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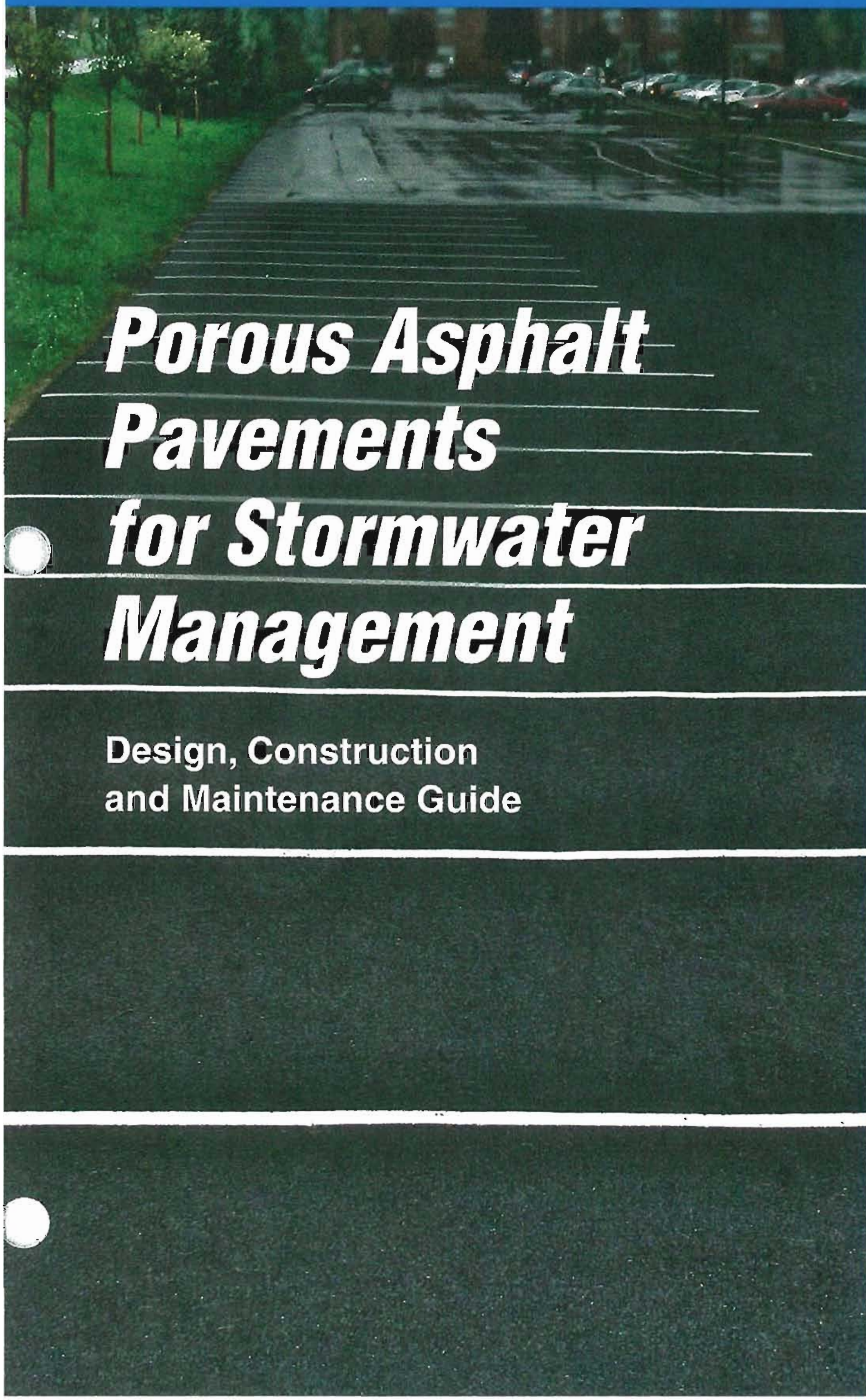

Porous Asphalt Pavements for Stormwater Management

Design, Construction and Maintenance Guide

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In a seniors' community in Iowa, a water truck demonstrates how porous pavement at the right drains quickly, while water stands on the conventional pavement at the left.

Porous Asphalt Pavements for Stormwater Management

Design, Construction and Maintenance Guide

Introduction

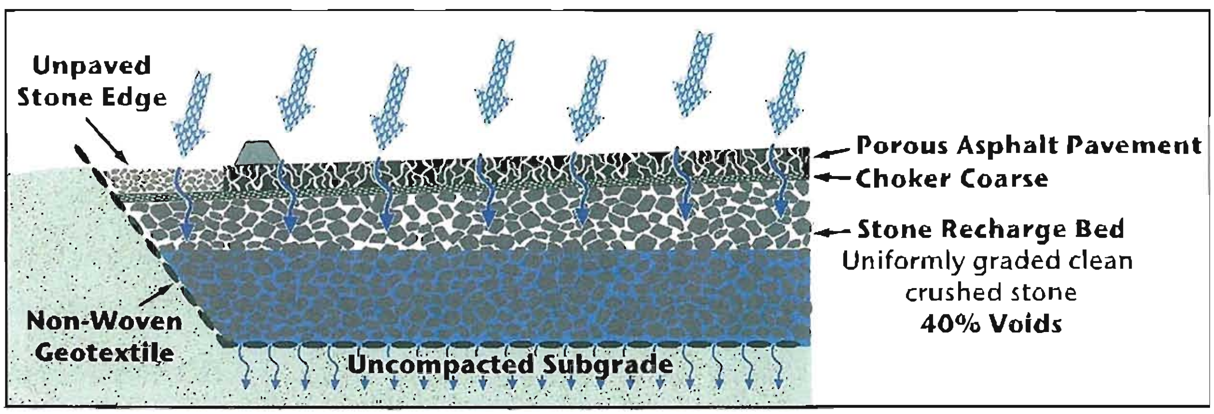
Porous asphalt pavements are designed for dual duty: they provide pavements for parking and roads and also serve as stormwater storage and infiltration systems. They are in demand because they offer site planners and public works officials the opportunity to manage stormwater in an environmentally friendly way. With the proper design and installation, porous asphalt structures can offer cost-effective, attractive parking lots with a long life span, while also providing stormwater management systems that promote infiltration, improve water quality, recharge groundwater, and keep peak and total volume of flow at or below pre-development values.

From the bottom up, the standard porous pavement structure consists of:

- An uncompacted subgrade to maximize the infiltration rate of the soil.
- A geotextile fabric that allows water to pass through, but prevents migration of fine material from the subgrade into the stone recharge bed.
- A stone recharge bed consisting of clean single-size crushed large stone with about 40 percent voids. This serves as a structural layer and also temporarily stores stormwater as it infiltrates into the soil below.
- A stabilizing course or "choker course" consisting of a clean single-size crushed stone smaller than the stone in the recharge bed to stabilize the surface for paving equipment.
- An open-graded asphalt surface with interconnected voids that allow stormwater to flow through the pavement into the stone recharge bed.

Porous pavements do not follow the traditional design of typical pavements. First, traditional pavement structures require the subgrade to be compacted to increase the soil strength. For porous pavements the subgrade should not be compacted since this would decrease the infiltration rate, requiring a thicker stone recharge bed or reducing the permeability enough to make a porous pavement ineffective. Second, typical pavements are constructed with a dense surface that is impermeable to water. For porous pavements, the water flows through the surface into the stone bed where it is temporarily stored and allowed to infiltrate through the soil.

FIGURE 1
Typical porous pavement cross section



A model home at Pringle Creek, a newly constructed (2007) green community near Salem, Oregon.

Overview and History

In the late 1960s, the concept of porous pavement was proposed to "promote percolation, reduce storm sewer loads, reduce floods, raise water tables, and replenish aquifers." (Thelen, 1978) Throughout the 1970s, the concept was discussed and refined to a point where the Environmental Protection Agency (EPA) contracted to "determine the capabilities of several types of porous pavements for urban runoff control, in terms of cost and efficiency." (Thelen, 1978) Some of the initial installations of porous asphalt pavement were in Delaware, Pennsylvania, and Texas. The Woodlands site in Texas, which was constructed under an EPA grant, was the only site where substantial scientific monitoring instrumentation was installed. (U.S. Environmental Protection Agency, 1980) In 1977, Edmund Thelen and L. Fielding Howe co-authored a design guide for porous pavement for the Franklin Institute in Philadelphia. This document has been widely referenced in subsequent years and provides a solid foundation for porous pavement designers.

Many additional porous pavement sites have been constructed since the late 1970s. While there have been both successes and failures, the overwhelming majority have succeeded. The most often cited reason for porous pavement failure was failure to control silts entering the porous pavement site, essentially clogging the pavement. Some of the benefits conferred by the successful installations include runoff control, aquifer recharge, reduction of drainage structures needed to comply with stormwater regulations, and increased skid resistance. Cahill Associates has been involved in the design and construction of more than 200 porous asphalt pavements since the 1980s and have reported no failures of pavements for which proper design and construction practices were followed.

This document provides guidelines and recommendations for design, construction, and maintenance of porous asphalt pavements. Factors considered for determining applicability include rainfall, soil infiltration capability, usage/loading, frequency of use, cost, and stormwater regulations.

Under the right conditions, a properly designed porous asphalt pavement will provide a best management practice (BMP) for stormwater runoff problems as well as groundwater recharge.

Economics and Feasibility

Porous pavement does not usually cost more than conventional pavement. On a yard-by-yard basis, the asphalt cost is approximately the same as the cost of conventional asphalt. The underlying stone bed is usually more expensive than a conventional compacted sub-base, but this cost difference is generally offset by the significant reduction in stormwater pipes and inlets. Additionally, because porous pavement is designed to "fit into" the topography of a site, there is generally less earthwork and there are no deep excavations. When the cost savings provided by eliminating the detention basin are considered, porous pavement is generally an economically sound choice. Cahill Associates has compared the costs of porous pavements to other stormwater management options. Generally the porous pavement has been the less expensive option.

Open-graded asphalt mix can be produced in any asphalt plant. Any qualified asphalt contractor can install a porous asphalt pavement system. Certification is not required.

Water Quality

Porous pavements are one of the most effective treatment methods for reducing pollution in stormwater runoff from pavements. Cahill reports that, although sampling on porous pavement systems has been limited, the available data indicate a high removal rate for total suspended solids (TSS), metals, and oil and grease. (Cahill, Adams, & Marm, 2005) Table 1 shows pollution removal efficiencies reported by Cahill.

Table 2 shows the pollution removal efficiency for a porous asphalt parking lot constructed at the University of New Hampshire (UNH) in 2004. (UNH Stormwater Center, 2007) The University reports that "The water quality treatment performance of the porous asphalt lot generally has been excellent. It consistently exceeds EPA's recommended level of removal of total suspended solids, and meets regional ambient water quality criteria for petroleum hydrocarbons and zinc. Researchers observed limited phosphorus treatment and none for nitrogen, which is consistent with other non-vegetated infiltration systems."

They also observed that the system did not remove chloride, but since it drastically reduced the salt needed for winter maintenance, it may prove effective at reducing chloride pollution. They reported that winter main-

TABLE 1
Water Quality Benefits of Porous Pavement with Infiltration (% Removal Efficiency)

	Infiltration BMP				
Water Quality Parameter	Trench 1	Trench 2	Porous Paving 1	Porous Paving 2	Average Removal Efficiency
Total Suspended Solids (TSS)	90	—	95	89	91
Total Phosphorus (TP)	60	68	71	65	66
Total Nitrogen (TN)	60	—	—	83	72
Total Organic Compounds (TOC)	90	—	—	82	86
Lead (Pb)	—	—	50	98	74
Zinc (Zn)	—	—	62	99	81
Metals	90	—	—	—	90
Bacteria	90	—	—	—	90
Biological Oxygen Demand (BOD)	75	—	—	—	75
Cadmium (Cd)	—	—	33	—	33
Copper (Cu)	—	—	42	—	42
Total Kjeldahn Nitrogen (TKN)	—	53	—	—	53
Nitrate	—	27	—	—	27
Ammonia	—	81	—	—	81

TABLE 2
Pollution removal efficiencies

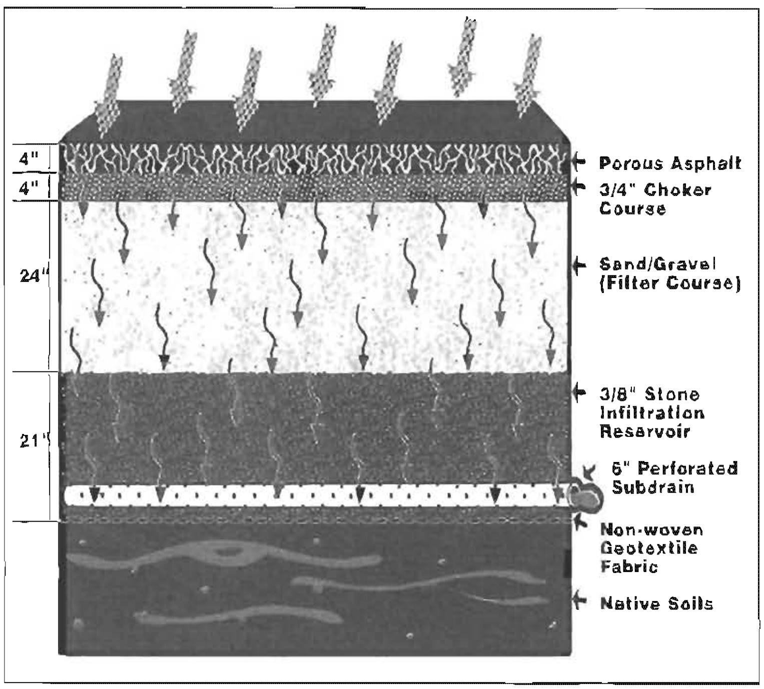
Treatment System	**Total Suspended Solids** (% Removal)	**Total Phosphorus** (% Removal)	**Total Zinc** (% Removal)	**Total Petroleum Hydrocarbons in the Diesel Range** (% Removal)
Porous Pavement	99	38	96	99

tenance requires "between zero and 25 percent of the salt routinely applied to impervious asphalt to achieve equivalent, or better, deicing and traction."

The design of the porous asphalt pavement at UNH is different from the standard design due to poor quality soils and high groundwater. The pavement structure is shown in Figure 2.

A Texas study examined the quality of runoff from a conventional asphalt pavement and a porous friction course (PFC). Porous friction course is the name commonly used in Texas for the pavements called open-graded friction course elsewhere in the U.S. In the project the porous asphalt mix was placed directly on a dense-graded asphalt pavement so that there was no infiltration. Even with no infiltration, concentrations of total suspended solids (TSS), total metals, and phosphorus were found to be significantly lower in the runoff from the PFC surface than in the runoff from the conventional impermeable asphalt surface. Concentrations of TSS as well as the total forms of lead and zinc were one order of magnitude lower from the porous asphalt than from the traditional asphalt in most samples. Average concentrations of total Kjeldahn nitrogen (TKN), chemical oxygen demand (COD), nitrate-nitrite, and the dissolved forms of lead, zinc, and phosphorus showed little change between the two surface types. The researchers concluded, "From these results it is evident that the runoff generated from the PFC surface is of better quality than that from the traditional asphalt surface." (Barrett & Shaw, 2007) This study indicates that even the porous asphalt surface removes some of the pollutants normally associated with runoff from pavement.

FIGURE 2
UNH porous pavement cross section



Dempsey and Swischer studied the hydrologic and chemical performance of a porous pavement/infiltration system at the Centre County/Penn State Visitor Center. (Dempsey & Swischer, 2003) They reported, "The system consists of porous pavement, a 462-m^3 (604 cubic yards) storage/infiltration bed with coarse aggregate (40% porosity), geo-textile filter fabric, and an average 2 m (6.5 feet) of un-compacted soil." "Eleven storm events generated at least 10 cm (4 inches) standing water in the 1.6 m (5 foot) reservoir, allowing sampling. There has been no surface runoff from the site, and infiltration rates have remained relatively constant at 17 cm/hr (6.7 in/hr)." "The aggressiveness of the water towards calcium carbonate was considerably reduced upon contact with limestone materials in the pavement and in the reservoir, decreasing the potential for sinkhole development. The concentrations of Zn, Cu, and Pb (zinc, copper, and lead) were low, and the total annual loading of metals onto the soil beneath the reservoir was much less than the annual loading of metals that is allowed during the application of soil-amendments to agricultural soils. Organic loadings were relatively low and there was evidence of an active community of organisms within the reservoir."

Sampling for water quality was from a sampling well that extended to the top of the geotextile filter fabric so this does not account for any treatment of water infiltrating through the subgrade soils. They also report, "Infiltrating water at the Visitor Center had low chemical oxygen demand (COD) values. This indicates low concentrations of organic materials such as petroleum hydrocarbons. The literature indicates that organic materials will be sorbed and bio-degraded within the top few cm of the sub-grade soil. Macro and microorganisms were consistently observed in the storage/infiltration bed at the Visitor Center. Therefore, there is little potential for contamination of groundwater by organic materials due to normal use of the porous pavement parking lots at the Visitor Center."

Design

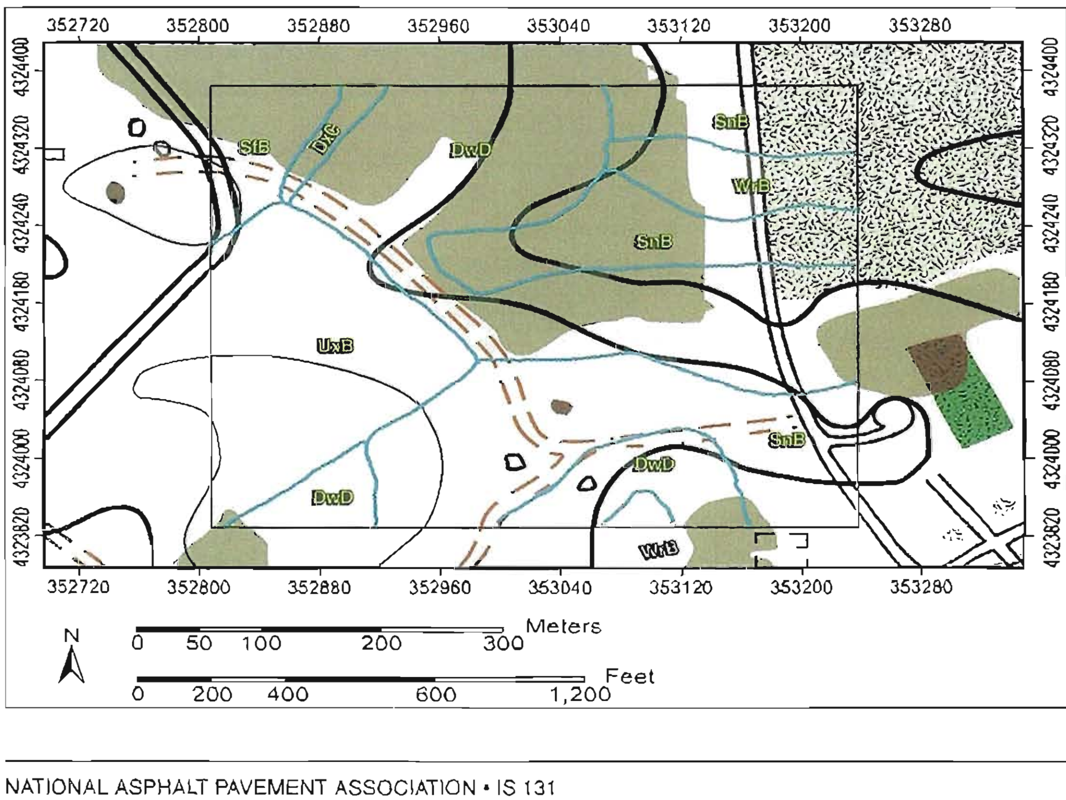
The design of a porous pavement can be broken down into location, hydrology and structural design.

The general guidelines for the porous asphalt pavement design are:

1. Consider the location for porous pavements early in the design process.
2. Soil infiltration rates of 0.1 to 10 inches/hour work best.
3. Minimum depth to bedrock or seasonal high water should be greater than two feet.
4. The bottom of the infiltration bed should be flat to maximize the infiltration area.
5. Limit the maximum slope of porous pavement surface to 5 percent. For parking areas on steeper slopes, terrace the parking areas with berms between parking areas.
6. Look for opportunities to route runoff from nearby impervious areas to the infiltration bed to minimize stormwater structures. Pretreatment may be required.
7. Spread out the infiltration. The maximum ratio of impervious to pervious area should be 5:1. For carbonate soils where there is a risk of sinkholes, the maximum ratio should be 3:1. Do not place porous pavements over known sinkhole areas.
8. The design should provide for an alternate path for stormwater to enter the stone recharge bed in the event that the pavement surface becomes plugged or experiences extreme storm events.
9. An overflow system should be included to prevent water in the stone bed from rising into the pavement surface during extreme storm events.
10. The stone recharge bed should be able to drain within 12 and 72 hours.

When a site is being newly developed, the location of the porous pavement should be considered early in the design process. In conventional construction plans, pavements are often placed at the lowest portion of a site, where high groundwater and poor soil infiltration rates may exist. Infiltration systems perform best on upland soils. (Cahill, Adams, & Marm, 2005) Soil Series and Hydrologic Soil Group Maps from the Natural Resources Conservation Service at http://websoilsurvey.nrcs.usda.gov are helpful in this initial design phase. Custom soil reports can also be generated from the same source. Figure 3 shows an example of such a map.

FIGURE 3
Example of hydrologic soil group map



Such maps serve as a good starting point early in the design. "Hydrologic soil groups (A) and (B) are ideal for porous paving sites. However, potential areas in soil groups (C) and (D) require more attention." (U.S. Environmental Protection Agency, 1980) Definitions of soil groups are available from the Natural Resources Conservation Service. Hydraulic conductivities for the different soil groups are shown in Table 3 and Table 4.

TABLE 3

Saturated hydraulic conductivity of hydrologic soil groups when a water impermeable layer exists at a depth between 20 and 40 inches

Hydrologic soil group A	Hydrologic soil group B	Hydrologic soil group C	Hydrologic soil group D
>5.67 in/h	≤5.67 to >1.42 in/h	≤1.42 to >0.14 in/h	≤0.14 in/h

TABLE 4

Saturated hydraulic conductivity of hydrologic soil groups when any water impermeable layer exists at a depth greater than 40 inches

Hydrologic soil group A	Hydrologic soil group B	Hydrologic soil group C	Hydrologic soil group D
>1.42 in/h	≤1.42 to >0.57 in/h	≤0.57 to >0.06 in/h	≤0.06 in/h

Another consideration early in the design process is to look for opportunities to use the stone recharge bed to infiltrate stormwater from nearby impervious areas on the site. The stone recharge bed is typically between 12 and 36 inches in depth. With 40 percent voids in stone this would mean that the recharge bed is capable of storing between 4.8 and 14.4 inches of precipitation. This will typically exceed most design storm volumes. Therefore, there may be opportunities to store and infiltrate stormwater from impervious areas at the site to avoid piping water long distances. Pretreatment of the runoff from these impervious areas may be required to reduce sediment or other pollutants, depending on the source of runoff. For example, an impervious pavement that is sanded as part of snow and ice control should not be allowed to flow to the porous pavement area without sediment control.

The bottom of the infiltration bed should be flat to maximize the infiltration area and reduce the amount of stone required, as illustrated in Figure 4.

Slope should also be considered in selecting the location of porous pavements. Porous pavements work best on flat or gently sloping areas. The slope of the surface of the porous pavement should not exceed 5 percent. For parking on sloping areas, consider terracing the parking areas with berms separating the parking bay as shown in Figure 5. These parking areas can be connected with conventional dense-graded asphalt pavement. "Orientation of the parking bays along the existing contours will significantly reduce the need for cut and fill." (Pennsylvania Department of Environmental Protection, 2006)

The thickness of the stone recharge bed will be determined by the amount of water that needs to be stored, the infiltration rate of the soil, and traffic loading. In most cases, the water quantity and soil infiltration rate will control the thickness of the stone recharge bed and traffic loads will control the thickness of the porous asphalt surface.

FIGURE 4

Keep bed bottom flat for maximum infiltration

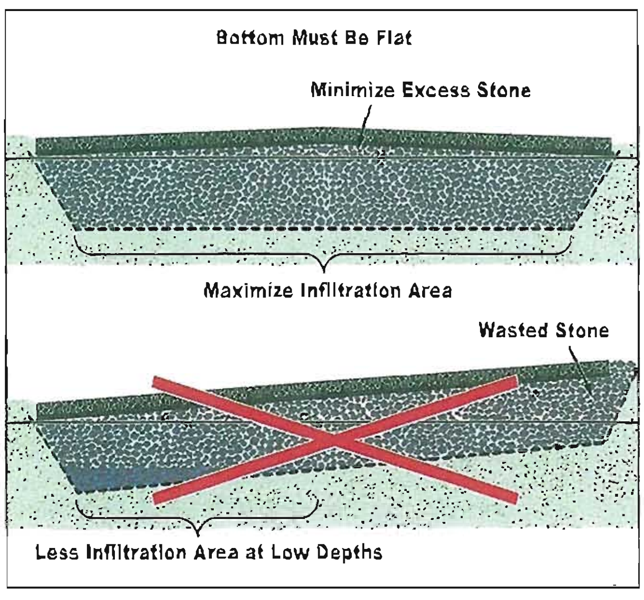
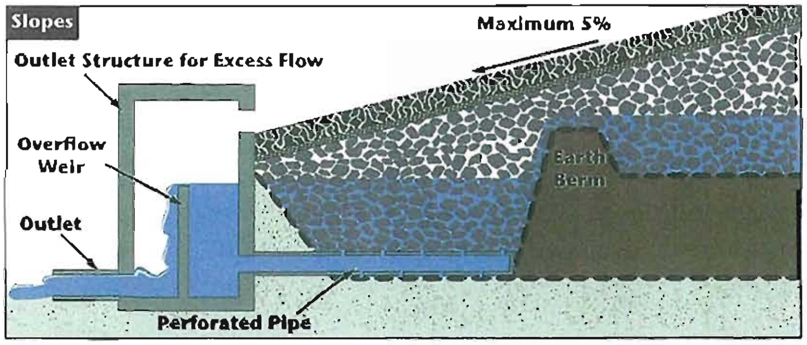
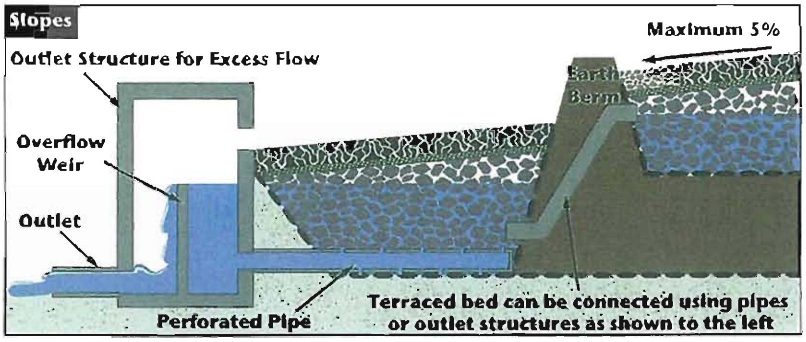


FIGURE 5
Terraced porous parking





Hydrologic Design

Detailed hydrologic design is beyond the scope of this publication. The hydrologic design of porous pavement should be performed by a licensed engineer proficient in hydrology and stormwater design. What is presented here is a summary of the concepts which are considered by the engineer.

The two most common methods for modeling stormwater runoff are the Curve Number (CN) method and the Rational method. The Rational method is generally not recommended for evaluating systems such as porous pavements and therefore will not be discussed.

The Curve Number method is used in a number of public domain computer models as well as proprietary programs. At this time no curve numbers have been determined for porous pavements. However, the porous pavement can be modeled assuming that the porous pavement has the same runoff coefficient as a conventional dense-graded pavement (e.g. Curve Number of 98) routing the runoff through the stone recharge bed. (HydroCAD Software Solutions LLC) Outflow from the stone recharge bed will be through infiltration and overflow devices.

The assumption of a high CN causes some concerns among persons modeling stormwater. It is important to note that using this high CN does not mean that the stormwater will be running off the site. Rainfall landing on porous pavement is directly transferred to the underlying stone bed with virtually no loss.

A sign at Walden Pond Visitor Center in Massachusetts informs visitors about the porous pavement that has been in place there for over 30 years.

A good starting point for the design of a porous pavement is to assume that all the rainfall for the storm events will enter the stone recharge bed from the pavement and any other adjacent impervious surfaces with the minimum allowable time of concentration (T_c). A simple spreadsheet can be used for this purpose. Figure 6 shows a graph that was developed using such a spreadsheet to determine the bed depth that would be required for two-year and 100-year storm events for rain that falls on the porous pavement as well as for stormwater that is routed from adjacent impervious areas to the stone recharge bed. The two-year storm was 3.5 inches in 24 hours, and the 100-year storm was 7.5 inches in 24 hours.

In this example, a very low soil permeability of 0.1 inches/hour was assumed and still a bed depth of only five inches would be required to store and infiltrate the two-year 24-hour storm for rain falling only on the pavement surface. If stormwater from other impervious surfaces on the site is routed to the stone bed, the depth would increase to about 12 inches. To completely store and infiltrate the 100-year 24-hour storm for rain falling only on the pavement and routing stormwater from other impervious areas, the required bed depths would be about 13 and 31 inches, respectively. It should also be noted that for a two-year 24-hour design storm, the bed would be able to drain between the recommend drain times of 12 to 72 hours for both conditions.

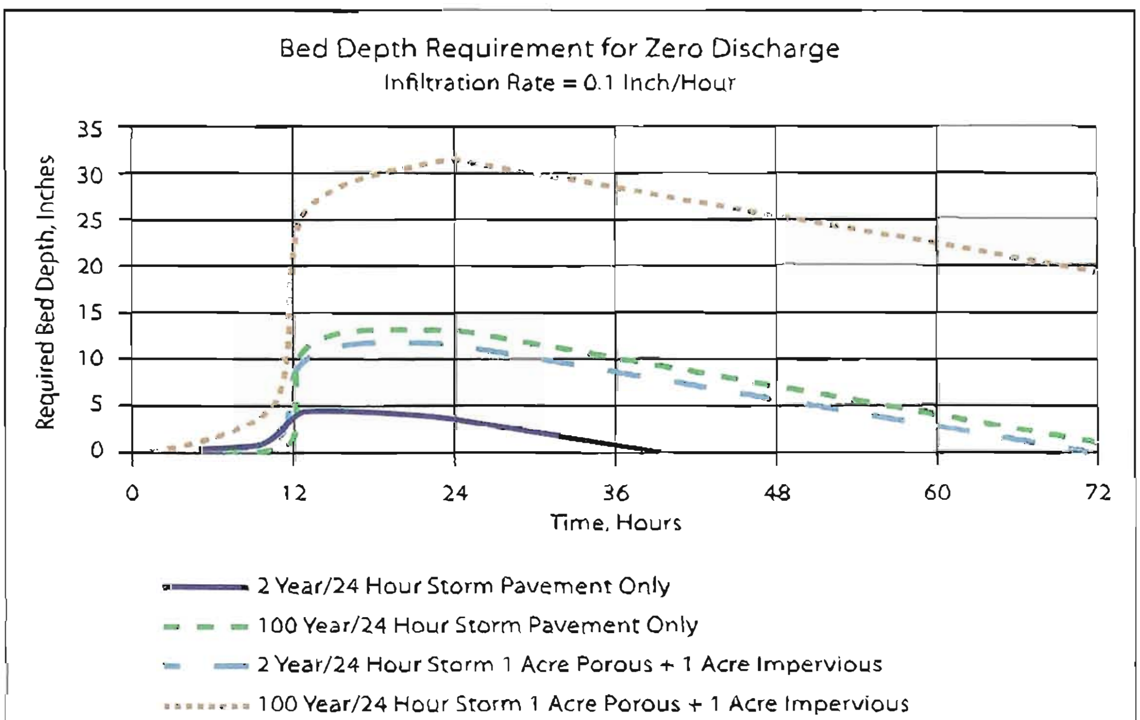
Structural Design

The vast majority of projects constructed to date were designed to carry light automobile traffic only. For these applications, the structural requirements are not significant. The material thicknesses are determined based on water storage capacity of the base aggregates and on minimum thickness requirements for the porous asphalt. For applications where the porous pavements will be required to carry truck loads, consideration for the structural requirements of the pavement section becomes more critical.

The structural design of porous pavement is based on data from a limited number of studies; however, suffice it to say that many porous pavements have served their traffic-supporting functions for over 20 years.

The most thorough structural evaluation of a porous pavement was on a porous roadway constructed by the Arizona DOT. This pavement was constructed in 1986 and consisted of 6 inches of an open-graded asphalt (3/8 inch maximum aggregate size) over 6 inches of asphalt-

FIGURE 6
Example of determining bed depth for zero discharge



Porous pavement is on the right in this San Diego parking lot.

TABLE 5
Layer equivalency for open-graded asphalt

Temp., °F	Based on Core Testing	Based on Lab-Prepared Specimens	Average
41	1.41	1.33	1.37
77	1.98	1.57	1.78
Average	1.70	1.45	1.57

treated permeable base (ATPB) over 8 inches of open-graded subbase (stone recharge bed). At this writing (in fall 2008), the pavement is still functioning well. It is located in Chandler, Arizona on the northbound lanes of Arizona Avenue between Elliott and Warner Roads.

The pavement designers selected structural coefficients of 0.40 for the open-graded surface, 0.20 for the ATPB, and 0.11 for the open-graded subbase. This compares to structural coefficients of 0.44 for dense-graded asphalt and 0.14 for dense-graded aggregate base. Gemayel and Mamlouk reported that 1.7 inches of open-graded asphalt surface is equivalent to 1.0 inches of dense-graded asphalt based on a layer elastic analysis. (Gemayel & Mamlouk, 1988) This is compared to the 1.1 equivalency used in the original design.

A final report on the Arizona project in 1991 reported the resilient modulus of the pavement layers based on falling weight deflectometer (FWD) tests. (Hossain & Scofield, 1991) Laboratory resilient modulus of cores for the porous pavement from the 1988 study were about 180 and 560 ksi for the open-graded and conventional pavement, respectively. This means that the resilient modulus of the open-graded asphalt is about 32 percent of the conventional pavement. On average the same comparison from the back-calculated moduli is about 45 percent.

Although the modulus values for the porous pavement were lower than the conventional pavement, the fact that the pavement has performed well for more than 20 years indicates that the original layer coefficients of 0.40, 0.20 and 0.11 for the porous asphalt, ATPB, and open-graded stone base, respectively, were adequate.

Other data are available on the strength of the different materials, open-graded aggregates, and ATPB. One study by the Oregon Department of Transportation (Zhou, Moore, Huddleston, & Gower, 1992) evaluated untreated and treated free-draining base materials using results from other research reports and testing of materials used by the Oregon DOT. The untreated free-draining aggregate base properties would be appropriate for the strength of the stone recharge bed. In this report a layer coefficient between 0.08 and 0.14 for the untreated aggregate base was recommended. This is similar to the layer coefficients typically assigned to dense-graded aggregate bases. ATPB layer coefficients between 0.14 and 0.19 were determined for Oregon materials. They also reported that ten states assign a layer coefficient for ATPB equivalent to aggregate base and six states assign layer coefficients between 0.20 and 0.30. The Oregon DOT Pavement Design Guide assigns layer coefficients of 0.42 for open-graded mixes and 0.24 for ATPB.

A study by the Vermont Agency of Transportation recommended a layer coefficient of 0.331 for ATPB based on FWD testing. (Pologruto, 2004) The Vermont Agency of Transportation Pavement Design Guide recommends a layer coefficient of 0.33 for ATPB.

Even though there is some uncertainty on structural design values for porous pavements, there is substantial anecdotal experience supporting the use of porous asphalt for applications with trucks. The previously mentioned Arizona project is a good case in point. In Oregon, agencies have designed and built open-graded cold mixes for farm to market applications for over 30 years. These pavements are generally 3 to 5 inches of open-graded cold mixes over dense aggregate, typically with a chip seal surface. They have performed better inch for inch than a dense mix would in the same application. Another example is the recent experience with the Pringle Creek subdivision (see Construction Guidelines, page 19,) in Salem, Oregon, in which the ATPB handled heavy construction truck traffic with no distress. The porous aggregate bases perform very well, both because they tend to be thick and because they are just as sound when wet as when dry, unlike conventional dense aggregate bases. It is probable that the layer coefficient of the open-graded base rock is substantially better than dense aggregate when seasonal effects are considered.

Table 6 provides recommended layer coefficients for structural evaluation of porous asphalt pavements. Table 7 provides recommended minimum thicknesses for the porous asphalt surface for different truck loadings.

Frost

In the past it has been recommended that the bottom of the recharge bed should exceed the depth of frost penetration in the region where the porous pavement is to be installed. More recently this has come into question since a number of porous pavements have been installed in freezing climates with total depths much shallower than this. These include pathways at Swarthmore College (Pennsylvania) at a depth of 12 inches and a Walden Pond Visitor Center (Massachusetts) parking lot with a bed depth of 12 inches. None of these pavements have shown damage due to frost heave. The only research on frost depth has occurred at the University of New Hampshire, where the frost depth is 48 inches. While the porous pavement at the site extends to below the frost depth, their data from 2006 shows frost penetration in the recharge bed of less than one foot. The University conservatively recommends the depth of the bed be 65 percent of the frost depth in their design specifications.

Soil Investigation

Before any infiltration system is designed, soil investigation must be done. This consists of two steps. First, simple test pits six to eight feet in depth are excavated with a backhoe and the soil conditions are observed. The depth of the test pits will vary depending on the anticipated depth of the bottom of the reservoir bed. The bottom of the excavation should extend a minimum of two feet below the planned recharge bed. While auger borings may be used, there are benefits to physically observing and describing the soil horizons. Test pits also facilitate the next step in checking the infiltration rate of the soils. According to the Pennsylvania Department of Environmental Protection (2006), observations that should be included are:

- Soil horizons (upper and lower boundary)
- Soil texture and color for each horizon

TABLE 6
Recommended layer coefficients for porous pavements

Material	Layer Coefficient
Porous Asphalt	0.40 – 0.42
Asphalt Treated Permeable Base (ATPB)	0.30 – 0.35
Porous Aggregate Base (Stone Recharge Bed)	0.10 – 0.14

TABLE 7
Minimum compacted porous asphalt thicknesses

Traffic Loading	Minimum Compacted Thickness, inches
Parking – Little or no trucks	2.5
Residential Street–Some truck	4.0
Heavy Truck	6.0

- Color patterns (mottling) and observed depth
- Depth to water table
- Depth to bedrock
- Observance of pores or roots (size, depth)
- Estimated type and percent coarse fragments
- Hardpan or limiting layers
- Strike and dip of horizons (especially lateral direction of flow at limiting layers)

Always follow safe operating procedures when entering test pits. OSHA regulations should always be observed.

The number of test pits varies depending on site conditions, variability, and the proposed development plan. General guidelines from the Pennsylvania Department of Environmental Protection are as follows:

- For single-family residential subdivisions with on-lot BMPs, one test pit per lot is recommended, preferably within 25 feet of the proposed BMP area. Verification testing should take place when BMPs are sited at greater distances.
- For multi-family and high-density residential developments, one test pit per BMP area or acre is recommended.
- For large infiltration areas (basins, commercial, institutional, industrial, and other proposed land uses), multiple test pits should be evenly distributed at the rate of four to six tests per acre of BMP area.

The recommendations above are guidelines. Additional tests should be conducted if local conditions indicate significant variability in soil types, geology, water table levels, bedrock, topography, etc. Similarly, uniform site conditions may indicate that fewer test pits are required.

Next, infiltration measurements are performed at the anticipated bed bottom location. There are a variety of field tests that are used to determine the infiltration rate of soils. The most commonly used tests are the double-ring infiltrometer and percolation tests (such as for onsite wastewater systems). The double-ring infiltrometer test estimates the vertical movement of water through the bottom of the test area. The outer ring helps to reduce the lateral movement of water in the soil from the inner ring. The percolation test allows water movement through both the bottom and sides of the test area. The infiltration rate for the percolation test needs to be adjusted to account for infiltration that occurs through the sides of the hole. Local stormwater regulations should be consulted to determine acceptable procedures for determining infiltration rates. These tests must be performed at multiple locations to determine the average infiltration rate for the site. Examples of infiltrometer tests are:

- Testing as described in the Maryland Stormwater Manual Appendix D.1 using 5-inch diameter casing.
- ASTM 2003 Volume 4.08, Soil and Rock (I): Designation D 3385-03, Standard Test Method for Infiltration Rate of Soils in Field Using a Double-Ring Infiltrometer.
- ASTM 2002 Volume 4.09, Soil and Rock (II): Designation D 5093-90, Standard Test Method for Field Measurement of Infiltration Rate Using a Double-Ring Infiltrometer with a Sealed-Inner Ring.

Most references suggest that the underlying soils should have a minimum infiltration rate of 0.50 in/hr for full exfiltration systems. Some reports suggest that soils with permeability less than 0.25 inch per hour are probably not suitable for porous pavement applications without substantial additional facilities. However, porous pavements have been successfully used with soil infiltration rates as low as 0.1 inches/hour. The key is to design the reservoir course to hold water for the design storm while making sure that the water will drain within a 24- to 72-hour period for proper water treatment. Other engineered options in combination with the permeable pavement may be considered for slow infiltration rates.

Underlying geology must also be considered in areas such as those underlain by limestone or dolomite formations. In that situation, more detailed site investigation may include borings and ground-penetrating radar. Contrary to popular belief, properly designed infiltration

FIGURE 7

The first step in designing any infiltration feature is field investigation of the soils

systems do not create sinkholes. A number of systems designed by Cahill Associates, including older systems, are located in carbonate areas. In several situations they have successfully installed porous pavement infiltration systems adjacent to areas where detention basins created sinkholes.

Routing Stormwater from Impervious Areas

Using the stone recharge bed for stormwater management for adjacent impervious areas such as roofs and roads can reduce project costs. This will reduce or eliminate the need for a detention basin and reduce stormwater structures and pipes. To achieve this, stormwater should be conveyed directly into the stone bed, where perforated pipes in the stone bed can distribute the water evenly. The ability to do this will depend on available porous pavement area, infiltration rate, and volume of runoff from impervious areas. Sediment control devices are strongly recommended to prevent transporting sediment to the recharge bed.

Provide Alternate Path for Stormwater to Enter Stone Recharge Bed

It is a good practice to provide an alternate means for stormwater to enter the stone recharge bed if the pavement surface should ever become plugged or sealed, or for extreme storm events. For pavements without curbs, this can be a two-foot-wide stone edge connected to the bed as shown in Figure 9. For curbed pavements, inlets such as shown in Figure 10 may be used.

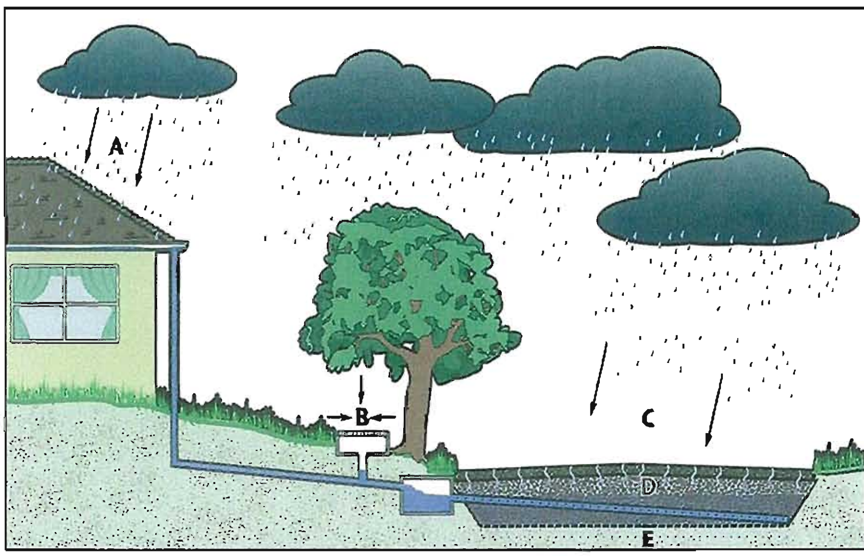
Overflow Structures

Porous pavements are not normally designed to store and infiltrate all stormwater from all storms. Therefore, it will be necessary to include some method of outlet control to prevent the water from rising into and over the porous asphalt surface. A common type of outlet control would be an inlet box with an internal weir and low-flow orifice. Examples of overflow devices are shown in Figure 9 and Figure 10.

Other Design Considerations

It is very important that porous pavements be protected from sediment during and after the construction process. Therefore, for larger projects where porous pavements are being considered, it may be advantageous to construct some pavement areas as impervious. It is very important that porous pavements be protected from sediment during and after the construction process. Because construction sites are inherently dirty there are advantages to constructing porous pavement late in the construction schedule. However, many building/fire codes require hard surfaces to be in place before structures are built. Therefore there may be advantages to constructing access roads and driveways of dense-graded asphalt and using other areas that may be constructed later for porous pavements. It is also possible to construct a porous pavement, either partially or entirely, early in the development process and cover it with a geotextileto protect it from clogging. The geotextile can then be removed at an appropriate time. This technique is discussed below under Construction Practices, page 19.

FIGURE 8
Roof leaders can be connected directly to the subsurface infiltration bed



A Precipitation is carried from roof by roof leaders to storage bed.

B Stormwater runoff from impervious areas and lawn areas is carried to storage bed.

C Precipitation that falls on porous parking enters storage bed directly.

D Stone bed stores water. Continuously perforated pipes distribute the stormwater from impervious surfaces evenly throughout the bed.

E Stormwater exfiltrates from storage bed into soil, recharging groundwater.

FIGURE 9
Example of stone edge for alternate path to bed and overflow device

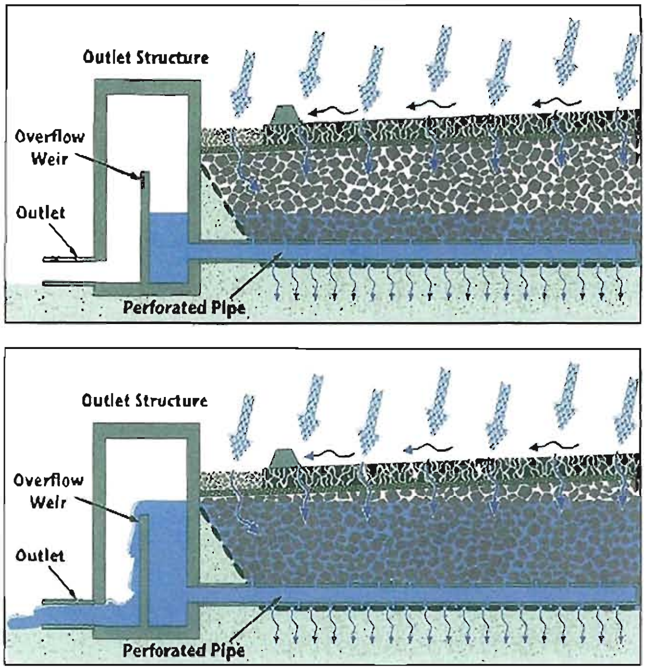
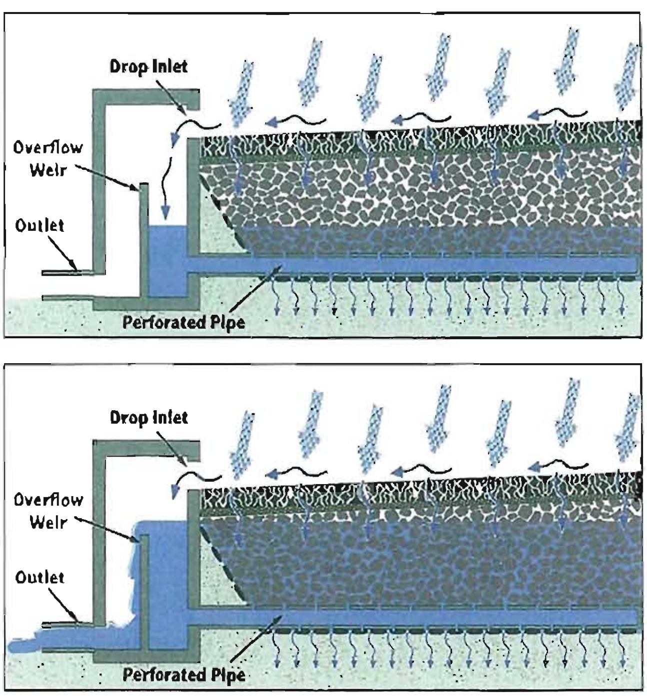


FIGURE 10
Example of drop inlet for alternate path to bed and overflow device



Paths

In addition to parking lots and roads, porous pavements have also been used successfully for paths and trails. One complication in using porous pavements for paths is that they normally follow the natural contours of the land, so the bed bottoms might not necessarily be flat. They do reduce the amount of impervious surface. They also mimic the natural infiltration of the surrounding terrain and will therefore reduce runoff and improve water quality. Because the pavement/infiltration system follows the surrounding contours, it is necessary to provide drains at low points as shown in Figure 11. In some cases it may be possible to terrace the bed bottom with short berms below the pavement surface to increase the storage capacity and improve infiltration as shown in Figure 12.

FIGURE 11
Porous asphalt path

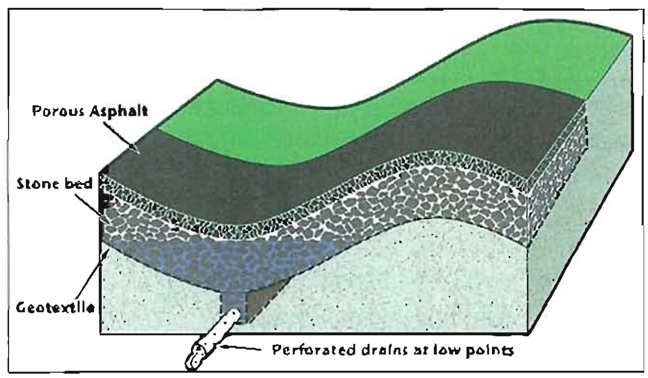
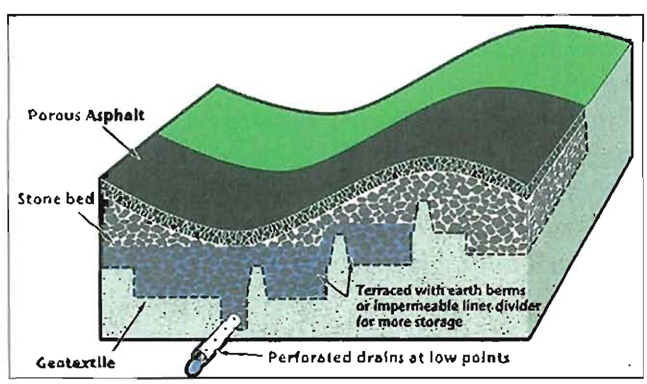


FIGURE 12
Porous asphalt path with berms for increased storage and infiltration



Materials

Geotextile (Filter Fabric)

Non-woven geotextiles are typically used to prevent fines in the subgrade from migrating into the stone recharge bed. The following is an example of a typical specification for this material:

TABLE 8
Requirements for filter fabric

Test	Requirement
Grab Tensile Strength (ASTM-D4632)	≥120 lbs
Mullen Burst Strength (ASTM-D3786)	≥225 psi
Flow Rate (ASTM-D4491)	≥95 gal/min/ft2
UV Resistance after 500 hrs (ASTM-D4355)	≥70 percent

Heat-set or heat-calendared fabrics are not permitted.
Acceptable types include Mirafi 140N, Amoco 4547, Geotex 451, or approved equivalent.

Stone Recharge Bed and Choker Course

Aggregate for the stone recharge bed needs to be clean, crushed stone. In many cases AASHTO No. 3 stone is specified; however, other aggregate gradations such as AASHTO No. 1, No. 2, and smaller have also been used successfully. The key to the aggregate is that it be clean, uniformly graded, and crushed with minimum voids of 40 percent as determined by ASTM C29. An additional grading requirement of 0 to 2 percent passing the No. 100 sieve is recommended to make sure the aggregate does not have excessive fines that could clog the bed.

In most cases when using an AASHTO No. 3 stone for the recharge bed, an AASHTO No. 57 stone has worked well as a choker course. If a larger or smaller stone is used for the recharge bed, the size of the choker stone will need to be adjusted. The thickness of the choker course is also important. It should be placed no more than one inch thick and be sufficient to fill the voids of the recharge bed stone in order to provide a smooth paving surface. A number of contractors have reported that they have found no advantage to using a choker course and have successfully constructed pavements without this course. Therefore, the choker course may be considered optional.

Porous Asphalt

Since the first porous asphalt pavements were constructed in the 1970s, we have learned much about the porous asphalt mixes, commonly referred to in the U.S. as open-graded friction courses (OGFC) when used on highways. The early mixes were typically specified using the Marshall mix design with the only requirements being aggregate quality, gradation, and minimum asphalt content. Originally, these mixes also used unmodified asphalt cement binders.

Today these mixes are designed using the Superpave or Marshall methods with requirements for higher air voids to assure permeability and low draindown for performance. In most cases, the mixes are made with polymer-modified asphalt and in some cases fibers. The polymer-modified asphalt helps to reduce draindown and improve the high-temperature performance of the mix (resistance to scuffing). Fibers are another way to reduce draindown. While modified asphalts should be used for most applications, these are not always necessary, or practical. Some asphalt plants do not have dedicated storage tanks for polymer-modified asphalts, making it impractical to provide modified asphalt in small quantities. One example of a recent successful project using a non-polymer-modified asphalt is the Port of Portland's terminal 6 project where a 35-acre porous pavement was constructed using an unmodified PG 70-22 binder. This project is performing well. It should be noted that while the standard grade of binder for the Portland area is a PG 64-22, the environmental criteria would only require a PG 58-22, so the binder used is two grades stiffer than what would be required for temperature.

There are a number of guides and specifications available for porous asphalt mixes. These include NAPA publication IS-115, *Design, Construction, and Maintenance of Open-Graded Asphalt Friction Course*, ASTM D7064, *Standard Practice for Open-Graded Friction Course (OGFC) Mix Design*, state department of transportation specifications, and state asphalt pavement associations. In most cases it is advantageous to use state DOT specifications since they have been developed for local

Placing a porous pavement on a large parking lot at the Port of Portland. By using the porous pavement BMP, the Port was able to save time that would have been consumed in the permitting process.

climates and materials, and contractors are familiar with them. While almost all states have specifications that are routinely used for ATPB materials, far fewer states routinely use open-graded friction courses. Therefore, when using a state DOT specification you should check to see if this is a standard practice in the state and if the following key properties are included as part of the specification:

- Air voids: 16 percent minimum — This assures permeability of the mix. It is important when testing air voids of open-graded mixes to measure the volume by dimension (ASTM D3203, *Standard Test Method for Percent Air Voids in Compacted Dense and Open Bituminous Paving Mixtures* or by ASTM D6857-03, *Standard Test Method for Maximum Specific Gravity and Density of Bituminous Paving Mixtures Using Automatic Vacuum Sealing Method*. **Do not determine the density of open-graded mixes using saturated surface dry (SSD) procedures.**
- Asphalt content: A good guideline is to require 5.75 percent minimum by weight of total mix. Adequate binder content is important for the durability of the mix. This minimum guideline above is for a 3/8-inch (9.5 mm) Nominal Maximum Aggregate Size (NMAS) such as is shown in the first two columns of Table 7. For larger NMAS mixes, a lower minimum asphalt content is acceptable. For ATPB, the asphalt content is typically between 3.0 and 3.5 percent.
- Draindown: 0.3 percent maximum — This test is important to make sure that the asphalt binder does not drain down during storage, transportation and placement. This test is performed in accordance with ASTM D6390-05, *Standard Test Method for Determination of Draindown Characteristics in Uncompacted Asphalt Mixtures*. This test is run at 15°C (27°F) above the expected production temperature. Other draindown tests may exist in some states; for example, Oregon has developed a draindown procedure based on visual evaluation and has used this test successfully for many years to design OGFCs.
- Moisture susceptibility — Because porous asphalt surfaces do not hold water, they have very low risk of moisture-related damage. A very low-risk approach to designing porous asphalt mixes is to follow the same practice used for dense mixes using the same aggregate and asphalt. If the dense mix from a given source requires an anti-stripping agent, then one should be used with the porous mix as well. If no history exists from a site, then a "surrogate" stripping test for moisture susceptibility may be run on dense mix using the same aggregate and asphalt.
  - ASTM D7064 includes a moisture susceptibility test that is a modification of the Modified Lottman test used on dense-graded mixtures. The following is a summary of this test procedure:
    - Compact using 50 gyrations
    - Vacuum saturate for 10 minutes (do not measure saturation level)
    - Use 5 freeze thaw cycles

- Keep specimens submerged in water during freezing
- Minimum tensile strength ratio (TSR) = 80 percent

This test is sometime problematic with open-graded mixes since the final step in the procedure places the specimens in a 140°F (60°C) water bath. In some cases the mix may fall apart under these conditions and it is not an indication of the mix's quality. In general, as stated previously, if the aggregate being used normally requires an anti-stripping agent in dense-graded mixes, the anti-strip should also be used in the open-graded mix. A "surrogate" test for open-graded mixes in which the same aggregates and asphalt are used to produce a dense-graded mix and this dense-graded mix is tested for moisture susceptibility using standard procedures may be used.

In most cases, a 3/8 inch (9.5 mm) NMAS is used for the surface of porous asphalt pavements. These surfaces have proven to be durable in many instances and provide an appearance that is pleasing. However, there are larger NMAS mixes that may be used in applications other than what most porous pavements have been used for. Table 10 provides examples of other open-graded mixes and their potential applications. For design thicknesses requiring multiple lifts, consideration should be given to using larger stone mixes with higher air void contents in the base lifts and finer stone mixes in the surface lifts. This approach will aid in maintaining the pavement's porosity over the long term, as particulate matter passing through the surface layer is unlikely to clog the underlying layers. The ATPB material contains a substantially higher air void content and much lower asphalt content than the listed surface course materials and as such makes a very economical base that is unlikely to clog.

TABLE 9
Example open-graded asphalt mix gradations

(Note: Check your state DOT and state asphalt pavement association for gradations commonly used for the project location.)

Sieve	NAPA IS-115	3/8"*	Oregon DOT Specifications		
			1/2"	3/4"	ATPB
	Percent Passing				
1" (25 mm)				99 – 100	99 – 100
3/4" (19 mm)	100	—	99 – 100	85 – 96	85 – 95
1/2" (12.5 mm)	85 – 100	99 – 100	90 – 98	55 – 71	35 – 65
3/8" (9.5 mm)	55 – 75	90 – 100	—	—	—
#4 (4.75 mm)	10 – 25	22 – 40	18 – 32	10 -24	2 – 10
#8 (2.36 mm)	5 – 10	5 – 15	3 – 15	6 – 16	0 – 5
#200 (0.075 mm)	2 – 4	1 – 5	1 – 5	1 – 6	0 – 2

* Asphalt Pavement Association of Oregon

TABLE 10
Potential applications for different open-graded mixes

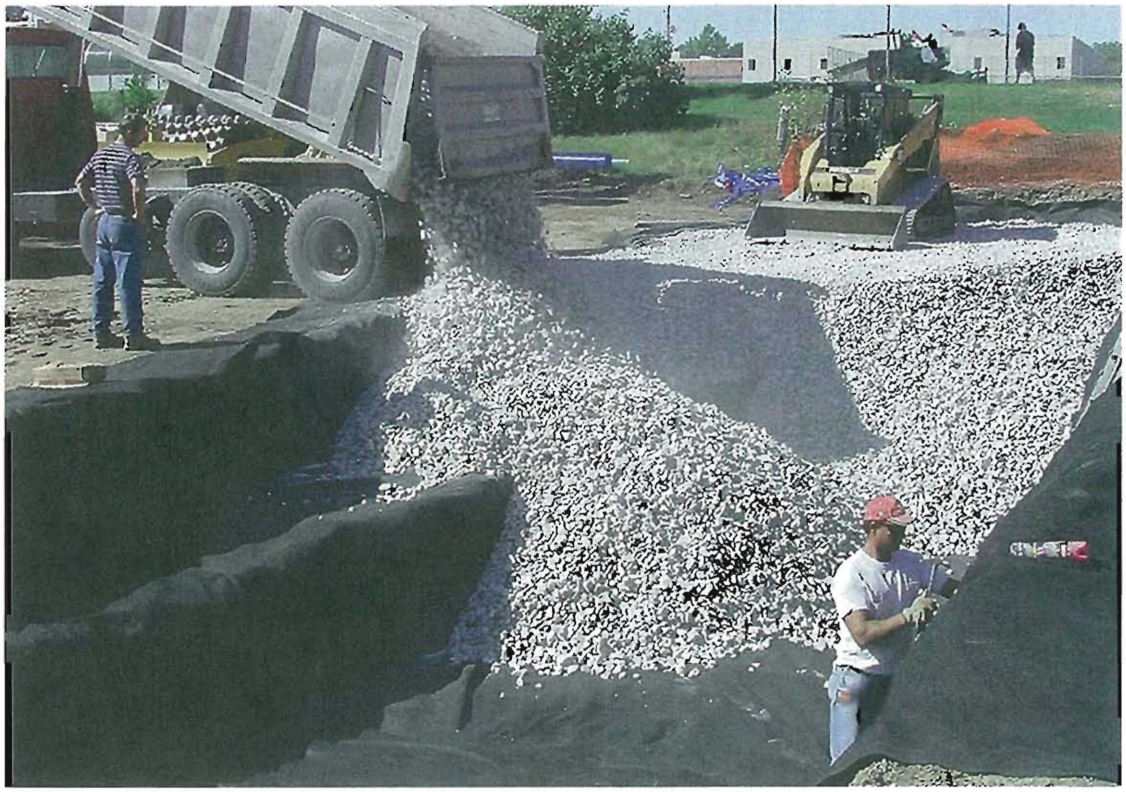
Mix Size	Application	Layer Thickness
3/8" (9.5 mm) open graded	Parking/Recreational Facilities	1.5 – 3.5 inches
1/2" (12.5 mm) open graded	Wearing Surface, Roads, Streets, Heavy Commercia	2.0 – 4.0 inches
3/4" (19 mm) open graded	Wearing Surface, Roads, Heavy Commercial	2.0 – 5.0 inches
3/4" (19 mm) ATPB	Base Course	3.0 – 6.0 inches

Construction Guidelines

Protecting the pavement from uncontrolled runoff from adjacent areas is critical. Temporary stormwater controls need to remain in place until the site is stabilized so that soil-laden stormwater does not wash onto the pavement, clogging the surface and filling the voids in the stone recharge bed. The porous pavement should be constructed late in the project schedule so that most of the dirty work such as grading and landscaping are completed first.

With regulations often requiring a hard paving surface before structures are constructed, conventional dense-graded pavements can be constructed for driveways and some of the other pavement surfaces. In rare cases this may not be possible. One example of this is Pringle Creek, a subdivision in Salem, Oregon constructed using porous pavement streets. In this case, the porous pavement needed to be constructed before the site work including utilities, sidewalks and landscaping was

FIGURE 13
At the Pringle Creek community, porous pavement was protected by geotextile fabric during construction (left). The geotextile was removed prior to final paving (right). The finished pavement is attractive and functional (bottom).



A construction crew "benches" a parking lot's stone recharge bed to fit around a key utilities connection.

constructed. Here, the porous asphalt was constructed in two layers — 3 inches of ATPB with 1.5 inches porous asphalt surface. The ATPB was placed in the late summer before the site work was complete. The ATPB was covered with a geotextile fabric to protect it. Once the site work was substantially complete the following spring, the geotextile was removed, the pavement surface was cleaned, and the porous asphalt surface was placed. Figure 13 shows the three distinct stages of this project; even under very difficult site conditions the contractor was able to maintain the cleanliness and porosity of the ATPB.

In some cases, the area where the porous pavement is to be constructed may be used for temporary sediment control during construction. In this scenario, the bed should be excavated at least one foot above the final elevation of the bed. In the later stages of the project, the sediment is removed, the bed is excavated to final grade, and the porous pavement system installed. This also avoids the need for a separate sediment basin during construction and limits the exposure of the porous pavement to clogging by construction debris.

Invariably, when an infiltration best management practice (BMP) fails it is due to difficulties and mistakes in the design and construction process. This is true for porous pavement and all other infiltration BMPs. Carelessness in compacting the subgrade soils, poor erosion control, and poor-quality materials are all causes of failure. For that reason, detailed specifications on site protection, soil protection and system installation are required. A preconstruction meeting should be held to discuss the need to prevent heavy equipment from compacting soils, the need to prevent sediment-laden waters from washing on to the pavement, the need for clean stone, etc. Designers should review the installation process with the project foreman and routinely stop by the site to provide construction advice. Successful installation of any infiltration BMP is a hands-on process that requires an active role for the designer. Often, the failure does not lie with the contractor or with poor soils, but instead is due to a lack of specific guidance for construction procedures.

The following are some general guidelines for construction of porous pavements:

- The site area for the porous pavement should be protected from excessive heavy equipment running on the subgrade, compacting soil, and reducing permeability.
- Excavate the subgrade soil using equipment with tracks or over-sized tires. Narrow rubber tires should

be avoided since they compact the soil and reduce its infiltration capabilities.

- As soon as the bed has been excavated to the final grade, the filter fabric should be placed. Overlap the filter fabric a minimum of 16 inches. The filter fabric should extend at least four feet outside the bed to prevent sediment-laden runoff from entering the bed. This excess fabric will be folded over the stone bed to temporarily protect it from sediment until the porous asphalt surface is placed.
- Install drainage pipes if required.
- Place aggregate for the stone recharge bed, taking care not to damage the filter fabric. Aggregate should be dumped at the edge of the bed and placed in layers of 8 to 12 inches using track equipment. Compact each lift with a single pass of a light roller or vibratory plate compactor.
- The use of a choker course over the top of the stone recharge bed has been standard practice since the early beginnings of porous pavements. The purpose of this course is to stabilize the surface for the paving equipment. The purpose is not to cover the large stone in the recharge bed but to fill some of the surface voids and lock up the aggregate. Therefore some of the large stones will be visible after the choker course has been placed and compacted.

  A number of contractors have reported that they are no longer using this layer since they see no benefit during the paving operation. The consensus is that the choker course should be optional. When using a choker course it is important that the aggregate be sized to interlock with the aggregate in the recharge bed.
- The porous asphalt layer is placed in 2- to 4-inch-thick lifts using track pavers, following state or national guidelines for the construction of open-graded asphalt mixes. Failure to follow these guidelines can lead to premature hardening of the asphalt and early failure of the pavement by raveling or loss of infiltration capacity. NAPA publication IS 115, *Design, Construction, and Maintenance of Open-Graded Asphalt Friction Courses*, provides guidance on constructing open-graded mixtures that can be used for porous pavements.
- The asphalt should be compacted with two to four passes of a ten-ton static roller. Normally, only a few passes are necessary. In many cases it will be necessary to let the mix cool before beginning compaction. Additional passes with a lighter roller may be required to remove roller marks at the surface; it is best to do this after the mix has cooled substantially.
- After final rolling, traffic should be restricted for the first 24 hours, as the pavement may be more tender during this time.
- **It is critical to protect the porous pavement during and after construction from sediment-laden water and construction debris that may clog it.**

Post Construction

- Where applicable, remove temporary stormwater drainage diversions after vegetation is established.
- Although snow and ice tend to melt more quickly on porous pavement, it may still be necessary to apply de-icing compounds such as salt or liquid de-icer. **Do not use sand or ash on the surface since clogging may occur.** As previously mentioned, the University of New Hampshire has shown that significantly less deicer may be applied than with conventional pavements.
- Signs are often posted at porous pavement sites to alert grounds keeping and maintenance personnel to keep silt and debris from entering the site, and to warn them not to seal the pavement or use sand or other abrasives for snow or ice conditions. In addition, these signs can include some educational information regarding the advantages of porous pavement.

When a fire hose pumps water onto a porous pavement, the water drains quickly.

Maintenance

As stated above, it is essential that porous pavements not be seal-coated by maintenance personnel. In addition, sand or ash must not be used for control of snow and ice.

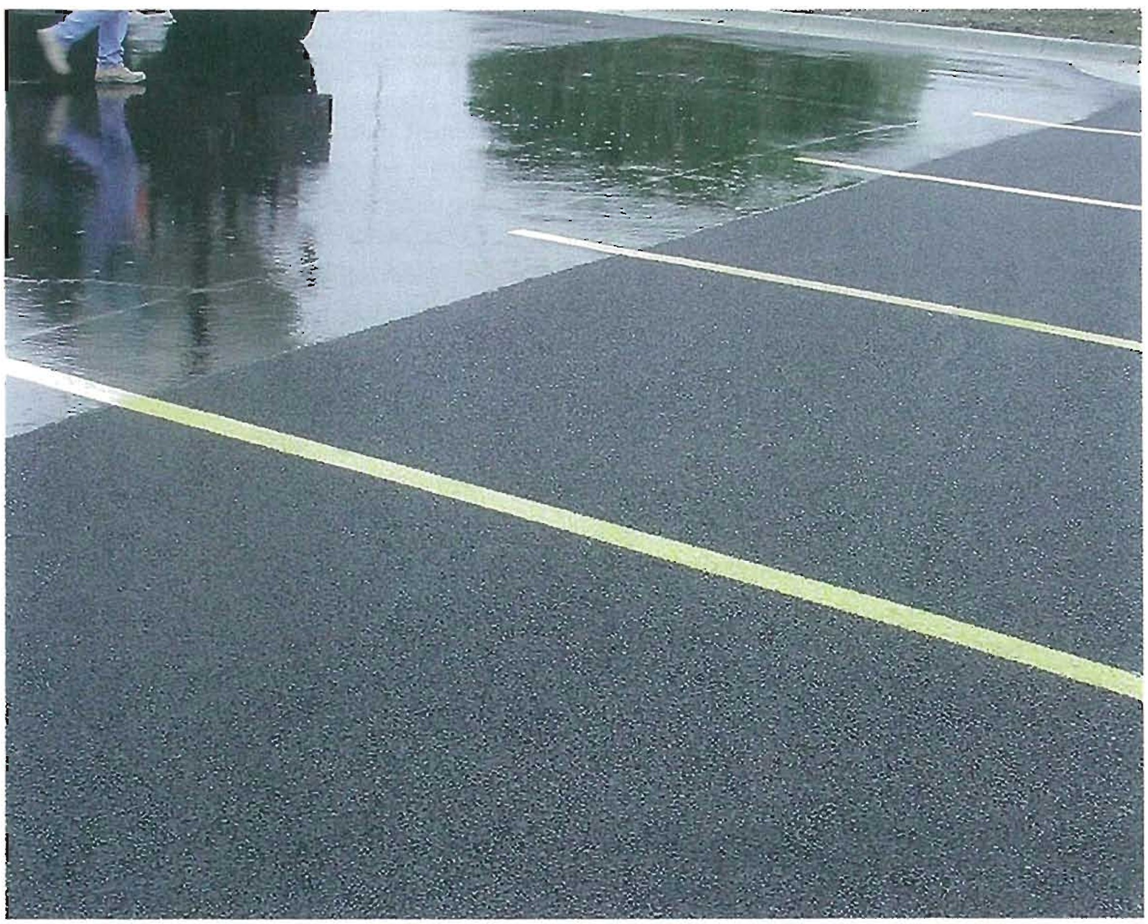
All porous pavements should be inspected several times in the first few months after construction, and at least annually thereafter. Inspections should be conducted after large storms to check for surface ponding that might indicate possible clogging. Little research has been done on restoring permeability to porous pavements. In Europe and Japan, large pressure washing/vacuum equipment has been used to restore permeability on porous pavements (referred to as open-graded friction courses in the US) for roadways. The University of New Hampshire has done limited research on cleaning their porous asphalt sites with a combination of pressure washing (not high-pressure) and vacuuming. Their report on this research has not been issued at this writing. To prevent clogging of porous pavements it is recommended that they be vacuum swept twice per year. As previously discussed, it is also very important that sanding not be used for winter maintenance.

Damage to the porous pavement can be repaired using conventional, non-porous patching mixes, as long as the cumulative area repaired does not exceed 10 percent of the paved area.

The photos show a parking lot at University of New Hampshire one hour after plowing, with a close-up of the porous asphalt portion of the lot at bottom. Porous and non-porous areas were evaluated for the degree (percentage) of snow and ice cover and the friction factor (measured by ASTM E303-93). A 75 percent reduction in salt application was possible: that is, with only 25 percent of the salt, the snow and ice cover on the porous asphalt was the same as on conventional dense-mix asphalt. For the friction factor, a 100 percent reduction was determined (porous asphalt, even with no salt, has higher frictional resistance than dense-mix asphalt with 100 percent of the normal salt application). Therefore, a sizable reduction in salt application rate is possible for porous asphalt without compromising braking distance or increasing the chance of slipping and falling.

Conclusion

Porous asphalt pavements have been used for more than thirty years around the United States to minimize the environmental impact of pavements. In addition to providing hard surfaces for parking and driving, they serve as stormwater storage and infiltration systems. Site planners and public works officials have found that they offer the opportunity to manage stormwater storage in an environmentally friendly way, as they promote infiltration, improve water quality, recharge groundwater, and keep the flow of runoff in line with non-developed areas. They have been used successfully in a variety of climates for parking lots and city streets. Recent advances in understanding of porous pavements have made it possible to modify the design of these systems so that they may be used more widely and at lower cost.



The porous asphalt in the foreground offers a dry surface when a conventional dense-graded asphalt remains wet.

References

Barrett, M. E., & Shaw, C. B. (2007). Stormwater Quality Benefits of a Porous Asphalt Overlay. *Transportation Research Record: Journal of the Transportation Research Board*.

Cahill, T. H., Adams, M., & Marm, C. (2005, March). Stormwater Management with Porous Pavements. *Government Engineering*, p. 6.

Dempsey, B., & Swischer, D. (2003). Evaluation of porous Pavement and Infiltration in Centre County, PA. *World Water Congress 2003*. Philadelphia, PA: ASCE.

Ferguson, B. K. (2005). *Porous Pavements*. CRC Press.

Gemayel, C. A., & Mamlouk, M. S. (1988). *Characterization of Hot-Mixed Open-Graded Asphalt Mixtures*. Transportation Research Board.

Hossain, M., & Scofield, L. A. (1991). *Porous Pavement for the Control of Highway Run-Off - Final Report*.

Hossain, M., & Scofield, L. A. (1991). *Porous Pavement for the Control of Highway Runoff*. Arizona Department of Transportation.

HydroCAD Software Solutions LLC. (n.d.). *Modeling Pavement*. Retrieved June 19, 2008, from HydroCADÆ Stormwater Modeling – Since 1986: http://www.hydrocad.net/pavement.htm

Michael Pologruto, P. (2004). *A Study of In Situ Pavement Material Properties Determined from FWD Testing*. Montpelier, VT: Vermont Agency of Transportation.

Pennsylvania Department of Environmental Protection. (2006, December 30). *Welcome to PA Department of Environmental Protection's eLibrary*. Retrieved June 17, 2008, from Pennsylvania Department of Environmental Protection: http://164.156.71.80/WXOD.aspx?fs=2087d8407c0e000080000719000007l9&ft=1

Thelen, E. a. (1978). *Porous Pavement*. The Franklin Institute Research Laboratories.

U.S. Environmental Protection Agency. (1980). *Urban Watershed Management Research*. Retrieved June 16, 2008, from Porous Pavement Phase I Design and Operational Criteria: http://www.epa.gov/ednnrmrl/publications/reports/epa600280135/ppdoc_2.pdf

United States Department of Agriculture, Natural Resources Conservation Service. (2007). *National Engineering Handbook Part 630*.

University of New Hampshire Stormwater Center. (2007). *University of New Hampshire Stormwater Center 2007 Annual Report*. Durham, NH: University of New Hampshire Stormwater Center.

Zhou, H., Moore, L., Huddleston, J., & Gower, J. (1992). *Free Draining Base Material Properties*. Oregon Department of Transportation.

Photos and Illustrations

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Pages 4, 19, 21: Photos by Jim Huddleston

Page 6, Figure 2: Based on University of New Hampshire illustration

Page 13: Photo by Cahill Associates

Page 14, Figure 8: Based on Cahill Associates illustration

Page 22: University of New Hampshire photos

Tables

All tables are the property of National Asphalt Pavement Association, unless otherwise stated.

Table 1: Cahill, Adams & Marm, 2005

Table 2: University of New Hampshire

Tables 3 and 4: U.S. Department of Agriculture, Natural Resources Conservation Service, 2007

Table 5: Gemayel & Mamlouk, 1988

Table 8: Pennsylvania Department of Environmental Protection, 2006

Table 10: Asphalt Pavement Association of Oregon

SI* (MODERN METRIC) CONVERSION FACTORS

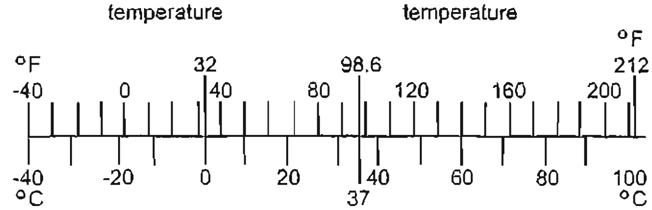
APPROXIMATE CONVERSION TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
inches	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in^2	square inches	645.2	millimeters squared	mm^2
ft^2	square feet	0.093	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometers squared	km^2
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
TEMPERATURE (exact)				
°F	Fahrenheit temperature	5(F-32)/9	Celsius temperature	°C

NOTE: Volumes greater than 1000 L shall be shown in m^3.

APPROXIMATE CONVERSION FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm^2	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometers squared	0.386	square miles	mi^2
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons(2000 lb)	T
TEMPERATURE (exact)				
°C	Celsius temperature	1.8C + 32	Fahrenheit temperature	°F



*SI is the symbol for the International System of Measurement.

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