Section 2. Design

Municipal Stormwater Management Objectives

The intent of many regional authorities, drainage districts, counties, cities and towns aim at preservation of natural drainage and treatment systems, or limit flows to drainage systems especially if they are working at or near capacity. Some agencies achieve this through a comprehensive stormwater management plan including operation and maintenance administered through stormwater utilities. Some governments use stormwater modeling and field calibration of watersheds and watercourses in their jurisdiction. Modeling can range from simple formulas like the Rational Method, NRCS TR-55 or more sophisticated models such HEC or EPA SWMM. These results inform drainage design guidelines for specific site development proposals brought to a government for approval. Sophisticated modeling can also demonstrate specific downstream impacts from a specific development proposal.

In approaching site design, municipalities incorporate some or all of the following design goals for managing stormwater.

1. Reduce the generation of additional stormwater and pollutants by restricting the growth of impervious surfaces.
2. Treat runoff to remove a given percentage of a pollutant or pollutants from the average annual post-development load. Target pollutant reductions can include total suspended solids (TSS) (typically 80% reduction) and total phosphorous (TS) (typically 40% reduction) as these are primary indicators of water quality. Reductions are measured on a mass basis.
3. Capture and treat a specific water quality volume defined as the initial depth of rainfall on a site (typically ranging from 0.75 in to 1.5 in. or 18 to 40 mm). This volume generally contains the highest amount of pollutants.
4. Enhance stream channel protection through extended detention (and infiltration) of runoff volume from a given storm event, e.g., a 1 or 2 year 24-hour storm. The difference in volumes between pre- and post development is often detained, infiltrated and/or slowly released.
5. Provide streambank erosion prevention measures such as energy dissipation and velocity control plus preservation of vegetative buffers along a stream.
6. Reduce overbank flooding through reducing the post-development peak discharge rate to the pre-development rate for a given storm, e.g., a 25-year, 24-hour event.
7. Reduce the risk of extreme flooding by controlling and/or safely conveying the 100-year, 24-hour return frequency storm event. This goal is also supported by preserving existing and future floodplain areas from development or restricting it in them as much as possible.
8. Maintain groundwater recharge rates to maintain stream flows and ecosystems as well as recharging aquifers.
9. Prevent erosion and sedimentation from construction through control practices provided on site development plans inspected during construction.

Permeable interlocking concrete pavements can play an important role in reaching all of these goals. These pavements help meet these goals with full, partial or no exfiltration of the open-graded stone base into the soil subgrade.

Figure 11. Portland, Oregon renovated streets with about 20,000 sf (2,000 m^2) of permeable interlocking concrete pavement after water and sewer line repairs in an older neighborhood. The city incorporated modeling to evaluate this pavement. The pavement decreased combined sewer overflows to the waste treatment plant and discharges to into the Willamette River.

Full or Partial Exfiltration

A design for full exfiltration means the water infiltrates directly into the base and exfiltrates to the soil. This is the most common application. Overflows are managed via perimeter drainage to swales, bio-retention areas or storm sewer inlets.

Partial exfiltration does not rely completely on exfiltration of the base into the soil to dispose of all the captured runoff. Some of the water may exfiltrate into the soil while the remainder is drained by perforated pipes. Excess water is drained from the base by pipes to sewers or a stream. Figures 12 and 13 show schematic cross-sections of full and partial exfiltration designs.

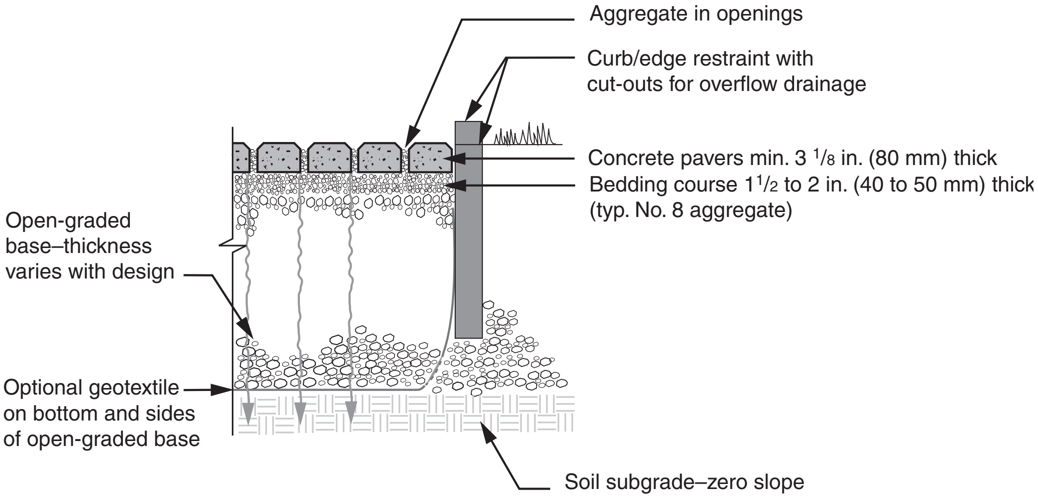


Figure 12. ***Full exfiltration*** *through the soil surface. Overflows are managed via perimeter drainage to swales, bio-retention areas or storm sewer inlets.*

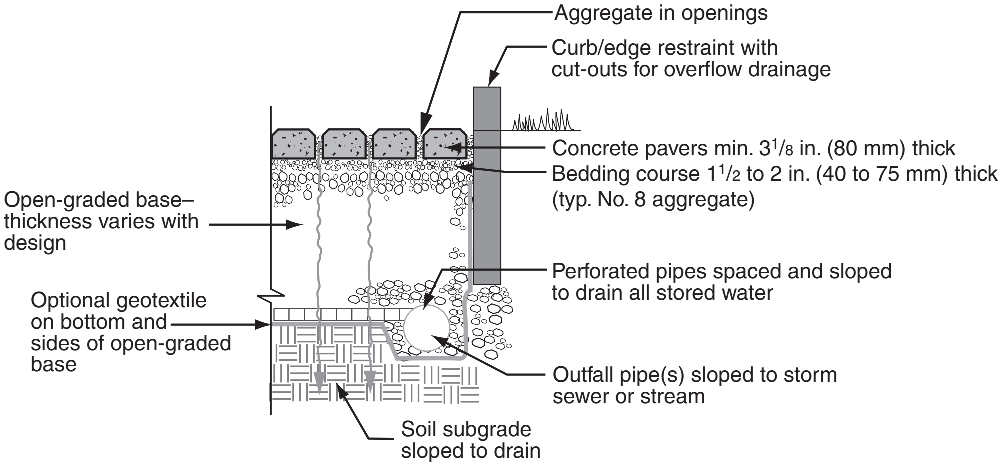


Figure 13. ***Partial exfiltration*** *through the soil. Perforated pipes drain excess runoff that cannot be absorbed by slow-draining soil.*

No Exfiltration

No exfiltration is required when the soil has low permeability and low strength, or there are other site limitations. An impermeable liner may be used if the pollutant loads are expected to exceed the capacity of the soil and base to treat them. The liner can be high density polyethylene (HDPE), ethylene propylene diene monomer (EPDM), rubber asphalt, or asphalt-based materials. Manufacturers of these materials should be consulted for application guidance. A liner may also be used if the depth to bedrock or to the water table is only a few feet (0.6 to 0.8 m). By storing water in the base for a time and then slowly releasing it through pipes, the design behaves like an underground detention pond. Figure 14 illustrates a cross-section design for no base exfiltration into the soil. In some cases, the soil may be stabilized to render improved support for vehicular loads. This practice almost reduces infiltration into the soil to practically zero.

There are four situations where permeable interlocking concrete pavements should not exfiltrate. Instead, an impermeable liner is used to capture, store and release runoff from the base.

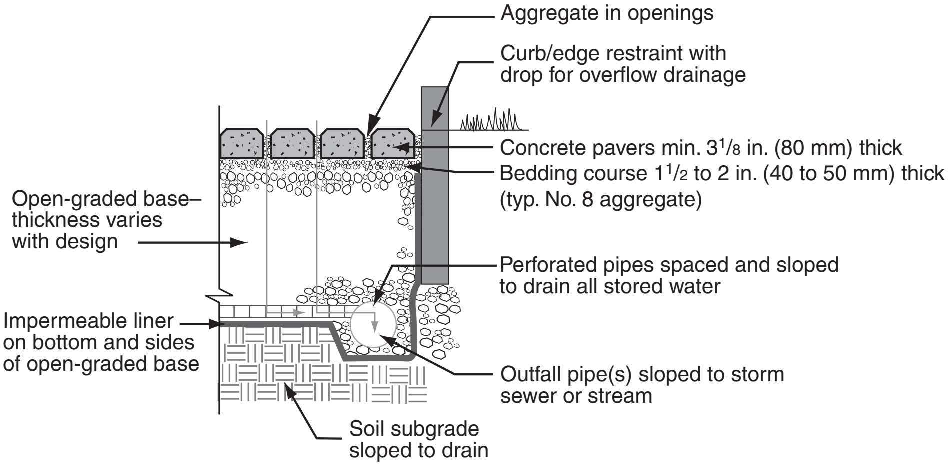


Figure 14. No exfiltration of water from the base is allowed into the soil due to the use of an impermeable liner at the bottom and sides of the base. Perforated drain pipes are sized to slowly release the water into a sewer or stream.

- When the depth from the bottom of the base to the high level of the water table is less than 2 feet (0.6 m), or when there is not sufficient depth of soil to offer adequate filtering and treatment of water pollutants.
- Directly over solid rock, or over solid rock with no loose rock layer above it.
- Over aquifers with isufficient soil depth to filter the pollutants before entering the ground water. These can include karst, fissured or cleft aquifers.
- Over fill soils, natural or fill, whose behavior when exposed to infiltrating water may cause unacceptable behavior. This might include expansive soils such as loess, poorly compacted soils, gypsiferous soils, etc.

While these limitations may not be present, the soil may still have low permeability. In these cases, the soil may hold the water in the base for slow drainage while providing a modest amount of infiltration. In a few cases, soil profiles may offer a more permeable layer further below the pavement. It may be cost-effective to drain the water via a french drain or pipes through the impermeable layer of soil under the base and into the lower soil layer with greater permeability.

Site Selection Criteria

Permeable interlocking concrete pavements are recommended in areas with the following site characteristics (11):

- Residential walks and driveways.
- Walks, parking lots, main and service drives around commercial, institutional, recreational and cultural buildings.
- Boat ramps and non-commercial boat landings (often owned by local, state or provincial recreation agencies).

- Industrial sites that do not receive hazardous materials, i.e., where there is no risk to groundwater or soils from spills.
- Storage areas for shipping containers with non-hazardous contents.
- The impervious area does not exceed five times the area of the permeable pavement receiving the runoff.
- The estimated depth from the bottom of the pavement base to the high level of the water table is greater than 2 feet (0.6 m). Greater depths may be required to obtain additional filtering of pollutants through the soil.
- The pavement is downslope from building foundations, and the foundations have piped drainage at the footers.
- The slope of the permeable pavement surface is at least 1% and no greater than 5%.
- Land surrounding and draining into the pavement does not exceed 20% slope.
- At least 100 ft (30 m) should be maintained between permeable pavements and water supply wells, streams, and wetlands. (Local jurisdictions may provide additional guidance or regulations.)
- Sites where the owner can meet maintenance requirements (see maintenance section).
- Sites where there will not be an increase in impervious cover draining into the pavement (unless the pavement is designed to infiltrate and store runoff from future increases in impervious cover).
- Sites where space constraints, high land prices, and/or runoff from additional development make permeable interlocking concrete pavements a cost-effective solution.

Permeable interlocking concrete pavements are not recommended on any site classified as a stormwater hotspot, i.e., if there is any risk that stormwater can infiltrate and contaminate groundwater. These land uses and activities may include the following:

- Vehicle salvage yards, recycling facilities, fueling stations, service and maintenance facilities, equipment and cleaning facilities
- Fleet storage areas (bus, truck, etc.)
- Commercial marina service and maintenance areas
- Outdoor liquid container storage areas
- Outdoor loading/unloading facilities
- Public works materials/equipment storage areas
- Industrial facilities that generate or store hazardous materials
- Storage areas for commercial shipping containers with contents that could damage groundwater and soil
- Land uses that drain pesticides and/or fertilizers into permeable pavements (e.g., agricultural land, golf courses, etc.)
- Other land uses and activities as designated by an appropriate review authority

Design Considerations for Pedestrians and Disabled Persons

Before a parking lot or plaza is constructed, existing pedestrian paths across the lot should be studied and defined. Vehicle lanes, parking spaces, pedestrian paths, and spaces for disabled persons can be delineated with solid concrete pavers. Paths with solid units will make walking more comfortable, especially for pedestrians with high-heeled shoes and for the elderly. Likewise, parking spaces accessible to disabled persons and for bicycles should be marked with solid pavers. Permeable interlocking concrete pavers with openings or wide joints should not be used in disabled-accessible parking spaces or on pedestrian ramps at intersections.

Infiltration Rates of Permeable Interlocking Concrete Pavement Systems

A common error in designing permeable interlocking concrete pavements is assuming that the amount or percent of open surface area is equal to the percent of perviousness. For example, an 18% open surface area is incorrectly assumed to be 18% pervious, or 82% impervious. The perviousness and amount of infiltration are dependent on the infiltration rates of joint filling material, bedding layer, and base materials, not the percentage of surface open area.

Compared to soils, permeable interlocking concrete pavements have a very high degree of infiltration. For example, a clay soil classified as CL using the Unified Soil Classification System might have an infiltration rate in the order of 1.4 x 10^{-5} in./hr (10^{-9} m/sec). A silty sand (SM) could have 1.4 x 10^{-3} in./hr (10^{-7} m/sec) infiltration rate. Open-graded, crushed aggregate placed in the openings of permeable interlocking concrete pavements will have an initial infiltration over 500 in./hr (over 10^{-3} m/sec), i.e, 10,000 times greater than the sandy soil and 100,000 times greater than the clay soil. The open-graded base material has even higher infiltration, typically 500 to 2,000 in./hr (10^{-3} to 10^{-2} m/sec). Therefore, the small percentage of open surface area is capable of providing a large amount of infiltration into the pavement.

Regardless of the high infiltration rate of the aggregates used in the openings and base, a key consideration is the lifetime *design* infiltration of the *entire* pavement cross-section, including the soil subgrade. Its infiltration rate is difficult to predict over time. There can be short-term variations from different amounts of antecedent water in it, and long-term reductions of infiltration from partially clogged surface or base, geotextiles or soil subgrade. So a conservative approach should always be taken when establishing the design infiltration rate of the pavement system.

Studies on permeable interlocking concrete pavers have attempted to estimate their long-term infiltration performance. Permeable concrete units (made with no fine aggregates) demonstrate lowest average permeability. Interlocking shapes with openings or those with enlarged permeable joints offer substantially higher infiltration performance over the long term.

Research on permeable pavements made with solid, nonporous units provides some guidance on long-term infiltration rates. German studies (6)(7)(8)(12), ICPI (43), and a review of the literature by Ferguson (44) reviewed parking lots with open-graded materials in the paver openings over an open-graded base. They showed a high initial infiltration when new and a decrease and leveling off as they aged. The decrease in infilitration is natural and is due to the deposit of fine materials in the aggregate fill and clogging of the base and geotextiles.

When tested, new pavements demonstrated very high infiltration rates of almost 9 in./hr (6 x 10^{-5} m/sec) and two four-year old parking lots indicated rates of about 3 in./hr (2 x 10^{-5} m/sec). Lower rates were exhibited on pavements where openings were filled with sand or aggregate and itinerant vegetation. In another study of two and five-year old parking lots, the infiltration rates were about 6 and 5 in./hr (4 and 3.5 x 10^{-5} m/sec) respectively. Infiltration was measured over approximately one hour for these two studies. In an ICPI study (44) ten sites indicated 1½ in./hr to over 780 in./hr. The lowest infiltration rates were sites clogged with fines.

The results of these studies confirm that the long-term infiltration rate depends on the intensity of use and the degree to which the surface and base receive sediment. This is also confirmed in the literature on the performance of infiltration trenches. Since there are infiltration differences between initial and long-term performance, construction, plus inevitable clogging, **a conservative design rate of 4 in./hr (2.8 x 10^{-5} m/sec or 280 L/sec/hectare) can be used as the basis for the design infiltration rate for a 20-year life**. This design infiltration rate will take in most storms.

Site Design Data

Desktop Assessment

A preliminary assessment should be conducted prior to detailed site and hydrological design. This initial assessment includes a review of the following:

- Underlying geology and soils maps
- Identifying the NRCS hydrologic soil groups (A, B, C, D)
- Verifying history of fill soil or previous disturbances or compaction
- Review of topographical maps and identifying drainage patterns
- Identifying streams, wetlands, wells and structures
- Confirming absence of stormwater hotspots
- Identifying current and future land uses draining onto the site

Rainfall and Traffic Data

The following data will be necessary to design the pavement:

1. The total area and percent of impervious surface draining on the permeable pavement.
2. The design storm with the return period and intensity in inches or millimeters per hour (usually supplied by municipality or other regulatory agency). Rainfall intensity-duration-frequency maps can be referenced to establish the design storm (13) (14).
3. The volume of runoff or peak flow to be captured, exfiltrated, or released using the design storm.
4. An estimate of the vehicular traffic loads expressed as 18,000 kip (80 kN) equivalent single axle loads (ESALs) over the design life of the pavement, typically 20 years.

Soil Subgrade Sampling and Analysis

The soil sampling and testing program should be designed and supervised by a licensed professional engineer knowledgeable of the local soils. This engineer should provide assessment of design strength, permeability, compaction requirements and other appropriate site assessment information. Some suggested guidelines follow on sampling and testing procedures.

Test pits dug with a backhoe are recommended for every 7,000 sf (700 m^2) if paving with a minimum of two holes per site. All pits should be dug at least 5 ft (1.5 m) deep with soil logs recorded to at least 3 ft (1 m) below the bottom of the base. More holes at various depths (horizens) may be required by the engineer in areas where soil types may change, near rock outcroppings, in low lying areas or where the water table is likely to be within 8 ft (2.5 m) of the surface. Evidence of a high water table, impermeable soil layers, rock or dissimilar layers may require a base design with no exfiltration.

The following tests are recommended on soils from the test pit, especially if the soil has clay content. These assist in evaluating the soil's suitability for supporting traffic in a saturated condition while exfiltrating. Other tests may be required by the design engineer. AASHTO tests equivalent to ASTM methods may be used.

1. Unified (USCS) soil classification using the test method in ASTM D 2487 (15).
2. Sampled moisture content in percent.
3. Onsite tests of infiltrate rate of the soil using local, state or provincial recommendations for test methods and frequency. All tests for infiltration should be done at the elevation corresponding to the bottom of the base. If there are no requirements for infiltration test methods, ASTM D 3385 (18), Test Method for Infiltration Rate of Soils in Field Using a Double-Ring Infiltrometer is recommended. ASTM D 5093 (19), Test Method for Field Measurement of Infiltration Rate Using a Double-Ring Infiltrometer with a sealed Inner Ring is for soils with an expected infiltration rate of 1.4 x 10^{-2} in./hr (10^{-7} m/sec) to 1.4 x 10^{-5} in./hr (10^{-10} m/sec). Percolation test results for the design of septic drain fields are not suitable for the design of stormwater infiltration systems (20).

Caution: Results from field tests are approximations because the structure and porosity of soils are easily changed. On-site tests do not account for loss of the soil's conductivity from construction, compaction and clogging from sediment. Nor do they account for lateral drainage of water from the soil into the sides of the base. Individual test results should not be considered absolute values directly representative of expected drawdown of water from the open-graded base. Instead, the test results should be interpreted with permeability estimates based on soil texture, structure, pore geometry and consistence (20).

For design purposes, a factor of safety of 2 should be applied to the average or typical measured site soil infiltration rate. For example a site infiltration rate of 1.0 in./hr is halved to 0.5 in./hr. for design calculations. This helps compensate for decreases in infiltration during construction and over the life of the permeable pavement. A higher factor of safety may be appropriate for sites with highly variable infiltration rates due to different soils or soil horizons.

USCS Soil Classification	Typical ranges for Coefficient of Permeability, k, in./hour (approximate m/s)	Relative Permeability when compacted and saturated	Shearing strength when compacted	Compressibility	Typical CBR Range
GW-well graded gravels	1.3 to 137 (10^{-5} to 10^{-3})	Pervious	Excellent	Negligible	30-80
GP-poorly graded gravels	6.8 to 137 (5×10^{-5} to 10^{-3})	Very pervious	Good	Negligible	20-60
GM-silty gravels	1.3×10^{-4} to 13.5 (10^{-8} to 10^{-4})	Semi-pervious to impervious	Good	Negligible	20-60
GC-clayey gravel	1.3×10^{-4} to 1.3×10^{-2} (10^{-8} to 10^{-6})	Impervious	Good to fair	Very low	20-40
SW-well graded sands	0.7 to 68 (5×10^{-6} to 5×10^{-4})	Pervious	Excellent	Negligible	10-40
SP-poorly graded sands	0.07 to 0.7 (5×10^{-7} to 5×10^{-6})	Pervious to semi-pervious	Good	Very low	10-40
SM-silty sands	1.3×10^{-4} to 0.7 (10^{-9} to 5×10^{-6})	Semi-pervious to impervious	Good	Low	10-40
SC-clayey sands	1.3×10^{-5} to 0.7 (10^{-9} to 5×10^{-6})	Impervious	Good to fair	Low	5-20
ML-inorganic silts of low plasticity	1.3×10^{-5} to 0.07 (10^{-9} to 5×10^{-7})	Impervious	Fair	Medium	2-15
CL-inorganic clays of low plasticity	1.3×10^{-5} to 1.3×10^{-3} (10^{-9} to 10^{-8})	Impervious	Fair	Medium	2-5
OL-organic silts of low plasticity	1.3×10^{-5} to 1.3×10^{-2} (10^{-9} to 10^{-6})	Impervious	Poor	Medium	2-5
MH-inorganic silts of high plasticity	1.3×10^{-6} to 1.3×10^{-5} (10^{-10} to 10^{-9})	Very impervious	Fair to poor	High	2-10
CH-inorganic clays of high plasticity	1.3×10^{-7} to 1.3×10^{-5} (10^{-11} to 10^{-9})	Very impervious	Poor	High	2-5
OH-organic clays of high plasticity	Not appropriate under permeable interlocking concrete pavements				
PT-Peat, mulch, soils with high organic content	Not appropriate under permeable interlocking concrete pavements				

Figure 15. Suitability of soils (per the Unified Soils Classification System) for infiltration of stormwater and bearing capacity (21)(22)(23). This table provides general guidance. Testing and evaluation of soils are recommended.

A minimum tested infiltration for full exfiltration subject to vehicular traffic is 0.52 in./hr (3.7×10^{-6} m/sec). Some sites may require higher rates and there may be cases where lower rates are used. Local requirements for the design of infiltration trenches may also specify minimum rates.

Soils with a tested permeability equal to or greater than 0.52 in./hr (3.7×10^{-6} m/sec) usually will be gravel, sand, loamy sand, sandy loam, loam, and silt loam. These are usually soils with no more than 10-12% passing the No. 200 (0.075 mm) sieve. These are characterized as A and B hydrologic group soils using the NRCS classification system. Silt and clay soils will likely have lower permeability and not be suitable for full exfiltration from an open-graded base. For cold climates in the northern U.S. and Canada, the lowest recommended design infiltration rate for the soil subgrade is 0.25 in./hr (2×10^{-6} m/sec).

To help maximize infiltration, the subgrade should have less than 5% passing the No. 200 (0.075 mm) sieve, although soils with up to 25% passing may drain adequately depending on site conditions and specific characteristics. Soils with a permeability lower than 0.52 in./hr (3.7×10^{-6} m/sec) can be used to infiltrate water as long as the soil remains stable while saturated, especially when loaded by vehicles. However, drain pipes will be required. Soil stability under traffic should be carefully reviewed for each application by a qualified geotechnical or civil engineer. Pedestrian applications not subject to vehicular traffic can be built over soils with a lower permeability.

Figure 15 characterizes the permeability of soils using the Unified Soil Classification System (USCS). It also shows typical ranges of the California Bearing Ratio (CBR) values for these classifications. These are general guidelines and do not substitute for laboratory and field testing.

This design procedure assumes a soil CBR (minimum 96-hour soaked per ASTM D 1883 or AASHTO T 193 (7)) strength of at least 5% or an R-value of 24 to qualify for use under vehicular traffic. The compaction required to achieve this will greatly reduce the infiltration rate of the soil. Therefore, the permeability or infiltration rate of soil should be assessed at the density required to achieve 5% CBR. If soils have a lower soaked CBR or are highly expansive, they should be treated to raise the CBR above 5%. Treatment can be with cement, lime or lime/flyash (to control expansive soils) while raising the CBR. Guidelines on the amount and depth of cement required for soil stabilization can be found in reference 24 by the Portland Cement Association.

An alternative approach to raising the CBR of non-expansive soils to over 5% is by placing a capping layer of compacted crushed stone on the subgrade. The layer should have a minimum soaked CBR of 20% and be a minimum of 8 in. (200 mm) thick. Geotextile is recommended between these layers and the soil subgrade.

Soil Compaction

For pedestrian applications, soil subgrade compaction is generally not required. It will likely not be required for vehicular applications with full exfiltration base designs placed over cleanly excavated, non-disturbed native sandy and silty soils. Compaction of some clay soils may be necessary especially those that drain slowly and sometime weaken under long-term saturation. These likely will be soils with low CBRs (<4%). Since compaction will greatly reduce infiltration, bases over compacted soils will partially exfiltrate into the soil with remaining water exiting through perforated drain pipes at the bottom of the open-graded base.

There are other factors on sites not specifically covered in this manual that influence design decisions. The guidance of an experienced civil or geotechnical engineer familiar with local site conditions and stormwater management should be sought to confirm the suitability of the soil characteristics and possible treatments for use under all permeable interlocking concrete pavements.

Geotextiles and Filter Layers

Fines particles suspended in slowly moving water will be deposited in the pores of the adjacent material. In the case of permeable interlocking pavements, particles will be deposited in another soil, the aggregate base, bedding course, the aggregate in the pavement openings or geotextile.

The build-up of fines eventually clogs and reduces permeability of these materials. To reduce this action, filter criteria must be met whenever there is a change in materials. Criteria must be met for joint and bedding materials (if different materials are used), the bedding course, the bedding course and the base, base and sub-base, and the soil subgrade. While aggregate materials can be used for filters, the use of geotextiles is more common. Figure 16 provides geotextile filter criteria from the U.S. Federal Highway Administration (FHWA) (25) and the American Association of State Highway and Transportation Officials (AASHTO) (26).

An aggregate subbase consisting of ASTM No. 2 crushed stone can be used in lieu of geotextile. This material ranges in size from 2 ½ in. to ¾ in. (63 to 19 mm) and provides a stable working platform for construction equipment to spread and compact the No. 57 stone base. After compacting the No. 2 stone, No. 57 stone is spread and compacted or choked into the openings of the No. 2 stone which rests directly on the soil subgrade.

Materials for the Base, Bedding and Openings

The following data is required on materials for the base and subbase, bedding course, and aggregate in the pavement openings:

1. Sieve analysis, including washed gradations per ASTM C 136.
2. Void space in percent for the open-graded base per ASTM C 29.

Crushed stone, open-graded base—This material should be a hard, durable rock with 90% fractured faces and a Los Angeles (LA) Abrasion of < 40. A minimum effective porosity of 0.32 and a design CBR of at least 80% are recommended. A water storage capacity of open-graded base will vary with its depth and the percent of void spaces in it. The void space of open-graded aggregate can be supplied by the quarry or from independently conducted tests.

The in-situ aggregate base should have a porosity of at least 0.32 to allow void space for water storage. The structural strength of the material should be adequate for the loads to which it will be subjected. ASTM No. 57 crushed aggregate is commonly used for open-graded bases and No. 2 for subbase. They are recommended for most permeable pavement applications. They often has a porosity (volume of voids ÷ total volume of the base) over 0.32 and storage capacity in its void spaces (volume of voids ÷ volume of aggregate), typically 20% to 40%. A 40% void space means that the volume of the base will need to be 2.5 times the volume of the water to be stored. The infiltration rate of No. 57 stone base is over 1,000 in./hr (over 7 x 10^{-3} m/sec).

The large size of the aggregates in No. 57 crushed stone creates an uneven surface when compacted. To smooth the surface, a bedding course of ASTM No. 8 crushed aggregate is placed and

U.S. Federal Highway Administration (FHWA)

For fined grained soils with more than 50% passing the No. 200 (0.075 mm) sieve:
Woven geotextiles: Apparent Opening Size (AOS) $\leq D_{85}$
Nonwoven geotextiles: $AOS_{geotextile} \leq 1.8D_{85\ soil}$
AOS $\leq$ 0.3 mm or $\geq$ No. 50 sieve

For granular soils with 50% or less passing the No. 200 (0.075 mm) sieve:
All geotextiles $AOS_{geotextile} \leq B \times D_{85soil}$
Where:
$B = 1$ for $2 \geq C_U \geq 8$
$B = 0.5$ for $2 < C_U < 4$
$B = 8/C_U$ for $4 < C_U < 8$
$C_U = D_{60}/D_{10}$

Permeability criteria: k (fabric) $\geq$ k (soil)

Clogging criteria
Woven: Percent of open area $\geq$ 4%
Nonwoven: Porosity $\geq$ 30%

American Association of State Highway and Transportation Officials (AASHTO)

For soils $\leq$ 50% passing the No. 200 (0.075 mm) sieve:
$O_{95} < 0.59$ mm ($AOS_{fabric} \geq$ No. 30 sieve)

For soils > 50% passing the No. 200 sieve:
$O_{95} < 0.30$ mm ($AOS_{fabric} \geq$ No. 50 sieve)

Notes:
1. D_x is particle size at which x percent of the particles are finer. Determined from gradation curve. Example: D_{10} is the size particle of a soil or aggregate gradation for which 10% of the particles are smaller and 90% are coarser.
2. O_x is geotextile size corresponding to x particle size base on dry glass bead sieving. Hence O_{95} is the geotextile size opening for which 95% of the holes are smaller.
3. AOS is apparent opening size is essentially the same but normally defined as a sieve number rather than as a size (ASTM D 4751). POA is percent open area for (woven fabrics only). Permeability, k of the soil and geotextile (nonwoven only) are designated k_S and k_G respectively.

Figure 16. Geotextile filter criteria

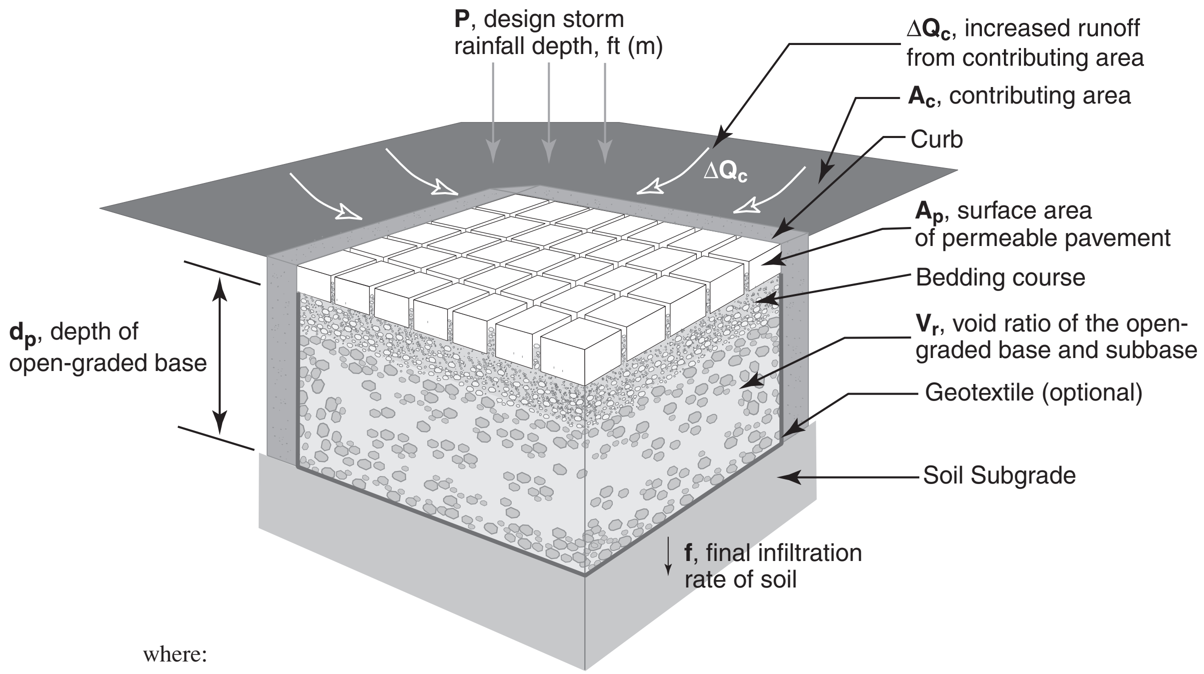
compacted into the top of the No. 57 open-graded base. The No. 8 bedding material is often called choke stone since it stabilizes and partially chokes or closes the surface of the open-graded base. The thickness of the No. 8 bedding layer should not exceed2 in. (50 mm) prior to compaction. Like No. 57, it should be hard material, having 90% fractured faces and an LA Abrasion < 40. The infiltration rate should be at least 1,000 in./hr (7 x 10^{-3} m/sec). The No. 8 material stabilizes the surface of the No. 57 and provides some filtering of water. Therefore the No. 8 choke stone should meet the following criteria:

$$\mathbf{D_{15\ open\text{-}graded\ base}/D_{50\ choke\ stone} < 5\ and\ D_{50\ open\text{-}graded}/D_{50\ choke\ stone} > 2}$$

$\mathbf{D_x}$ is the particle size at which x percent of the particles are finer. For example, $\mathbf{D_{15}}$ is the particle size of a soil or aggregate gradation for which 15% of the particles are smaller and 85% are coarser.

If the bedding material can't meet this filter criteria (i.e., the bedding stone is smaller or the base material is larger), a layer of geotextile may be used between the bedding and base course. This adds stability to the structure. Geotextile has been shown to accelerate digestion of oils through moisture and microbial action (45).

Besides use as a bedding material, No. 8 crushed stone aggregate is also recommended for fill material in the paver openings. Smaller sized aggregate such as No. 89 may be needed to enter nar-



where:

f = the final (design) infiltration rate in in./hr (m/hr) of the soil under the pavement (infiltration rates are determined from permeability tests and engineering judgement);

$\mathbf{T_s}$ = the maximum allowable storage time of 72 hours; and

$\mathbf{V_r}$ = the void ratio (space) of the crushed stone base and subbase (typically 0.4).

The maximum allowable depths are given in Figure 19 for selected values of **f**, $\mathbf{T_s}$, and $\mathbf{V_r}$.

$\mathbf{A_c}$ = contributing area, sf (m^2)

$\Delta\mathbf{Q_c}$ = increased runoff from contributing area, ft (m) per a given design storm

$\mathbf{A_p}$ = surface area of permeable interlocking concrete pavement, sf (m^2)

P = design storm rainfall depth, ft (m)

$\mathbf{d_p}$ = depth of crushed stone base, ft (m)

T = effective filling time of the base, hours (2 hours is typical)

Figure 17. Design parameters for calculating the base depth for permeable interlocking concrete pavements.

row joints between interlocking shapes. Ferguson (43) provides additional filter criteria for aggregate layers. The void space in the bedding and joints is not considered in water storage calculations. Nonetheless, they provide an additional factor of safety since they have capacity for storing water.

Concrete units for permeable pavement—The following data is needed on the pavers:

1. Minimum thickness = $3^1/_8$ in. (80 mm).
2. Percent of open area of the surface.
3. Test results indicating conformance to ASTM C 936, *Standard Specification for Solid Interlocking Concrete Paving Units* (27), or CSA A231.2, *Precast Concrete Pavers* (28) as appropriate. If the dimensions of the units are larger than those stated in these standards, then CSA A231.1, *Precast Concrete Paving Slabs* (29) is recommended as a product standard.

Sizing an Open-Graded Base for Stormwater Infiltration and Storage

The following design method is adapted from *Standard Specifications for Infiltration Practices* (30) and the *Maryland Stormwater Manual* published by the State of Maryland, Department of the Environment (31). The procedure is from "Method for Designing Infiltration Structures." This method assumes familiarity with NRCS TR 55 method (32) for calculating stormwater runoff. References 11, 33, 34, and 35 provide other methods. Provinces, states, and cities may mandate the use of other methods. The Maryland method is provided because it has been refined over many years and it illustrates important aspects of infiltration design.

Like porous asphalt pavement, permeable interlocking concrete pavement relies on an open-graded aggregate base into which water rapidly infiltrates for storage. The pavement base functions as an underground detention structure. Therefore, pavement base storage can be designed with the same methods as those used for stormwater management ponds. The design method in this section assumes full exfiltration, e.g., removal of water from the base by infiltration into the underlying soil subgrade.

The catchment for permeable interlocking concrete pavement consists of the surface area of the pavement and an area that contributes runoff to it. A schematic cross-section and the design parameters are shown in Figure 17. The base is sized to store the runoff volume from the pavement area and the adjacent contributing areas.

Soil with infiltration rates or permeability less than 0.27 in./hr (2×10^{-6} m/sec) are generally silt loam, loam, sandy loam, loamy sand, and sand. Soils with lower permeability will limit the flow of water through the soil. They will require a high ratio of bottom surface area to storage volume. Therefore, careful consideration should be given to designing drain pipes to remove excess water in these situations.

The method described below does not provide guidance on drain pipe design within the base. This can be found in reference 35. Reference 36 includes methods for determining the diameter and spacing of pipes in open-graded bases for highway pavement drainage, as well as general guidance on pavement drainage design. This method accounts for monthly variations in the water generated from background flows in the soil and infiltration area, as well as that from the runoff from the design storm. It does not include structural design for base thickness under vehicular traffic.

The Maryland method finds the maximum allowable depth of the pavement (d_{max}) for a maximum storage time of 3 days. Shorter storage times are desirable to minimize risk of continually saturated and potentially weakened soil subgrade for areas subject to vehicular traffic. In that light, calculations should be done for 1 and 2 days, as well as 3 days, to compare differences in base thickness. In some instances, the calculated depth of the base for storage may be too shallow to support vehicular traffic. In these cases, the minimum base thickness would then be the depth required to accommodate traffic per Figure 18.

The values in Figure 18 are adopted from thickness designs for permeable asphalt pavement (49) (50). Their use rests on the assumption that $3^1/_8$ in. (80 mm) thick concrete pavers provide a structural contribution similar to an equivalent thickness of porous asphalt, or an AASHTO layer coefficient of 0.25 to 0.4 per in. (25 mm) including the No. 8 bedding material. The base thicknesses assume that the strength of the soil subgrade is at least 5% CBR (elastic modulus of 7,500 psi or 50 MPa).

Climate	No Frost	No Frost	No Frost	No Frost	Frost	Frost	Frost	Frost
ESALs*	Soaked CBR Base Subbase	>15	10-14	5 to 9	Gravelly Soils	Clayey Gravels, Plastic Sandy Clays	Silty Gravel, Sand, Sandy Clays	Silts, Silty Gravel, Silty Clays
Pedestrian	No. 57 No. 2	4 (200) 6 (150)	4 (100) 6 (150)	4 (100) 6 (150)	4 (100) 6 (150)	4 (100) 6 (150)	4 (100) 6 (150)	4 (100) 6 (150)
50,000	No 57 No. 2	4 (100) 8 (200)	4 (100) 8 (200)	4 (100) 8 (200)	4 (100) 8 (200)	4 (100) 8 (200)	4 (100) 8 (200)	**
150,000	No. 57 No. 2	4 (100) 8 (200)	4 (100) 8 (200)	4 (100) 8 (200)	4 (100) 8 (200)	4 (100) 8 (200)	4 (100) 10 (250)	**
600,000	No. 57 No. 2	4 (100) 8 (200)	4 (100) 8 (200)	4 (100) 10 (250)	4 (100) 8 (200)	4 (100) 14 (350)	4 (100) 18 (450)	**

* ESALs = 18 kip (80 kN) Equivalent Single Axle Loads

** Strengthen subgrade with crushed-stone sub-base to full frost depth.

Notes:

1. All thicknesses are after compaction and apply to full, partial and no base exfiltration conditions.
2. Pedestrian applications should use a minimum base thickness of 10 in. (250 mm).
3. Thicknesses do not include No. 8 bedding course and permeable pavers.
4. Geotextile over the subgrade is optional.
5. Silty soils or others with more than 3% of particles smaller than 0.02 mm are considered to be frost susceptible.

Figure 18. Recommended minimum open-graded base and subbase thicknesses for permeable interlocking concrete pavements in inches (mm) (after ref. 37 and 38)

		Soil Subgrade Texture/Infiltration Rate Inches/Hour (m/sec)										
		Sand	Loamy Sand	Sandy Loam	Loam	Silt Loam	Sandy Clay Loam	Clay Loam	Silty Clay Loam	Sandy Clay	Silty Clay	Clay
Criterion	T_s (hrs)	8.27 (6×10^{-5})	2.41 (2×10^{-5})	1.02 (7×10^{-6})	.52 (4×10^{-6})	.27 (2×10^{-6})	.17 (1×10^{-6})	.09 (6×10^{-7})	.06 (4×10^{-7})	.05 (3×10^{-7})	.04 (2×10^{-7})	.02 (10^{-7})
$f \times T_s/V_r$	24	496 (12.6)	145 (3.7)	61 (1.5)	31 (0.8)	16 (0.4)	10 (0.25)	5 (0.12)	4 (0.1)	3 (0.07)	2 (0.05)	1 (0.02)
for	48	992 (25.2)	290 (7.4)	122 (3.1)	62 (1.6)	32 (0.8)	20 (0.5)	11 (0.3)	7 (0.17)	6 (0.15)	2 (0.15)	2 (0.05)
$(V_r=0.4)$	72	1489 (37.8)	434 (11)	183 (4.6)	93 (2.4)	149 (1.2)	31 (0.8)	16 (0.9)	11 (0.13)	9 (0.2)	7 (0.17)	4 (0.1)

T_s = Maximum allowable storage time V_r = Voids ratio ▨ = Lowest values unless base exfiltration is supplemented with drain pipes.

Figure 19. Maximum allowable depths, inches (m) of storage for selected maximum storage times (T_s in hours), minimum infiltration rates, inches/hours (m/sec)(31).

The NRCS method typically uses 24-hour storm events as the basis for design. Therefore, this design method is based on controlling the increased runoff for a specific 24-hour storm. The specific duration and return period (e.g., 6-months, 1-year, 2-year, etc.) are provided by the locality. If the increase in peak discharge associated with the storm event cannot be managed, a first flush event should be the minimum selected for design.

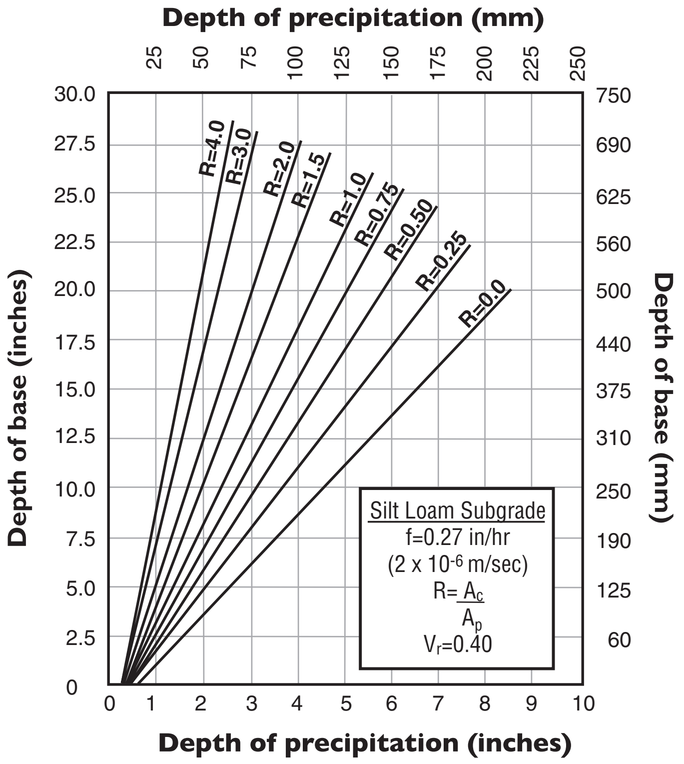


Figure 20. Open-graded base and subbase depth for silt loam subgrade.

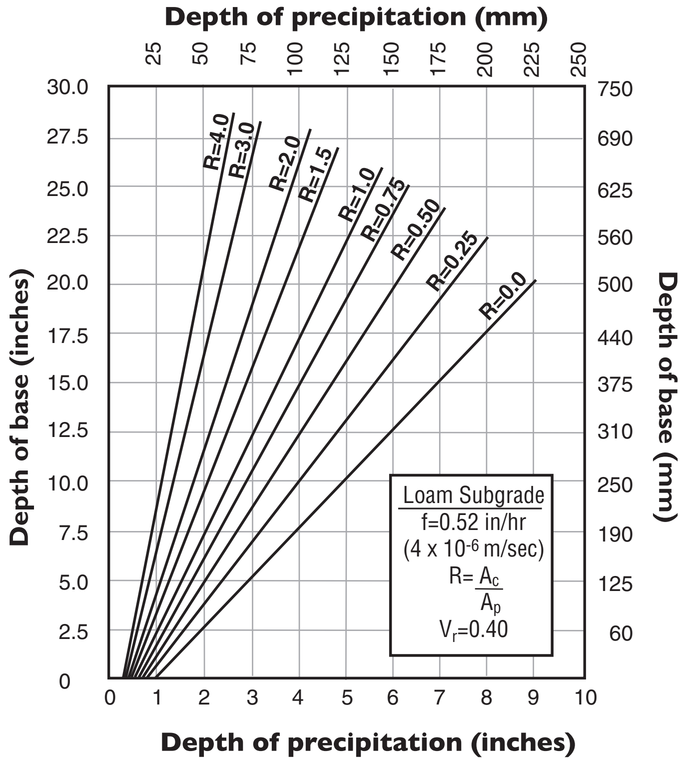


Figure 21. Open-graded base and subbase depth for loam subgrade.

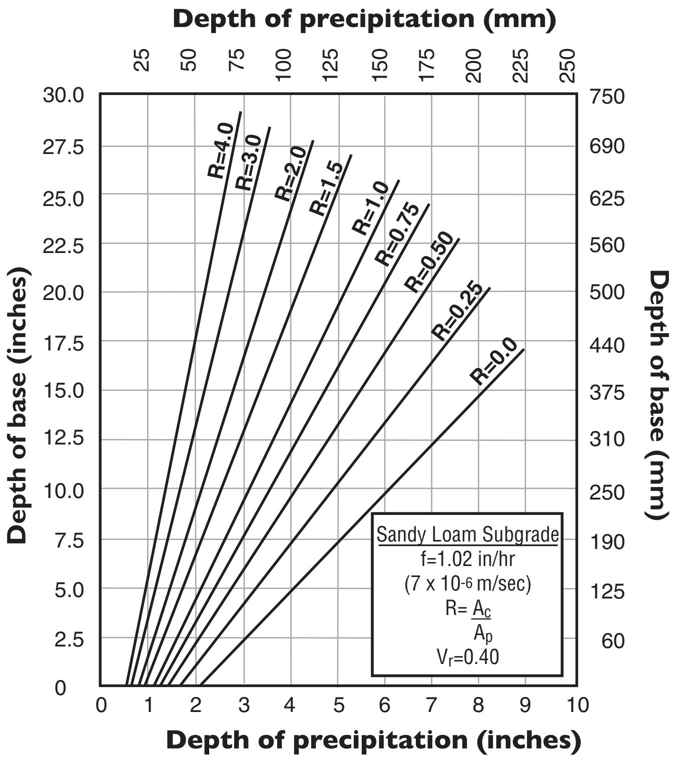


Figure 22. Open-graded base and subbase depth in sandy loam subgrade.

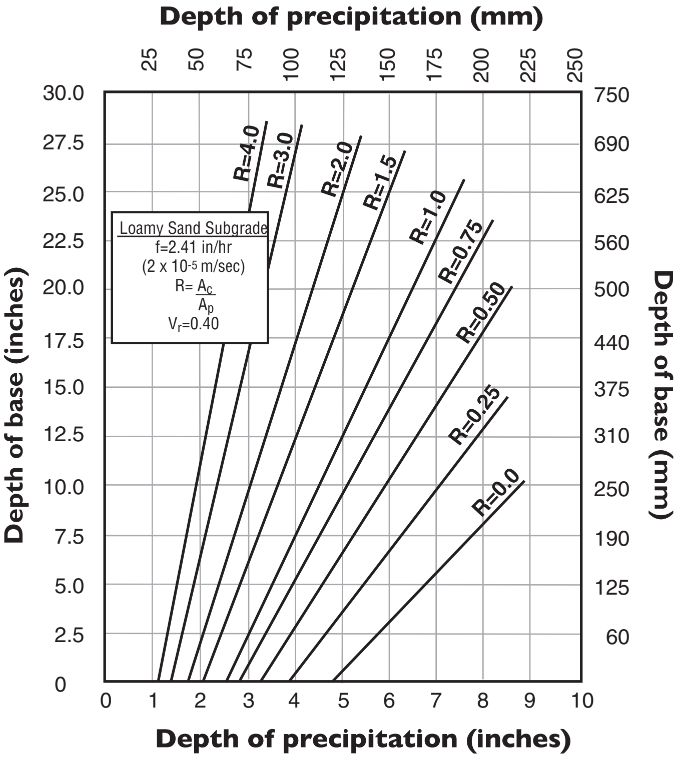


Figure 23. Open-graded base and subbase depth for loamy sand subgrade.

For runoff storage, the maximum allowable base depth in inches (m) should meet the following criteria:

$$d_{max} = f \times T_s / V_r$$

As shown in Figure 17, the design volume of water to be stored in the pavement base (V_w) is:

the runoff volume from the adjacent contributing area;	plus	the rainfall volume falling on the permeable pavement	minus	the exfiltration volume into the underlying soil
= $\Delta Q_c A_c$	+	PA_p	—	fTA_p

Values of **f** for infiltration rate should be obtained from Figure 19 for preliminary designs and checked against field tests for the infiltration rate of the soils.

For designs based on the Soil Conservation Service or NRCS Type II storm, the permeable pavement base filling time (**T**) is generally less than a 2-hour duration where the flow into the pavement exceeds the flow out of the pavement. Thus, a duration of 2 hours is used for **T**. The volume of water that must be stored (V_w) may be defined as:

$$V_w = \Delta Q_c A_c + PA_p - fTA_p$$

The volume of the stone base and subbase can also be defined in terms of its geometry:

$$V_p = V_w / V_r = d_p A_p$$

Where:
d_p = the depth of the stone base (including subbase),
A_p = the permeable pavement surface area, and
V_r = the stone base and subbase void ratio (typically 0.4).

Setting the previous two equations equal will result in the following relationship:

$$d_p A_p V_r = \Delta Q_c A_c + PA_p - fTA_p \qquad \text{(Equation 1)}$$

The surface area of the permeable pavement (A_p) and the depth of the base (d_p) can be defined in the following forms from the above equation:

$$A_p = \frac{\Delta Q_c A_c}{V_r d_p - P + fT} \qquad \text{(Equation 2)}$$

and

$$d_p = \frac{\Delta Q_c R + P - fT}{V_r} \qquad \text{(Equation 3)}$$

Where:
R = equal to the ratio of the contributing area and the permeable pavement area (A_c/A_p).

Equation 3 will be used most often since the surface area of the pavement is normally known and the depth of the stone base is to be determined. All units in the above two equations are in terms of feet. Metric equivalents can be substituted.

The solution to Equation 3 is shown graphically in Figures 20 through 23. The graphs are based on storing the entire contributing area runoff volume ($Q_c A_c$) based on the NRCS curve number for an impervious area, CN = 98. The NRCS method offers a chart to assist in finding the depth of runoff from a given 24 hr. design storm for less than completely impervious areas, i.e., curve numbers lower than 98. This chart is shown in Figure 24. Since many localities use 24-hour storms for storm water management.

Design Procedure—There are two methods to design the base storage area. The first method computes the minimum depth of the base, given the area of the permeable pavement. This is called the *minimum depth method*. The other is compute the minimum surface area of the permeable pavement given the required design depth of the base. This is the *minimum area method*. The minimum depth method generally will be more frequently used.

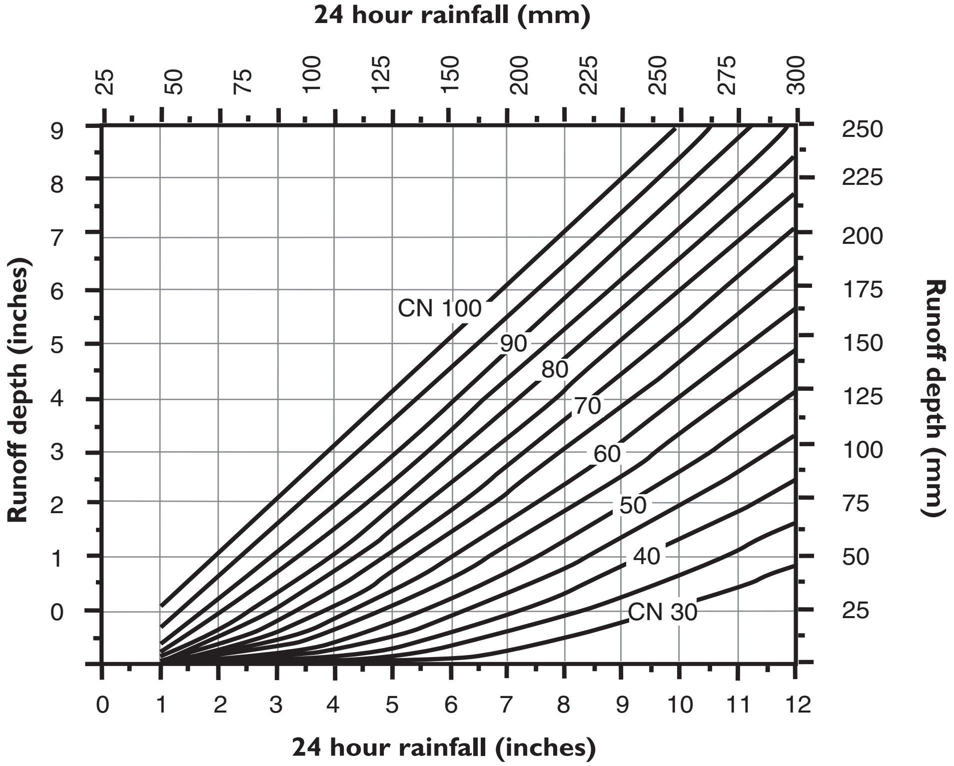


Figure 24. NRCS chart for finding runoff depth for various curve numbers.

Minimum Depth Method

1. From the selected design rainfall ($\mathbf{P}$) and the NRCS runoff curve number, compute the increased runoff volume from the contributing area ($\Delta \mathbf{Q}_c$).
2. Compute the depth of the aggregate base ($\mathbf{d}_p$) from Equation 3:

   Figures 20 through 23 may be used to determine the approximate stone base and subbase depth if the total runoff depth ($\mathbf{Q}_c$) is to be stored.
3. Compute the maximum allowable depth ($\mathbf{d}_{max}$) of the aggregate base and subbase by the feasibility formula:

   $$\mathbf{d}_{max} = \mathbf{f} \times \mathbf{T}_s / \mathbf{V}_r$$

   where $\mathbf{d}_p$ must be less than or equal to $\mathbf{d}_{max}$ and at least 2 feet (0.6 m) above the seasonal high ground water table. If $\mathbf{d}_p$ does not satisfy this criteria, the surface area of the permeable pavement must be increased or a smaller design storm must be selected.

Minimum Area Method

1. From the selected design rainfall ($\mathbf{P}$) and the NRCS runoff curve number for the contributing area to be drained, compute the increased runoff depth from the contributing area ($\mathbf{DQ}_c$).
2. Compute the maximum allowable depth ($\mathbf{d}_{max}$) of the aggregate base from the feasibility formula:

   $$\mathbf{d}_{max} = \mathbf{f} \times \mathbf{T}_s / \mathbf{V}_r$$

   Select a design depth of the aggregate base ($\mathbf{d}_p$) less than or equal to $\mathbf{d}_{max}$ or the depth at least 2 feet (0.6 m) above the seasonal high ground water table, whichever is smaller.
3. Compute the minimum required surface area of the permeable interlocking concrete pavement ($\mathbf{A}_p$) from Equation 3:

$$A_p = \frac{\Delta Q_c A_c}{V_r d_p - P \times fT}$$

Design Example

Step 1—Assess site conditions. A parking lot is being designed in an urbanized area where storm sewers have limited capacity to convey runoff from an increase in existing impervious surfaces. Runoff from a 1 acre (4,047 m^2) asphalt parking lot (100% impervious: NRCS curve number or CN = 98) is to be captured by a 2 acre (8,094 m^2) permeable interlocking concrete pavement parking area over an open-graded base. The project is not close to building foundations nor are there any wells in the area. Soil borings revealed that the seasonal high water is 10 ft (3 m). The soil borings and testing indicated a USCS classification of SP (poorly-graded sandy soil) with 4% passing the No. 200 (0.075 mm) sieve. Permeability was tested at 1.02 in./hr (5×10^{-5} m/sec). While this was the tested permeability rate, the designer is taking a conservative position on design permeability by assuming it at half or 0.51 in./hr (3.6×10^{-6} m/sec).This approach recognizes that there will be a loss of permeability from construction, soil compaction and clogging over time. The 96-hour soaked CBR of the soil is 12%. An estimated 300,000 ESALs will traffic this parking lot over 20 years. The pavers have an 8% or 0.08 open surface area. The site is in an area that receives frost.

Local regulations require this site to capture all runoff from a 2-year 24 hour storm. This is 5 in. (0.125 m) based on weather maps and local historical storm data. (Other localities often may require capturing the difference in runoff from before and after development for a given design storm or storms. A fairly rigorous requirement is given here of capturing all the runoff due to the limited capacity of the storm sewers. This is also done to simplify the design example.) This 5 inch depth meets the local water quality volume capture of 1.2 in. (30 mm) needed to meet pollutant reduction requirements.

The void space in the No. 57 open-graded, crushed stone base and No. 2 subbase provided by the local quarry is 40% or 0.40. A 1-day drainage of the base (or 24-hour drawdown) is the design criteria.

Step 2—Check the required permeability of the surface openings: 1 in./hr ÷ 0.08 = 12.5 in./hr (9×10^{-5} m/sec). This will require the use of No. 8 aggregate in the openings since the permeability of this material well exceeds 12.5 in./hr.

Since the area of the permeable interlocking concrete pavement parking lot is established, the depth of the base needs to be determined with the Minimum Depth Method

Step 3—Compute the increased runoff depth from the contributing area (ΔQ_c) from the selected design rainfall (P) and the NRCS runoff curve number.

Since the contributing area is impervious asphalt with a curve number = 98, all of the rainfall from design storm, or 5 in.(0.125 m), will flow from it into the permeable pavement.

Step 4—Compute the depth of the aggregate base (d_p) from Equation 3:

$$d_p = \frac{\Delta Q_c R + P\text{-}fT}{V_r} = \frac{0.42 \text{ ft } (1 \text{ ac.}/2 \text{ ac.}) + 0.42 \text{ ft} - 0.0425 \text{ ft/hr } (2 \text{ hr}) = 1.36 \text{ ft } (0.4 \text{ m})}{0.4}$$

As a short cut, Figure 21 may be used to determine the approximate stone base depth if the total runoff depth (Q_{cc}) is to be stored. Use this figure to find 16.3 in. or 1.36 ft (0.4 m).

Step 5—Compute the maximum allowable depth (d_{max}) of the base by the feasibility formula:

$$d_{max} = f \times T_s / V_r$$

where d_p must be less than or equal to d_{max} and at least 2 feet (0.6 m) above the seasonal high ground water table. If d_p does not satisfy this criteria, the surface area of the permeable pavement must be increased or a smaller design storm must be selected. The drainage time is 24 hours.

$$d_{max} = 0.0425 \text{ ft/hr} \times 24 \text{ hr}/0.40 = 2.5 \text{ ft } (0.75 \text{ m})$$

Step 6—Check the structural base thickness to be sure it has sufficient thickness to meet the storage requirements plus function as a base for 300,000 ESALs. The Frost Condition side of Figure 18 under sand with interpolation yields a thickness close to 18 in. (0.45 m). This is slightly thicker than what is required, 16.3 in. (0.4 m), to infiltrate and store the water in the base.

In no case should the structural thickness be reduced for the sake of economy. In some cases, the designer may wish to provide a thicker base due to expected heavy loads, or from spring thawing conditions that leave the soil completely saturated and weak. A frost protection layer of sand with drains can be placed under the base (separated by geotextiles) to reduce heave from highly susceptible soils in freeze-thaw conditions. This layer of sand offers additional filtering and reduction of pollutants, and construction details are discussed elsewhere.

It is very unlikely that the base and leveling courses will heave from ice. There is typically sufficient void space in them to allow frozen water to expand (9%) without heaving because it is rare that the base will be entirely and thoroughly saturated when freezing.

Step 7—Check to be sure the bottom of the base is at least 2 ft (0.6 m) from the seasonal high water table. The total thickness of the pavement will be:

3 $^{1}/_{8}$ in. (80 mm) thick concrete pavers
3 in. (75 mm) No. 8 stone leveling course
18 in. (450 mm); 4 in. (100 mm) No. 57 base and 14 in. (350 mm) No. 2 subbase
Total thickness = 24 in. (600 mm)

Two feet (0.6 m) minus 10 ft (3 m) leaves 8 ft (2.4 m) to the top of the seasonal high water table. This is greater than the 2 ft (0.6 m) minimum distance required.

A somewhat hidden consideration is the storage capacity of the layer of No. 8 crushed stone. As a factor of safety, the void space in the No. 8 layer is not part of the storage calculations. This additional volume in the leveling course can serve as a safety buffer for storage in heavy rainfall.

Step 8—Check geotextile filter criteria. Sieve analysis of the soil subgrade showed that 4% passed the No. 200 (0.075 mm) sieve, and the gradation also showed the following:

	D_{10}	D_{15}	D_{50}	D_{60}	D_{85}
Soil subgrade	**0.10**	**0.12**	**0.25**	**0.32**	**0.63**

If geotextile is used the following criteria apply. FHWA geotextile filter criteria—For granular soils with ≤50% passing the No. 200 (0.075 mm) sieve, the following selection criteria is used for geotextiles taken from Figure 18.

All geotextiles: $\mathbf{AOS_{geotextile} \leq B \times D_{85\,(soil)}}$

$\mathbf{C_U = D_{60}/D_{10} = 0.32/0.10 = 3.2}$

Where:
$\mathbf{B}$ = 1 for 2 $\geq \mathbf{C_U} \geq$ 8, 3.2 is okay.
$\mathbf{B}$ = 0.5 for 2 < $\mathbf{C_U}$ < 4, 3.2 is okay.
$\mathbf{B}$ = 8/$\mathbf{C_U}$ for 4 < $\mathbf{C_U}$ < 8

8/3.2 = 2.5 which does not satisfy 4 < 2.5 < 8. (Do not use for **B**.)

Therefore, select a geotextile with an **AOS** (or **EOS**) between 0.5 x 0.63 = 0.32 mm and 1.0 x 0.63 = 0.63 mm.

Permeability criteria: k (fabric) ≥ k (0.52 in./hr)
Clogging criteria:
Woven: Percent of open area ≥ 4%
Nonwoven: Porosity ≥ 30%

AASHTO geotextile filter criteria (36)—For soils ≤ 50% passing the No. 200 (0.075 mm) sieve:

$\mathbf{O_{95} < 0.59\ mm\ (AOS_{geotextile} \geq No.\ 30\ sieve)}$

The FHWA and AASHTO criteria provide similar guidance in selecting the **AOS** of a geotextile. In both cases, the **AOS** should be less than the No. 30 (0.600 mm) sieve, but greater than 0.32 mm.

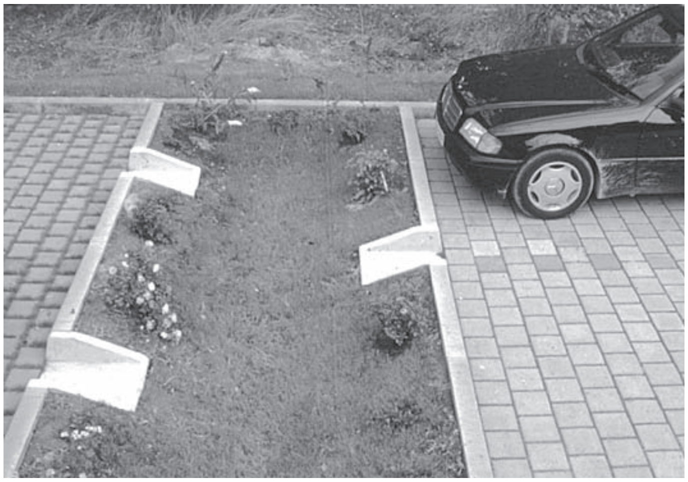


Figure 25. Curbing and drainage swale handle flows that exceed the design rainstorm.

Other Design Methods

Like most structural BMPs, the hydrological and pollution abatement characteristics of permeable interlocking concrete pavements should be incorporated into managing runoff within the large catchment, sub-watershed or watershed. The NRCS method is well-established, easy to use and easy to adapt to various BMPs. For example, reference 35 applies the NRCS method to infiltration trench design. For the permeable pavements themselves, the curve number can be estimated at 65 assuming a very conservative, life-time design infiltration rate of 1.1 in./hr (28 mm/hr) with an initial abstraction of 0.2. Lower curve numbers apply to NRCS A and NRCS B hydrologic group soils. Users of other quantitative models (HEC-1, EPA SWMM, etc.) are encouraged to modify their programs to include permeable interlocking concrete pavements.

Some caution should be exercised in applying the NRCS method to calculating runoff in catchments as small as 5 acres (2 ha). This method is intended to calculate runoff from larger storms (2, 10, and 100 year return periods) with 24-hour durations. Therefore, the NRCS procedure tends to underestimate runoff from smaller storms in small drainage areas. Permeable interlocking concrete pavements control runoff from smaller storms. Typically, they generate the most amount of non-point water pollution. Claytor and Schueler suggest methods to calculate runoff from small areas from smaller storms especially when water quality needs to be controlled (9).

Rational Method Calculations

The NRCS method is commonly used for calculating runoff volumes and peak discharges. The Rational Method is only useful for estimating peak runoff discharges in watersheds up to 200 acres (80 ha). Peak flow is derived from the formula

$Q = CIA$

Where:

Q = peak discharge in cubic feet per second
I = design rainfall intensity in inches per hour
A = Drainage area in acres
C = Coefficient of runoff

Since the formula does not account for volume, *it cannot be used in water quality calculations*. For peak runoff calculations, the coefficient of runoff, C for the design life of interlocking concrete pavements can be estimated with the following formula: $C = \frac{I - \text{Design infiltration rate, in./hr}}{I}$

Protection Against Flooding From Extremely Heavy Rainstorms

There may be cases of extreme rainfall completely saturating the entire pavement structure. Drainage pipes should be built into the open-graded base to handle over-flow conditions. As an added measure of protection, there should be provision for an overflow area, by-pass or a drainage swale adjacent to the parking lot should it be completely saturated and flooded. An example of a drainage swale designed to handle overflows from an adjacent pervious parking lot is illustrated in Figure 25. Placing filter areas upslope from the pavement to reduce pollutants are recommended when space allows.

Cold Climate Design

The following design considerations apply to freezing climates with extended winters having large, rapid volumes of snow melt in the late winter and early spring. These areas are mostly in the northern U.S. and Canada (39).

1. Permeable interlocking concrete pavements should not be used in permafrost regions.

2. Chlorides and road abrasives (sand) can be concentrated in snowmelt. It's impossible for any best management practice, including permeable interlocking concrete pavements, to remove chlorides found in deicing materials. In addition, road sand can clog and reduce the infiltration capacity of these pavements. It is best to stockpile snow with chlorides and/or sand away from permeable interlocking concrete pavements. Possible locations include parking lot islands or bioretention areas.

3. If salts are used for deicing, then the groundwater should be monitored for chlorides. This

can be done through sampling water in observation wells located in the pavement base and soil. Chloride levels in the samples should be compared to local or national criteria for the particular use of the water in the receiving lake, stream, or river (e.g., drinking water, recreation, fishing, etc.).

4. When the frost depth exceeds 3 ft. (1 m), all permeable parking lots should be set back from the subgrade of adjacent roads by at least 20 ft (6 m). This will reduce the potential for frost lenses and heaving of soil under the roadway.

5. Plowed snow piles and snow melt should not be directed to permeable interlocking concrete pavements if groundwater contamination from chlorides is a concern. However, this may not be avoidable in some situations. If high chloride concentrations in the runoff and groundwater are anticipated, then consideration should be given to using one or two design options below:

   (a) Runoff from snow melt can be diverted from the pavement during the winter. The diversion of runoff away from the pavement is typically through channels or pipes. Pipe valves must be operated each winter and spring. Snowmelt, however, is not treated but diverted elsewhere.
   (b) Oversized drainage pipes can be used to remove the runoff during snowmelt, and then be closed for the remainder of the year.

   The owner of the pavement must take responsibility for operating pipe valves that divert snowmelt. This may not be realistic with some designs.

6. Maintenance should include annual inspection in the spring and vacuum removal of surface sediment, as well as monitoring of groundwater for chlorides. This is paramount to continued infiltration performance.

Design for Control of Water Quality

Since urbanization significantly alters the land's capacity to absorb and process water pollutants, an increasing number of localities are regulating the amount of pollutants in stormwater. This is particulary the case when drinking-water supplies and fishing industries need to be protected. Urban stormwater pollutants and their sources are shown in Figure 26.

Permeable interlocking concrete pavements designed as an infiltration area over an open-graded base can reduce nonpoint source pollutants in storm water. Figure 27 illustrates the projected average annual pollutant removal capability of infiltration practices. Figure 27 demonstrates their effectiveness in reducing typical pollutants.

Keep in mind that the type of soil subgrade affects the pollution reduction

Pollutant Category Source	**Solids**	**Nutrients**	**Bacteria**	**Dissolved oxygen demands**	**Metals**	**Oils (PAHs)* SOCs***
Soil erosion	*	*		*	*	
Cleared vegetation	*	*		*		
Fertilizers		*				
Human waste	*	*	*	*		
Animal waste	*	*	*	*		
Vehicle fuels and fluids	*			*	*	*
Fuel combustion		*			*	
Vehicle wear	*			*	*	
Industrial/household chemicals	*	*	*	*	*	*
Industrial processes	*	*	*	*	*	*
Paints and preservatives				*	*	*
Pesticides				*	*	

PAHs = polynuclear aromatic hydrocarbons
SOCs = synthetic organic compounds

Figure 26. Common sources of pollution in urban stormwater runoff (3)

Pollutant	Infiltration Trench Design Type*			Infiltration Trenches & Porous Pavement
	0.5 in. (13 mm) of Runoff per Impervious acre	1.0 in. (25 mm) of Runoff per Impervious acre	2-year Design Storm Treatment	Median Pollutant Removal**
Total Suspended Solids	60-80	80-100	80-100	95
Total Phosphorous	40-60	40-60	60-80	70
Total Nitrogen	40-60	40-60	60-80	51
Biological Oxygen Demand	60-80	60-80	80-100	—
Bacteria	60-80	60-80	80-100	—
Metals	60-80	60-80	80-100	99 (Zn)

*Note: These rates are not based on actual data since monitoring what enters and leaves any infiltration facility is difficult to measure. These data are based on land application of pollutants and their treatment through soils.

**Actual monitored removal rates.

Figure 27. Projected average annual pollutant removal capability of infiltration areas in percent (from Debo and Reese (11) after Schueler) and actual, monitored removal rates documented by Winer (42)

capabilities of infiltration areas. Clay soils with a high cation exchange capacity will capture more pollutants than sandy soils. Debo and Reese (11) recommend that for control runoff quality, the storm water should infiltrate through at least 18 in. (0.45 m) of soil which has a minimum cation exchange capacity of 5 milliequivalents per 100 grams of dry soil. However, some clay soils that are effective pollutant filters do not have a sufficiently high infiltration rate or sufficient bearing capacity when saturated to be used under infiltration areas subject to vehicular loads.

Other approaches to reducing pollutants include filtering runoff from impervious areas through sand filters to help reduce sediment and oils. The typical application involves a small area that pretreats runoff prior to entering a detention or retention pond. The sand absorbs and helps treat the concentrated pollutants found in the first flush of a rainstorm. Design of sand filtering systems is found in reference 9.

The U.S. Environmental Protection Agency recognizes permeable interlocking concrete pavement as a BMP in reducing non-point source pollutants in runoff. In 2003 the U.S. EPA issued a New Development Management Measure for protection of coastal waters near urban areas (47). These measures appear in some non-coastal state and local BMP or stormwater design manuals.

Key measures require at least 80% reduction of total suspended solids (TSS) on an average annual basis, or post-development TSS loadings not exceeding predevelopment loadings. As part of that management measure for new development, to the extent practicable, postdevelopment peak runoff rates and volumes should be similar to predevelopment levels based on rainfall from a 2-year, 24 hour storm. This helps reduce or prevent streambank erosion and scouring.

Permeable interlocking concrete pavement can achieve this reduction in peak flows and volumes. Regarding TSS reduction, several studies have demonstrated reductions at or near the 80% level:

- Rushton (48) monitored runoff and pollutants in a Tampa, Florida parking lot for two years. Eight sub-catchments included permeable pavement, concrete and asphalt pavement. Permeable pavement had the highest load removal efficiency for ammonia, nitrate, total nitrogen, total suspended solids, copper, iron, lead, manganese and zinc. Most removal rates exceeded 75%.

Figure 28. Besides expected decreases in stormwater, runoff monitored from permeable interlocking concrete pavement projects such as Glen Brook Green Subdivision, Waterford, Connecticut in the Jordan Cove Watershed demonstrate substantial reductions of pollutants compared to those from conventional pavements.

- Bean (49) compared runoff quantities and quality over 18 months from a small asphalt and permeable interlocking concrete pavement parking lot with an open-graded aggregate base at a bakery in Goldsboro, North Carolina. The study summarizes the statistical mean pollutant concentrations from 14 rainstorms and illustrates substantial pollutant reductions for including . TSS reductions of 76%.
- Scholes (50) reports on pollutant removal efficiencies of various BMPs in the United Kingdom and identifies porous paving has having an average of 82% removal efficiency with data ranging between 64% and 100% removal rates.
- Clausen (51) monitored runoff from driveways for one year in a small residential subdivision in Waterford, Connecticut. The driveways consisted of asphalt, crushed stone and permeable interlocking concrete pavement (over a dense-graded base). Annual pollutant export in kg/ha/yr was 86% lower on the paver driveways than on the asphalt ones.
- James (52) examined surface runoff from nine rainstorms over four months from asphalt, concrete pavers and permeable interlocking concrete pavers. He also measured pollutants in the base and subbase of the permeable pavement. Permeable interlocking concrete pavements rendered a 97% reduction of total suspended solids compared to that generated by the asphalt surface. Similar differences were indicated by solids sampled in water leaving the permeable pavement subbase.

Permeable interlocking concrete pavements clearly improve water quality by capturing and filtering runoff from most commonly occurring storms. These are the ones with the highest concentration of pollutants. Some localities require capturing a given volume or depth of rainfall to reduce pollutants such as total suspended solids and nutrients such as phosphorous. A method for estimating the amount of water to treat or "water quality capture volume" has been developed by the Water Environment Federation in WEF Manual of Practice No. 23, *Urban Runoff Quality Management* (pages 175-178). The Manual also provides BMP selection and design guidance (53).

The WEF method can be used to calculate the base water storage requirements needed for permeable interlocking concrete pavements to help ensure pollutant treatment. Estimated stormwater quantity storage volumes required by the locality should be compared to the water volume that needs to be captured and treated for improving water quality. In most cases, water volume captured to control stormwater quantities will exceed the volume needed to be captured and treated for improved water quality. In such cases, the water volume captured to improve water quality is automatically included in the water quantity calculations for the design storm.