key pavement structural design elements and typical values is provided below:

W The AASHTO design procedure characterizes traffic loads in terms of Equivalent Single Axle Loads (ESALs). One ESAL is represented as the application of a single 80 kN (18,000 lb) axle load. Permeable pavements in North America have typically been designed for applications not exceeding about 1 million ESALs [Smith 2011]. Design procedures have recently been developed in Europe that accommodates ESAL loadings into the 10 million range [Interpave 2010]. Highway pavements are typically designed for ESAL loading in the order of 5 to 100 million ESALs. Shoulders; however, receive much less traffic unless they are utilized for expanded capacity during rush hour for example. A typical shoulder pavement would be exposed to much fewer than 100,000 ESALs during its design life. It should be noted that procedures used by a particular agency to calculate ESALs will be required. This may include differences in the calculation of ESALs for flexible and rigid pavements.

Z_R The design reliability level (factor of safety) is the reliability level selected by the designer to take into account the probability that the pavement as designed may not provide satisfactory service during the intended period of service. The increase in the design reliability level results in more substantial (stronger) pavement with higher probability that the pavement will perform as designed.

For the AASHTO design procedure, the higher the selected reliability and standard deviation, the higher the design ESALs used in the design and the thicker the pavement design for a specified loading. Critical facilities are typically assigned reliability factors of 95 percent or higher. Low traffic volume roadways and less critical facilities may be assigned reliability values of 75 percent or less. For permeable shoulder pavements, a reliability factor in the order of 80 percent (Z_R=-0.841) would be considered appropriate. This represents a low to medium level of reliability.

S_0 The overall standard deviation takes into account the variability associated with design and construction inputs, including variability and material properties, subgrade, traffic, and environmental exposure. Other factors that contribute to the overall standard deviation include lack-of-fit of the AASHTO model and replicate section errors (errors due to other unaccounted factors). For shoulder pavements, a standard deviation of 0.44 is appropriate for flexible pavements and pavers and 0.34 for rigid pavements.

SN The Structural Number (SN) of the pavement is a dimensionless value that represents the “strength” of a pavement section. It is determined by multiplying the thickness of a pavement layer (d_i) by its layer coefficient (a_i) which is a representation of the strength of the layer and then summing this value for all layers. The higher the SN, the stronger the pavement section.

a_i The layer coefficient is a measure of the strength of an individual layer. This value typically ranges from about 0.06 for subbase layers to 0.44 of bound layers such as asphalt concrete layers. Typically, layer coefficient values for permeable pavement layers are lower than for conventional dense graded pavement layers. For example, the layer coefficient for a new dense graded asphalt layer would typically range from 0.4 to 0.44. Porous asphalt concrete is produced by modifying the aggregate gradation to permit water to flow through the pavement. In doing so, the strength of the layer is reduced. As such, porous asphalt has a layer coefficient in the range of 0.2 to 0.3 as well as the paver and bedding materials used as permeable interlocking concrete pavement. A similar reduction applies to open graded base and subbase layers [Hein 2006]. Dense graded base, for example, would have a layer coefficient in the order of 0.12 to 0.14. An open graded base would be between 0.06 and 0.09. This reduction reflects the reduced load carrying capacity of the open graded layer. Open graded base layers are sometimes stabilized with either asphalt cement or Portland cement, which may increase their layer coefficient.

p_i This is the initial serviceability of the as-constructed pavement. For the design of both flexible and rigid pavements, the AASHTO Guide uses present serviceability index (PSI). This index was developed through regressions between slope variance measurements, key distress types (rutting, alligator cracking, and patching for flexible pavements and cracking and patching for rigid pavements), and subjective present serviceability ratings (PSR). The index, like PSR, is based on a scale of 0 to 5, with 0 representing a completely failed pavement and 5 representing a perfectly even and unblemished pavement. The initial serviceability of a new highway pavement would typically range from about 4.1 to 4.5. An initial serviceability of 4.2 would be considered reasonable for a shoulder pavement.

p_t This is the terminal serviceability of the pavement or the point in time at which rehabilitation of the pavement would be considered necessary to keep it in a serviceable condition. The terminal serviceability is typically higher for more important pavement sections such as interstate highways that are subjected to more frequent traffic. Terminal serviceability for highway lanes is typically in the 2.2 to 3.2 range. A value of 2.5 would be considered reasonable for shoulder pavements.

M_R The characterization of subgrade soils is one of the most challenging parts of pavement design. Subgrade soil consists of native soil left after the removal of the existing overlaying material, as well as soils used as earth borrow to construct embankment fills or to replace existing unsuitable soils. The objective of the subgrade construction is to provide a uniform foundation for the pavement structure. The ability of subgrade soil to support a pavement structure is characterized by its laboratory-determined M_R. The design modulus used in the AASHTO design is based on the support capability determined after the subgrade material has been 'soaked' for 96 hours, i.e. saturated. The AASHTO design equation is very sensitive to this input. The common approach in providing guidance in the selection of resilient modulus is to group soil types into common categories and assign typical M_R values to each category. The selection of an appropriate design value for M_R depends on a number of factors and a suitability qualified geotechnical engineer should be consulted for its determination. In general, coarse grained soils such as sands and gravels have higher M_R values than fine grained soils such as silts and clays. As such, the required pavement thickness for a given traffic level is higher for fine grained soils.

The characterization of the subgrade is not only for structural design purposes. It is also important if one of the goals of the permeable pavement design is to infiltrate water into the subgrade. It is important to establish the relationship between soil permeability and insitu soil density achieved during construction. This is important to establish a relationship between subgrade infiltration capability and the structural capacity necessary to support the design traffic. For example, a resilient modulus determined at a soil compaction level of 95 percent of the standard Proctor maximum dry will have lower infiltration capacity and higher structural capacity than a resilient modulus determined at a soil compaction level of 90 percent. Further, in the event that the field density is less than the design density, it may be necessary to decrease the design resilient modulus, which decreases the structural capacity especially when the soil is saturated, requiring a thicker pavement structure.

It should be noted that some of the current permeable pavement design documents require that the subgrade not be compacted to promote infiltration. This would be very difficult to achieve in a highway construction environment as a uniform subgrade cross-section is desirable to provide lateral drainage and it would be very difficult to control the movement of construction equipment which would tend to compact the subgrade during construction operations. A geotechnical engineer should be consulted for further detailed information.

5.1.2 Pervious Concrete Structural Design

The structural design of pervious concrete pavements is different than that used for porous asphalt and PICP. The most common procedure used in North America is that outlined by the American Concrete Paving Association [ACPA 2012]. This procedure uses fatigue of the pervious concrete as the primary failure mode for the pavement. The fatigue/damage equation for the pavement is:

$$FD_{total} = FD_{single} + FD_{tandem} + FD_{tridem} \qquad \text{[EQN 5.2]}$$

where:

FD_{total}	=	Total fatigue damage, %
FD_{single}	=	Fatigue damage from single axle loads, %
FD_{tandem}	=	Fatigue damage from tandem axle loads, %
FD_{tridem}	=	Fatigue damage from tridem axle loads, %

Fatigue damage for each axle type in Equation 5.3 is determined using Miner's damage hypothesis [Miner 1945].

$$FD = \frac{n}{Nf} \qquad \text{[EQN 5.3]}$$

where:

n	=	number of load applications
Nf	=	allowable applications before failure

The number of load applications is determined using the same traffic analysis as outlined in the AASHTO design procedure except the heavy vehicles are divided into the number of single, tandem and tridem axle load categories. The total allowable applications to failure can be estimated as:

$$logN_f = \left[\frac{-SR^{-10.24}\log(1-P)}{0.0112}\right]^{0.217} \qquad \text{[EQN 5.4]}$$

where:

Nf	=	allowable applications before failure
SR	=	stress ratio, %
P	=	probability of failure, %

The stress ratio is a function of flexural strength and the equivalent stress, which is a function of load weight. The higher the number of load repetitions the lower the stress ratio. For load repetitions of 100 axel loads, the stress ratio would be in the range of 0.8. For load repetitions greater than 1 million, the stress ratio is 0.5. For pervious shoulder applications, a stress ratio of about 0.5 would be appropriate.

The probability of failure is calculated as:

$$P = 1 - R * \frac{SC}{50} \qquad \text{[EQN 5.5]}$$

where:

P	=	probability of failure, %
R	=	reliability, %
SC	=	percent slabs cracked at the end of the design life (assumed at 15 %), %

The stress ratio is the stress divided by the strength of the material.

$$SR = \frac{\sigma_{eq}}{MR} \qquad \text{[EQN 5.6]}$$

where:

SR = stress ratio, %
σ_{eq} = equivalent stress, MPa (psi)
MR = flexural strength of the concrete, MPa (psi)

The flexural strength of typical conventional concrete pavement ranges from about 4.5 to 6.5 MPa (650 to 945 psi). The flexural strength of pervious concrete typically ranges from about 2 to 3 MPa (290 to 435 psi).

5.2 Hydrologic Design of Permeable Shoulders

Conventional roadway pavements are designed to remove water from the pavement surface and within the structure as quickly as possible. Water remaining on the pavement surface may pose safety issues, including hydroplaning and spray of water. Water within the pavement structure may reduce the strength of the pavement layer and subgrade thereby reducing the overall structural capacity of the pavement and increasing the potential for frost heaving. Permeable pavements, in general, are intended to remove water from the pavement surface by infiltrating it through the surface layer and channel it into the underlying stone reservoir where it can be stored and slowly released to either the underlying soils or the underdrain system. The application of permeable pavements on shoulders of roadways presents a special case of permeable pavement application, where travel lanes are constructed of traditional pavement that drain to shoulders that receive inflow via sheet flow runoff from the travel lanes as well as direct precipitation.

The hydrological design for permeable shoulders involves several components:

- Infiltrate water into the pavement structure, including sheet flow runoff from travel lanes and impermeable sections of shoulder, plus direct rainfall over shoulder and potential inflows from upstream areas of permeable shoulders;
- Provide temporary storage capacity for water in the stone reservoir;
- Filter contaminants in the water as it flows through a filtering course and/or the permeable stone reservoir;
- Infiltrate water into the subgrade (where possible);
- Convey excess water to an appropriate discharge points; and
- Provide flow control for water leaving stone reservoir.

The approach used for hydrologic design of permeable shoulders depends on the hydrologic design goals of the project. Hydrologic design goals may take a number of forms, including:

- Capture and infiltrate or treat runoff from a specified water quality design storm to address pollutant loads; water quality design storms specified in regulations are typically a smaller storm representative of more frequent events that result in the bulk of cumulative runoff volume.

- Capture and infiltrate or treat a specified fraction of long term average runoff volume to address pollutant loads; common percent capture goals specified in regulations range from about 80 and 90 percent capture of long term runoff volume. Water quality design storms are frequently set to meet the 80 to 90 percent capture goal.
- Capture and detain runoff to provide flow duration control to match pre-development peak runoff flowrates and durations over a specified range of flows; flow ranges of interest typically span from less than the 2 year flowrate to the 10 year or greater flowrate to provide protection against channel erosion.
- Capture and detain and/or infiltrate runoff to match pre- vs. post-project peak flowrates and/or volumes for a specified design storm to meet water quality, channel protection, and/or flood control goals; events of interest may range from smaller, more frequent storms (less than 1 year recurrence interval) to infrequent, extreme events (greater than 25 year recurrence interval).
- Opportunistic implementation, intended to achieve the maximum feasible pollutant load and/or peak flow and/or volume reduction given the constraints of the site.
- Reduction of pollutants to help meet total maximum daily loads (TMDLs).
- A combination of multiple goals.

As evidenced by these examples, hydrologic goals can consist of a broad range of storm events of interest, can be referenced to pre-project or pre-development conditions or referenced only to post-development conditions, may or may not include flow control goals, can be based on a single design event or the cumulative performance over a long term period. Clearly the hydrologic design approach used for different goals would differ by necessity. Table 5.1 provides a summary of the general hydrologic analysis and design approach associated with each type of goal listed above.

Table 5.1. Analysis and design approaches for different hydrologic design goals

Example Hydrologic Design Goal	**Example Underlying Goal(s)**	**General Analysis and Design Approach**
Capture and infiltrate or treat runoff from a specified water quality design storm depth	Control pollutant loads and volumes Improve recharge of groundwater Comply with regulations	1. Estimate runoff volume from design storm depth 2. Provide capacity to capture storm in stone reservoir 3. Demonstrate that water can be drained via infiltration or surface outlet in a specified time (typically 24 to 48 hours) to accommodate subsequent storms

Example Hydrologic Design Goal	Example Underlying Goal(s)	General Analysis and Design Approach
Capture and infiltrate or treat a specified fraction of long term average runoff volume	Control pollutant loads and volumes Improve recharge of groundwater Comply with regulations	1. Conduct continuous simulation of long term period of record for proposed condition 2. Account for transient inflow, storage, outflows on continuous basis 3. Tabulate long term cumulative runoff volume reduction, treated volume, and overflow volume in comparison to specified standards 4. Iterate hydrologic design parameters to meet goals
Capture and detain runoff to provide flow duration control to match baseline peak runoff flowrates and durations over a specified range of flows Baseline may be pre-development of pre-project	Reduce the risk of channel instability in receiving channels that are susceptible to erosion Provide incidental benefits for water quality and flood control	1. Conduct continuous simulation of long term period of record for pre-development (or pre-project) and proposed conditions 2. Account for transient inflow, storage, outflows on continuous basis 3. Tabulate cumulative durations of flows over range of interest and compare baseline vs. proposed 4. Iterate hydrologic design parameters to meet goals
Capture and detain and/or infiltrate runoff to match pre- vs. post-project peak flowrates and/or volumes for a specified design storm	Provide adequate roadway drainage for peak storm events Avoid detrimental effects on downstream capacity for peak storm events Provide water quality benefits	1. Conduct hydrologic calculations to generate design storm hydrograph for pre-project and proposed conditions 2. Route hydrograph through permeable pavement system 3. Iterate hydrologic design parameters to meet goals
Opportunistic implementation to achieve maximum feasible pollutant load reduction	Opportunistic water quality improvement Contribute to meeting TMDL (s)	Usually analyzed using continuous simulation approach or surrogate load reduction approach, such as performance under a specified storm event

Example Hydrologic Design Goal	Example Underlying Goal(s)	General Analysis and Design Approach
Opportunistic implementation to achieve maximum feasible peak flow reduction	Opportunistic flood control and/or channel stability improvement Element of long term control plan for combined sewer overflow mitigation	Usually analyzed for a specific surrogate storm event; may be analyzed via continuous simulation to provide a statistical expression of reduction in peak flows
Combination of multiple goals	Address various combinations of the goals in a single stormwater management feature	Depends on goals

5.2.1 General Hydrologic Analysis Framework

There are numerous stormwater models that could be used to complete the hydrological design for permeable shoulder pavements. Depending on the hydrologic design goals, appropriate models may include:

Simple volumetric runoff estimation methods. These models generate an estimated runoff volume for a specified design storm depth, but do not assign a hydrograph "shape" to this runoff volume. Examples include the NRCS Curve Number method, the volumetric runoff coefficient method, and others.

Event-based hydrograph estimation methods. These models generate an estimated runoff hydrograph for a specified design storm. Examples include the Watershed Hydrology Program (WinTR-20), Small Watershed Hydrology (Win TR-55), Santa Barbara Unit Hydrograph (SBUH), HEC-1 Flood Hydrograph Package, HydroCAD Stormwater Modelling (HydroCAD), and others. Note that the assumed "peaky" design storm (for example SCS Type 1A distribution) could result in over-design of permeable pavement area/storage required as compared to continuous modeling approaches below.

Continuous simulation modelling programs. These models generate long term runoff hydrographs from multiple storms based on a real observed continuous rainfall record and other hydrologic inputs; many also have the capability to route the hydrograph through stormwater management facilities that conduct continuous analysis of transient inflows, outflows, and storage levels. Examples include the USEPA Stormwater Management Model (SWMM), the Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS), Source Loading and Management Model for Windows (WinSLAMM), Integrated Design Evaluation and Assessment of Loadings (IDEAL), others.

In general, the hydrological analysis assesses if the design runoff volumes or hydrographs can be infiltrated, stored and released by the pavement structure provided. The quantity of water in the pavement system is described as a water balance [NRCS 1986]:

$$\text{Water Volume (Time)} = \text{Initial Water Level} + \int_0^{Time} \text{Inflows (Time)} - \text{Surface Outflows (Time)} - \text{Volume Reduction (Time)} \quad \text{[EQN 5.7]}$$

Variations on this general framework are presented below for specific hydrologic analysis applications.

5.2.2 Design Hydrologic Calculation Framework for Simple Volumetric Sizing Approaches (Presumptive Sizing)

It is common in sizing of water quality control measures to simply evaluate whether the runoff from a given design rainfall depth can be captured and then drained in an adequate time to allow capture of subsequent events. This approach is specifically suited for cases where water quality improvement and volume reduction are the key goals, and a design storm depth has already been developed for the region as a surrogate for long term performance. Systems that capture the runoff from the design storm depth are presumed to achieve a given level of performance. In this sizing approach, the designer first calculates the runoff volume from the design storm depth. Runoff volume can be calculated via a number of approaches. The simple volumetric runoff coefficient method has been commonly applied for this need:

$$RV = C \times D \times A \times (1\text{ ft}/12\text{ in.}) \qquad \text{[EQN 5.8]}$$

where:

RV = runoff volume, ft^3

C = volumetric runoff coefficient, unitless

D = design storm depth, in.

A = tributary area, ft^2

For roadways, it is common to assume a volumetric runoff coefficient (the estimated amount of precipitation that will runoff) of 0.80 to 0.98 depending on surface type, grade, and storm size.

The designer then demonstrates that the permeable shoulder system has the capacity to capture this volume. The volume of storage provided can be calculated based on the volume of voids in the stone reservoir that are available to store water. A porosity of 0.3 to 0.4 is common for stone reservoirs.

In this calculation, it is important to account for the slope of the bottom of the stone reservoir and calculated stored volume based on a level water surface. For sloped reservoirs, the storage volume may be a “triangular” prism rather than a “rectangular” volume. Information about the specific roadway and shoulder geometry is needed to calculate the effective storage volume.

Supplemental calculations are generally needed to demonstrate that the volume can be drained at an adequate rate to allow for capture of subsequent events. For infiltration systems, the drawdown time can be estimated as a function of the “effective depth” of water stored in the stone reservoir (calculated as the total depth multiplied by the porosity, expressed in units of depth), divided by the design infiltration rate into the subgrade (expressed in units of depth per unit time). The infiltration rate of the subgrade may be reduced due to the presence of the stone reservoir aggregate. To account for the fact that aggregate may “cover” the subgrade at the stone reservoir/subgrade interface, the effective area of subgrade for infiltration may be reduced by the area covered by aggregate, i.e. for a stone reservoir with a porosity of 40 percent, the effective infiltration area of the subgrade will only be 40 percent of the total plan area. For systems with underdrain discharges, it is necessary to develop a stage-discharge relationship for the underdrains, as well as infiltration, if present, to estimate the drawdown time. In computing system drainage, appropriate corrections should be made to account for the effect of compaction on subgrade permeability.

Compaction can have a significant effect on infiltration rates [Pitt 1999]. It is important to establish the relationship between soil permeability and insitu soil density achieved during construction. This is important to establish a relationship between subgrade infiltration capability and the structural capacity necessary to support the design traffic. For example, subgrade strength determined at a soil compaction level of 95 percent of the standard Proctor maximum dry density will have lower infiltration and higher structural capacity than subgrade strength determined at a soil compaction level of 90 percent. Further, in the event that the field density is less than the design density, it may be necessary to decrease the design subgrade strength, which decreases the structural capacity of the pavement especially when the soil is saturated, requiring a thicker pavement structure.

This approach assumes that the capacity of the permeable surface course is greater than the peak runoff rates that would be generated during water quality design storms, which is generally a reliable assumption with regular maintenance.

5.2.3 Design Hydrologic Calculation Framework for Design Event Hydrograph and Continuous Simulation Sizing Approaches (Performance Based Sizing)

To evaluate the capture efficiency, volume reduction and flow control performance of a system under a design event (real or constructed) or over a long term continuous simulation period, it is necessary to conduct rainfall-runoff-routing calculations. A hydrograph generation and routing procedure uses small time steps to estimate the expected water inflow from direct precipitation onto the design surface and runoff contributed by the adjacent catchment areas. Catchment areas may include the highway driving lane (s), areas of non-permeable shoulder, overflow from sections of permeable shoulder upstream, etc.

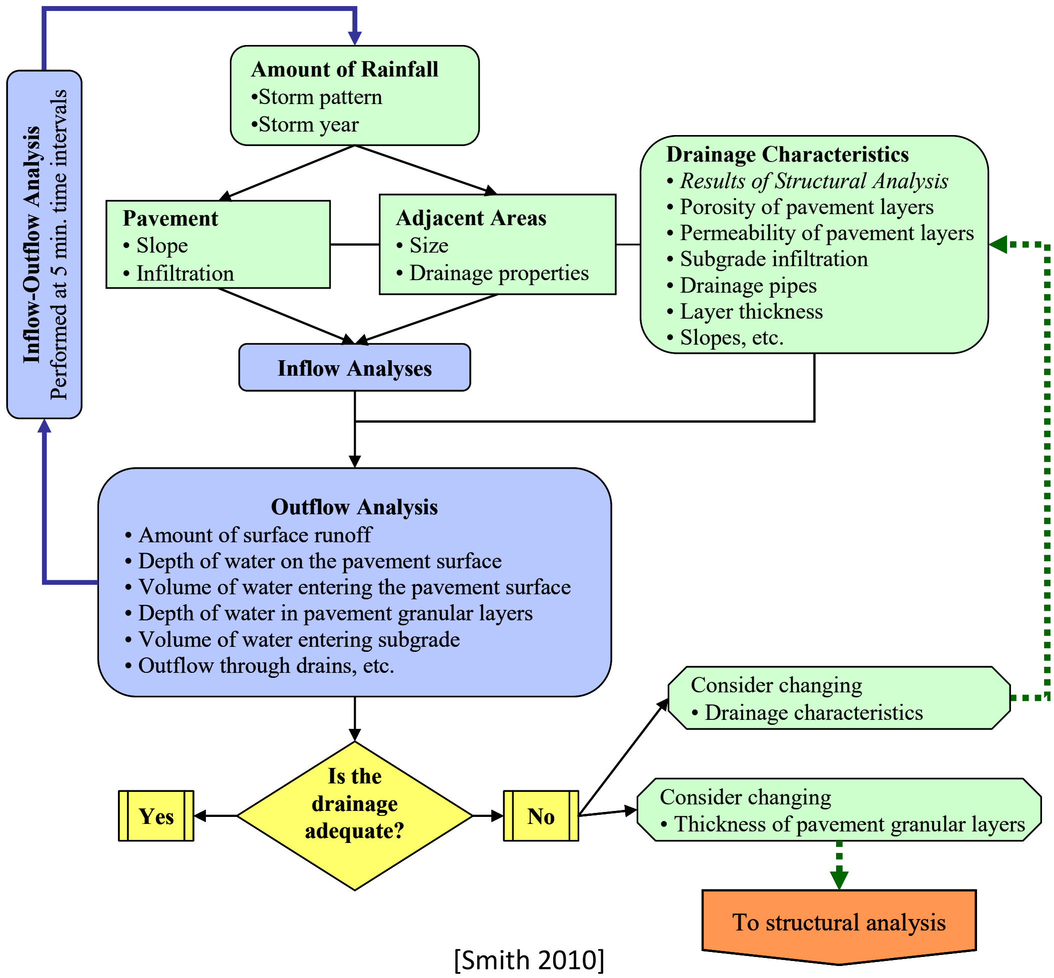
The outflow is also estimated in terms water infiltrated into the subgrade and stormwater drainage to the surface conveyance system during each time step. The combined process allows the water level in the pavement system to be estimated at any time during the design storm, while draining and after the rainfall has stopped. Model results are then interpreted in comparison to the hydrologic performance goals established for the project to determine if goals are met. If they are not, then the permeable shoulder design is adjusted until goals are met or until goals are determined to be infeasible and revised. This approach is generally referred to as a "performance-based" approach, as the estimated performance of the system for the design storm is the basis for demonstrating compliance.

A flowchart for the hydrological analysis involving hydrograph routing is shown in Figure 5.2. Various hydrologic methods may be appropriate for evaluating the hydrologic performance of permeable shoulders. The specific hydrologic methods used for a project may be dictated by:

Preference of local agency, plan review agency, and/or project designer. For example, a jurisdiction may have a list of acceptable hydrologic methods and/or models that may be used. A review of local standards and correspondence with plan reviewers is recommended for as part of selecting an analysis method/model.

Form of the hydrologic performance goal for the project. For example, it would not be appropriate to use an event-based simulation to evaluate the attainment of a hydrologic performance goal that is expressed as a certain degree of long term volume reduction. See Section 5.2.3.1 for guidance on selecting methods/models that are compatible with hydrologic goals.

Sensitivities of the specific design scenario. For example, if it is known that the capacity of the permeable top course may limit performance under peak runoff events, then a more complex model framework may be needed that is capable of accounting for this limiting factor as well as the outflows from the stone reservoir. If the peak intensity of the design storm is significantly different than most storms that occur in the area, that may be a reason to use a continuous simulation approach. Using the peak intensity will usually result in over design in regions where typical storms are not as intense. Other specific design conditions that may influence model selection are discussed in Section 5.2.3.3.



[Smith 2010]

Figure 5.2. Hydrological design process.

The following sections provide guidance on methods for generating hydrographs and routing hydrographs through permeable shoulder systems. Specific analysis considerations that may influence model selection and application are also discussed.

5.2.3.1 Inflow Hydrograph Generation

The inflow hydrograph to a permeable shoulder system (i.e., the time series of flows incident on the top course of the pavement) consists of the precipitation that falls directly on the permeable shoulder and flow from precipitation that runs off of adjacent pavement. Key model inputs and forcing data for hydrograph generation include:

Catchment area. The catchment area tributary to permeable shoulders is a function of the width of the travel lanes and the topography of the road. The permeable shoulder area should generally be included in the catchment area unless direct rainfall on the permeable shoulder is accounted for separately, outside of the model framework. If landscaped areas or other run-on to the roadway is present than that area should also be accounted for in the modeling.

Catchment properties. Due to relative homogeneity of surface types in a roadway environment, catchment properties for roadways are generally well understood and are not highly sensitive to analyses. Key conceptual parameters include the depression storage (or initial abstraction) on the catchment, the slope of the catchment, and the roughness of the catchment. These properties are represented in different ways in different modeling frameworks. Imperviousness of the tributary area is important in some environments, but is typically 100 percent in roadway drainage to shoulders. Routing of substantial areas of pervious surfaces to permeable shoulders should be avoided to help limit sediment input.

Overland flow patterns. The overland flow patterns of a catchment (i.e., the paths that water flows), coupled with catchment properties, are important factors that describe how quickly water is conveyed off of the catchment and the relative "peak" of the hydrologic response. Some hydrologic methods use the "time of concentration" of the catchment as an input, while others calculate the timeframe of hydrologic response based on physically-referenced input parameters such as path length, slope, and roughness. In addition, it is necessary to understand that sheetflow onto a permeable pavement surface from a sloped area, i.e. adjacent highway lanes, will be different than water deposited directly onto the pavement surface [Grahl 2013].

Precipitation. For highway runoff, rainfall and snowmelt are the most important forcing parameters. Relatively high spatial resolution, preferably five minute resolution or finer, is preferred for generating runoff hydrographs intended to reliably approximate peak runoff rates. For long term simulations that are focused primarily on volume of runoff, and where the peak flow into permeable shoulders is not a limiting factor, the use of lower resolution data such as hourly precipitation data is generally reliable. Note that design storms assume an artificial shape (Peaky hydrograph) for purposes of conservatism for flood evaluations and can result in over-design for water quality and/or volume control purposes.

Evaporation. Evaporation is not generally a significant factor in hydrograph estimation for medium to large storms; however may have an effect on volumes of runoff during smaller storms, particularly during warm weather. For continuous simulation models, evaporation is an important factor in recovery of depression storage between events and contributes to appreciable volume reduction.

A variety of well documented methods are available for hydrograph estimation. A partial list of example methods/tool and their applicability are provided in Table 5.2 .

Table 5.2. Example methods/tools for hydrograph generation

Example Hydrograph Estimation Methods/ Tools	**Applicability**	**Example Modeling Software**	**Reference**
NRCS Hydrology for Small Watersheds (TR-55) SCS curve number method	Single-event simulation Hydrograph generation only; routing via custom or proprietary add-on	WinTR-55 (freeware) available from NRCS Various proprietary modeling packages	NRCS 1986 Model Download: http://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/water/?&cid=stelprdb1042901
Santa Barbara Urban Hydrograph (SBUH)	Same as above	Can be implemented in spreadsheet Various proprietary models, such as HydroCAD	http://www.portlandoregon.gov/bes/article/55823

Example Hydrograph Estimation Methods/ Tools	Applicability	Example Modeling Software	Reference
Modified Rational Method	Same as above	Watershed Modeling System (WMS, proprietary) HydroCAD (proprietary) Other	Various hydrology manuals. Example: http://dpw.lacounty.gov/wrd/publication/engineering/2006_Hydrology_Manual/2006%20Hydrology%20Manual-Divided.pdf
Stormwater Management Model (SWMM) Non-linear reservoir method	Single event, multiple event, or continuous simulation Also provides conveyance and storage routing capabilities	EPA SWMM (freeware) Various proprietary modeling packages, such as PCSWMM and XPSWMM	http://www.epa.gov/nrmrl/wswrd/wq/models/swmm/
Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS) Various unit hydrograph methods, including Snyder, Clark, synthetic, and SCS	Same as above	HEC-HMS, GeoHEC-HMS (freeware)	http://www.hec.usace.army.mil/software/hec-hms/index.html
Hydrologic Simulation Program-Fortran (HSPF)	Same as above	HSPF, WinHSPF (freeware) Various proprietary modeling packages	http://water.usgs.gov/software/HSPF/

5.2.3.2 Storage Routing

Storage routing consists of tracking the inflows, outflows, and change in transient storage volume over sequential time steps through a simulation period. Throughout the analysis period, water leaves the system while simultaneously entering the system. Difference between inflow and outflow rates is reflected in a change in storage conditions. Storage routing is conducted for a single event in much the same manner that it would be conducted for a multiple event or continuous simulation.

Inflow to the permeable shoulder is estimated as described in Section 5.2.3.1. If other inflows are presents, such as drainage from upstream segments of permeable shoulder, then this should also be accounted as an inflow. The main pathways for outflow drainage include infiltration into the soil (which contributes to groundwater recharge, or may move laterally as shallow subsurface flow), outflow from the underdrain system, and overflow to a secondary drainage system.

A variety of methods and tools are available for storage routing, as indicated in Table 5.2. For single-event simulation, routing can also be conducted in a spreadsheet using the “storage indication method” (see Highway Hydrology [FHWA 2002] for more guidance) or other simple approaches. Except in certain special conditions, as discussed in Section 5.2.3.3, most models/methods can provide reliable representation of storage routing for permeable shoulders. The following paragraphs provide guidance on representing outflows and transient storage in permeable shoulders:

Infiltration into subgrade. Where a liner is not used, infiltration from the storage reservoir will occur. The amount of water entering the subgrade is determined by the subgrade hydraulic conductivity as well as the rate at which water dissipates within the subgrade. Infiltration rates of subgrade material are an important design parameter that should be assessed insitu as part of the design process.

Water that enters the permeable pavement may contain particles washed into the pavement from the non-permeable surfaces. These particles may be washed completely through the system (depending on the flow of the water and the size/shape of particles) or may be deposited within the stone reservoir or on top of the subgrade surface. Over time, this may cause a reduction in the permeability of the surface course (reducing the peak flows that can enter the pavement system) and/or the subgrade (reducing the amount of water infiltrating into the subgrade). For fine grained soils such as silts and clays, which generally have already low permeability, the impact of the deposited material may be minimal. For coarse grained soils such as sand, the deposited material may significantly reduce its permeability. Designers may consider apply a long term permeability reduction factor (PRF) to the as-constructed permeability of the subgrade to account for this reduction [Smith 2010]. A PRF may also be appropriate to account for significant variability in soil properties, the effect of compaction on infiltration rates of subgrade materials and uncertainty about construction methods that will be used, which leads to significant uncertainty regarding the actual as-built permeability.

$$Q_{\inf iltration} = k_{Subgrade} \cdot PRF \qquad \text{[EQN 5.9]}$$

where:

$Q_{infiltration}$	=	Flow rate of water into subgrade, m/day (ft/day)
$k_{Subgrade}$	=	Measured or estimated hydraulic conductivity of the subgrade material, m/day (ft/day)
PRF	=	Permeability reduction factor

As the depth of stored water increases, the static pressure is expected to increase which will directly affect the rate of drainage; however, because the depth of the controlling subgrade layer is typically much thicker than the depth of ponded water in the stone reservoir, a steady infiltration rate is typically assumed for routing calculations.

Some models provide more sophisticated algorithms for simulating infiltration into the subgrade, such as Green-Ampt or Horton formulations, which take into account the initial unsaturated state of the subgrade material and simulate higher initial infiltration rates at the beginning of an event, declining with cumulative time or infiltrated volume; however, given the uncertainty of infiltration rate estimates, and because saturated infiltration tends to occur for majority of time in significant storm events, more sophisticated methods are not generally necessary.

Where underlying water table is relatively close the water surface, a more sophisticated modeling approach may be needed to account for reduction in infiltration rate resulting from mounding of groundwater below the system.

Outflow from underdrains. The outflow from the underdrains may be controlled by the hydraulic capacity of the underdrain pipe, by an outlet control device (such as orifice or other restriction) affixed to the end of the underdrain pipe, or a combination of the two. The depth at which outflow begins is controlled by the elevation of the underdrains and/or the lowest discharge elevation of the outlet control device. While a number of simulation options exist in different models to simulate outflow from underdrains, the most universal approach is to develop a stage-discharge relationship (tabular) that can be used to estimate the outflow from the underdrains at each time step based on the depth of storage in the system. Standard hydraulic analysis guidance, such as provided in Highway Hydrology [FHWA 2002], coupled with information about the geometry of the specific design, can be used to generate stage-discharge relationships.

The design of underdrain and outlet structures is a function of the hydrologic design goals for the project. Some agency specifications require detention of stormwater for a certain time (i.e., a minimum drawdown time, e.g., 72 hours) to ensure adequate retention time for treatment. For flow control purposes, outlet configurations should be designed to meet the specific flow control objectives of the project. For example, for control of the 10 year peak runoff flowrate to match pre-development peaks, a relatively large outlet may be appropriate to provide "peak shaving" (i.e., functioning similar to a peak flow control detention facility). In contrast, to provide flow duration control from 50 percent of the pre-development 2-year peak to the 10 year peak, a very small low-flow outlet control may be needed, with supplemental outlets at higher elevations to effectively manage flows and durations to pre-development levels across a broad range of storm events.

Overflow from storage reservoir. While typical highway drainage criteria dictate that ponded water should not be present on the road surface, there may be events that exceed the capacity of the storage volume and the various outflow pathways. This may lead to overflow of the storage reservoir. If this occurrence is possible for a given design, the model used for performance analysis should allow for this possibility. Similarly to representing underdrain outflow, an overflow pathway can be represented by a stage-discharge curve or by elements built into specific models.

Storage reservoir representation. The storage reservoir of a permeable shoulder system consists of the void space in the stone reservoir. At each computation time step, the difference between inflow and outflow results in a change in the transient storage in the storage reservoir. While models offer various options for representing storage volume, the most universal approach is the use of a stage-area relationship (table, curve) as input to the model. Most simulation frameworks do not allow a porosity to be assigned to a storage volume, therefore the user usually must account for the porosity of the stone reservoir in developing model inputs, specifically, by applying an appropriate reduction in effective area within the stage-area relationship. The same datum used for storage-discharge relationships for underdrains and overflows should be used to describe the storage-area relationship.

5.2.3.3 Specific Hydrologic Analysis Considerations

The following considerations may be applicable for specific project applications and may influence the hydrologic analysis approach and associated modeling method that is used.

Surface infiltration. Determination of the rate of surface infiltration is key to the performance of permeable pavements. While the entire pavement may have significant permeability, if water cannot enter the surface due to clogging, the system will not function as designed. The American Society for Testing Materials (ASTM) has developed surface infiltration testing procedures for both pervious concrete (ASTM 1701-09) and for PICP (ASTM 1781-13) which can be used to measure the initial and long-term infiltration rates of permeable pavements.

Peak flow limitations on inflow to storage reservoir. While permeable pavements tend to exhibit very high rates of infiltration, the capacity for water to be transmitted through the surface course into the storage reservoir may be exceeded in scenarios where a large amount of tributary area is routed to the permeable shoulder, precipitation intensities are very high, or the permeable pavement has become partially clogged. If these conditions are relevant to a hydrologic analysis, the peak flow limitation into the storage reservoir should be represented, in addition to the storage routing calculations. Many models allow for a peak flow "diversion" to be simulated. Models that do not allow for a peak flow diversion may not be suitable in these scenarios.

Flow from upstream storage reservoirs. Permeable shoulder designs may allow for water to cascade from upstream storage reservoirs to downstream storage reservoirs when capacity of upstream storage reservoirs is exceeded. A model capable of analyzing storage compartments in series would be required to represent this design configuration.

Effects of Compaction on Infiltration Rate. The infiltration rate of subgrade soil may be an important design parameter, and is understood to vary greatly with changes in compaction [Pitt 1999]. At the design phase, it may be challenging to estimate the actual infiltration rate post-construction. In part this may be accounted in selection of a permeability reduction factor. Tests of remolded compacted soil samples can also be used to help determine the influence of compaction on permeability in site soils and help select an appropriate infiltration rate to use in design.

Groundwater mounding. In cases with shallow groundwater tables and infiltrative soils, groundwater mounding may have an important effect on infiltration rates, particularly during extended wet weather periods. Groundwater mounding can reduce the rate of infiltration into the subgrade or even prevent flow into the subgrade altogether. One approach for accounting for groundwater mounding is to select a design infiltration rate that accounts for critical wet weather conditions. This may be appropriate for a given design scenario; however it may be limited in some cases as it would tend to over-predict infiltration in extreme conditions and under-predict infiltration during normal operations. Where groundwater mounding is important, a more robust method may be considered that accounts for transient groundwater mounding and dynamically adjusts infiltration rates.

Sloping storage reservoirs. For roadways with longitudinal grades, the storage reservoir below permeable shoulders will tend to slope longitudinally, creating a prismatic storage volume with variable depth, where the downstream portion will fill first. It is important that a level water surface is assumed in calculations so that storage volume and infiltration losses are not over-estimated. Additionally, when developing stage-area and stage-discharge relationships, the sloping base should be considered.

Tailwater conditions. In systems with low hydraulic gradients between the road shoulder and the receiving water or conveyance system, it is possible that the underdrain outlet from the permeable shoulder may be partially or fully submerged on the downstream side (i.e., a tailwater condition) at some times. For example, during a peak runoff event, the hydraulic grade line in a trunk storm sewer may be above the outlet elevation of the discharge pipe from the permeable shoulder. Where these conditions are significant in the assessment of hydrologic performance, a model should be selected that reliably accounts for tailwater effects and the reduced outflow that would occur when tailwater conditions occur.

Variable terrain. Another difference between the design of permeable pavements for roadway shoulders and that for parking areas is the impact of variable terrain on the hydrology and potential subgrade infiltration. The roadway subgrade will vary with cut and fill conditions along the roadway platform for rolling or mountainous terrain. While there may be some subgrade undercut and re-compaction for cut sections (typically 300 mm (12 in.)), the underlying subgrade will be in its natural state. For fill conditions, the subgrade is usually placed in layers and compacted to a dense state to ensure stability of the roadway platform and possible embankment. Limiting the compaction under only the shoulder to promote infiltration could be problematic.

Responsible application of a permeability reduction factor (PRF). For the reasons described in Section 6.2.3.2, a PRF may be warranted to provide a factor of safety on drawdown calculations and ensure that long term performance, with clogging and compaction remains acceptable; however, use of a PRF in the assessment risks of groundwater contamination, geotechnical issues, or other factors may mask the magnitude of these risks by simulating a lower infiltration rate than may occur upon initial installation. Therefore, a realistic estimate of the initial infiltration rate should be used to assess these risks instead of the long term design infiltration rate. Additionally, application of an excessively high PRF, if not warranted by site conditions, may render permeable shoulders infeasible in cases where they may actually be an effective option.

5.3 Design for Cold Climate Frost Considerations

In northern climates, concerns of pavement damage from frost heave are a significant issue. In northern climates, freeze thaw is one of the principal causes of pavement damage. Guidance for pavement design typically includes the use of a coarse stone reservoir that acts a capillary barrier and therefore prevents the wicking of moisture either from an infiltration reservoir or from the subgrade into the pavement subbase. The use of thickened pavement subbase, well drained subbase materials, and the use of subdrains has been shown to effectively limit freeze thaw damage [Roseen 2012].

The depth of the pavement subbase as reported by [Ferguson 2005] is determined as follows:

> Pavement system and subbase thickness are > 0.65 * design frost depth for area.
>
> Example: Durham, New Hampshire, 122 cm (48 in.) = $M_{\text{aximum frost}}$, therefore the minimum depth to the bottom of the subbase = 0.65 (122 cm) = 81 cm (32 in.).

As in standard pavement design, pavement durability needs are balanced with anticipated traffic load, and usage. In many instances such as low use roadways, driveways, and sidewalks, substantially thinner pavement thickness are used. This would be evaluated by the DOT design engineer as should the costs of stormwater treatment in the pavement/shoulder vs. construction and maintenance of other BMPs in the right-of-way.

5.4 Balancing Structural and Hydrological Designs

If the hydrological design results in a stone reservoir thickness that is sufficient to accommodate the vehicular traffic loading, then the design is feasible. If the stone reservoir thickness required for hydrological design is significantly thicker than required for structural capacity and would therefore be cost-prohibitive, the designer may modify some of the design parameters to make the design more cost-effective. This may include:

- Modify the stone reservoir materials to increase porosity to permit greater storage.
- Modify the stone reservoir materials to increase permeability to permit more rapid drainage of water from the pavement section.
- Increase the frequency, diameter or slope of outlet pipes to increase water outflow.
- Other stormwater storage and conveyance systems.

As previously indicated, the life cycle cost of off-road, regular BMP treatment should also be considered in the tradeoff analysis.

The depth of the granular layers for the pavement shoulder would likely have to match or exceed that of the pavement structure to maintain transverse subgrade cross slope. This may in fact govern the overall thickness of the permeable shoulder. If the stone reservoir thickness required for structural design is significantly thicker than required for hydrological design, the designer must improve the structural capacity of the pavement or accept a lower design life. Improvements may include:

- Increase the thickness of the surface layer (i.e. asphalt, concrete or pavers). These layers have a higher structural strength capacity than the stone reservoir layers. Slight increases in the thickness of these layers may provide the necessary structural strength capacity improvement.
- Increase the thickness of the stone reservoir layers.
- Improve the quality of the stone reservoir layers to provide a higher layer coefficient.
- Use additional stabilized layers below the surface such as asphalt or cement stabilized open graded drainage layers.

This may result in excess capacity for hydrologic functions. The designer can choose to accept this surplus as a factor of safety against long term clogging; however, it may also be possible to accept a higher degree of compaction of the subgrade, which would reduce the infiltration rate, but strengthen the base material, thereby moving the design toward a more optimal balance.

6. Permeable Shoulder Use and Configurations

There are many different configurations of permeable shoulders that could be considered for roadway pavements. There are several conditions that may influence the type and configuration of the permeable system. These may include:

- Urban versus suburban versus rural
- Location (median or outside shoulder pavement)
- Subgrade strength and permeability
- New construction versus retrofit of existing pavement

In an urban environment, conventional roadway shoulders act as an emergency pull-off area and access for maintenance and emergency vehicles. They typically are constructed adjacent to an urban section designed with curbs, catchbasins and underground piping to capture and transmit stormwater away from the pavement. In rural areas, shoulders may or may not be paved with stormwater draining from the pavement, over the shoulder to either ditches or onto the surrounding natural grades.

For urban area permeable shoulder design, the conventional shoulder surface, base and subbase can be replaced with the permeable pavement system. Catchbasins may be completely eliminated in some situations or at least reduced in terms of frequency. Underground stormwater pipes could be eliminated or their use limited to specific high water volume locations. In rural areas, permeable shoulders could assist in channeling stormwater to assist in mitigating localized washouts, capturing stormwater, reducing peak runoff volumes and promoting water filtration. In the cases above, the reduced infrastructure may result in overall reduced project costs.

In addition, a complete permeable shoulder design would need to include design details for the locations and spacing of stormwater discharge points. The water flow within the stone reservoir could also be controlled through the use of flow barriers placed transversely to the water flow to delay and treat stormwater.

Permeable shoulder systems may offer a good solution for highway median drainage. Current urban highway configurations typically consist of an inside shoulder varying in width with a median barrier system (e.g. Jersey barrier, cable and post or metal guiderail) between traffic directions. Depending on the width of the median and number of traffic lanes draining towards the median, the inside shoulder could be replaced with a permeable shoulder system. Water draining towards the median would drain into the system and then either be infiltrated into the subgrade, where possible, or to conventional drainage outlets. While permeable shoulders could also be used in the rural environment, most inside median areas are relatively narrow and typically not paved and therefore, a permeable pavement section may not be practical.

Subgrade strength and permeability will impact the thickness design for permeable pavements. Low strength and low permeability subgrade may require a thicker granular stone reservoir layer to support the design traffic and stormwater management. High strength, high permeability subgrade would typically require much thinner stone reservoir layers; however, most pavements are designed to ensure lateral drainage across the pavement section by providing shoulder granular depths that exceed that required for the roadway lanes. As such, the thickness of the stone reservoir will likely exceed that required for both structural and hydrological design.

Permeable shoulder construction for new pavements is relatively straight forward. Given that the current focus in North America is on pavement maintenance and rehabilitation, there is more opportunity for the retrofit of existing shoulders using permeable systems. For example, in urban areas where existing stormwater systems are aging or are undersized for current storm events, permeable shoulders may offer the opportunity to reduce and/or supplement existing drainage systems thereby mitigating the needs for expensive excavation and traffic disruption during construction and could result in overall reduced project costs.

6.1 Conceptual Designs

There are many potential configurations for permeable shoulder systems. The designs need to consider many features such as local or rural environment, design traffic, storm intensity, subgrade type, geometric restrictions, stormwater management objectives, etc. A few generic/conceptual designs are provided in Figure 6.1 through Figure 6.3. The cross-sections shown are for a rural design. For urban designs, the granular rounding may be reduced in width and hard surfaced. Curb and gutter, gutter, barrier walls, safety barriers may also be present beyond the permeable shoulder. Additional design element guidelines are discussed in Section 9.

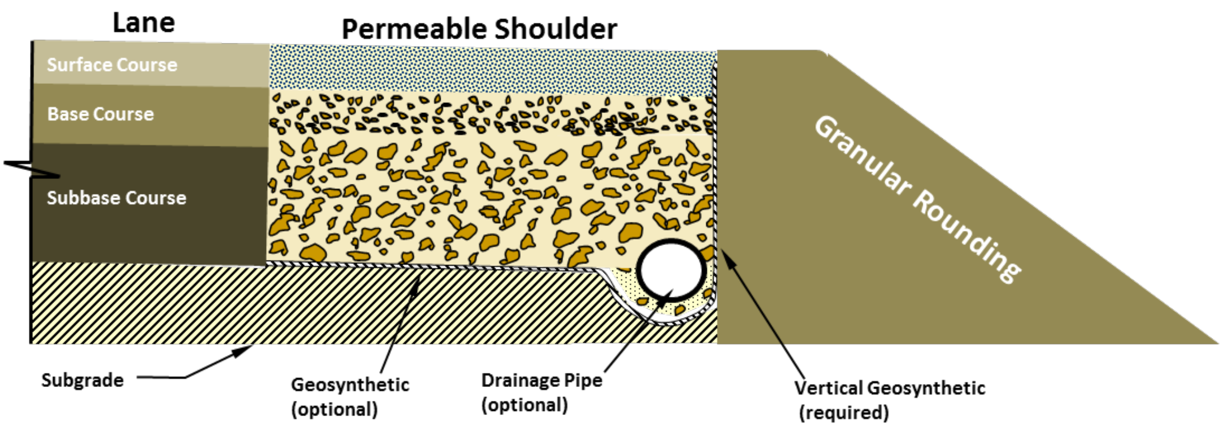


Figure 6.1. Basic permeable shoulder configuration.

The above configuration could be modified to accommodate various driving lane surfaces. For example, in some areas, open grade friction course (OGFC) is used as a surface for the driving lanes. The thickness of this layer is typically 25 to 30 mm (1 to 1 1/4 in.). The OGFC layer could be placed over the dense graded asphalt driving lane and then daylighted at the edge of the driving lane, distributing surface runoff into the permeable shoulder. Alternatively, the OGFC layer could be placed as the surface course of both the driving and shoulder lanes.

Should additional strength be required for the permeable shoulder, an asphalt stabilized base or a perforated dense graded asphalt concrete layer could be placed directly beneath the permeable surfacing.

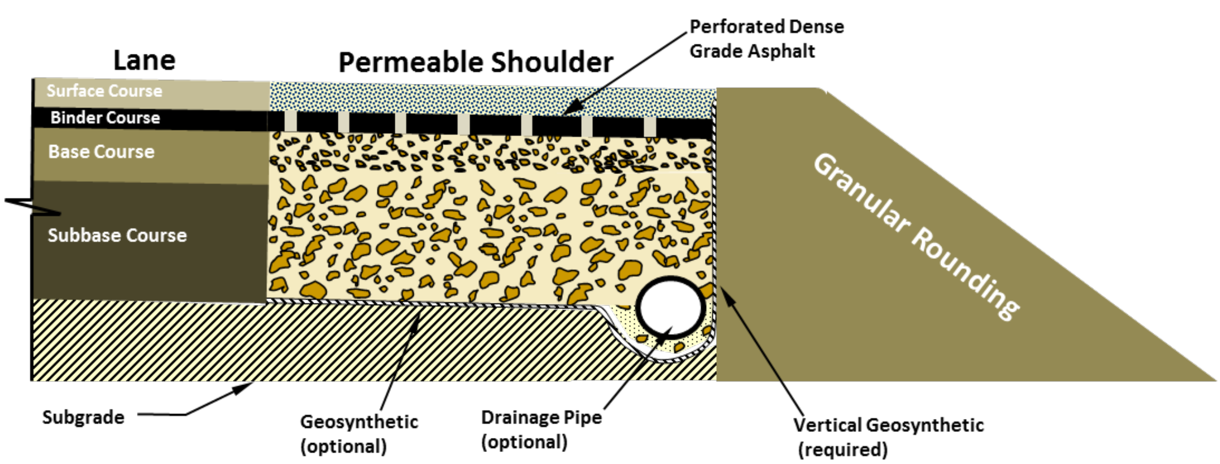


Figure 6.2. Conceptual strengthened permeable shoulder.

This configuration has been used successfully in the United Kingdom [Interpave 2010]. The conventional and permeable pavements are constructed up to the upper binder course level. The dense graded binder course would be extended across the whole width of the pavement including the shoulder. Upon completion of the remainder of the roadwork, holes are drilled into the shoulder binder course at a frequency dependent on the design rainfall intensities for the system. The holes are filled with open graded aggregate and then the permeable surface is placed. While this may result in a reduction in surface permeability, a significant increase in strength for the pavement is possible. In another variation, the dense graded perforated asphalt concrete on the shoulder could be replaced with an asphalt treated permeable base or cement stabilized layer such as cement stabilized open graded drainage layer or pervious concrete.

A channeled permeable shoulder design would possibly be used for urban roadways, permeable shoulder retrofit applications or to provide edge support to prevent damage to the outside edge of the shoulder under heavy vehicular traffic. An example of this configuration is shown in Figure 6.3.

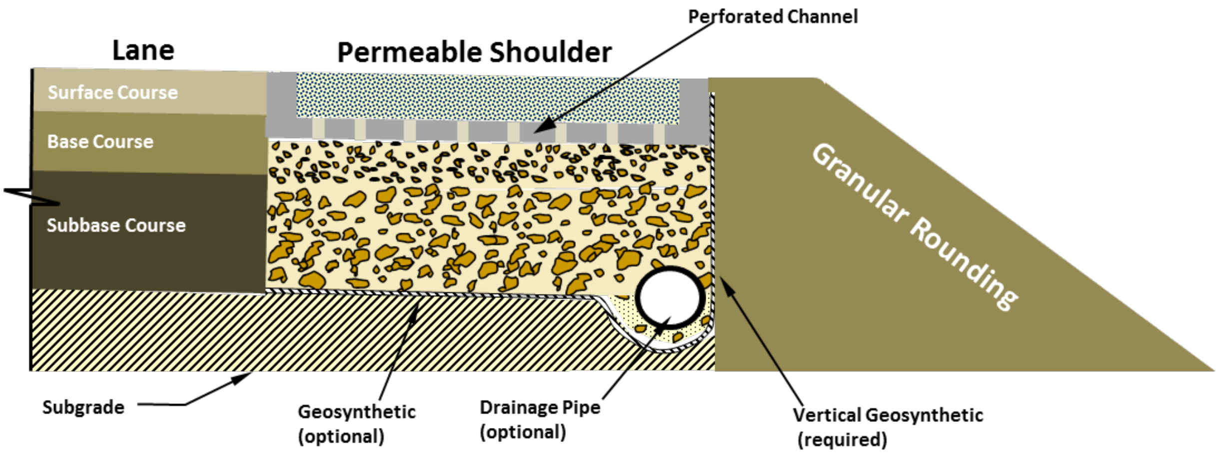


Figure 6.3. Conceptual channeled permeable shoulder.

The perforated channel could consist of a wide variety of products including cast in-place concrete, precast concrete, recycled plastic wood, etc. The channel provides strength for the shoulder pavement, lateral support for the permeable shoulder material and support for the granular rounding, which would force stormwater to enter the permeable shoulder and prevent scouring of the surface of the adjacent granular shoulder. The channel also provides a 'clean' edge with the adjacent travel lane edge. If desired, the top of the channel adjacent to the travel lane could be constructed wide enough to accommodate rumble strips.

7. Detailed Design Element Guidance and Discussion

This section provides more detailed guidance on various design aspects for permeable shoulder pavements including highway geometrics, materials, safety, and other design considerations.

Highway Geometrics. General grade guidance is provided in the permeable shoulder suitability decision matrix. Permeable shoulders would be designed to accommodate stormwater runoff. In most situations, two or possibly three lanes of roadway would drain at a cross-slope in the order of 2 percent to the permeable shoulder. For superelevated sections, or multi-lane highways (> 3 lanes), a standard width permeable shoulder pavement may not be able to accommodate the total volume of water from significant storms.

Impact on Mainline Pavement. The permeable shoulder pavement must be properly designed to accommodate both vehicle and hydrological loading. If water cannot enter into the surface of the shoulder, it will either pond on the surface and potentially back up onto the travelled portion of the roadway or overrun the shoulder edge. Careful consideration must be given to the duration that water is retained in the stone reservoir. While pavement bases and subbases are typically dense graded and have low permeability, water remaining in the stone reservoir may infiltrate the mainline pavement structure and subgrade. If the site subgrade materiel is coarse grained, i.e., sandy material, the impact will likely be minimal. If the subgrade is fine grained, i.e., silt or clay, it is possible that the water may weaken the subgrade and reduced the structural capacity of the mainline pavement.

Porous Asphalt. For permeable pavement applications, the porous asphalt layer is typically 75 to 125 mm (3 to 5 in.) in thickness. The thickness for a specific project is determined based on the anticipated traffic loading. It is recommended to construct a thicker pavement primarily using coarser open graded mixes below the surface.

Some aggregates used to make asphalt concrete are susceptible to stripping. This occurs when the electrical charges of the asphalt cement and aggregate are similar, resulting in the asphalt cement being stripped from the aggregate surface. This results in degradation of the asphalt concrete. Water flowing through strippable aggregates may accelerate the problem. It may be necessary to be selective in the materials used for porous asphalt or use supplementary materials such as hydrated lime or anti-stripping agents.

The durability of porous asphalt may be improved through modification of the asphalt cement using polymers, rubber, fibers, and fillers, etc.

Pervious Concrete. Pervious concrete is typically placed 75 to 200 mm (3 to 8 in.) in thickness. This is to provide sufficient flexural strength to withstand traffic loadings. As with porous asphalt, concrete is made permeable by removing the fine materials from the aggregate gradation. This open gradation has reduced strength and is more susceptible to raveling than conventional concrete. This is further exacerbated by vehicle turning movements and freeze-thaw cycles which tend to break the bonds between the aggregate particles. This can be mitigated by ensuring uniform density and compaction during construction and through mix design modification using additives such as natural or synthetic fibers.

Permeable Interlocking Concrete Pavers. Pavers have the advantage that properties are known before placement. The paving units themselves are not permeable. Permeability is achieved by spacing the pavers a set distance from each other and filling the space with a permeable aggregate. Standard permeable pavers come in 6, 8 and 10 cm thicknesses (2 3/8, 3 1/8 and 3 7/8 in.). 6 cm pavers are typically used for pedestrian trafficked areas such as walkways and sidewalks. The standard thickness for vehicular traffic is 8 cm. The thicker, 10 cm, pavers are used for heavy-duty applications such as ports and intermodal pavers. Permeable pavers are specifically manufactured for the permeable pavement market. Many include locking mechanisms and other performance enhancement features to prevent them from shifting under traffic. Pavers require lateral support to ensure that the units act as a system to transfer loading. Without lateral support, the units will separate and lose structural integrity.

Aggregate Layers. Aggregates used for the stone reservoir layers should be hard, durable, clean, be low in fines content and graded for maximum porosity; i.e. maximum storage capacity. Open graded aggregates provide reduced structural capacity compared to dense graded aggregates. In situations where more strength is desired, a more graded aggregate could be used, recognizing that there will be a reduction in porosity and associated storage capacity. Stone reservoir aggregates typically have a maximum size in the order of 75 mm (3 in.). The permeable pavement is designed to maximize the thickness of the stone reservoir layer as these materials are the least expensive. This large gradation is difficult to fine grade for the pavement surface so another layer (base layer) is typically placed on top of the stone reservoir layer. The base layer is graded finer with a maximum aggregate size of 37.5 mm (1 1/2 in.). The selection of the gradation of the base layer should be checked using choking criteria to reduce the risk of aggregate movement between the base and the stone reservoir layer.

The choking criteria also applies to the use of a bedding course of stone chip which is provided between the pavers and the open grade base layer.

Shoulder Erosion Protection. If water is unable to enter the permeable pavement shoulder, it may overrun the surface onto the shoulder rounding potentially causing erosion and undermining of the pavement. The erodibility of the shoulder material and/or adjacent native soils should be assessed to determine its potential for erosion. For high risk areas, increased erosion protection through the use of erosion blankets, rip rap, granular sealing, placement of drainage gaps, etc. may be required.

Water may also enter the shoulder rounding area laterally from the stone reservoir. Depending on the type of shoulder material and its construction, water may try to exit the reservoir through the shoulder/rounding. This can be mitigated through the use of an impermeable liner placed vertically between the stone reservoir and the shoulder rounding. The stability of granular shoulder round and shoulders may be improved through the use of sealing materials such as emulsified asphalt or calcium chloride application.

Expansive soils. Some subgrade soils are susceptible to swelling and/or heaving. Silt and fine sands tend to hold water which expands when frozen potentially resulting in differential frost heaving. High plasticity clays in some areas expand if subjected to changes in moisture content. This can be mitigated by minimizing the amount of water infiltrated into the subgrade. This can be accomplished by ensuring rapid drainage of water from the stone reservoir and through the use of an impermeable liner. In general, permeable pavements are not recommended for these soil conditions.

Geosynthetics. Impermeable liners may be used to prevent shoulder rounding washout as well as frost heaving or expansive of moisture sensitive subgrade soils. Impermeable liners typically consist of heavy-duty polyethylene. For infiltration and partial infiltration designs, an impermeable liner should not be placed horizontally between the bottom of the stone reservoir layer and subgrade; however, it would still be prudent to include an impermeable liner between the vertical edge of the stone reservoir and shoulder rounding. If there is concern for water infiltrating from the stone reservoir back into the mainline pavement, consideration may be given to using an impermeable liner vertically between the stone reservoir and the mainline pavement; however, it should be recognized that the liner would prevent water in the mainline pavement from draining horizontally away from the pavement and additional design features may be required to drain the pavement. Liner selection is site specific and should be selected to ensure that it is puncture resistant given the aggregates to be used in the stone reservoir and that they are capable of holding up during construction.

It should be noted that the use of an impermeable liner can also affect the water filtration capacity of the system. When a liner is not used, contaminants will be deposited on the subgrade. If a liner is present, contaminants that deposit on top of the liner may be "washed" from the surface by fast moving stormwater thus reducing the effectiveness of water quality treatment measures.

Geotextiles should conform to subsurface drainage requirements in AASHTO M-288 *Geotextiles for Highway Applications* [AASHTO 2006]. Geotextile strength properties should conform to Class 1 (highest strength) if exposed to severe installation conditions with greater potential for geotextile damage. Geotextile requirements for separation are provided in Table 7.1. Requirements for subsurface drainage are provided in Table 7.2. Overlap requirements are provide in Table 7.3.

Table 7.1. AASHTO geotextile requirements for separation

Geotextile Class	**ASTM Test**	**Class I** [a]		**Class II** [a]		**Class III** [a]	
Elongation		< 50%	> 50%	< 50%	> 50%	< 50%	> 50%
Grab Strength [b]	D4632	1400 N [315 lb]	[900 N] 202 lb	[1100 N] 247 lb	700 N [157 lb]	800 N [180 lb]	500 N [112 lb]
Sewn Seam Strength [b,c]	D4632	1260 N [283 lb]	810 N [182 lb]	990 N [223 lb]	630 N [142 lb]	720 N [162 lb]	450 N [101 lb]
Tear Strength [b]	D4533	500 N [112 lb]	350 N [79 lb]	400 N[d] [90 lb]	250 N [56 lb]	300 N [67 lb]	180 N [40 lb]
Puncture Strength [b]	D6241	2750 N [618 lb]	1925 N [433 lb]	2200 N [495 lb]	1375 N [309 lb]	1650 N [371 lb]	990 N [223 lb]
Permittivity [b,e]	D4491	0.02 sec^{-1}					
Apparent Opening Size	D4751	0.60 mm [0.024 in.] maximum average roll value					
Ultraviolet Stability	D4355	> 50% after 500 h exposure					

[a] The severity of the installation conditions generally dictates the required geotextile class. Class 1 is the most severe and Class III is the least severe.

[b] All numeric values represent MARV in the weaker principal direction.

[c] When sewn seams are required.

[d] The required tear strength for woven monofiliment geotextiles if 250 N [56 lb].

[e] Default Value. Permittivity of the geotextile should be greater than the soil.

Table 7.2. AASHTO subsurface drainage geotextile requirements

			Requirements Percent Insitu Soil Passing 0.075 mm		
Test/Methods		Units	<15	15-50	>50
Geotextile Class			Class II from Table 7.1		
Permittivity	ASTM D4491	Sec-1	0.5	0.2	0.1
Apparent Opening Size	ASTM D4751	mm	0.43 Max avg Roll value	0.25 Max avg Roll value	0.22 Max avg Roll value
Ultraviolet stability (retained strength)	ASTM D4335	%	50 % after 500 h of exposure		

Table 7.3. AASHTO overlap requirements for geotextiles

Soil CBR	Overlap
> 3.0	0.3 m [1.0 ft] to 0.45 m [1.5 ft]
1.0 to 3.0	0.6 m [2.0 ft] to 1.0 m [3.0 ft]
0.5 to 1.0	1.0 m [3.0 ft] or sewn
< 0.5	Sewn
All roll ends	1.0 m [3.0 ft]

Class 2 geotextiles are typically used in PICP which often has less severe installation conditions. Geotextile is typically not placed in interstitial open graded aggregate layers. Geotextile should be placed vertically against the walls of excavated soil for all applications that do not use a full-depth concrete curb to separate the PICP pavement stone reservoir from adjacent soils. Geogrids may also be used in PICP. They may be used to improve aggregate containment over low strength subgrades.

Geomembranes may be used to vertically separate the stone reservoir from adjacent structures and from dense-graded bases supporting impermeable pavement surfaces. Geomembranes can include minimum thickness 0.762 mm (30 mil) polyvinyl chloride (PVC), ethylene propylene diene monomer (EPDM) also used as single-ply waterproof roofing membrane, or high density polyethylene (HDPE). Geomembranes typically require overlay of geotextile to protect them from aggregates damaging or puncturing them during construction.

Subdrains. While some soil conditions may allow for infiltration of the full storage volume, it is considered best practice to install subdrains for all permeable shoulder applications and connect to a positive outlet away from the pavement structure. The longitudinal subdrains should be placed below the bottom of the stone reservoir elevation to ensure that it is protected during construction and ensure that complete drainage can be provided if needed. The amount of water stored in the stone reservoir for infiltration can be controlled by the elevation at which the underdrains begin to discharge to surface water – this can be controlled by an upturned elbow or similar control structure on the underdrain pipe at the outlet point.

Edge restraint. Edge restraints are required for PICP unless a channel system is used. While the industry has developed numerous types of edge restraints, for roadway applications the edge restraint should consist of concrete curbing placed on both sides of the shoulder. This will ensure a competent joint between the mainline pavement and shoulder and provide support for the PICP at the shoulder/rounding interface.

Urban design features. In urban areas, the complete cross section of the pavement is usually underlain by granular materials. The supporting granular materials are protected from erosion from stormwater flow by providing them with a hard surface. Subsurface water flow is typically directed to longitudinal subdrains connected to the storm drain system. Other urban design features such as curbs, gutters, safety barriers, retaining walls, noise barrier walls, etc. may also be present within the highway right-of-way.

Rumble strips. In recent years, many agencies have begun using rumble strips to warn motorists of their proximity to the shoulder. Rumble strips are either formed during pavement construction or milled into the surface of the completed pavement. They are typically located on the roadway shoulder just off the edge of the travel lane. It may not possible to incorporate rumble strips into a permeable surface. Unless a channel type design is used, the outside driving lane would have to be widened to accommodate the rumble strips.

Clogging. A newly constructed permeable pavement will typically have an infiltration capacity exceeding 200 cm/hr (80 in./hr). Over time, this surface permeability will be reduced due to the infiltration of sediment and debris. Newly constructed permeable pavements are highly permeable and can accommodate the vast majority of storm events in North America. Routine maintenance should include vacuum sweeping. For winter maintenance, deicing salt and/or chemicals can be used; however sand use should not be used. As the pavement clogs over time, its permeability is reduced and water may pond or runoff the pavement during high intensity storm events. Therefore, it may be necessary to restore permeability through additional vacuum sweeping or provide supplementary drainage features to accommodate infrequent, large storms.

8. Shoulder Construction

The construction of shoulders with stone reservoirs is similar to the construction of a pavement incorporating an open graded drainage layer. Care must be taken during construction to prevent damage and contamination of the permeable pavement system. Guidelines for general construction practices for both new and retrofit construction are provided in the following sections.

Careful consideration of site operations for the construction of permeable shoulder pavements is critical to the success of the permeable shoulder system. For example:

- Up-gradient surfaces that may contribute run-on to the permeable pavement during construction should be stabilized or the permeable shoulder pavement protected by using silt fences; ideally the permeable shoulder should only be installed after the upstream tributary area is stabilized.
- Shoulders are long and narrow and are not generally supported at the outside of the shoulder surface (unless supported by an end slope or retaining wall). Therefore, control of construction operations and the sequencing of construction are important and may differ from that of construction for a traditional permeable parking area.
- Compaction of the subgrade is necessary to support the design traffic and it would not be practical to limit compaction of the subgrade directly below the permeable shoulder while specifying high compaction under main line travel lanes immediately adjacent to the shoulder.
- Due to the diversity of activities taking place during roadway construction, protecting the permeable shoulder materials from contamination is critical; contamination of the permeable shoulder materials could potentially result in subsequent migration of contaminants to surface water and/or groundwater. Construction of the shoulders should be completed as late as possible in the construction process.
- A preconstruction meeting with all construction trades is highly recommended to identify sequencing and controls to reduce the potential for clogging of the permeable pavement surface as well as the other unique construction considerations for permeable pavement.
- Specific locations should be identified as construction access points so that travel of equipment across the permeable shoulder is avoided.
- As with all roadway construction, underground utilities should be protected from damage due to construction activities. As the permeable pavement infiltrates water into the subgrade, it may be necessary to protect some utilities from water damage, such as water

intrusion and/or preferential flow of infiltrated water through utility trenches. Each utility company should be contacted to determine if they require special attention.

8.1 New Construction Sequencing

The general construction sequencing for a roadway permeable shoulder system should consist of the following steps:

1) Excavate and prepare subgrade of travel lanes and shoulders.
2) Place and compact dense graded subbase across the entire width of the paved lanes.
3) Place and compact dense graded base under the travel lanes.
4) Place and compact travel lane surface.
5) If required by design, remove dense graded subbase from shoulder area as necessary.
6) Excavate below the outside edge of the shoulder and for all outlet pipes to provide underdrain trench to design depth.
7) Ensure adequate protection from construction activities and soil runoff is in place to prevent contamination.
8) Place geosynthetics as required by design.
9) Fill and compact open graded aggregate in the underdrain trench.
10) Place choke stone layer between aggregate in underdrain trench and stone reservoir, if required per design.
11) Place and compact stone reservoir under shoulder. The stone reservoir aggregate should extend under the shoulder rounding to ensure overall support for the placement of the permeable shoulder surface.
12) Place a bedding layer (PICP only) over top of the stone reservoir, if included in design.
13) Conduct compaction and infiltration testing at key points of stone reservoir placement to ensure optimal density and permeability.
14) Place the permeable shoulder surface (in lifts if required).
15) Place and compact the remaining shoulder rounding base material.

Care must be taken to ensure that all placed pavement materials are adequately supported during each construction step and that stone reservoir layers are protected during construction to avoid contamination. This is of particular importance for rural cross sections with granular shoulder rounding.

8.2 Retrofit Construction Sequencing

For retrofit construction, the following sequence of construction is recommended:

1) Sawcut and remove the existing shoulder material.
2) Excavate to provide the necessary stone reservoir depth.
3) Excavate below the outside edge of the shoulder and all outlet pipes to provide underdrain trench to design depth.

4) Follow Steps 7 through 14 in Section 8.1, as applicable.

Care must be taken to avoid undermining of the travel lanes of the existing pavement.

9. Installation and Materials

The construction installation and materials for permeable shoulders are similar to conventional shoulder pavement construction, with several key differences that introduce specific considerations in development of specifications for installation and construction materials. The following sections provide construction guidance for the installation of permeable shoulders and the specification of construction materials.

9.1 Subgrade Preparation

Most guidelines for permeable pavement construction recommend that the subgrade not be compacted to help in promoting water infiltration; however, for highway and municipal roadway applications, compaction of the subgrade under the roadway is necessary to provide support for traffic. It is not considered practical to treat the narrow strip of shoulder pavement differently than that under the trafficked portion of the roadway. As a result of compaction, the infiltration of water into the subgrade will be reduced, and the thickness design of the stone reservoir and supplementary drainage features may need to be designed to accommodate reduced infiltration.

Subgrade preparation should be completed during dry weather conditions. The placement of the stone reservoir and surfacing should be completed as close to the same time as possible to minimize the potential for contamination of the permeable pavement system. Sub-surface drainage of water away from the travelled lanes is critical for the performance of the main line traditional pavement system. Care must be taken during construction to ensure that there is positive sub-surface drainage away from the main line pavement.

9.2 Geosynthetic Applications and Installation

Geosynthetics including geotextiles and geomembranes may be used in the design of permeable pavements. Geotextiles can be used to separate different material types and prevent the movement of fine materials from one layer to another. Geomembranes may be used to resist the passage of water between layers.

Geotextiles are typically used vertically against the walls of excavated soil for all applications to separate the permeable pavement stone reservoir from adjacent soils. Geotextiles are typically non-woven fabric and should be protected from contamination during installation. Geotextiles should meet the requirements specified in Table 7.1 to Table 7.3.

Geomembranes may be used to vertically separate the stone reservoir from adjacent structures and from dense-graded bases supporting impermeable pavement surfaces. Geomembranes are typically polyvinyl chloride (PVC), ethylene propylene diene monomer (EPDM) also used as single-ply waterproof roofing membrane, or high density polyethylene (HDPE). Geomembranes should be protected from damage during placement of the stone reservoir aggregates; some types of geomembranes have specific bedding material requirements such as maximum particle size.

An example of the placement of a geomembrane for a shoulder application is shown in Figure 9.1 and Figure 9.2.

Figure 9.1. Installation of a geomembrane.

Figure 9.2. In-place geomembrane (geotextile ready to be folded to enclose the shoulder).

9.3 Drainage Features

Supplemental drainage features are critical for permeable shoulder designs in cases where the storage volume in the stone reservoir cannot be infiltrated in a reasonable time. Appropriate design details and construction specifications for supplemental drainage features are needed to ensure that the system will be constructible and will function as intended. Table 9.1 provides guidance for the development of design details and construction specifications for supplementary drainage features.

Table 9.1. Recommendations for supplemental drainage elements

Element	Recommendations for Design Details and Specifications
Underdrain Provide adequate drainage.	• Use slotted underdrain pipe, rather than circular perforations, to help preserve permeability. • Utilize standard pipe materials, such as high density polyethylene (HDPE) conforming to AASHTO M252 or class PS46 PVC conforming to AASHTO M278. • Specify a diameter of 100-150 mm (4-6 in.) or greater to allow cleanout and provide adequate capacity, as needed. • Underdrain pipe should be non-perforated and smooth walled within 25 mm (1 in.) of outlet structure or as needed to provide a sealed connection to the outlet structure. • The pipe should be installed in a trench on the outside of the shoulder at the lowest point of the shoulder subgrade to allow positive drainage as well as provide adequate cover for structural integrity. They may be installed in a trench excavated into the subgrade. • Provide minimum longitudinal slope of 2 percent to provide

Element	Recommendations for Design Details and Specifications
	re-suspension velocity. • Underdrain pipe should be underlain by at least 50 mm (2 in.) of clean, open graded aggregate below and above the pipe.
Underdrain Outlet Control Provide increased detention time/infiltration and decreased peak flows.	• Use standard approved plastic pipe products, such as Class PS46 PVC conforming to AASHTO M278. • Where flow control is provided by orifices, they should be machined to exact specified dimensions; minimum orifice diameter of 13 mm (1/2 in.) is recommended to help prevent clogging. • Use of a raised underdrain outlet (i.e., upturned elbow) or weir structure is recommended to regulate detention times and peak flows. Use of the raised outlet structure simulates the placement of a physical sump in the reservoir layer. In this case, the sump is formed by the controlling elevation of the raised underdrain outlet. • Outlet pipes should not be perforated. • Provide screw-cap cleanout at base of outlet (in line with underdrain pipe) to allow access for maintenance, as well as to provide a secondary drainage point in the event of pavement clogging. • Pipe outlets should be directed to control structures or other protective systems to prevent soil erosion. A typical outlet detail is shown in Figure 9.3 and Figure 9.4.
Catch Basin/Control Structure Provide housing for underdrain outlet and collection of infiltrated stormwater for routing away from roadway.	• Specify precast reinforced concrete structures for both the manhole and catch basin sections conforming to applicable standards, for example ASTM C478. Sections to be installed with a flexible plastic or rubber gasket. Base of structure to be placed on a well-compacted level layer of crushed stone. • Conform to local standard details for pipe connections. • Provide adequate clearance for maintenance of underdrain outlet structure.
Additional Drainage Design Features	• The interface between the driving lane pavement and the stone reservoir should include an appropriate geotextile to prevent fines migration into the stone reservoir while maintaining water flow in the pavement away from the travel lanes. An impermeable membrane is not recommended for this interface as it will potentially trap water entering the roadway pavement under the travel lanes.

Element	Recommendations for Design Details and Specifications
	• The interface between the stone reservoir and the roadway embankment should include an impermeable liner to prevent water in the stone reservoir from exiting the pavement section in locations other than infiltration into the subgrade or through the designed outflow. • Observation wells may be installed to measure the elevation of standing water in the stone reservoir. The observation well should be fitted with a cap installed flush with the pavement surface. An observation well detail is shown in Figure 9.5. • Drainage gaps for rural sections, curb cutouts for urban roadways, secondary access to drainage outlets, etc. should also be provided for high intensity storms. An example of a curb cutout is shown in Figure 9.6.

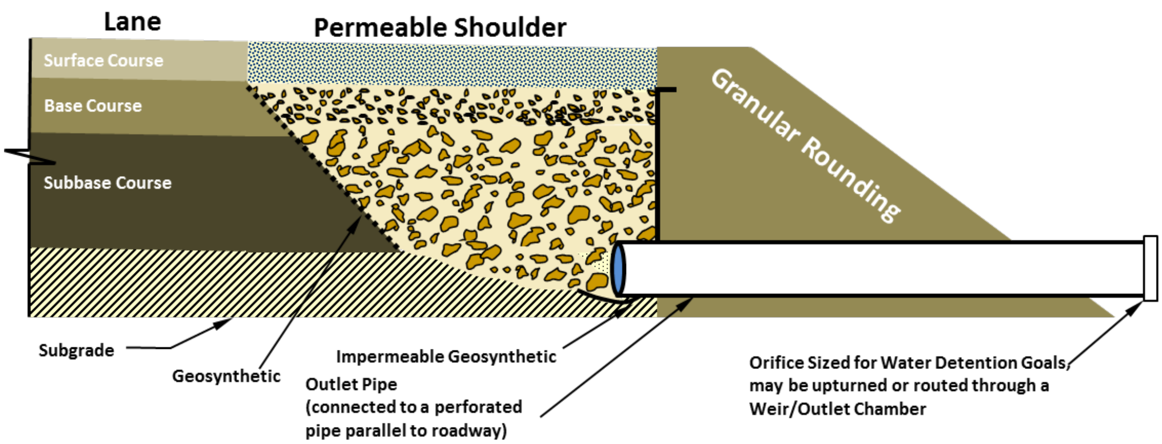


Figure 9.3. Typical underdrain outlet detail (rural section).

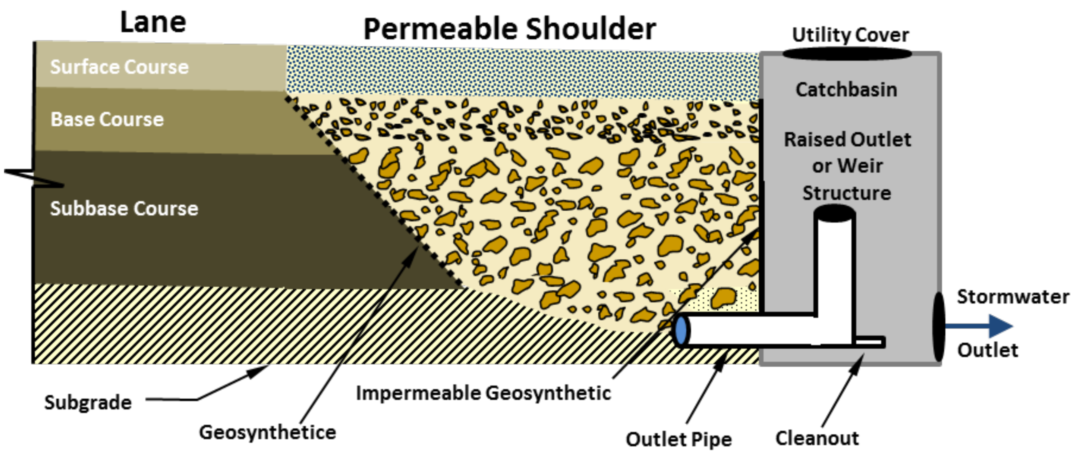


Figure 9.4. Typical underdrain outlet detail (urban section).

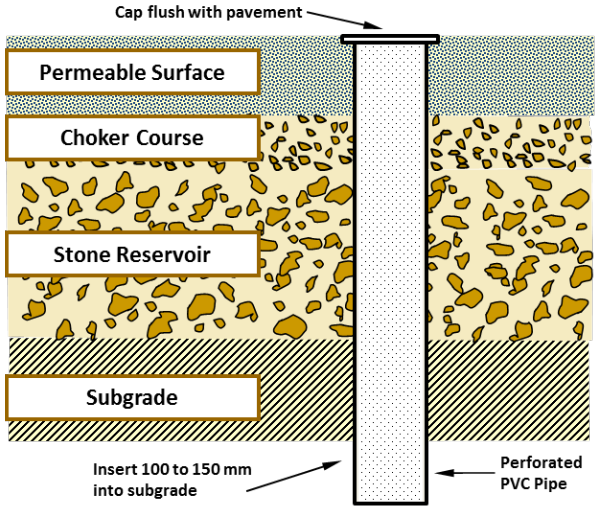


Figure 9.5. Observation well detail.

Figure 9.6. Example of a curb cut-out.

9.4 Aggregate Stone Reservoir

The permeable shoulders would typically utilize open graded aggregates to provide both structural and hydraulic capacity for the pavement. The aggregates should be hard, durable and have a low percentage of material passing the 75 µm (ASTM No. 200) sieve size. Other aggregate type and quality recommendations are as follows:

- Double washing of the aggregate may be necessary to ensure a fines content of less than 2 percent.
- Porosity of the aggregate when compacted should be in accordance with the water storage objects for the stone reservoir. Typically, aggregates are selected to have a porosity of at least 30 percent.
- Sieve analysis of washed gradations should be per ASTM C136 or AASHTO T-27. Stone reservoir base aggregate material typically follows the grading requirements of ASTM No. 57 stone with stone reservoir aggregates meeting the requirements for ASTM No. 2, 3 or 4 stone.

- Stone reservoir aggregates used for shoulder pavements should be crushed with minimum 90 percent fractured faces and a Los Angeles (LA) abrasion <40 per ASTM C131 or AASHTO T-96 for typical aggregate, and ASTM C535 for aggregate larger than 37.5 mm (1 1/2 in.). For stone reservoir materials, a minimum CBR of 80 percent is recommended.
- To prevent migration of smaller base aggregate material into the larger subbase aggregate, aggregate gradations should satisfy the following "choking" criteria:

  D_{50} Subbase/D_{50} Base < 25
  D_{15} Subbase/D_{85} Base < 5

  For example, the ratio of the D_{50} Subbase (subbase aggregate size at which 50 percent of the material is larger than this size and 50 percent is smaller) to D_{50} Base (base aggregate size at which 50 percent of the material is larger than this size and 50 percent is smaller) must be less than 25.
- Some state and provincial highway agencies specify graded aggregates as permeable bases (drainage layers) under conventional pavements. These graded aggregates can be used for stone reservoirs. These aggregate materials should have less than 2 percent passing the 75 µm (ASTM No. 200) sieve size. The graded nature of the aggregates provides a more stable platform for construction; however, the hydrologic design will have to account for their reduced porosity and water storage capacity.
- Open graded aggregates should be stockpiled at the construction site on an impervious surface to prevent contamination.
- If allowing the use of non-traditional sources of stone reservoir (e.g. recycled concrete aggregate, non-traditional materials, etc.), require testing to insure source will not impair pH of outflow due to leaching, or contribute to any other water quality issues.
- If there is a possibility that sand will be source is from historic agricultural lands, include specifications to test for high nitrate/phosphorus levels that could leach from sand.

9.4.1 Compaction

Compaction of the open graded aggregate is required for shoulder applications. This will provide a stable platform for the placement of the surface course, provide structural capacity for traffic and the prevention of settlement.

A dual or single smooth 10 ton (min) vibratory drum roller or a 60 kN (13,500 lb centrifugal force) reversible vibratory plate compactor which provides maximum compaction effort without crushing the drainage layer aggregate should be used to compact the stone reservoir aggregates.

Testing to determine the compaction of the stone reservoir should use the "target" density method. Field density tests should be completed using the procedures outlined in ASTM D2922 Standard Test Methods for Density of Soil and Soil-Aggregate In-Place by Nuclear Methods (Shallow Depth). It should be noted that that nuclear density testing using ASTM C2922 (backscatter method) is only useful on aggregates up to or around 1 in. top size. This test method renders too much variability for larger sized stones such as ASTM No. 2 and 3. The infiltration rate of the compacted subgrade should be determined by ASTM D3385 or approved alternate at the discretion of the supervising engineer. The infiltration rate shall be no less than 50 percent of the hydraulic conductivity (D2434) at 95 percent standard proctor compaction.

After initial placement of the aggregate material, the compaction equipment should make two passes over the entire surface of a control strip using vibratory compaction. Field densities and field moisture contents, using the backscatter/indirect method, should be determined at five randomly selected locations at least 5 m (15 ft) apart. The dry density and moisture content should be calculated for each of these locations and the averages used as initial compaction values. The compaction equipment should then make two additional passes without vibratory compaction over the entire surface of the control strip. Three separate, random field density and moisture content determinations should be completed, using the backscatter/indirect method, and a new average dry density and moisture content should be calculated.

If the new average dry density exceeds the previous value by more than 20 kg/m^3 (1.2 pcf) then two additional passes of the equipment should be out as described above. If the new average dry density does not exceed the previous value by more than 20 kg/m^3 (1.2 pcf), then compaction of the control strip is considered satisfactory and complete.

Upon completion of the control strip, an additional seven field density tests should be taken at random locations. The final dry density and moisture content of the control strip is the average of these seven values plus the three most recent values obtained upon completion. Photographs of proper and inappropriate compaction equipment are shown in Figure 9.7 and Figure 9.8.

Figure 9.7. Appropriate compaction equipment for open graded aggregate.

Figure 9.8. Inappropriate (too small for size of project) for compaction.

9.5 Permeable Pavement Surface Installation

Most common surfacing of permeable pavement systems are porous asphalt, pervious concrete or permeable interlocking concrete pavers. Other proprietary systems are also available and could potentially be used to surface shoulder pavements. There are many resources available for the design, specification and construction of permeable pavement surfaces. Guidelines such as those shown in Figure 9.9 to Figure 9.11 are published by industry associations. In addition, many state and provincial highway agencies as well as groups such as the American Association for Civil Engineers and various other stormwater and environmental associations have also developed guidelines.

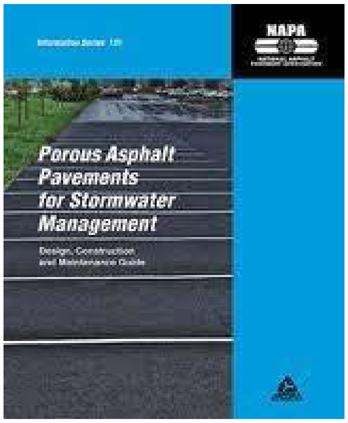


Figure 9.9. National Asphalt Pavement Association Guidelines

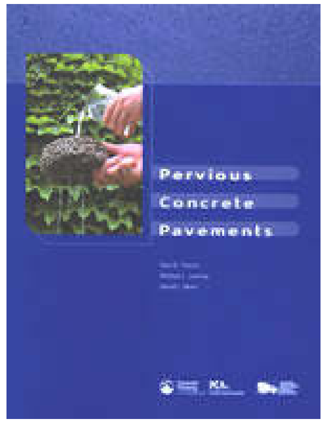


Figure 9.10. Portland Cement Association Guidelines

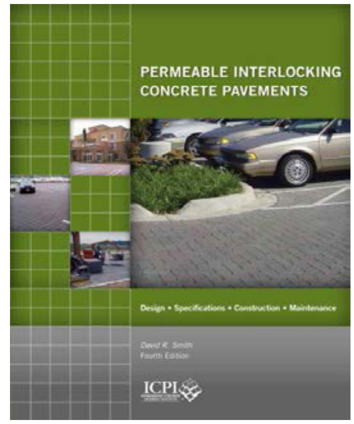


Figure 9.11. Interlocking Concrete Pavement Institute Guidelines

9.5.1 Porous Asphalt

Asphalt is made porous by reducing the fine portion of the aggregate gradation. Conventional asphalt has in-place air voids content in the order of 6 to 8 percent. Porous asphalt is designed to have an in-place air voids content in the order of 25 percent. As a result, the structural capacity of porous asphalt is less than that of conventional asphalt. It is more prone to oxidation due to the high air voids and drain down of the asphalt cement during mixing, transportation and placement. Proper aggregate and asphalt cement selection as well as appropriate construction procedures and quality assurance is of paramount importance for both conventional and porous asphalt pavements. Other considerations for the successful installation of porous asphalt include:

- Porous asphalt is manufactured at the asphalt plant similar to dense graded asphalt. Additives such as fibers, fillers, anti-stripping agents and modified binders can be used to improve the strength and durability of the porous asphalt. NAPA guidance suggests using a binder with a high temperature grade 2 steps higher than the standard PG rating used in a given location for dense mix asphalt. For example, in New Hampshire the prevailing binder is PG 64-28; for permeable asphalt, the recommended binder would be PG 76-28 (increments of 6 degrees Celsius are standard).
- Conventional placement and compaction equipment is used such as static steel wheel rollers are used to achieve compaction. A Rubber tire roller is not recommended.
- Due to its open texture, porous asphalt may cool more rapidly than conventional asphalt and should therefore be compacted as soon as possible using the appropriate compaction rollers.

An example of placed and compacted porous asphalt is shown in Figure 9.12.

Figure 9.12. Completed porous asphalt installation.

9.5.2 Pervious Concrete

Concrete is made pervious by removing fine aggregate from the concrete mix. Conventional concrete typically has air voids in the order of 6 to 8 percent. Pervious concrete has air voids in the order of 15-25 percent. This results in a concrete layer with reduced structural capacity compared to conventional concrete. Pervious concrete is more prone to ravelling, freeze/thaw damage and cracking under heavy traffic. Other considerations for the successful installation of pervious concrete are as follows:

- Pervious concrete may be placed using forms and roller screeds, asphalt pavers, concrete floor finishers or conventional concrete paving equipment.
- Pervious concrete cannot be pumped.
- The stone reservoir should be wetted prior to the placement of the pervious concrete to prevent moisture loss of the pervious concrete.
- The placed concrete requires special curing practices to ensure that the cement hydrates and uniform strength is achieved.
- Consolidation of pervious concrete should be completed as soon as possible (<15 minutes) to achieve uniformity and provide a consistent surface.
- Conventional surface finishing practices are not recommended as they can reduce the permeability of the surface.
- Pervious concrete pavements may or may not be specified to have joints. Pervious concrete pavement tends to shrink less due to the open nature of the concrete mix. Where joints are specified, they are typically specified to be 5 to 6 m (16 to 20 ft) apart. Joints must be installed soon after consolidation and are usually formed using a rolling joint tool (pizza cutter). Sawcutting is difficult due to ravelling potential of the joints and it is not desirable to have the concrete slurry from cutting entering the permeable pavement structure.
- Curing of the pervious concrete is very important. The surface must be protected using an evaporation retarder or other method such as fog misting and the placement of plastic sheeting or insulated blankets on the surface during the curing period (typically 7 days).

Other methods to improve pervious concrete surface durability, such as adding a hydration stabilizing admixture or applying a surface stabilizer have been used.

- Pervious concrete infiltration can be verified using ASTM C1701/C1701M-09, Standard Test Method for Infiltration Rate of In-Place Pervious Concrete.

An example of the placement, jointing and curing of pervious concrete pavement is shown in Figure 9.13.

Figure 9.13. Pervious concrete placement, jointing and curing.

9.5.3 Permeable Interlocking Concrete Pavement

Conventional interlocking concrete block pavements are not permeable. The concrete pavers are made of high strength concrete and have very low absorption rates. The joints are very narrow and filled with sand. Permeable interlocking concrete pavements utilize the same concrete mixes as conventional pavers except the pavers themselves have spacers that create a larger joint opening. The joints are filled with open graded aggregate to provide access for water to enter the pavement structure. The wider joints and open graded aggregate do not provide the same structural capacity as conventional interlocking concrete pavements. Other considerations for the successful installation of a PICP include:

- Unlike pervious concrete and porous asphalt, a bedding layer is required between the stone reservoir and the concrete pavers. An open graded bedding layer consisting of ASTM No. 8, No. 89 or No. 9 gradation (depends on the paver type selected) crushed stone, 50 mm (2 in.) in thickness is required for final grading and to provide the concrete pavers with a stable base.
- All interlocking concrete block paving surfaces require adequate edge restraints to ensure the interlock of the system.
- Depending on the concrete paver type, the joints are filled with ASTM No. 8, 89 or 9 gradation crushed stone.
- Pavers may be placed manually or by the use of mechanical laying equipment.

- The pavers should be installed 3 to 6 mm (1/8 to 1/4 in.) above the adjacent pavement to allow for consolidation of the open graded aggregate layers.
- A plate compactor is used to vibrate the pavers into the bedding layer and to ensure that the joint material is placed the full-depth of the joints.
- PICP infiltration can be verified using ASTM C1781-13, New Test Method for Determining the Surface Infiltration Rate of Permeable Unit Pavement Systems.

A typical permeable interlocking concrete pavement installation is shown in Figure 9.14.

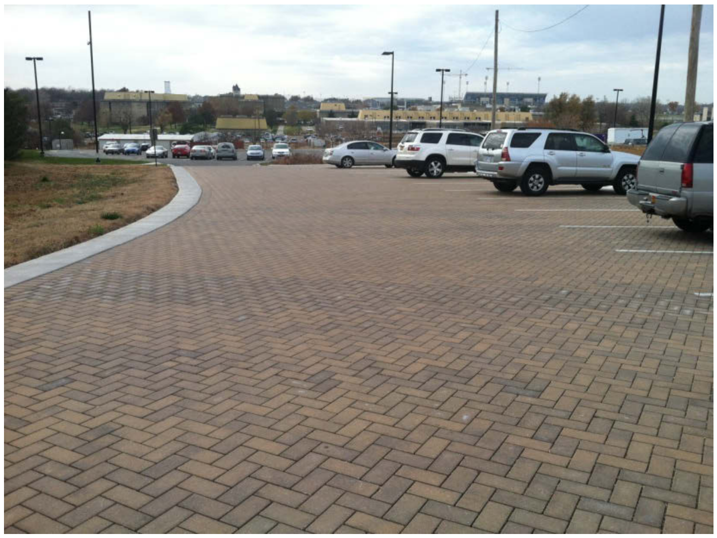


Figure 9.14. Typical permeable interlocking concrete pavement installation.

9.6 Edge Restraints, Loss of Support and Interface with Roadway Pavement

All permeable surfaces should have some form of edge restraint to prevent lateral movement of the surface both during construction and under traffic. This could consist of concrete curbs, adjacent pavement surfaces, granular base, landscape architectural features, etc. This is particularly important for permeable shoulder applications for vehicles traversing on the shoulder to the travelled lanes. Vehicle wheel loading near an unsupported edge may damage the permeable pavement.

Water moving within the pavement structure may erode the aggregate base/subbase and/or subgrade and adjacent support features such shoulder rounding, curbs and embankments. The permeable pavement design should account for possible water flow erosion. An example of a permeable pavement failure due water erosion of the aggregate base/subbase is shown in Figure 9.15.

Figure 9.15. Pavement failure due to water erosion.

The joint between the travelled lanes and the permeable shoulder must be vertical, straight and provide support for the installation of the permeable shoulder surface.

9.7 Expansive Soils and Fill Conditions

It is not recommended to have permeable shoulder pavement infiltration into expansive clay soils. Expansion may be reduced or eliminated by removal and replacement of subgrade soil materials or stabilizing with additives such as lime or cement; however it should be noted that some stabilization approaches may further reduce the permeability of these soils. Designs over expansive clay soils or other fill soils may require the use of a geomembrane under the stone reservoir or at the interface between the stone reservoir and the shoulder rounding to prevent water from leaving the stone reservoir from areas other than the designed outlets.

9.8 Selection of Materials with Consideration of Potential Groundwater and Surface Water Quality Impacts

Permeable shoulders are intended to improve water quality of roadway runoff before discharge to surface waters. Other design features such as the use of sand filters, geotextiles and engineered aggregates may also be used to improve water quality; however, if materials are not appropriately selected, permeable shoulders also have the potential to introduce pollutants as water passes through the permeable shoulder. With respect to groundwater, permeable shoulders may present a more direct pathway for pollutants to migrate to groundwater compared to more traditional drainage configurations. Elevated risks to surface water and groundwater quality may be mitigated through appropriate selection of materials. Table 9.2 lists possible elevated risks associated with the use of permeable shoulders, and provides guidance in material selection to help avoid or reduce these risks.

Table 9.2. Potential elevated risks and associated material recommendations

Potential Elevated Risk Factor	Guidance for Selection of Construction and Repair Materials to Mitigate Elevated Risk
pH impacts from cementitious materials Leaching from shoulder fill materials, if composed of cementitious materials.	• Limit the use, or pre-treat high pH recycled concrete aggregate (RCA) used for permeable pavement stone reservoirs. • Test all sources of RCA prior to placement to evaluate potential increase in pH.
Dissolved solids from cementitious materials Leaching from shoulder fill materials, if composed of cementitious materials.	• In areas with high background soluble calcium levels in surface or groundwater, monitor use of Portland cement concrete (PCC) and RCA, as it may increase soluble calcium in runoff and percolated water.
Turbidity from stone reservoir Mobilization of fine sediments as water moves through stone shoulder reservoir layers.	• Wash all aggregate materials prior to placement to remove fines; double washing may be needed. • Consider flushing of permeable shoulder during construction (with capture of effluent) to remove residual fines and prevent initial turbidity loadings to surface waters.
Turbidity (and associated particle-bound pollutants) from adjacent subbase/subgrade materials Mobilization of subgrade sediments below permeable shoulder reservoir; mobilization of fine particles from traditional subbase adjacent to permeable shoulder reservoir.	• Select a geotextile to prevent migration of traditional subbase or permeable pavement subgrade materials; as needed.
Other impurities in subbase materials Leaching of impurities from traditional subbase materials into permeable shoulder reservoirs.	• If non-traditional subbase material is proposed for main line roadway, evaluate potential for impurities to leach laterally into permeable shoulder reservoir.

Potential Elevated Risk Factor	Guidance for Selection of Construction and Repair Materials to Mitigate Elevated Risk
Aquatic toxicity to groundwater or surface water Leaching and transport of contaminants from materials	In general, most construction and repair materials pose minor risk to aquatic toxicity. Materials generally pose higher potential risks in their "raw" form, not necessarily in the form in which they would be applied in the field. For instance, Portland cement and asphalt cement alone have higher risks than when they are mixed with aggregates. Limit use of: • Asphalt concrete materials containing municipal solid waste incinerator bottom ash (MSWIBA), crumb rubber, shingles, and foundry sand. (This is primarily a short term effect and does not relate to traditional pavement used in travel lanes. Leaching tests could be done to support their use). • Ammoniacal copper zinc arsenate (ACZA)-treated wood.
Trace metal leaching from design elements Leaching of zinc and/or copper from metal elements of design features.	• Avoid use of galvanized metal and copper features in permeable shoulder design specifications, including drainage structures, piping, fittings, access ladders, and other elements that may contact water. • Prohibit contractor substitutions containing these materials.
Contaminant spills during construction-phase Permeable shoulders may create a more direct pathway to groundwater and surface water.	• Provide secondary containment for hazardous materials, such as fuel, stored on the construction site. • Consider presence of permeable shoulder in spill contingency plan; in the event of spill, deploy measures to contain spill before it enters the permeable reservoir; remediate soil contamination in reservoir as needed. • Hold meeting to inform all contractors and subcontractors regarding spill contingency plan and the sensitivity of permeable shoulder to spills.

9.9 Contractor Certifications and Experience

The production and placement of permeable pavements generally require more attention to detail to ensure that a durable pavement is produced. In addition, contractors and trades working at or near the permeable pavement site must be cognizant of the need to ensure that the site is not contaminated with particles that may clog the permeable pavement. This may require installation of cattle guards and/or washing stations to ensure that the construction traffic does not contaminate the pavement.

The porous asphalt industry indicates that any qualified asphalt paving contractor can produce and place porous asphalt. No specific certification is required. The concrete paving industry has a certification program for pervious concrete production and placement. Contractors installing the pervious concrete should be certified through independent organizations such as the American Concrete Institute or National Ready Mix Concrete Association. The Interlocking Concrete Pavement Institute offers a PICP specialist course and certification.

9.10 Quality Control and Assurance

Contractors installing permeable pavements should have internal quality control plans and procedures to ensure that they are in control of their operation and that all materials and placement are in accordance with the contract specifications. Quality control plans and procedures are the same as for conventional construction with the exception of the following items:

- If a partial or full infiltration design is being used, the insitu infiltration capacity of the subgrade should be verified prior to placement of the stone reservoir.
- The fines content of the stone reservoir aggregates should be checked regularly to ensure that only clean materials are installed.
- Ensure that all drainage pipes and outlets are installed, connected and properly sloped to the appropriate outlets.
- Verify that the correct geosynthetics are delivered and are properly installed.
- The construction site should be monitored closely to ensure that no contaminants enter the permeable pavement during construction.
- Proposed construction methods and sequencing should be described in the construction specifications or specifications should require that this information be submitted by the contractor for review and approval by the project engineer prior to construction
- The compaction and permeability of the stone reservoir should be closely monitored to ensure that compaction methods are consistently meeting design goals.
- The installed permeability of the pavement should be verified. The surface infiltration rate of pervious concrete and PICPs can be verified using ASTM C1701-09 and ASTM C1781-13 respectively.
- All product substitutions should be reviewed and approved by the project engineer.

10. Permeable Pavement Cost

The initial per unit cost of permeable pavements is typically higher than a comparable conventional pavement section. This is due to the fact that the materials used in the permeable pavement do not have the same strength and characteristic as conventional pavement materials and may require thicker reservoir layers, and as such, permeable pavements are thicker; however, if the permeable pavement contributes to overall stormwater management and it is possible to eliminate conventional stormwater conveyance systems such as curbs, storm drains, underground piping and detention ponds, the cost of the permeable pavement system overall may be less expensive.

11. Permeable Pavement Maintenance Guidelines

Proper and timely maintenance is considered critical for all pavement types, and this is particularly important for permeable pavement systems. The surface of the permeable pavement should be properly maintained to provide a durable and safe driving surface. The ability of the permeable pavement system to effectively infiltrate water can be affected by pavement use and maintenance practices. For example, extensive use of winter sanding, biomass loading from surrounding vegetation (trees, grass, weeds, etc.) can substantially reduce system infiltration.

Runoff water quality discharged from permeable pavements has been shown to be roughly equivalent to that achieved by treating highway runoff with a sand filter system. Importantly, [Eck 2012] indicated that performance of TSS levels were 90 percent lower on permeable asphalt friction courses than from conventional pavement and lower effluent concentrations for total amounts of phosphorus, copper, lead, and zinc last through the design life of the pavement. Based on six years of data collection in Texas and two in eastern North Carolina, Eck et al documented that this performance is sustained without maintenance. Eck said the North Carolina results were consistent with the longer series results in Texas and that the findings from their 1,565 individual water quality measurements there "were consistent with earlier studies from France, the Netherlands, and Germany." This level of treatment is sufficient to meet stormwater requirements in many jurisdictions and for many receiving water conditions and has substantial implications for DOTs, stormwater treatment, and maintenance thereof in the future.

In the past, conventional wisdom has been that regular preventive maintenance activities such as vacuum sweeping could help maintain system permeability. In areas, such as with the Montreal case where permeability was reduced by sanding, areas of reduced permeability can be restored by more aggressive maintenance practices such as power washing, regenerative air vacuuming, and removal and replacement of the surface and possible reservoir courses. Guidelines and recommendations for permeable pavement maintenance and restoration are provided in the following sections. Sand and gravel often accumulate on the pavement shoulder where it is bounced by passing cars but not any further, as it would be if in a travel lane. Thus, winter sand should not be used for areas with permeable shoulders.

11.1 Preventive Maintenance

Preventive maintenance activities for porous asphalt, pervious concrete and PICP include:

- Inspect and monitor the integrity and function of the permeable pavement as a part of normal roadway maintenance inspections. Permeability checks should be completed using standard infiltration tests, (ASTM C1701-09 and ASTM C1781-13). As well as visual inspection of clogging and durability.
- Inspect permeable pavements after major rain events to ensure pavement structural integrity and surface infiltration.
- Perform vacuum sweeping at regular intervals in high risk areas, such as areas where sources of sediment or organic debris are higher, and/or where the ratio of tributary to pervious area is high. Twice per year is recommended and should be increased in areas subject to higher concentrations and deposition rates of dust and debris, biomass loading, etc. [Henderson 2011].
- Restore any joint filler loss for PICP.

- Properly maintain upstream landscaping to minimize run-on of sediment and debris.
- Maintain drainage pathways from upstream pervious and landscaped areas to minimize potential for run-on to pavement.
- Inspect and clean all outlet structures to ensure positive water flow from the permeable pavement.
- Provide inspection ports and regularly monitor drainage rates of the stone reservoir to identify if clogging of underlying soils or outlet structures has occurred; remedy to avoid damage associated with extended ponding below the roadway.
- Eliminate the use of sand for winter maintenance activities.
- Clear snow after every storm is recommended. Special plow blades can be used but are not necessary. Raised snow plow blades are not recommended and any bouncing movement of the vehicle may result in damage to the permeable pavement surface [UNHSC 2011].
- Clearing of snow completely from the permeable pavement surface.
- Limit the use of winter deicing chemicals for sensitive vegetation areas, sensitive receiving waters, or for pavements designed to capture and reuse water. See Winter Maintenance Considerations section below.

11.1.1 Winter Maintenance Considerations

Properly design permeable surfaces can be resistant to freeze-thaw related damage [NRMCA 2004]. Due to the higher porosity of the surface material, use of winter deicing chemicals are rarely required [NRMCA 2007]. Sanding operations should be avoided as the sand can lead to increased clogging. Deicing chemicals should be used moderately. Studies have shown that porous asphalt exhibits greater frictional resistance and can become clear of snow and ice faster than conventional pavements. Substantial reductions of up to 77 percent in annual salt loads for anti-icing/deicing practices were shown to be effective. Provided that plowing was regularly performed, only minimal salting was needed for events unless freezing rain created icy conditions. No salt was required on days when refreezing of meltwater was a problem on standard asphalt.

Winter maintenance of porous asphalt pavements is different than standard pavements. There are two primary elements of winter maintenance: intra- and inter-storm maintenance. Intra-storm maintenance is typically not as effective as on standard pavement surfaces. The deicing mechanism on a standard pavement is through the creation of a brine solution as the salt rests on the surface, melts the ice below it and this brine then expands to melt nearby ice on the surface. On porous pavements, once the salt melts the ice below it, that liquid infiltrates into the porous pavement system. For this reason intra-storm maintenance may require more salt on PA; however, the need for inter-storm maintenance is considerably diminished in the days or weeks between storms. Inter-storm, when snow stockpiles melt, pool, and refreeze on a standard pavement, black ice forms requiring additional application of salt or chemical deicer. On porous pavements, no standing water occurs and thus, in some instances with good solar exposure, plowing at the time of snowfall is sufficient for winter maintenance resulting in a virtual elimination of the use of deicer. Although porous pavement surfaces do freeze during the winter in cold climates, it is a frozen porous media that maintains high infiltration capacities [Roseen 2012]. Much of the salt applied to a porous pavement remains on the pavement days after it is applied. It should be recognized that the porous pavements are one of the very few salt reduction strategies for cold climates. Freezing rain will require salt, and possibly sand, irrespective of the pavement type.

These findings are not applicable to other types of permeable pavements including pervious concrete because of differences in surface color (light and dark) and its role in pavement temperature and differences in surface type such as permeable interlocking concrete pavers which are permeable at the joints rather than the uniform surface.

After snow plowing operations snow may remain in the open voids of the surfaces temporarily. Studies have shown that heat stored within the permeable pavement will assist in melting the snow trapped in the open pore structure immediately following snow plowing operations [Delatte 2007]. In cold weather climates snow plows may cause abrasion of the surface. Snow plow damage may be reduced by using wide blades, and minimizing back-blading [Kevern 2010].

11.2 Permeability Restoration

Early research on permeable pavements suggested that permeability of the shoulders would be reduced over time due to clogging. Typically, restoration of pavement permeability can be achieved through:

- Restorative vacuum sweeping using specialized, full or pure vacuum street cleaning equipment.
- Powerwashing the pavement. While not common, it may be possible to break up and drive contaminants from the surface and upper layers of the stone reservoir deeper in the pavement. This can result in a reduction in the service life of the overall pavement as a result of forcing particles to deeper strata where they can cause clogging. This would eventually require more substantial reconstruction of the permeable shoulder to mitigate. Therefore, power washing should be considered a “last resort” in maintaining the surface course. Specialty equipment for cleaning porous friction courses has been developed in Europe and Japan which could be very applicable to shoulders.

11.3 Permeable Shoulder Structural Rehabilitation

If permeability cannot be effectively restored and/or the pavement surface is damaged, more substantial rehabilitation may be required. Damage that may be encountered and ways to address that may include:

- Localized ravelling of pervious concrete and porous asphalt. These issues may be addressed through the use of partial or full-depth patching. While the preference for patching material is the same as the existing pavement, it is recognized that similar material may not be readily available. Patching with dense graded asphalt or concrete should be limited to no more than 5 percent of the permeable pavement surface.
- Removal and replacement of damaged paver units for PICP installations.
- For rural roadways, it is important to maintain lateral support for the permeable pavement. This would include restoration of localized scour and undermining of the pavement due to water flow, restoration of granular edge support and rounding, etc.
- Contamination spills may require complete removal and replacement of the permeable pavement.

11.4 Permeable Shoulder Maintenance for Water Quality and Hydrologic Performance

There are several items that should be considered to maintain water quality and hydrologic performance of permeable pavements:

- Contamination spills may require complete removal and replacement of the permeable pavement to prevent washout.
- Long term migration of sediment fines into the sub-surface strata may result in long term decline in infiltration rates. Full depth excavation, removal of sediment, and scarification of the underlying surface is required to mitigate clogging of this nature.
- In underdrain systems, clogging of underdrain pipes via gravel or sediment migration can potentially occur over time. This can potentially be remediated via traditional drain cleaning methods (accessing from the downstream outlet structure).
- The outlet structure configuration may need to be adapted to changing subsurface conditions, for example opening outlet control valves further or lowering the elevation of the outlet control to continue to provide reliable drainage and flow-through treatment in the event of long term declines in underlying soil infiltration rate. The flexibility for later adaptations can be enhanced at the design phase by including a capped underdrain, even if initial infiltration rates appear to be adequate to support infiltration.
- If scour of sub-grade materials or export of accumulated sediment materials is occurring and causing washout of sediments and sediment bound pollutants, investigation of sources of scour is needed. Remediation may require rehabilitation down to base material on a localized or extensive basis.

In flow-through underdrain systems, sorption sites on granular reservoir materials can be saturated by accumulation of metals, phosphorus, and/or other constituents with resulting decline in water quality treatment performance; granular filter material may need to be replaced to restore treatment performance.

Examples of permeable pavement deficiencies and maintenance and restoration practices are shown in Table 11.1.

Table 11.1. Examples of deficiencies and maintenance and restoration practices

	• Small scale permeability improvement equipment. Traditional vacuum equipment used for cleaning catchbasins and be used to address small areas of reduced permeability.

	• Large scale permeability improvement equipment. For regular surface cleaning regenerative air sweepers may be sufficient to improve the pavement permeability. For permeability restoration for significantly clogged pavements, a true vacuum sweeper may be required.
	• Removal of localized areas. Restoration of severely clogged pavements may require removal and replacement of the pavement surface and part or all of the underlying reservoir layer if completely clogged.
	• Scouring/undermining of edge support. Careful consideration of subsurface water flow needs to be considered when designing the permeable pavement to prevent pavement or adjacent feature blowouts such as that shown here.
	• Clear snow away from shoulders. It is important to clear snow from the shoulders as soon as possible after a storm event to prevent deposition of materials from the adjacent pavement lanes and to promote water infiltration.

12. Future Research

Many studies have been conducted and continue to be conducted on the design and installation of permeable pavement systems. Most studies focus on full-depth permeable pavements designed to manage stormwater from low to moderate traffic parking areas, sidewalks, pathways and driveways. Studies and implementation of full-depth permeable pavement systems on low-speed/low volume roadways and highways have begun to increase, but the body of knowledge is still lacking in a number of areas. Further research is needed on roadway and highway installations of full-depth permeable pavements to obtain a greater depth of knowledge on the cost and operation and maintenance required for these systems long term. Additionally, the water quality benefits of full-depth permeable pavements require further research; specifically water quality information from underdrained permeable systems. These systems act as underground detention systems but preliminary research indicates greater water quality benefits than many traditional stormwater detention systems. Potential additional research topics identified by the research team include:

- Water quality performance studies for both infiltrated water and underdrain discharges
- Volume reduction performance studies
- Long term durability and performance of permeable pavement surface and infiltration capacity. Compare performance to impermeable pavements.
- Impact and cost of winter maintenance equipment and activities.
- Potential impacts of freeze thaw conditions.
- Evaluation of potential impact of icing conditions.
- Effectiveness of surface infiltration under sheet flow conditions from adjacent roadway lanes.
- Potential impact of moisture conditions and possible reduced structural support of the adjacent pavement subgrade.
- Investigation of methods for managing water transfer to and from the stone reservoir below the shoulder and the traditional subbase.
- Stability of shoulders during emergency pull off conditions, particularly for heavy vehicles.
- Impact of traffic under temporary detour conditions.
- Potential risks or benefits due to chemical spills.
- Recyclability of the shoulder materials.
- Infiltration testing techniques for all surface types.
- Standardized condition rating systems.
- Establishing equivalency to other BMPs and coordination and accreditation.
- Evaluation of permeable asphalt mix designs and admixtures for heavier loadings and long term durability.
- Development and adaptation of a field QC standard for compaction testing of permeable asphalt.
- Development and adaptation of a laboratory QC standard for pavement durability testing.

- Evaluation of compaction methods for permeable asphalt pavements and consolidation of pervious concrete.
- Development of vacuum sweepers and sweeping methods specifically for the high volume maintenance of permeable pavements that would be associated with widespread implementation.
- Recommended curing time for permeable asphalt and concrete as a function of pavement strength and temperature.
- Study of road sanding and real versus perceived impacts on permeable pavements.
- Development of simplifying assumptions to streamline the combined structural/hydrologic design process, where possible.
- Correlation of site factors (e.g., landscaped area, trees, roadway AADT) and design factors (e.g., tributary area ratio, permeable pavement surface type) with the required frequency of vacuum sweeping.
- Effect of chloride deicers on curing time and strength of pervious concrete; evaluation of alternative deicing materials.
- Comparative analysis of maintenance costs associated with permeable pavements versus traditional pavement of similar size and function.
- Lessons learned of existing permeable pavement sections, both during construction and operation.
- Continued full-scale testing and evaluation of unstabilized and stabilized open graded base material and the permeable pavement surfaces for refinement into reliable design methods and design charts
- In-service measurement and modeling of the hydraulic capacity of permeable surfaces to receive horizontal sheet flow from adjacent impervious travel lanes
- Development of alternative paths for (high intense) stormwater to enter the stone reservoir in cases if the surface becomes clogged.

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Appendix A

Literature Review

Introduction

This technical memorandum provides a review of current literature and research on design methods and standards for porous asphalt pavements, pervious concrete pavements, and permeable pavers, all with stone reservoirs for use in highway shoulders. While several universities have conducted relevant research, very few have permeable pavement construction experience that can be leveraged for this study.

This literature review also includes other applications of permeable pavement technologies, such as low traffic travel lanes, parking stalls, and parking lots, where the bulk of permeable pavement has been installed and studied in the past. However, permeable shoulders with stone reservoirs are a specific implementation of permeable pavement technology. While the unit treatment processes provided in permeable pavement shoulders are the same as those provided in permeable pavement used in other applications, permeable shoulders with stone reservoirs have specific attributes. Permeable pavement shoulders are designed to accept run-on from adjacent travel lanes, so the area provided for treatment and storage is a fraction of the total area treated. Many other permeable pavement applications share this attribute; however, some applications of permeable pavement that have been studied accept only the precipitation that is directly incident. Pavements that receive run-on are expected to experience surface clogging more quickly than pavements accepting only direct precipitation and may provide lower levels of treatment and volume reduction due to a lower ratio of surface area to tributary area.

This memorandum also discusses potential issues with infiltration on groundwater conditions, including water quality from infiltrating stormwater, impacts of spills, changes to water balance/hydrologic regime and potential changes to habitat, infiltrating in areas with natural or anthropogenic plumes, and other potential considerations when evaluating the feasibility of installing permeable shoulder systems. Note that much of the literature available regarding potential groundwater impacts pertains to stormwater infiltration in general, via a variety of stormwater control measures globally referred to as “best management practices” (BMPs), and not specifically permeable pavement shoulders. As such, this literature review considered studies that focused both on permeable pavement systems and on other stormwater infiltration systems. As applicable, studies are interpreted with respect to how findings apply to permeable pavement shoulders, specifically.

A summary of highlights is provided in the following sections. A more detailed annotated bibliography of key references is provided at the end of this document.

Summary of key design factors for permeable pavements

- In 2006, Clark et al., on behalf of the Water Environment Research Foundation (WERF) noted that the efficiency of infiltrating BMPs to remove or mitigate groundwater pollutants is dependent on pollutant characteristics, infiltrating capacity, soil characteristics, rainfall intensity, and BMP configuration. Performance data for infiltrating BMPs are presented by comparing concentrations of pollutants in the inflow and outflow, which can be used as an indication of the quantity of pollutants that are retained in the infiltration system or migrate to groundwater.

- Soil saturating hydraulic conductivity may be the most sensitive factor in hydraulic performance. A permeable pavement could be considered impractical where soil saturated hydraulic conductivity values were lower than 10^{-5} cm/sec. (Kayhanian and Chai, 2011).
- Caltrans test results indicated that the aggregate particle size distribution in the mix and the binder type were the two most critical factors in selecting the appropriate mix for porous asphalt surface mixes. Sufficient permeability was obtained for typical California conditions. Resistance to rutting varied between different mix types, but all the mixes provided adequate durability (resistance to raveling) when compared to the dense-graded control. (Caltrans, 2010).
- For pervious concrete surface mixes, Caltrans' test results (2010) indicated a clear relationship between aggregate grading, cement content, water-to-cement ratio, and strength and permeability. All mixes exceeded the anticipated permeability requirements, which indicates that aggregate grading and cement content can be adjusted to increase the strength of the material while still retaining adequate permeability. The water-to-cement ratio appears to be critical for constructability.
- Collins, Hunt, and Hathaway (2007) found that since the majority of flow from the permeable sections was in the form of subsurface drainage out of an under drain pipe, the flow can be controlled through the inclusion of a sump or restriction to allow more water to infiltrate. Therefore, the flow leaving the cells can be significantly modified by design. However, permeable pavement and traditional asphalt concrete showed little difference in hydrology for large rainfall events (>50 mm) in North Carolina. Different results were obtained in Washington State. There, Horner and St. John (1997) found that porous asphalt shoulders have a higher potential for runoff reduction, with an 85 percent reduction observed compared to conventional asphalt during typical wet season storms in Washington. For larger storms (> 1.27 cm), the reduction was 60 percent.
- Subsurface soil migration into unlined cells can prevent significant reductions of total phosphorus and total suspended solids (TSS). (Collins, Hunt, and Hathaway, 2007).
- Henderson and Tighe (2011) provided design factors/advice to maximize the durability of pervious concrete pavements in colder Canadian climates with winter maintenance activities. The mix design and construction method are crucial in achieving durability:
  - Aggregate selection is important to minimize fracturing.
  - Mixes with fine aggregate content have shown better durability.
  - Compaction during construction provides a more durable surface that leads to less ravelling.
  - Construction joints should be considered before placement begins to ensure adequate performance in the long term.
  - Freeze–thaw cycles have not led to the development of distress.
  - It is necessary to agitate the debris in the voids during maintenance to improve the permeability.
  - Cracks will develop if no joints are cut or formed, or if the joints are widely spaced.

Feasibility factors in selecting infiltration BMPs

In Strecker and Poresky's case study in Orange County, California (2010), where infiltration approaches and stormwater retrofits are being explored, more than 70 percent of the area of the County would potentially be restricted by one or more infiltration feasibility/desirability factors.

- Infiltration is most appropriate where underlying soils have adequate ability to infiltrate water (typically Natural Resources Conservation Service [NRCS] Type A and B soils). To achieve the same degree of infiltration in areas with low rates would require shallower ponding depths and larger surface areas.
- Natural (e.g., selenium) and anthropogenic (e.g., solvent) plumes or contaminated soils should be identified when considering infiltration because of the potential to mobilize and spread contaminants.
- Infiltration should be implemented carefully to prevent groundwater contamination, with necessary pre-treatment or maintenance as needed. Land use activities, groundwater plumes, soil contamination, separation to groundwater, soil type, and other factors should be considered.

Orange County Public Works (2011) produced a technical guidance document with comprehensive feasibility criteria for retaining stormwater "on-site." Their investigation criteria for evaluating if infiltration is feasible and desirable included the following key elements:

- Factors that physically restrict the flux into the ground:
    - Low soil infiltration rates.
    - Groundwater mounding.
    - Limiting soil horizons.
- Factors with the potential to result in undesirable impacts on human health, property, and/or environmental resources (risk-based):
    - Geotechnical instability.
    - Degradation of groundwater quality.
    - Increase in base flows of ephemeral channels, and associated habitat impacts.
    - Increase in inflow and infiltration (I&I) into the sanitary sewer.

The technical guidance document provides guidance for evaluating these factors:

- Infiltration rate is impacted by compaction, subsurface depth, clogging, and temperature/freezing. Rates under permeable pavement including asphalt, concrete, and interlocking concrete block pavers in right-of-ways may be lower due to necessary structural compaction.
- The presence of shallow groundwater can reduce infiltration rates below a BMP, cause groundwater discharge into the stormwater drainage system, and result in locally elevated groundwater tables (or mounding).
- Shallow groundwater below a BMP can increase the risk of groundwater contamination. Special consideration should be given for situations where there is direct connectivity between the BMP and an unconfined aquifer.

- The following factors must be considered in determining whether infiltration can be safely done while protecting groundwater quality:
    - Separation to groundwater. A separation to groundwater of 10 feet must be provided; this may be reduced to 5 feet where BMPs are shallow and infiltrate from the surface, through more biologically active soils.
    - Sources of pollutants from the tributary area. Different land covers and uses are assigned different ranges of risk.
    - Limited treatment capacity for groundwater contaminants provided in the BMP or in underlying soils. For example, subsurface BMPs that infiltrate through inert sandy material pose a higher risk than surface BMPs that infiltrate through biologically active soil layers.
    - Presence of contaminated soils, groundwater plumes, or septic systems such that infiltrated water could mobilize pollutants or spread them within the aquifer.
    - Proximity to wellhead protection zones.
- Implementing infiltration BMPs with the goal of matching pre-development runoff volumes has the potential to change the natural water balance by increasing the amount of water infiltrated to groundwater and reducing the amount evapotranspired. Increased groundwater recharge may be desirable in “managed aquifers” with adequate capacity, but in some groundwater systems, an increase in infiltration volume may cause issues with slope stability, extend unseasonal base flows in down gradient channels, and increase liquefaction and seismic risks.
- Infiltration can increase the risk of geotechnical hazards, which include steep or sensitive slopes/landslide hazard zones, manufactured fill, liquefaction hazard zones, foundation and subbase issues, and infrastructure damage associated with expansive clays.
- Infiltration may be incompatible with existing or proposed underground infrastructure, such as subsurface construction, sanitary sewers, and dry utilities.
- Roadways with average daily traffic (ADT) greater than 5,000 but less than 25,000 are classified as having “moderate” potential for groundwater contamination. Roadways with ADT greater than 25,000 are classified as having a “high” risk for groundwater contamination. The traffic level criterion was specified in the municipal separate storm sewer system (MS4) permit for the area, but no technical citation was provided in the permit as the basis for this number.

Interpretation: *How does the risk posed by permeable shoulders compare to the risk posed where roadways are currently allowed to sheet flow and infiltrate?*

Where highways drain to shoulders under existing conditions, stormwater runoff may pose risks to groundwater quality. The degree of risk varies depending on the site conditions. In cases where water is dispersed over grass or other vegetation and infiltrates through biologically active soil (surface soil, containing plant roots, microbes, etc.), risks are generally fairly low – much of the water that infiltrates tends to be evaporated from the soil column. Additionally, treatment tends to be provided in the biologically active soil layer. However, where soils have limited treatment capacity, where depth to groundwater is shallow, and/or where water pools and infiltrates in concentrated areas, roadway runoff may be posing risks to groundwater quality.

Permeable shoulders with stone reservoirs concentrate infiltration in relatively small areas and allow the water to infiltrate below the biologically active zone of the soil. This tends to elevate the potential for groundwater contamination. In conditions such as this, a minimum separation between the bottom of the BMP and the seasonally high groundwater table is commonly recommended. Subsequent guidance will be provided regarding assessing the feasibility and applicability of permeable pavement shoulders. It is expected that depth to groundwater will be a recommended screening criterion.

Summary of design requirements for permeable pavement to be used in shoulders

- Strong enough to function as a shoulder pavement.
- Durable enough to prevent excessive concrete/asphalt material-related maintenance.
- High enough permeability to minimize clogging maintenance.
- Proper hydrologic design to minimize lateral water movement.
- Rapid aggregate base draining for subgrade protection.
- Rapidly constructible.
- Able to be cured (pervious concrete) without plastic.

In test sections in a study by Kevern (2012), these requirements were met by a concrete mix design with hardened properties of 28 percent voids, a unit weight of 114.75 lb/ft^3, permeability of 2,050 in/hr, and a 28-day compressive strength of 3,355 lbf/in^2.

Multiple researchers have indicated that construction site runoff must be diverted because of high suspended solids concentrations and expedited clogging that may occur. Likewise, runoff from manufacturing industrial areas should be diverted because of high soluble toxicant potential. Perhaps most problematic for departments of transportations (DOTs), Pitt et al. (1994, 1999) indicated that roadway runoff should be diverted due to stormwater pollution from chlorides applied for road safety purposes. Salts have a high potential for contaminating groundwater because they are water soluble, non-filterable, not readily sorbed to solids, and leach into groundwater as infiltration occurs. Other design recommendations include the following:

- If there are any concerns about infiltration mobilizing pollutants from contaminated soils to the groundwater, the system should be constructed with an impermeable membrane, and treated discharge should be piped to the acceptable drainage system. (Miklas and Grabowiecki, 2006).
- As noted above, Kevern (2012) reported concrete mix designs with hardened properties of 28 percent voids, a unit weight of 114.75 lb/ft^3, permeability of 2,050 in/hr, and a 28-day compressive strength of 3,355 lbf/in^2 met design requirements.
- Dierkes et al. suggest a minimum of 16 in of unsaturated soil to serve as a buffer for groundwater. (Dierkes et al., Germany, unknown date).

- Collins, Hunt, and Hathaway (2007) recommended lining cells; otherwise, total phosphorus (TP) and TSS in under drain discharge may not be significantly reduced.

Ability to use regular materials and accepted design approaches

- Testing of commercially available permeable base course aggregates indicated that these materials would most likely provide sufficient support for typical traffic load including highway shoulders while serving as the reservoir layer. (Caltrans, 2010).
- Mechanistic-empirical pavement design equations developed for Caltrans' project were effective in estimating required structural thicknesses to carry heavy truck traffic.
    - The stress calculations for concrete and the strain calculations for asphalt were used to estimate the required thicknesses for preventing fatigue cracking. The results were used to develop structural design tables to be used with hydraulic design calculations. The pavement structure was considered feasible for all pavements less than 5 feet in total thickness.
    - Design tables were developed with the following inputs:
        - Subgrade permeability.
        - Truck traffic levels (Traffic Index).
        - Two temperature climate regions (Sacramento and Los Angeles).
        - Two traffic speeds.
        - Three design storms.
        - Various numbers of adjacent impermeable lanes.
    - Construction and maintenance experts reviewed the design cross sections developed for shoulder retrofit of highways as well as low-speed trafficked areas, and these designs were considered feasible to construct and maintain.

Long-Term Benefits and Sustainability Considerations

Durability, relating to long-term use of resources (staff time, materials, funding)

Sustainability for general DOT maintenance staff most often means sustainability of the highway system (National Cooperative Highway Research Program [NCHRP] 25-25/73, unpublished), beyond the environmental matters normally connoted by the term. For DOTs, the ability of permeable pavements with stone reservoirs to reduce flooding and safety issues, as well as reduce undermining of the road base (and the greater staff, physical, and fiscal resources that would entail), addresses the "triple bottom line" of social, economic, and environmental issues, an approach to long-range assessment of benefits discussed by the American Association of State Highway and Transportation Officials (AASHTO), the Federal Highway Administration (FHWA), and others. (FHWA INVEST Sustainability Rating Tool, NCHRP 25-25/73.)

To better address the sustainability or long-range benefits of permeable pavement shoulders with stone reservoirs, for DOTs, flooding elimination, road preservation, and safety benefits of the following could be quantified:

- **Calverton, New York.** To eliminate a persistent flooding issue on New York State Route 25 in Calverton, a pervious concrete shoulder was installed in June 2011. A 500-foot section of pervious concrete shoulder (8 feet wide) was installed at the roadway low point. Prior to the installation, maintenance crews were responding to many flooding events, even after minor rainfall. Since the installation, no flooding has been reported.

- **Orient Point, New York.** A pervious concrete shoulder was installed in November 2011 along NY State Route 25 in Orient Point. Similar to the situation in Calverton, maintenance crews were responding to many flooding events. A 250-foot pervious concrete shoulder (7 feet wide) was installed at the roadway low point. Some minor flooding has been reported at this location since the installation on heavy rain events, but the roadway is cleared of water within an hour of the rain event.

Caltrans' *Laboratory Testing and Modeling for Structural Performance of Fully Permeable Pavements Under Heavy Traffic: Final Report* includes a life-cycle cost analysis of fully permeable pavements that demonstrated cost-effectiveness for shoulders and other areas with light/slow truck traffic. Insufficient data were available to complete a life-cycle cost analysis for a fully permeable pavement. (Caltrans, 2010).

Sustainability of pervious pavements in cold weather climates has been a concern for a number of DOTs. For example, even as far south as North Carolina, former NCDOT Chief Engineer Steve Varnedoe said permeable pavements were "a skating rink" when they froze. Evaluation of pervious concrete pavement performance in cold weather climates has occurred since that time, though, including in a number of Canadian sites in Ontario, British Columbia, and Quebec with pavements designed to meet local loading and climactic conditions. (Henderson and Tighe, 2011).

Los Angeles County's Groundwater Augmentation Model (GWAM) estimated that 16 percent of precipitation (164,000 acre-ft) currently percolates to groundwater in the Los Angeles region, and that 50 percent (601,000 acre-ft) becomes runoff that is conveyed to the ocean. This in turn has long-term fiscal benefits for the region: for imported water and associated costs, reduced reliance on uncertain water supply, avoided cost of treatment for highway runoff volumes that breach wastewater conveyance systems, diminished need to enhance storm drain conveyances, water conservation, new recreational and community uses, and enhancement of habitat, open space, and ecosystems.

Attention to durability of pervious pavements and the efficiency of stormwater treatment is an extension of the accountability, performance management, and cost-effectiveness concerns of DOTs, FHWA, and AASHTO. Evidence-based decision making is now an expectation, on many levels. The U.S. National Surface Transportation Policy and Revenue Study Commission presented a "Call to Action," saying the future of the Nation's well-being, vitality, and global economic leadership is at stake, and the U.S. needs to "create a system where investment is subject to benefit-cost analysis and performance-based outcomes." The public, Congress, and other agencies expect increased transparency and rational decision making.

Stormwater Quality Benefits and Long-Term Performance

Treatment of stormwater is mostly accomplished through filtration, sedimentation, and sorption. (Pitt et al., 1994). In the U.S., the stormwater benefits of permeable pavement have been amply documented by Eck, Barrett, and others, in addition to European research that has occurred, but very few studies exist on long-term benefits or life-cycle costs of stormwater treatment with pervious pavements. Caltrans' life-cycle cost analysis included a comparison with conventional stormwater best management practices for the Sacramento region, which indicated that fully permeable pavement should cost less than conventional pavement over a 40-year life-cycle. Eck presented water quality measurements for permeable friction courses (PFC) and conventional pavement collected over 6 years near Austin, Texas, and 2 years in eastern North Carolina. The data showed that concentrations of total suspended solids from PFC were more than 90 percent lower than from conventional pavement. Lower effluent concentrations were also observed for total amounts of phosphorus, copper, lead, and zinc. The combined data sets showed that the benefits of a PFC last through the design life of the pavement, that results in Texas are consistent with those from North Carolina, and that both are consistent with earlier studies from France, the Netherlands, and Germany.

As Miklas and Grabowiecki (2006) and others have noted, porous concrete products, including paving stones or interlocking blocks, can function as pollution sinks due to the particle retention capacity of the concrete during filtration. Geotextiles at the base of a permeable pavement system may help to prevent sand from migrating upwards into the system and can also assist with the retention and degradation of oil in the module if clogging is not an issue. They also retain particulate matter and can keep micro-pollutants, such as cadmium, zinc, and copper out of the groundwater. The fate and transport of stormwater – infiltration to the base material, evaporation, and overland flow – are mainly controlled by the particle size distribution of the bed material and retention of water in the surface blocks. Infiltration through a permeable pavement system supports groundwater recharge, denitrification in the ground or eventual plant uptake, and, in some cases, can decrease groundwater salinity through dilution (where stormwater is not a source of salt). It can also add pollutants to underlying soils and groundwater if they are not removed from runoff prior to infiltration. Miklas and Grabowiecki (2006) reported that filtration in permeable pavement systems can remove suspended solids and lead at levels of 64 percent and 79 percent, respectively, and that filtration through specific adsorption media can remove up to 95 percent of dissolved zinc and copper. Clark et al. (2006), in a study for WERF, determined that rainfall is the primary controlling factor for depth of migration of pollutants.

Due to inadequate source control from brake pads (copper), formerly from gasoline (lead), and spray onto vehicle undersides, etc., roadway runoff can have a high concentration of heavy metals. Nearby soils can provide a natural buffer capacity, unless that is exceeded. In a test of four porous pavement systems with different sub-base materials with heavy metal-spiked runoff, Dierkes et al. found that all pavements were highly effective at retaining dissolved heavy metals. The highest retained concentrations were in the upper 2 cm (0.8 inch) of the pervious concrete. The researchers found that buffer capacities in the concrete are high enough to prevent mobilization by acids in rain. Higher concentrations of metals were measured in the sub-base up to 20 cm (7.9 inches) deep for cadmium and lead, and up to 10 cm (3.9 inches) for copper. Concentrations of cadmium and copper only reached the applicable limits in Germany in the effluent for very coarse sub-base materials. Brattebo and Booth (2003) found that zinc concentrations in infiltrated water and surface runoff can increase significantly over time.

Few DOTs have conducted studies of the infiltration performance and water quantity and quality impacts of the use of pervious pavement in a shoulder area. Florida DOT did so for Portland cement pervious concrete in a shoulder area along Interstate 4 in central Florida (pervious concrete depth of 12 inches, underlain by a 12-inch reservoir of pollution control materials). The University of Central

Florida measured flows and water quality of the filtrate through the concrete and the reservoir at two locations: at the edge of the concrete and 7 feet away. They found that that the open graded structure of pervious concrete promotes infiltration, and a pollution control media reservoir can help remove pollutants prior to infiltration to groundwater or piping to drainage. They further found that almost all water piped to the permeable concrete and all rainfall on the shoulder for the analysis period was infiltrated and that the concentrations of orthophosphate (dissolved phosphorus) and nitrate (dissolved nitrogen fraction) decreased in the filtrate samples relative to the stormwater runoff (between 43 and 86 percent reductions). (Wanielista and Chopra, 2007).

In Washington State, Collins, Hunt, and Hathaway (2007) found that in addition to volume/runoff reductions of 85 percent compared to traditional asphalt for regular storms and a 60 percent reduction for larger storms (>1.27 cm [0.5 inch]), runoff from porous asphalt had reduced pollutants concentrations – biological oxygen demand (BOD) and chemical oxygen demand (COD), total phosphorus (TP) and orthophosphate as phosphorus (OP), metals, and petroleum fractions – during the wet seasons of 30 to 60 percent less than conventional asphalt. For storms following sanding of the roads, the pollutant and solids concentration reductions from porous asphalt were 40 to 50 percent lower than from traditional asphalt. Furthermore:

- Pollutant and solids load reductions from porous asphalt were up to 90 percent lower than from traditional asphalt during the wet season. Loads following sanding were 75 percent lower.
- Pollutant removal rates were highest for contaminants associated with suspended solids, indicating that settling and filtration were critical processes in media.
- Soluble contaminants were also removed, particularly OP, via infiltration to soils below the pavement.

These studies and benefits accord with earlier findings from Berbee et al. (1999). This Netherlands-based research had found that:

- Pollutant concentrations from pervious asphalt are significantly lower than runoff from impervious asphalt (heavy metals, polycyclic aromatic hydrocarbons [PAHs], mineral oil, suspended solids, and oxygen-consuming substances). Copper, lead, and zinc are the most prevalent heavy metals, with lead primarily found in or attached to particulates. Copper and zinc concentrations in the permeable asphalt runoff are also significantly reduced, but the percent attached to particulates significantly decreases compared to the impervious asphalt runoff condition, indicating that the metals discharged from the under drains are more dissolved.
- Settling is a significant factor in the removal of copper, lead, and zinc, but it has a smaller effect in pervious asphalt runoff because of the reduced fraction of particulate-bound metals. A similar pattern was observed with filtration, due to the already reduced concentrations of heavy metals in the runoff from pervious asphalt.

DOTs have been researching the effectiveness of roadside filter strips to treat the pollutants that remain after running off from permeable or impermeable pavement. The NCHRP 25-25/83 study (in progress) has found that filter strips adjacent to roadway shoulders are the most common BMP in use. Less information is available on the water quality performance of filter strips outside the growing season. Barrett, in a study for WERF (2012) has characterized these benefits as being essentially free.

Drinking Water/Spill Risk Protection

According to Miklas and Grabowiecki (2006), large hydrocarbon spills can be contained in a permeable pavement system due to its ability to function as a hydrocarbon trap and in situ bioreactor. Naturally developed microbial communities have degraded oil (PAHs) successfully where there is a prolonged aerobic, sulphate reducing, and denitrifying environment. Soils in permeable pavement systems can adsorb large concentrations of hydrocarbons. Oil interceptors can also be incorporated in the design where there is anticipated to be a need. Pratt, Newman, and Bond (1999) examined the capacity of permeable pavement to sustain an effective microbial population for the treatment of petroleum-derived pollutants through in situ bio-degradation and found that permeable pavement can be an effective in situ aerobic bioreactor, reducing the petroleum concentration in the effluent to 2.4 percent of the concentration applied to the permeable pavement. The limiting factor in biodegradation is nutrient supply, but a slow-release fertilizer with an affinity for oils may be able to sustain treatment. In case of a spill and treatment in this fashion, nutrients must be effectively managed to prevent eutrophication and leaching to groundwater.

DOT Maintenance Burden and Maintenance/Sustainability of Water Quality Benefit

Miklas and Grabowiecki (2006), Pitt (1994 and 1999), Berbee et al. (1999), and research funded by the Environmental Protection Agency (EPA) stress the importance of maintenance to sustain surface infiltration and storage capacity. Berbee et al. (1999) noted that suspended solids removed from stormwater accumulate in the porous asphalt. The researchers suggested that this could result in clogging and reduced drainage, and that highway shoulders in particular may be susceptible to clogging because of limited vehicular use and the lack of turbulence created by high speed vehicles to keep voids open.

There also have been studies to assess the maintenance of permeability as part of regular winter maintenance in northern states and Canadian provinces. Henderson and Tighe (2010) provided advice to maximize durability (related to sustainability and long-term benefit factors of DOT materials usage, fiscal aspects/cost-effectiveness) and longevity of water quality benefits, which were covered earlier in this report. While Eck et al. did not find maintenance to be much of a factor in water quality performance of permeable pavements in Texas, where winter road treatments are fewer, Henderson and Tighe found that in Canada, even with maintenance activity, it was difficult to restore initial permeability rates.

Two permeable pavement studies are currently being conducted at the Minnesota Department of Transportation's Cold Weather Road Research Facility. (www.dot.state.mn.us/mnroad/projects/). These studies involve documenting maintenance procedures and results, in terms of when to vacuum and sweep roads based on stormwater monitoring data as well as the volume of stormwater runoff in comparison to a standard asphalt roadway. MnDOT is testing for water quality, such as solids, pH, chloride, phosphorus, nitrogen, and heavy metals.

Air Quality Benefits

Pervious shoulders with stone reservoirs are not constructed for their air quality benefits; however, concrete for shoulder applications can also utilize photocatalytic cement for air quality improvement. (Kevern, 2012).

ANNOTATED BIBLIOGRAPHY

Current Design, Maintenance, and Construction Practices

Existing Highway or Roadway Shoulder Permeable Pavement Installations

Village of Canal Winchester, Ohio.
(http://www.canalwinchesterohio.gov/mediacenter/pressrel/071408ColumbusStreetEvent.pdf)
In 2008, the Village of Canal Winchester reconstructed one of their oldest historic residential streets (W. Columbus Street) using pervious concrete to create “bump outs” –areas of the street separated from the roadway that allow for safer street parking while maintaining many mature trees along the roadway as well as improving traffic flow. To reduce the impervious footprint, pervious concrete was selected for the construction of the bump outs. The total area of pervious concrete is in the order of 1,000 square yards. The structure consists of 7 inches of pervious concrete over 11 inches of ASTM #4 aggregate stone reservoir. It was estimated that there was a 32 percent net reduction of impervious area.

The following two examples were provided by Roy K. Reissig, PE, New York State Department of Transportation Resident Engineer:

- **Calverton, New York.** To eliminate a persistent flooding issue on New York State Route 25 in Calverton, a pervious concrete shoulder was installed in June 2011. A 500-foot section of pervious concrete shoulder (8 feet wide) was installed at the roadway low point. Prior to the installation, maintenance crews were responding to many flooding events, even after minor rainfall. Since the installation, no flooding has been reported.
- **Orient Point, New York.** A pervious concrete shoulder was installed in November 2011 along NY State Route 25 in Orient Point. Similar to the situation in Calverton, maintenance crews were responding to many flooding events. A 250-foot pervious concrete shoulder (7 feet wide) was installed at the roadway low point. Since the installation, some minor flooding has been reported at this location during heavy rain events, but the roadway is cleared of water within an hour of the rain event.

Pavement Design, Construction, and Maintenance Issues

Bruce K. Ferguson, *Porous Pavements,* CRC Press, 2005.
This textbook provides background information on all types of porous pavements, including asphalt, concrete, and pavers. It also includes porous pavement structure and hydrology.

Industry Association Design Guides
Design guides for porous asphalt, pervious concrete, and permeable interlocking pavers are available from each of the various industries. They include the following:

- **National Asphalt Pavement Association (NAPA)**, *Porous Asphalt Pavement for Stormwater Management, Design, Construction and Maintenance Guide,* November 2008.

This guide provides information on structural design, soil investigation, hydrologic design, water quality, materials, construction, cost, and maintenance for porous asphalt pavements. The focus of this guide is predominately lower volume roads, parking lots, and trails.

- **Michael L., Leming, H. Rooney Malcom, Paul D., Tennis**, *Hydrologic Design of Pervious Concrete*, Portland Cement Association and National Ready Mixed Concrete Association, 2007.
  This publication provides an overview of design techniques for determining the hydrological performance of pervious concrete.
- **American Concrete Paving Association (APWA)**, *PerviousPave Technical Guide*, 2012.
  This document details the background, purpose and assumptions made during the development of this integrated structural and hydrological design software.
- **Interlocking Concrete Pavement Institute (ICPI**), *Permeable Interlocking Concrete Pavements Manual - Design, Specification, Construction, Maintenance* (4th Ed.), 2012.
  This manual provides information on current permeable pavement research on stormwater management, structural design, and performance.

Masoud Kayhanian and Lin Chai, "Hydraulic Performance Simulation of Fully Permeable Highway Shoulder," World Environmental and Water Resources Congress, American Society of Civil Engineers, 2011.

This paper discusses the results of simulations performed using HYDRUS software to assess the hydraulic performance for fully permeable highway shoulders. It evaluated two different designs for retrofits for permeable highway shoulders. The first structure consisted of impermeable geo-membranes on both sides of the shoulder (one-dimensional flow), while the second design consisted of a single impermeable geo-membrane on the pavement side only (two-dimensional flow). The study concluded that soil saturating hydraulic conductivity is the most sensitive factor. A permeable pavement could be considered impractical where soil saturated hydraulic conductivity values were lower than 10^{-5} cm/sec.

California Department of Transportation, *Laboratory Testing and Modeling for Structural Performance of Fully Permeable Pavements Under Heavy Traffic: Final Report,* California Department of Transportation Division of environmental Analysis Storm Water Programs, CALTRANS Document No. CTSW-RT-10-249.04, November 2010.

This research report summarizes the results of laboratory testing, computer performance modeling, and life-cycle cost analysis of fully permeable pavements. The objective of the research is to develop preliminary designs for fully permeable pavements in California. The research indicates that fully permeable pavements could be a cost-effective stormwater BMP for highways through retrofitting the shoulders. Likewise, it could be a cost-effective BMP for maintenance yards, parking lots, and other areas with slow moving truck traffic. A summary of key findings from the laboratory testing includes:

- Testing of commercially available permeable base course aggregates indicated that these materials would most likely provide sufficient support for typical traffic load including highway shoulders, while serving as the reservoir layer.

- For the porous asphalt surface mixes, test results indicated that the aggregate particle size distribution in the mix and the binder type were the two most critical factor in selecting the appropriate mix. Sufficient permeability was obtained for typical California conditions. Resistance to rutting varied between different mix types, but all the mixes provided adequate durability (resistance to ravelling) when compared to the dense-graded control.
- For pervious concrete surfaces mixes, test results indicated a clear relationship between aggregate grading, cement content, water-to-cement ratio, and strength and permeability. All mixes exceeded the anticipated permeability requirements, which indicates that aggregate grading and cement content can be adjusted to increase the strength of the material while still retaining adequate permeability. The water-to-cement ratio appears to be critical for constructability.

A summary of the key findings from the computer modeling includes the following:

- Mechanistic-empirical pavement design equations developed for Caltrans' project were effective in estimating required structural thicknesses to carry heavy truck traffic.
- The stress calculations for concrete and the strain calculations from asphalt were used to estimate the required thicknesses for preventing fatigue cracking. The results were used to develop structural design tables to be used with hydraulic design calculations. The pavement structure was considered feasible for all pavements less than 5 feet in total thickness.
- Design tables were developed with the following inputs:
  - Subgrade permeability.
  - Truck traffic levels (Traffic Index).
  - Two temperature climate regions (Sacramento and Los Angeles).
  - Two traffic speeds.
  - Three design storms.
  - Various numbers of adjacent impermeable lanes.
- Construction and maintenance experts reviewed the design cross sections developed for shoulder retrofit of highways as well as low-speed trafficked areas, and these designs were considered feasible to construct and maintain.

The key findings from the life-cycle analyses for full permeable pavements were as follows:

- Example life-cycle cost analysis comparison with conventional stormwater best management practices for the Sacramento region indicated that full permeable pavement should cost less than conventional pavement over a 40-year life-cycle.

John T. Kevern, "Pervious Concrete Shoulders for Stormwater Management," Proceedings, International Conference on Long-Life Concrete Pavements, September 2012.

This paper discusses the requirements for using pervious concrete for highway shoulder applications and the concrete mixture development for a shoulder application in St. Louis, Missouri. It utilizes photocatalytic cement for air quality improvement and stormwater management. The paper identifies the following requirements for pervious concrete to be used in shoulders:

- Strong enough to function as a shoulder pavement.
- Durable enough to prevent excessive concrete material-related maintenance.
- High enough permeability to minimize clogging maintenance.
- Proper hydrologic design to minimize lateral water movement.
- Rapid aggregate base draining for subgrade protection.
- Rapidly constructible.
- Able to be cured without plastic.

Four test sections were constructed. The hardened properties of the mix design included 28 percent voids, a unit weight of 114.75 lb/ft^3, permeability of 2,050 in/hr, and a 28-day compressive strength of 3,355 lbf/in^2. The mixture developed was able to achieve all of the desire properties.

Vimy Henderson and Susan Tighe, "Evaluation of Pervious Concrete Pavement Performance in Cold Weather Climates," *International Journal of Pavement Engineering*, DOI:10.1080/10298436.2011.572970, 2011.

This paper presents the performance of five pervious concrete sites in cold climates. The five sites are located in Georgetown, ON; Campbellville, ON; Barrie, ON; Maple Ridge, BC; and Laval, QC. The pavement structures were designed to meet the local loading and climate conditions for each site. Multiple construction methods were evaluated, ranging from hand placement to various pavers. Two types of maintenance activities were evaluated: maintenance to maintain permeability and winter maintenance activities. The key findings of this research are as follows:

- Aggregate selection is important to minimize fracturing.
- Mixes with fine aggregate content have shown better durability.
- Compaction during construction provides a more durable surface that leads to less ravelling.
- Construction joints should be considered before placement begins to ensure adequate performance in the long term.
- Freeze–thaw cycles have not led to the development of distress.
- It is necessary to agitate the debris in the voids during maintenance to improve the permeability.
- Cracks will develop if no joints are cut or formed, or if the joints are widely spaced.

The conclusion of this study is that the permeability of the pervious concrete has not been the determining factor in the overall performance of the pavement. The mix design and construction method are crucial in achieving durability. Even with maintenance activity, it is difficult to restore initial permeability rates.

Minnesota Department of Transportation Cold Weather Road Research Facility (MnRoad). http://www.dot.state.mn.us/mnroad/projects/

Two permeable pavement studies are currently being conducted at this facility:

- **Permeable Pavement Performance in Cold Regions**

  The objectives of this research are to evaluate the durability, hydrologic characteristics, and environmental effects of porous asphalt pavement when used on a low volume roadway in a cold climate. The research will include:

- Constructing a fully instrumented test section on the MnROAD Low Volume Road.
- Monitoring pavement performance on a regular basis in terms of low temperature cracking, rutting, and ride.
- Documenting the maintenance procedures and results, in terms of when to vacuum and sweep roads based on stormwater monitoring data.
- Monitoring the volume of stormwater runoff for comparison to a standard asphalt roadway.
- Testing for water quality, such as solids, pH, chloride, phosphorus, nitrogen, and heavy metals.

- **Pervious Concrete Pavement Study**
  In 2005, MnDOT, in collaboration with the Aggregate Ready Mix Association of Minnesota, constructed a pervious concrete pavement in a parking lot. The parking lot was done on a small scale with minimal instrumentation. This study will provide validation of the mix design recommendations in the laboratory based on a previous concrete study in Iowa.

John Harvey and David Jones, "Development of Design Table for Permeable Interlocking Concrete Pavement and HVS Validation," Draft Project Proposal: UCPRC-PP-2011-01, September 2011.

This draft report was prepared for the Cement Masonry Association of California and Nevada by the University of California Pavement Research Center to develop design tables for permeable interlocking concrete pavement with Heavy Vehicle Simulator (HVS) validation. This current study has the following goals:

- Measure deflection to characterize layer stiffness.
- Perform mechanistic-empirical calculations to produce draft design tables.
- Using design tables, construct several sections to be tested using an HVS for validation.

This proposal has moved forward to a project funded by the CMACN, the California and Nevada Cement Association and the Interlocking Concrete Pavement Institute Foundation for Education & Research which include full-scale testing of PICP sections to develop base/subbase thickness design tables. Completion of this project is expected in mid-2014.

Scott Taylor and Scott McGowen, "Best Practices in Addressing NPDES and Other Water Quality Issues in Highway System Management: A Report from NCHRP 20-68A, Scan 08-03," TRB 2010 Annual Meeting, Washington, DC, January 2010.
http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP20-68A_08-03.pdf

Permeable pavements are identified as a stormwater quality management measure, but there are questions about its utility, appropriate design standards, necessary maintenance, etc. The University of Central Florida has been researching porous pavement longevity. Some of their key findings are summarized below:

- Installation is a key parameter for long-term performance.
- Rejuvenation of clogged pavement using vacuum sweepers.

- Asphalt binder tends to melt and move down into pavement sections, potentially re-solidifying and creating an impermeable layer. More research may be required in hot climates.

Water Infiltration Issues

This section provides a review of the literature concerning water infiltration on groundwater, including water quality, impact of spills during accident events, water balance, water quality, and so on.

Groundwater Quality

The following references focus mostly on groundwater quality impacts from the infiltration of stormwater. They discuss common contaminants present in urban stormwater flows, the fate and transport of these contaminants in an infiltrating system, and possible options for treatment or other mitigation of associated risks.

Robert Pitt, Shirley Clark, and Keith Parmer, *Protection of Groundwater from Intentional and Nonintentional Stormwater Infiltration*, U.S. Environmental Protection Agency, 1994.

This book identifies potential groundwater problems that arise from increased development and stormwater infiltration, and it addresses how conventional stormwater controls can mitigate the effects. It includes a comprehensive description of the characteristics of urban runoff and particular contaminants and sources that may affect groundwater. Major findings are summarized below:

- Urban runoff can be separated into a number of separate phases, such as dry-weather base flows, stormwater runoff, combined sewer overflows, and snowmelt. Seasonality and tributary land use areas (usage, impervious areas, and connectedness) are important factors for determining base flows and runoff quality.
- There are a number of pollutants commonly found in urban runoff, such as heavy metals and toxic organics, and this book describes their most significant sources.
- Constituents of concern for groundwater were categorized as follows:
    - Nutrients: Nitrates are commonly encountered as contaminants in groundwater due to their mobile nature and the use of fertilizers and the location of groundwater tables underneath pervious urban surfaces. Leaching is most common during cool, wet seasons because the lower temperature reduces rates of denitrification, ammonia volatilization, microbial immobilization, and plant uptake. Residual nitrate is highly soluble and will stay in solution until it reaches groundwater when percolated.
    - Pesticides: Pesticides in groundwater are usually a result of municipal or homeowner application for pest control, and concentrations found in groundwater vary significantly based on usage, soil texture, and total organic carbon of the soil, persistence, and depth to groundwater. The highest mobility of pesticides occurs in coarse-grained or sandy soils without a hardpan layer, with low clay and organic matter content and high permeability. Decomposition is possible in soil and water,

but the time can range between days and years depending on the conditions and the specific compounds.
    - Other organics: The most common other organics are phthalate esters and phenolic compounds, with PAHs detected in some groundwaters near industrial sites. Contamination is more prevalent where there are sandy soils and a high water table. Removal of organics can occur via volatilization, sorption, and degradation.
    - Pathogenic microorganisms: Enteric viruses are the most common stormwater contaminant identified in groundwater due to their resistance to environmental factors. They are typically detected where stormwater recharge basins are located short distances from an aquifer, and they can move laterally within aquifers until they are adsorbed or otherwise inactivated.
    - Heavy metals and other inorganics: Most heavy metals, with the exception of zinc, are highly associated with particulates in stormwater and can be removed through sedimentation. Filterable (dissolved) forms of heavy metals can be removed via sorption to sediments in BMPs or in the vadose zone. Groundwaters that have an acidic pH have been measured with elevated heavy metal concentrations, as pH has an effect on sorption equilibrium. The drying of infiltration media between storms may weaken sorption bonds between metals and sediment/organic matter.
    - Salts: Salt application often increases in the winter to aid with traffic safety, and the increase in salt application results in the percolation of sodium and chloride into groundwater with little attenuation. Soils are not effective at removing salts, so the concentration may not decrease until the source is removed.
- Roadways have been observed to be a major source of groundwater contamination in urban areas in large part due to vehicular exhaust onto roads and nearby soils, and from landscaped roadside fertilization. Fertilization also introduces pesticides and associated chemical compounds into runoff. Phosphorus also is present in most runoff because of motor oil use. Additionally, phosphorus and bacteria concentrations increase from animal droppings, especially on roads that are conducive for dog walking. Road salting adds to the chloride content and salinity of runoff, which is not generally treated via filtration through soils.
- Treatment of stormwater is mostly accomplished through filtration, sedimentation, and sorption. This book contains a list of contaminants and their filterable fractions, along with suggestions for sedimentation pre-treatment facilities.
- General guidelines for the infiltration of stormwater across BMP types in the absence of comprehensive site-specific evaluations include:
    - Dry-weather storm drainage effluent should be diverted due to probably high concentrations of soluble heavy metals, pesticides, and pathogens.
    - Snowmelt runoff should be diverted because of high potential concentrations of soluble salts. Because permeable shoulders collect water primarily via sheet flow from travel lanes, diversion of runoff during critical loading periods is not generally practicable. As such, certain conditions, such as high degrees of salting and

snowmelt, may eliminate permeable shoulders as a viable option because of the threat to groundwater contamination.

- Runoff from manufacturing industrial areas should be diverted because of high soluble toxicant potentials.
- Construction site runoff must be diverted because of high suspended solids concentrations and expedited clogging of infiltration systems.
- Runoff from critical source areas, such as vehicle service facilities and large parking areas, should receive adequate pre-treatment to eliminate contaminant potential. This recommendation logically can be extended to high volume roadways.
- Runoff from residential areas should be considered for infiltration and should require minimal pre-treatment.
- Interpretation for permeable shoulders: Because permeable shoulders collect water primarily via sheet flow from travel lanes, diversion of runoff during critical loading periods is not generally practicable. As such, certain conditions, such as high degrees of salting and snowmelt, may eliminate permeable shoulders as a viable option for treatment in terms of groundwater contamination potential.

Peter T. Weiss, Greg LeFevre, and John S. Gulliver, *Contamination of Soil and Groundwater Due to Stormwater Infiltration Practices,* University of Minnesota, St. Anthony Falls Laboratory, 2008.

This paper summarizes common stormwater infiltration practices, common contaminants and their fates in infiltrating systems, and the potential for groundwater and soil/media contamination.

- The paper discusses removal mechanisms, groundwater contamination, and case studies for nutrients, specifically nitrogen and phosphorus.
- Heavy metals can be removed from infiltrating stormwater via adsorption to soil particles, settling pre-treatment, precipitation, diffusion into solid particles, occlusion, and biological uptake.
- Suspended solids are removed in infiltration systems primarily by filtration, which is dependent on particle size and the size of pore openings.
- Man-made organic compounds, including priority pollutants like petroleum hydrocarbons, are commonly found in runoff from roads and parking areas. Most compounds can be removed via volatilization, sorption, and degradation to levels that would not affect groundwater. Hydrocarbons are generally trapped within the first few centimeters of soil.
- Pathogens are more likely to occur in groundwater where there is a high groundwater table and near MS4 outfalls. Contamination depends on a number of environmental and pathogen factors, but transport to groundwater may be caused by infiltration through BMPs.
- Salts have a high potential for contaminating groundwater because they are water soluble, non-filterable, not readily sorbed to solids, and leach into groundwater as infiltration occurs.
- Groundwater is more susceptible to contamination from infiltrating BMPs in karst aquifers.

Robert Pitt, Shirley Clark, and Richard Field, "Groundwater Contamination Potential from Stormwater Infiltration Practices," *Urban Water*, 1999.

This study analyzes the potential effects of stormwater infiltration on groundwater quality for a number of constituents as a part of a multi-year study for the U.S. Environmental Protection Agency.

- For each constituent, the potential for groundwater contamination can be characterized based upon:
  - Likelihood of abundance in stormwater.
  - Mobility in soils.
  - Treatment prior to infiltration.
  - Method of infiltration used.
- The paper identifies the prevalence of each of the following contaminants, along with their associated removal processes and fate during infiltration, in depth: nutrients, pesticides, organic compounds, pathogens, metals, and dissolved minerals.
- In general, groundwater contamination is more probable when contaminants have one or more of the following characteristics: highly mobile in the vadose zone, highly abundant in stormwater, and/or highly soluble fractions in stormwater.
- The pollutants of most concern to contaminate groundwater and that have the most adverse effects were identified to be nutrients (nitrate), pesticides (lindane and chlordane), other organics (volatile organic compounds [VOCs], pyrene, 1, 3-dichlorobenzene, etc.), pathogens (enteroviruses), heavy metals (nickel and zinc), and salts.
- All dry weather flows, runoff from manufacturing areas, and combined sewer overflows should be diverted from infiltrating areas.
- In areas where snow and ice are common, the first snowmelt and early spring rainfalls should be diverted from infiltrating areas due to higher concentrations and their more saline and acidic nature. Note that this may not be practicable for permeable shoulders with stone reservoirs because they receive runoff as sheet flow.
- Pre-treatment in the form of filtration, sedimentation, or detention should be used to minimize the potential for groundwater contamination and prolong the life of the infiltration device.
- Surface percolation devices that have a substantial depth to groundwater are preferred over subsurface infiltration devices because they utilize the natural soil pollutant removal capacity.

David Fischer, Emmanuel G. Charles, and Arthur L. Baehr, "Effects of Stormwater Infiltration on Quality of Groundwater beneath Retention and Detention Basins," *Journal of Environmental Engineering*, 2003.

This paper presents the results of a comparative study in New Jersey between groundwater from 16 monitoring wells installed in stormwater treatment basins and 30 wells with shallow groundwater in areas of new-urban land use. The main findings are:

- Dissolved oxygen concentrations were significantly lower in areas below detention basins, possibly resulting from increased microbial activity induced by higher organic compound concentrations in infiltrating stormwater. These conditions favor nitrate reduction and denitrification and also are associated with high dissolved-iron concentrations and high alkalinity.

- The concentrations of VOCs and pesticides in the wells varied based upon land use within the tributary areas. Areas draining to treatment basins typically consisted of roads and parking lots.
    - These areas had higher concentrations of accumulated petroleum hydrocarbons, such as benzene and toluene, which decrease in volatilization as temperature decreases. This is present in higher detected levels in the winter as the concentrations are preserved.
    - Concentrations of two herbicides, metolachlor and prometon, were detected more frequently in basins due to their application to right-of-ways along highways. Other pesticides, such as atrazine and desethyl-atrazine, varied seasonally in detention-basin groundwater due to increased application during summer months.
    - The four most common VOCs—chloroform, trichloroethane (TCA), carbon disulfide, and perchloroethylene (PCE)—were detected more frequently and at higher concentrations in the background samples than in the basin samples. This may be due to dilution from infiltration water, and, with the exception of choloform, their high volatility relative to other contaminants under the detention basins.
- Infiltration rates were generally high, and large volumes of water were infiltrated through the basins, leading to high loading potential. These large volumes of water can reduce certain contaminants through dilution and increase the concentrations of others through application.

Water Balance

The first three references in this section analyze the impacts on the natural water balance from urban development and the infiltration of stormwater, and the fourth reference defines the natural, or "greenfield," condition. A summary table of natural water balance estimates is provided at the end of the section.

Patricia Gobel, Holger Stubbe, Mareike Weinert, Julia Zimmermann, Stefan Fach, Carsten Dierkes, Holger Kories, Johannes Messer, Viktor Mertsch, Wolfgang F. Geiger, and William G. Coldewey, "Near-natural Stormwater Management and its Effects on the Water Budget and Groundwater Surface in Urban Areas Taking Account of the Hydrogeologic Conditions," *Journal of Hydrology*, 2004.

This paper provides an analysis of the impacts on groundwater tables that may result from "near-natural" stormwater management in an urban area. This paper is based on a study area in Germany and three computer models. Near-natural stormwater management focuses primarily on retention, with delayed surface runoff, partial infiltration, and partial evaporation. The main findings in the study include:

- The water budget is a balance of evaporation, surface runoff, and groundwater recharge. When development occurs, evaporation and groundwater recharge are initially reduced, and surface runoff often increases when no controls are used.

- If infiltration practices are used in developed areas, the amount of new groundwater formed increases and may rise above the natural state due to approximately matching natural surface runoff and reductions in evapotranspiration (ET).
- Elevated groundwater levels may cause a number of severe problems: flooding and damage to buildings through buoyancy, damage to vegetation and beds of receiving waters, and formation of connections with contaminated sites and cemeteries and subsequent mobilization of pollutants.
- Parameters were varied in the model to analyze the effects of infiltration on the water budget and groundwater levels. These parameters included the size of developed area, degree of imperviousness in the developed area, infiltration rate, and the precipitation conditions. The factors that produced the greatest effects on infiltration were precipitation and infiltration rate.
- Development of an average density without infiltration caused the groundwater recharge to decrease from 221 to 163 mm/a. When 100 percent of the average rainfall for the region (799 mm/a) was infiltrated, the area-averaged groundwater recharge nearly doubled from 163 mm/a to 245 mm/a.
- The changes in depth to groundwater from infiltration varied widely and increased by up to 2.34 meters (approximately 7 feet) in some areas. In areas where the groundwater table was high prior to infiltration, there was some spreading of the high table and water logging. The water table near water courses showed the smallest changes. The infiltration rate in the soils correlated to the magnitude of changes in level.
- Modeling of the receiving water courses showed a potential increase in low-flow discharge from the initial state of 89 m^3/h up to 124 m^3/h as development and infiltration was increased.

Eric W. Strecker, Aaron L. Poresky, *Stormwater Retention On-Site,* The Water Report, 2009.

This paper discusses the implications of retention-based stormwater regulations and introduces decision criteria for determining whether retention is desirable and feasible based on climate patterns, project types, and site conditions. This paper provides a synthesis of literature, analysis, and the authors' experience implementing these types of standards.

- Among "retain on site" options, infiltration tends to have the highest potential where it is feasible and desirable.
- Infiltration is most appropriate where underlying soils have adequate ability to infiltrate water (typically A and B type soils). To achieve the same degree of infiltration in areas with low rates would require shallower ponding depths and larger surface areas.
- Natural (e.g., selenium) and anthropogenic (e.g., solvent) plumes or contaminated soils should identified when considering infiltration because of the potential to mobilize and spread contaminants.
- Infiltration should be implemented carefully to prevent groundwater contamination, with necessary pre-treatment or maintenance as needed. Land use activities, groundwater

plumes, soil contamination, separation to groundwater, soil type, and other factors should be considered.

- Geotechnical issues, such as steep slopes or expansive soils, may limit the feasibility to infiltration as well.
- Infiltration in some cases may extend base flows in ephemeral streams, which may result in changes in vegetation and habitat and associated environmental impacts downstream.
- Areas where the groundwater aquifer is actively managed for water supply provide the best opportunities for infiltration because of the unlikelihood of water balance issues.
- A typical water balance in semi-arid climates in the natural condition has 70 percent going to ET, 20 percent percolating, and 10 percent discharging to the surface. In scenarios where the area is developed with an infiltrating BMP (no under drain), the water balance changes to 70 percent percolating, 20 percent ET, and 10 percent surface discharge.
- A case study is presented that applies several of these factors to Orange County, CA. This case study found that many areas (up to more than 70 percent of the area of the County) would potentially be restricted by one or more infiltration feasibility/desirability factors.

Los Angeles and San Gabriel Rivers Watershed Council, *Water Augmentation Study-Research, Strategy and Implementation Report*, Los Angeles and San Gabriel Rivers Watershed Council, 2010.

The Los Angeles Basin Water Augmentation Study (WAS) is part of a long-term research project that started in 2000 and presents the regional groundwater recharge strategy. The overall recommendation is to use decentralized BMPs to increase infiltration in new and existing development and aid in groundwater recharge. Important findings leading to this conclusion are:

- The effect of stormwater infiltration on groundwater quality was evaluated at six sites through surface sampling, groundwater wells, and soil-pore samplers in the vadose zone. No apparent trends were present to indicate that infiltration would negatively impact groundwater. Water quality for some constituents was improved by infiltration where there was shallow groundwater.
- The GWAM estimated that 16 percent of precipitation (164,000 acre-ft) currently percolates to groundwater in the Los Angeles region, and that 50 percent (601,000 acre-ft) becomes runoff that is conveyed to the ocean. Implementing BMPs that are designed to infiltrate the first ¾ inches of each rain storm could add 384,000 acre-ft to groundwater recharge. The new water supply is valued at $311 million, using the Metropolitan Water District of Southern California (MWD) Tier 2 rate for 2010.
- Increase in groundwater recharge is a desirable outcome in the study area, where aquifers are actively managed for water supply. Additionally, in this area, the groundwater table tends to be relatively deep, and some soils have relatively high permeability.
- Benefits to infiltration across the basin include reduced demand for imported water and associated costs, reduced reliance on uncertain water supply, avoided cost of treatment for highway runoff volumes that breach wastewater conveyance systems, diminished need to

enhance storm drain conveyances, water conservation, new recreational and community uses, and enhancement of habitat, open space, and ecosystems.

- Some challenges and barriers facing decentralized infiltration include institutional barriers in governing bodies, existing developmental rules, stormwater regulations, groundwater management, cost and funding, and education and awareness.

Undeveloped Water Balance

Several studies were reviewed to provide estimates of the undeveloped (natural) condition water balance. For these studies, water balance elements consisted of (1) direct runoff, (2) baseflow resulting from infiltrated water entering channels as groundwater, (3) ET, and (4) recharge or change in water storage. Depending on study methods, some of these terms were grouped for some studies. Full citations are provided below the table. Findings are summarized as follows:

- The natural water balance varies greatly by region and by watershed conditions.
- Runoff tends to be a minor element of the water balance for natural conditions.
- The percentage of rainfall lost to ET varies from approximately 30 percent to more than 90 percent. In many cases, particularly in warmer climates, ET is the largest element of the water balance.

Using infiltration BMPs can alter the natural water balance of a site through changes in the distribution of water that infiltrates, goes to ET, and runs off on the surface or becomes baseflow. Table 1 demonstrates the variability in the natural water balance and indicates that the alterations due to infiltration will also be variable based upon site. Changes in the water balance may or may not be desirable, depending on site-characteristics. This information is presented as an initial basis for further investigation as part of developing feasibility and applicability guidelines.

Table 1. Evaluation of Variability in Undeveloped Water Balance by Region based on Selected Studies

Source:	Location:	Annual Fluxes (as percent of precipitation):
Church et al., 1995	Northeastern U.S.	Runoff and Baseflow = 55% ET and Recharge = 45%
Jefferson et al., 2008	Northwest (Cascade Mountains); the two study watersheds adjoin each other in the upper McKenzie River watershed on the west side of the Oregon Cascades	Runoff and Baseflow = 70%; ET = 30%; Water Storage Change = 0%
Milly, 1994	East of the Rocky Mountains	Runoff and Baseflow = 27%; ET = 73%; Water Storage Change = 0%
Mohseni & Stefan, 2001	The Baptism River watershed in northern Minnesota. The watershed is heavily timbered with both deciduous and coniferous trees.	Runoff and Baseflow = 55% ET and Recharge = 45%
Mohseni & Stefan, 2001	The Little Washita River watershed in Oklahoma. One-third of the watershed is cultivated, and the rest is either pasture or wooded pasture.	Runoff and Baseflow = 7% ET and Recharge = 93%

Source:	Location:	Annual Fluxes (as percent of precipitation):
Najjar, 1999	Susquehanna River Basin	Runoff and Baseflow = 49% ET = 51% Water Storage Change = 0%
Ng & Miller, 1980	Southern California Chaparral (average of 2 years of monitoring)	South facing: Runoff and Baseflow = 3%; ET = 97%, Storage Change Negligible North facing: Runoff and Baseflow = 9%, ET = 83% and Storage Change = 8%
Rose, 2009	Southeastern U.S.: five-state study area (Georgia, South Carolina, North Carolina, Virginia, and Maryland)	Runoff and Baseflow = 37% ET and Recharge = 63%
Ward, 1993	Texas	Runoff = 12.5 %; ET = 86 %; Recharge = 1.5%

Citations:

Church, M. R., G. D. Bishop and D. L. Cassell, 1995. Maps of regional evapotranspiration and runoff/precipitation ratios in the northeast United States. Journal of Hydrology. 168, 283-298.

Jefferson, A., A. Nolin, S. Lewis and C. Tague, 2008. Hydrogeologic controls on streamflow sensitivity to climate variation. Hydrol. Process. 22, 4371–4385.

Milly, P. C. D., and P. S. Eagleson, 1987. Effects of Spatial variability on annual average water balance. Water Resources Research, Vol. 23, No.11, 2135-2143.

Milly, P.C.D, 1994. Climate, soil water storage, and the average annual water balance. Water Resources Research, Vol. 30, No. 7, 2143-2156.

Moheseni, O., and H. G. Stefan, 2001. Water budgets of two watersheds in different climate zones under projected climate warming. Climatic Change 49: 77–104.

Najjar, R.G., 1999. The water balance of the Susquehanna River Basin and its response to climate change. Journal of Hydrology 219, 7–19.

Ng, E.. and P. C. Miller, 1980.Soil Moisture Relations in the Southern California Chaparral. Ecology, Vol. 61, No. 1, pp. 98-107.

Rose, S., 2009. Rainfall–runoff trends in the south-eastern USA: 1938–2005. Hydrol. Process. 23, 1105–1118.

Ward, G.H., 1993. A water budget for the state of Texas with climatological forcing. The Texas journal of Science, Vol. 45, Iss. 3, 249-264.

Permeable Pavement-Specific Studies

The references in this section are specific to the implementation of permeable pavement systems and address potential impacts on groundwater quality, treatment capacity, limitations, and various design configurations for a variety of systems.

Scholz Miklas and Piotr Grabowiecki, "Review of Permeable Pavement Systems," *Building and Environment*, 2006.

This paper outlined the most up-to-date research on permeable pavement systems at the time of publication. It also is the only paper identified that specifically addresses the potential impacts of large spills on roadways. The main points are summarized below:

- Porous concrete products, including paving stones or interlocking blocks, can function as pollution sinks due to the particle retention capacity of the concrete during filtration. Filtered pollutants can be removed during cleaning of the pavement.
- Geotextiles at the base of a permeable pavement system may help to prevent sand from migrating upwards into the system and can also assist with the retention and degradation of oil in the module if clogging is not an issue. They also retain particulate matter and can keep micro-pollutants, such as cadmium, zinc, and copper out of the groundwater.
- The possible fates of water reaching a permeable pavement system are infiltration to the base material, evaporation, and overland flow. These fates are mainly controlled by the particle size distribution of the bed material and retention of water in the surface blocks. Maintenance is necessary to sustain surface infiltration and storage capacity.
- Infiltration through a permeable pavement system supports groundwater recharge and, in some cases, can decrease groundwater salinity through dilution (where stormwater is not a source of salt). It can also add pollutants to underlying soils and groundwater if they are not removed from runoff prior to infiltration.
- Permeable pavement systems with ground infiltration are effective at removing suspended solids and nitrogen through denitrification in the ground or eventual plant uptake.
- Large hydrocarbon spills can be contained in a permeable pavement system due to its ability to function as a hydrocarbon trap and in situ bioreactor. Naturally developed microbial communities have degraded oil (PAHs) successfully where there is a prolonged aerobic, sulphate reducing, and denitrifying environment. Soils in permeable pavement systems can adsorb large concentrations of hydrocarbons. Oil interceptors can also be incorporated in the design where there is anticipated to be a need. The paper did not address potential spills of solvents or other mobile contaminants.
- Filtration in permeable pavement systems can remove suspended solids and lead at levels of 64 percent and 79 percent, respectively. Filtration through specific adsorption media can remove up to 95 percent of dissolved zinc and copper.
- If there are any concerns about infiltration mobilizing pollutants from contaminated soils to the groundwater, the system should be constructed with an impermeable membrane, and treated discharge should be piped to the acceptable drainage system.

C.J. Pratt, A.P. Newman, and P.C. Bond, "Mineral Oil Bio-Degradation within a Permeable Pavement. Long-term Observations," *Water Science Technology*, 1999.

This paper examines the capacity of permeable pavement to sustain an effective microbial population for the treatment of petroleum-derived pollutants through in situ bio-degradation. The main findings of importance are:

- Permeable pavement can be an effective in situ aerobic bioreactor, reducing the petroleum concentration in the effluent to 2.4 percent of the concentration applied to the permeable pavement.
- The limiting factor in biodegradation is nutrient supply, but a slow-release fertilizer with an affinity for oils may be able to sustain treatment. Nutrients must be effectively managed to prevent eutrophication and leaching to groundwater.

C. Dierkes, A. Holte, and W.F. Geiger, *Heavy Metal Retention within a Porous Pavement Structure*, Department of Civil Engineering, Urban Water Management, University of Essen. (1999).

This paper summarizes a study that analyzed the infiltrated water quality from four porous pavements systems with different sub-base materials. The systems were inundated with synthetic runoff spiked with heavy metals to determine whether they provided adequate treatment before reaching groundwater. This study only considered porous concrete. Other pavement surface types may have different patterns of metal retention due to different chemical properties and removal mechanisms.

- Roadway runoff has the highest concentrations of heavy metals and organic compounds, which may endanger groundwater if the natural buffer capacity in nearby soils is exceeded.
- All pavements are highly effective at retaining dissolved heavy metals.
- The highest retained concentrations are in the upper 2 cm of the porous concrete. Buffer capacities in the concrete are high enough to prevent mobilization by acids in rain.
- Higher concentrations of metals were measured in the sub-base up to 20 cm deep for cadmium and lead, and up to 10 cm for copper.
- Concentrations of cadmium and copper only reached the applicable limits in Germany in the effluent for very coarse sub-base materials.
- The results of this study suggest a minimum of 40 cm of unsaturated soil to serve as a buffer for groundwater.

Benjamin O. Brattebo and Derek B. Booth, "Long-term Stormwater Quantity and Quality Performance of Permeable Pavement Systems," *Water Research*, 2003.

This study monitored the durability, infiltration capacity, and water quality of four commercially available permeable pavement systems over the course of 6 years for daily parking usage. The site was selected with deep, good infiltrating soils. Surface runoff and subsurface infiltrate were analyzed for the following products: Grasspave^{2}®, Gravelpave^{2}®, Turfstone®, and UNI Eco-Stone®.

- Almost all water infiltrated for the models in all storms. Most surface runoff that occurred was attributed to leakage into the surface measuring trough and the parking of cars over pavers that saturated the surface. Grasspave2® had notable surface runoff for two events.

- Infiltrated concentrations were significantly lowered for motor oil, copper, and zinc: 89 percent of samples were below detection limits for motor oil, 72 percent for copper, and 22 percent for zinc.
- Hardness and conductivity were significantly higher in the infiltrated water, especially in the concrete-based systems (Turfstone® and UNI Eco-Stone®).
- Zinc concentrations in the infiltrated water and surface runoff increased significantly over time. Copper decreased over time for the Grasspave2® and the UNI Eco-Stone®.
- The flow path for the measured infiltrate was 10 cm, which is likely much less than the depth to groundwater for most systems, indicating that a greater attenuation of pollutants may occur and decrease the potential for long-term groundwater impacts.

Marty Wanielista and Manoj Chopra, *Performance Assessment of a Pervious Concrete Pavement Used as a Shoulder for an Interstate Rest Area Parking Lot*, Stormwater Management Academy, University of Central Florida, 2007.

This paper analyzes the infiltration performance and water quantity and quality impacts of the use of Portland cement pervious concrete in a shoulder area along Interstate 4 in central Florida. A pervious concrete depth of 12 inches was used, with an underlying 12-inch reservoir of pollution control materials below it. Flows and water quality of the filtrate through the concrete and the reservoir were measured at two locations: at the edge of the concrete and 7 feet away. The main findings are listed below:

- Untreated and unmitigated road shoulders affect water quality and water balance through (1) a decrease in groundwater recharge due to lack of infiltration, (2) an increase in the volume of runoff that will need to be treated, and (3) transport of contaminants to surface and subsurface waters.
- The open graded structure of pervious concrete promotes infiltration, and a pollution control media reservoir can help remove pollutants prior to infiltration to groundwater or piping to drainage.
- The concentrations of orthophosphate (dissolved phosphorus) and nitrate (dissolved nitrogen fraction) decreased in the filtrate samples relative to the stormwater runoff (between 43 and 86 percent reductions).

Kelly A. Collins, William F. Hunt, and Jon M. Hathaway, *Hydrologic and Water Quality Comparison of Four Types of Permeable Pavement and Standard Asphalt in Eastern North Carolina*, Interlocking Concrete Pavement Institute, 2007.

The purpose of this study was to compare the hydrologic and water quality differences among four types of permeable pavements and standard asphalt over a 1-year period. The four types of permeable pavements that were studied were pervious concrete, concrete grid pavers filled with sand, and two types of permeable interlocking concrete pavement with small sized aggregate in the joints and having 12.9 percent and 8.5 percent open surface area. The main conclusions are:

- All permeable pavements performed significantly better than asphalt in reducing runoff and peak flow mitigation. There were slight differences between pavements, but these differences were insignificant when compared to the improvement over asphalt.
- The majority of flow from the permeable sections was in the form of subsurface drainage out of an under drain pipe, the quantity of which can be controlled through the inclusion of a sump or flow restriction to allow more water to infiltrate. Therefore, the flow leaving the cells can be significantly modified by design.
- Seasonally high groundwater tables likely affected the total subsurface runoff from the permeable sections, particularly during the winter months.
- Rainfall intensity was the best indicator of permeable pavement surface runoff generation and time to peak of runoff. Rainfall depth was the best indicator of total outflow volumes from permeable pavement and peak flow reductions.
- Permeable pavement and traditional asphalt concrete showed little difference in hydrology for large rainfall events (>50 mm).
- All pavements buffered acidic rainfall pH effectively; leaching of metals through pavements into groundwater is unlikely.
- Permeable pavement drainage had lower ammonium as nitrogen (NH4-N) and Kjeldahl nitrogen (TKN) concentrations than asphalt runoff and rainfall. The concentration of NO2, 3-N was higher from all pavements other than concrete grid pavers, possibly due to nitrification.
- TP and TSS in under drain discharge were not significantly reduced, probably because of the migration of subsurface soils into the unlined cells.

Matthias S. St. John and Richard R. Horner, *Effect of Road Shoulder Treatments on Highway Runoff Quality and Quantity*, Washington State Transportation Center, 1997.

This study compared the differences between the stormwater runoff from three types of road shoulder materials: conventional asphalt, gravel, and porous asphalt. The main conclusions from the study pertain to reductions in efficiency following sanding and the infiltration of soluble contaminants to soils below the pavement:

- Porous asphalt shoulders have a higher potential for runoff reduction, with an 85 percent reduction observed compared to conventional asphalt during typical wet season storms in Washington. For larger storms (> 1.27 cm), the reduction was 60 percent.
- Runoff from porous asphalt had reduced pollutants concentrations (BOD and COD, TP and OP, metals, and petroleum fractions) during the wet seasons of 30 to 60 percent less than conventional asphalt. For storms following sanding of the roads, the pollutant and solids concentration reductions from porous asphalt were 40 to 50 percent lower than from traditional asphalt.
- Pollutant and solids loads from porous asphalt were up to 90 percent lower than from traditional asphalt during the wet season. Loads following sanding were 75 percent lower.

- Pollutant removal rates were highest for contaminants associated with suspended solids, indicating that settling and filtration were critical processes in media.
- Soluble contaminants were also removed, particularly OP, via infiltration to soils below the pavement.

Rob Berbee, Gerard Rijs, Rene de Brouwer, and Lood van Velzen, "Characterization and Treatment of Runoff from Highways in the Netherlands Paved with Impervious and Pervious Asphalt," *Water Environment Research*, 1999.
This paper presents the results of a study on the quality of runoff from pervious and impervious asphalt surfaces and the effects of sand filtration and settling on the runoff water quality. The paper analyzes pollutants that discharge from the under drains of the system, and it outlines which pollutants enter the pervious asphalt layer and bind to the material or may potentially infiltrate to groundwater. The major findings are summarized below:

- Pollutant concentrations from pervious asphalt are significantly lower than runoff from impervious asphalt (heavy metals, PAHs, mineral oil, suspended solids, and oxygen-consuming substances). Copper, lead, and zinc are the most prevalent heavy metals, with lead primarily found in or attached to particulates. Copper and zinc concentrations in the permeable asphalt runoff are also significantly reduced, but the percent attached to particulates significantly decreases compared to the impervious asphalt runoff condition, indicating that the metals discharged from the under drains are more dissolved.
- Settling is a significant factor in removal of copper, lead, and zinc, but has a smaller effect in pervious asphalt runoff because of the reduced fraction of particulate-bound metals. A similar pattern was observed with filtration, due to the already reduced concentrations of heavy metals in the runoff from pervious asphalt.
- The suspended solids removed from stormwater accumulate in the pervious asphalt, which may result in clogging and reduced drainage. Highway shoulders in particular may be susceptible to clogging because of limited vehicular use and the lack of turbulence created by high speed vehicles to keep voids open. Maintenance is required periodically.
- Pervious pavements provide for higher evaporation than traditional pavements do, which further reduces the runoff pollutant load.
- The study suggested that pervious asphalt can require higher doses of salt in the winter to prevent slipping, which may result in mobilization of metals and higher chloride levels in water that infiltrates to groundwater.

General Infiltration Issues

The references in this section address the use of infiltration as a means for managing stormwater in general. Both publications address the benefits and limitations of implementing infiltration, as well as the potential impacts on the groundwater water quality and water balance.

Shirley E. Clark, Katherine H. Baker, J. Bradley Mikula, and Catherine S. Burkhardt, *Infiltration vs. Surface Water Discharge: Guidance for Stormwater Managers*, Water Environment Research Fund, 2006.

This comprehensive research report identifies the potential effects of infiltration on surface water quality, groundwater quality, microbial communities, and water balance. The document also includes tools to help stormwater managers determine whether infiltration is feasible, what criteria need to be evaluated for infiltrating BMPs, and identifies a number of useful regulatory documents with guidance for BMP development. The main findings include:

- A number of studies addressed the potential of groundwater contamination from infiltration.
- Retention of pollutants with the media and filtration of sediment and associated pollutants in porous pavements were observed in a number of cases.
    - The efficiency of infiltrating BMPs to remove or mitigate groundwater pollutants depends on pollutant characteristics, infiltrating capacity, soil characteristics, rainfall intensity, and BMP configuration.
    - Performance data from a number of studies for infiltrating BMPs are presented by comparing concentrations of pollutants in the inflow and outflow. These data can be used as an indication of the quantity of pollutants that are retained in the infiltration system or migrate to groundwater.
- The publication identifies and categorizes 28 pollutants according to their potential for groundwater pollution based upon their mobility, abundance, and soluble fractions.
- The publication reports the results of a computer model (SESOIL) that was developed for the EPA to help predict the fate and transport of pollutants in unsaturated soil during infiltration, with a focus on three main soil properties affecting migration: intrinsic permeability, organic content, and pH. Rainfall was determined to be the primary controlling factor for depth of migration of pollutants.
- The effects of hydrology and geomorphology following urbanization in watersheds were summarized as increased frequency of flooding and peak flows, decreased base flows, increased sediment loading, changes in morphology and habitat modification, increased stream temperature, and changes in pollutant concentrations in runoff.
    - Base flows typically decrease when infiltration is reduced, due to added impervious area. This may drop the groundwater level and reduce the water that can enter streams through springs or groundwater seepage.
    - The use of infiltration basins may aid in recharging the groundwater and elevating base flow by increasing the water in the soil within/around the basin and forcing soil water to migrate outwards.
    - The water infiltrated may also be detained and released more slowly over time, allowing for eventual groundwater recharge.
- A literature review is provided for a number of studies that address stream health impacts from urban runoff and stormwater.
- Finally, the report outlines some knowledge gaps pertaining to infiltration: microbial pollution and its impacts, the effects of pollutants on stream integrity, the possibility and effectiveness of stream restoration, and better modeling on pollutant migration below BMPs.

Orange County Public Works, *Technical Guidance Document for Preparing WQMPs*, http://www.ocwatersheds.com/DocmgmtInternet/Download.aspx?id=638, May 19, 2011.

This Technical Guidance Document (TGD) was one of the first of its kind to develop comprehensive feasibility criteria for retaining stormwater "on site," including criteria for evaluating if infiltration is feasible and desirable. The MS4 permit in Orange County requires project proponents to conduct a rigorous technical analysis to determine whether it is feasible to infiltrate the runoff from the 85th percentile rainfall event. The TGD was developed by Orange County Public Works to provide guidance for making these determinations. A summary of key elements is as follows:

- There are a number of factors and conditions that may limit the feasibility of infiltration.
    - Factors that physically restrict the flux into the ground:
        - Low soil infiltration rates.
        - Groundwater mounding.
        - Limiting soil horizons.
    - Factors that with potential to result in undesirable impacts on human health, property, and/or environmental resources (risk-based).
        - Geotechnical instability.
        - Degradation of groundwater quality.
        - Increase in base flows of ephemeral channels, and associated habitat impacts.
        - Increase in I&I into the sanitary sewer.
- The TGD provides guidance for evaluating these factors:
    - Infiltration rate is impacted by compaction, subsurface depth, clogging, and temperature/freezing.
    - Rates under permeable pavement including asphalt, concrete, and interlocking concrete block pavers in right-of-ways may be lower due to necessary structural compaction.
    - The presence of shallow groundwater can reduce infiltration rates below a BMP, cause groundwater discharge into the stormwater drainage system, and result in locally elevated groundwater tables (or mounding).
    - Shallow groundwater below a BMP can increase the risk of groundwater contamination. Special consideration should be given for situations where there is direct connectivity between the BMP and an unconfined aquifer.
    - The following factors must be considered in determining whether infiltration can be done safely while protecting groundwater quality:
        - A separation to groundwater of 10 feet must be provided; this may be reduced to 5 feet where BMPs are shallow and infiltrate from the surface, through more biologically active soils.
        - Sources of pollutants from the tributary area. Different land covers and uses are assigned different ranges of risk.
        - Limited treatment capacity for groundwater contaminants provided in the BMP or in underlying soils. For example, subsurface BMPs that infiltrate

    through inert sandy material pose a higher risk than surface BMPs that infiltrate through biologically-active soil layers.
    - Presence of contaminated soils, groundwater plumes, and septic systems such that infiltrated water could mobilize pollutants or spread them within the aquifer.
    - Proximity to wellhead protection zones.
  - Implementing infiltration BMPs with the goal of matching pre-development runoff volumes has the potential to change the natural water balance by increasing the amount of water infiltrated to groundwater and reducing the amount evapotranspired. Increased groundwater recharge may be desirable in "managed aquifers" with adequate capacity, but in some groundwater systems, an increase in infiltration volume may cause issues with slope stability, extend unseasonal base flows in down gradient channels, and increase liquefaction and seismic risks.
  - Infiltration can increase the risk of geotechnical hazards, which include steep or sensitive slopes/landslide hazard zones, manufactured fill, liquefaction hazard zones, foundation and subbase issues, and infrastructure damage associated with expansive clays.
  - Infiltration may be incompatible with existing or proposed underground infrastructure, such as subsurface construction, sanitary sewers, and dry utilities.
- The TGD requires consultation with applicable groundwater agencies for cases with greater potential to cause impacts to groundwater quality. The guidance was developed in coordination with the Orange County Water District, which is the groundwater manager for much of the region.
- The TGD provides guidance that is specific to transportation uses:
  - Roadways with ADT greater than 5,000 but less than 25,000 are classified as having "moderate" potential for groundwater contamination. Pre-treatment should be selected to address potential groundwater contaminants potentially found in stormwater runoff.
  - Roadways with ADT greater than 25,000 are classified as having a high risk for groundwater contamination. Infiltration is prohibited unless pre-treatment and spill isolation are feasible and enhanced monitoring and inspection are implemented. The traffic level criterion was specified in the MS4 permit for the area, but no technical citation was provided in the permit as the basis for this number.

Long-Term Benefits

Little is available in the literature on the long-term performance and sustainability benefits of pervious pavements, but the design approach is promoted as more sustainable or desirable in the long run in numerous design systems and policies. Sustainability benefits cited in the literature in previous sections are not duplicated here, but rather included in the summary at the front of this document.

Sustainability and long-term benefit calculation are now high-level objectives at both AASHTO and FHWA. In 2009, AASHTO President Allen Biehler included sustainability among the agency's critical areas of emphasis, explaining, "Transportation's mission is no longer about just moving people and goods. It's much broader. Transportation fundamentally allows us to achieve economic, social, and environmental sustainability. Transportation supports and enhances our quality of life." (AASHTO Emphasis Areas, 2009).

Water Quality Benefit and Long-Term Maintenance Research

Bradley J. Eck, Ryan J. Winston, William F. Hunt, and Michael E. Barrett, M.ASCE, "Water Quality of Drainage from Permeable Friction Course," ASCE, 2012.

Eck et al. reviewed overlays of PFC as an innovative roadway material that improves both rainfall to drain within the porous layer rather than on top of the pavement. The paper presents water quality measurements for PFC and conventional pavement collected over 6 years near Austin, Texas, and 2 years in eastern North Carolina. The data show that concentrations of total suspended solids from PFC are more than 90 percent lower than from conventional pavement. Lower effluent concentrations are also observed for total amounts of phosphorus, copper, lead, and zinc. The combined data sets show that PFC's benefits last through the design life of the pavement, that results in Texas are consistent with those from North Carolina, and that both are consistent with earlier studies from France, the Netherlands, and Germany.

Marie Venner and Marc Leisenring, NCHRP 25-25/83, *Stormwater Management at DOTs*, 2012. Under NCHRP 25-25/83, researchers developed a comprehensive list of BMPs, in cooperation with state DOTs and in light of categorizations used in the WERF BMP database and elsewhere in the literature. The study included a survey of all 50 state DOTs, the District of Columbia, and Puerto Rico to identify which BMPs were used frequently, sometimes, rarely, or never. All 52 responded. Permeable shoulders with stone reservoirs were found to be used infrequently or never by DOTs, as of mid-2012.

Denver Urban Drainage and Flood Control District (UDFCD) *BMP-REALCOST tool.*
The Denver Urban Drainage and Flood Control District BMP-REALCOST tool produces "order-of-magnitude" approximations, for use primarily at the planning level, and includes:

- **Construction Costs**: Construction costs are estimated using a parametric equation that relates costs to a physical parameter of a BMP: total storage volume (for storage-based BMPs), peak flow capacity (for flow-based or conveyance BMPs), or surface area (for permeable pavements).
- **Maintenance Costs**: Maintenance costs are estimated using a derived equation that relates average annual costs to a physical parameter of the BMP.
- **Contingency/Engineering/Administration Costs**: The additional costs of designing and permitting a new BMP are estimated as a percentage of the total construction costs. For Denver-area projects, a value of 40 percent is recommended if no other information is available.
- **Land Costs**: The cost of purchasing land for a BMP is estimated using a derived equation that incorporates the number of impervious acres draining to the BMP and the land use designation in which the BMP will be constructed.
- **Administration Costs**: The costs of administering a stormwater management program are estimated as a percentage of the average annual maintenance costs of a BMP. For Denver-area projects, a value of 12 percent is recommended if no other information is available.

- **Rehabilitation/Replacement Costs**: After some period in operation, a BMP will require "major" rehabilitation. The costs of these activities (including any salvage costs or value) are estimated as a percentage of the original construction costs and applied near the end of the facility's design life. The percentages and design lives vary according to BMP.

NCHRP 25-40, *Life Cycle Costs of Stormwater BMPs (in process) – excerpt* (2012-2014).

UDFCD's BMP-REALCOST tool produces net present value (NPV) of the whole life costs of the BMP(s) implemented, the average annual mass of pollutant removed (PR, lb/year) and the average annual volume of surface runoff reduced (RR, ft/year), which can then be used to compute a unit cost per lb of pollutant (CP) or cubic feet of runoff (CR) removed over the economic life (n, years) of the BMP. WEF (2012) and Lampe et al. (2005) produced life-cycle cost analyses for a variety of BMP types. Some of the concluding highlights are noteworthy:

- Maintenance costs of wet basins make up almost 50 percent of the whole life cost when basins are implemented in high-visibility locations, where aesthetics are at a premium. Dry basins tend to be easier and less expensive because there is little or no standing water in the facility. Wet and dry basins cost the same to construct.
- The primary maintenance cost of bioretention is associated with vegetation management. The frequency of this activity was assumed similar to swales, but with a greater cost because many bioretention facilities would require weeding, mulch replacement, and other activities beyond the mowing required for most swales.
- For swales and filter strips, water quality benefits can effectively be considered free when compared to conventional drainage systems, as well as when the maintenance is performed by the property owner.
- Infiltration trenches may require little routine maintenance outside of litter and debris removal. The whole life cost driver is the frequency with which the trench must be rehabilitated. Intervals of 4, 8, and 12 years were assumed based on low, medium, and high scenarios, at which time the cost is essentially the same as the original construction cost. For infiltration basins, the capital cost and routine maintenance are essentially the same as those for a dry basin, but an infiltration basin can incur much higher costs associated with maintaining sufficient infiltration rates. In addition to sediment removal, an infiltration basin may require additional activities to remove and replace clogged soils on the floor of the basin. The frequency of this activity largely depends on the initial soil texture and the rate at which sediment accumulates in the basin.
- With pervious pavement in the same location as a conventional surface, the cost for the water quality control facility is the incremental cost difference between a conventional pavement and the pervious pavement. The difference in whole life cost depends on the frequency of sweeping. DOTs have expressed interest in the safety and livability co-benefits offered: better visibility and traction in storm events, reduced splash and hydroplaning, and

> reductions in deflected noise from highway traffic. Porous asphalt overlays have been constructed in Georgia, California, California, and Utah. PFC was up to 8.1 percent of all pavements in Texas in 2010. The pavement is assumed to need replacement more frequently (every 25 years vs. 35 and 40 years) at a cost equal to original construction. Water quality monitoring of three locations in the Austin area indicates up to a 90 percent reduction in pollutant discharges from PFC compared to conventional pavement. This reduction is the result of accumulation of pollutants within the pavement and the reduction in pollutants washed off vehicles during storm events.

With the exception of infiltration trenches, which may clog/fail and require total reconstruction on a shorter timeframe than many other facilities, the higher level maintenance cost scenario is driven by aesthetics and local expectations for frequency of mowing, rather than functioning of the water quality facility. In initial NCHRP 25-40 interviews, Hydraulics staff at the Maryland State Highway Administration reported, “infiltration BMPs are failing more quickly and the reasons are not always clear. Mechanical filters are meant to be maintained regularly but stormwater systems are not maintained to this degree. Removing the top layer of soil, some infiltration facilities can be restored to initial conditions, but some do not. Facilities may prematurely fail due to generally poor soil characteristics, rising groundwater or groundwater mounding.”

DOTs can preserve functioning and extend the life cycle of BMPs if they prevent sedimentation of permanent BMPs during construction on the project or upstream, as the majority of sediment problems in permanent controls are caused by inadequate erosion and sedimentation control from construction upstream of the structure. In a stable urban watershed, WEF estimates that normal annual accumulation of sediment would be less than 1 cm per year. A UK survey identified that no upstream pre-treatment was provided in 85 percent of the stormwater controls where sediment was a problem, a particular issue in the more expensive maintenance involved in wet basins. Heavier solids, leaves, trash, and debris frequently outweigh the load based on total suspended solids.

Some DOTs and municipalities have tried to control the maintenance costs of permanent BMPs by constructing larger facilities. In other cases, municipalities have enacted preferences for small landscaped systems like bioretention, where hundreds of facilities could be contained within a single site.

To facilitate the comparison of costs among BMP types, Barrett et al. normalized the whole life cost for each system for high, medium, and low maintenance scenarios for each BMP type, based on the equivalent water quality volume.

Table 2. Whole Life Costs of Common BMPs per Cubic Meter of Stormwater Treated (WEF, 2012)

Stormwater Control	**Whole Life Cost ($/m^3)**		
	Low Maintenance	Medium Maintenance	High Maintenance
Swales/Strip	500	660	2200
Wet Ponds/Wetlands	520	600	925
Dry Extended Detention Basins	330	375	575
Sand Filter	450	520	670
Bioretention	1900	2200	5100
Infiltration Trench	1200	1600	2700
Infiltration Basin	330	400	700
Permeable Pavement	570	640	1400

The WEF publication released in 2012 adapts, summarizes, and extends in some places the 2005 work by Lampe et al. that identifies the maintenance required for various types of stormwater controls, at low, medium, and high levels and associated costs, in order to assist agencies in planning and budgeting.

FHWA, *Pavement Management Roadmap,* 2012
http://www.fhwa.dot.gov/pavement/management/roadmap/pdf/problemstatements.pdf.

FHWA's Pavement Management Roadmap research statements do not include pervious or permeable pavements. FHWA Asset Management Program, http://www.fhwa.dot.gov/asset/index.cfm. FHWA's Asset Management Program is incorporating a broader vision of preservation, efficiency, and sustainability. FHWA now publicizes their priorities and how they do business:

- Preserve our assets and minimize their whole life cost.
- Operate in a financially sustainable manner.
- Provide a framework to improve performance on a long-term basis.

Sustainability Research

Marie Venner and Parsons Brinkerhoff, NCHRP 25-25/04: *AASHTO Compendium of Environmental Stewardship Practices, Policies, and Procedures in Construction and Maintenance,* 2005.

The Design section of this manual discusses permeable pavements and the benefits thereof. At the time of publication, permeable pavements were being used primarily in parking lots and alleyways (EPA also promoted the latter as part of their Green Infrastructure program for water quality). DOTs were also beginning to use PFCs or open-graded friction courses for safety purposes. The compendium is maintained by AASHTO online at:
environment.transportation.org/environmental_issues/construct_maint_prac/compendium/manual/
.

Marie Venner and ICF, NCHRP 25-25/63: *Corridor Environmental Management,* 2012.

This NCHRP project studied permeable pavement overlays as a water quality solution for state DOTs.

CH2M Hill, *Best Practices Background Paper on Transportation and Sustainability, Sustainability Peer Exchange*, AASHTO Center for Environmental Excellence, May 27-29, 2009.

Sustainability rating systems are used to support decision making by quantifying the performance of transportation decisions or projects, as well as for benchmarking, acknowledging good performance, and determining where performance could be improved. As AASHTO's Sustainability and Transportation white paper notes, rating systems can be used in the following ways:

- Defining basic transportation sustainability attributes. A list of sustainable transportation attributes can be useful to those seeking to design/construct a more sustainable roadway.
- Garnering greater participation in transportation sustainability. The idea of rating systems is to present transportation and sustainability in a straightforward manner so that everyone can understand and participate in sustainability, particularly at a project level.
- Evaluating sustainability tradeoffs. Every project involves tradeoffs. Rating systems can compare two different items using a common point system to determine their relative impact.
- Providing a means for sustainability assessment. Rating systems can help track sustainability progress.
- Confer market recognition for sustainability efforts. Rating systems can help increase awareness of sustainability efforts and gives recognition to those who participated in the effort.

Centre for Sustainable Transportation, "Definition and Vision of Sustainable Transportation," 2002. http://cst.uwinnipeg.ca/documents/Definition_Vision_E.pdf.

The definition of a sustainable transportation system developed by the Centre for Sustainable Transportation has been used and endorsed both in North America and in Europe. Such a system:

- Allows the basic access needs of individuals and societies to be met safely and in a manner consistent with human and ecosystem health, and with equity within and between generations.
- Is affordable, operates efficiently, offers choice of transport mode, and supports a vibrant economy.
- Limits emissions and waste within the planet's ability to absorb them, minimizes consumption of non-renewable resources to the sustainable yield level, reuses and recycles its components, and minimizes the use of land and the production of noise.

United Nations World Commission on Environment and Development (Brundtland Commission) Report – Our Common Future, 1987.

The United Nations World Commission on Environment and Development (Brundtland Commission) Report states that sustainable development "meets the needs of the present without compromising the ability of future generations to meet their own needs."

AASHTO Center for Environmental Excellence, "Environmental Management Systems," 2009. http://environment.transportation.org/environmental_issues/environ_mgmt_sys/#bookmarkEMSFundamentals.

Environmental management systems (EMSs) are designed to help an agency reduce its environmental impacts and manage a full range of environmental, public health, and safety issues. The goal of an

EMS is to continually improve environmental performance and provide benefits like reduced costs through energy and water conservation, reduced chemical usage, reduced risk of noncompliance, and so on. One organization that provides certification for the implementation of an EMS is the International Organization for Standardization, or ISO. ISO standard 14001 is the specification for environmental management. ISO 14001 requires annual auditing, after initial certification, to ensure that processes are maintained to meet the standards for reliable water and wastewater services.

Josias Zeitsman and Tara Ramani, NCHRP Project 8-74: *A Guidebook for Sustainability Performance Measurement for Transportation Agencies*, 2011.

NCHRP 8-74 references planning and programming projects that maintain and improve the quantity and quality of water and aquatic ecosystems. By including more permeable pavements, DOTs would be able to achieve this performance measure.

Oregon DOT, *Permeable Pavements Experience and Sustainability Plan, Volume 1*. September 2008. http://www.oregon.gov/ODOT/SUS/docs/Sustain_Plan_Volume1.pdf.

Oregon DOT has explored permeable pavements in alleyways in recent years. Also, the DOT uses an open graded mix for a wearing course mostly on its higher volume highways. A 1994 evaluation of porous pavements used in Oregon (Younger et al.) noted that, "porous pavements or open-graded asphalt mixtures have been in use in Oregon since the late 1960s. The use of this pavement type has increased over the years because the pores in the mat provide an efficient way for water to drain from the pavement surface. This greatly increases safety in the areas of skid resistance and splash and spray."

In 2004, the City of Portland paved three blocks of streets in the Westmoreland neighborhood with permeable pavement that allows water to go through the street surface and into the ground. Similar materials are used locally in parking lots and private driveways.

The 2008 Oregon DOT Sustainability Plan includes strategies to manage both internal agency operations and the statewide transportation system towards sustainability. The plan contains strategies for achieving sustainability goals, indicators for tracking progress, and a description of implementation activities. The goals, indicators, strategies, and actions in the plan are divided into seven focus areas, which include: (1) Health and Safety, (2) Social Responsibility/Workforce Well-Being and Development, (3) Environmental Stewardship, (4) Land Use and Infrastructure, (5) Energy/Fuel Use and Climate Change, (6) Material Resource Flows, and (7) Economic Health. Since 2004, the Oregon DOT has incorporated sustainability into the 2006 update of the Oregon Transportation Plan and the State Bridge Repair Program, and they have begun the implementation of a comprehensive Sustainability Program. The Sustainability Program seeks to institutionalize the concept of sustainability and create a structured framework in which the agency's sustainability initiatives are carried out.

Relevant DOT Policies, Plans, and Reports

Georgia Department of Transportation, *Progress in Open-Graded Friction Course Development*, December 2007. http://www.dot.state.ga.us/doingbusiness/research/Documents/reports/r-OGFC.pdf

The Georgia DOT requires that all interstates and state routes with daily traffic volumes more than 25,000 vehicles use porous asphalt as the final ride surface. This improves safety for drivers as well as providing environmental benefit. GDOT uses a type of porous asphalt known as open-graded friction course (OGFC). While OGFC has caused problems for state DOTs in the past, the addition of materials such as hydrated lime, stabilizing fibers, mineral fibers, and polymer modified asphalt concrete have improved its performance. According to the GDOT Assistant State Materials Engineer, the use of OGFC reduces highway noise and increases surface drainage. In addition, the porosity of the pavement has resulted in reduced potential for hydroplaning, a reduction of splash and spray, improved friction; better nighttime visibility, and better visibility of traffic striping.

Bradley J. Eck, Ryan J. Winston, William F. Hunt, and Michael E. Barrett, M.ASCE, "Water Quality of Drainage from Permeable Friction Course," *Journal of Environmental Engineering,* ASCE, 2012.

A PFC overlay is an innovative method for improving both driving conditions in wet weather and water quality. Placed in a layer 25 to 50 mm thick on top of regular impermeable pavement, PFC allows rainfall to drain within the porous layer rather than on top of the pavement. This paper presents water quality measurements for PFC and conventional pavement collected over 6 years near Austin, Texas, and 2 years in eastern North Carolina. The data show that concentrations of total suspended solids from PFC are more than 90 percent lower than from conventional pavement. Lower effluent concentrations are also observed for total amounts of phosphorus, copper, lead, and zinc. The combined data sets show that PFC's benefits last through the design life of the pavement, that results in Texas are consistent with those from North Carolina, and that both are consistent with earlier studies from France, the Netherlands, and Germany.

Rating Systems

New York State DOT, *GreenLITES Design Certification.*

The New York State DOT (NYSDOT) has developed a program called GreenLITES (Leadership in Transportation and Environmental Sustainability), a self-certification program that awards transportation projects based on the extent to which they incorporate sustainable design choices. GreenLITES is an internal management program for NYSDOT to measure performance, recognize good practices, and identify improvements where needed. The program allows transportation project designs with environmentally sustainable features to be eligible for green certification. GreenLITES distinguishes transportation projects based on the extent to which they incorporate sustainable design in the following categories: (1) Sustainable Sites, (2) Water Quality, (3) Materials and Resources, (4) Energy and Atmosphere, and (5) Innovation/Unlisted. Projects are scored according to their impact and contribution to advancing the state of practice in furthering sustainability. Points can be accrued for permeable pavements. NYSDOT also has a GreenLITES Operations Certification Program; please see https://www.nysdot.gov/programs/greenlites/operations-cert for details.

Steve Muench, "Greenroads," paper and presentation from the TRB 2009 Annual Meeting, Washington, DC, January 2009. Also see http://www.greenroads.us/

Greenroads is a prototype rating system specifically for the sustainable design and construction of roadways. It was jointly developed by CH2M HILL and the University of Washington. It is modeled after the Leadership in Energy and Environmental Design (LEED) green building rating system administered by the U.S. Green Building Council (USGBC). The system outlines key prerequisites that a project must meet to qualify for Greenroads certification. It also carries a variety of optional credit categories under the following headings: Environment and Water, Access and Equity, Construction Activities, Materials and Resources, Pavement Technologies, and Exemplary Performance. One key benefit is that the credit categories lend themselves to quantifiable performance. While many of the data/metadata needed to inform these performance indicators are likely not part of current data collection regimen, they are quite specific to project improvements. This data collection could be tasked to contractors, with state DOT or transportation agencies providing oversight. Points can be accrued for permeable pavements.

The Federal Highway Administration (FHWA), Infrastructure Voluntary Evaluation Sustainability Tool *INVEST Version 1.0.*

The FHWA launces and sustainable highways self-evaluation tool in October 2012. It is intended to assist transportation agencies integrate sustainability into their policies, processes, procedures, practices and projects. It considers the full lifecycle of projects and has three modules to self-evaluate the entire lifecycle of transportation services, including system planning, project development, and operations and maintenance.

American Society of Civil Engineers (ASCE), *Envision™ Sustainable Infrastructure Rating System.*

The Institute for Sustainable Infrastructure (ISI) launched, the sustainable infrastructure rating system Envision™, in January 2012. The system evaluates, grades and gives recognition to infrastructure projects that contributes to a sustainable future. .

Appendix B

Lessons Learned

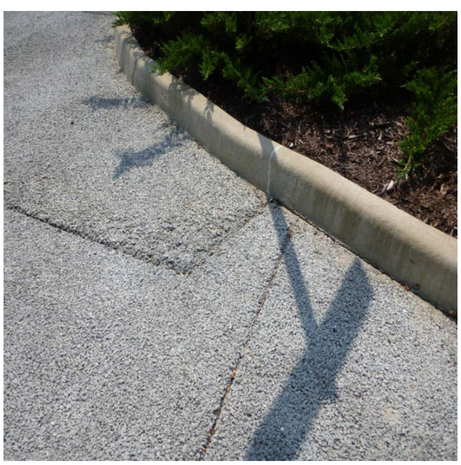
	During construction, it is recommended that the infiltration capacity of the subgrade is verified prior to the placement of the stone reservoir. This will ensure that the hydrological condition of the pavement is adequate.
	Stone reservoir aggregate should be protected from contamination from the surrounding area by grading the area away from the stone reservoir or using protection devices such as silt fences. (Photograph shows poor protection).
	Site conditions should be kept as clean as possible to avoid contamination of the subgrade and stone reservoir.

	Contamination of the subgrade should be avoided by end dumping the stone reservoir aggregate and spreading it forward using a bulldozer.
	Compaction should be completed using appropriate equipment for the area and thickness of the aggregate layers. The equipment shown would likely result in non-uniform compaction.
	Smooth wheel steel drum compaction equipment for permeable base aggregate.

	Installed permeable pavement should be protected from damage and contamination from construction vehicles.
	ASTM No. 57 gradation stone. Note that it is crushed, cubical and free of fines.
	ASTM No. 2 gradation stone. Note that it is crushed, cubical and free of fines.

	Proper stockpiling of landscaping materials over a permeable pavement.
	Failure to properly protect the permeable pavement during an intense storm at the time of construction.
	Permeable shoulder pavement completely covered with construction materials.

	Permeable strip paving to improve localized drainage issues. Note the concrete curb adjacent to the asphalt paving to the right.
	Settlement and ponding at a transition between a permeable and non-permeable pavement. The transition is poorly chosen as a low point.
	Pervious concrete parking area. Note the surface ponding, leave contaminants on the pavement and cracking of the slabs. Small aggregate was used and the resulting higher cement content may have contributed to the surface cracking.

	Severe raveling caused by late season concrete placement, inconsistent consolidation and inadequate curing of the concrete.
	Minor joint raveling. Poor selection of joint locations leading to cracking of the pervious concrete.
	Surface raveling and poor joint treatment.

	Well consolidated pervious concrete constructed using a fixed form.
	Consistent pervious concrete surface.
	Good quality concrete joint.

	Mechanical installation of interlocking concrete block pavers.