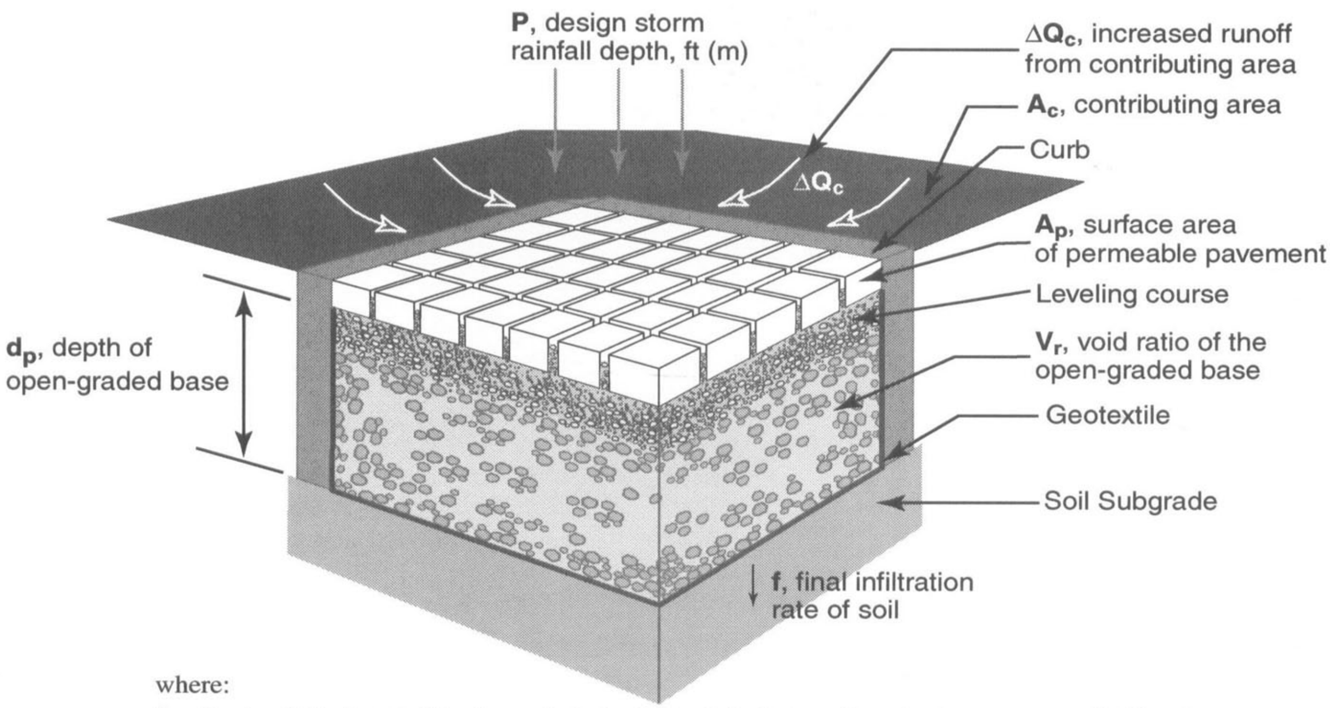
Concrete units for permeable pavement—The following data is needed on the pavers:

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 SCS (NCRS) 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.



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 (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 (m²)

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

$\mathbf{A_p}$ = surface area of permeable interlocking concrete pavement, sf (m²)

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.

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 ($\mathbf{d}_{max}$) 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.

	Soaked CBR of Subgrade Soil			Frost Conditions			
ESALs* over 20 yrs.	>15	10 to 14	5 to 9	Gravelly Soils	Clayey Gravels, Plastic Sandy Clays	Silty Gravel, Sand, Sandy Clays	Silts,Silty Gravel, Sand, Silty Clays
50,000	6 (125)	8 (175)	10 (225)	9(175)	10 (250)	12 (300)	**
150,000	8 (150)	10 (200)	12 (275)	10 (250)	12(300)	14 (350)	**
600,000	10 (175)	12 (225)	14 (350)	12 (300)	18 (450)	22 (550)	**

*ESALs = 18 kip equivalent single axle loads

Note: All thicknesses are after compaction and apply to all exfiltration conditions. Greater thicknesses may be required in soils subject to frost heaving. Pedestrian applications should use a minimum base thickness of 6 in. (150 mm).

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

Note: Silt soils or others with more than 3% of particles smaller than 0.02 mm in size are considered to be frost susceptible.

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

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. 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).

The SCS (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.

		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   [shaded] = 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).

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 SCS 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 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,
A_p = the permeable pavement surface area, and
V_r = the stone base void ratio (typically 0.4).

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

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

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:

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

and

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

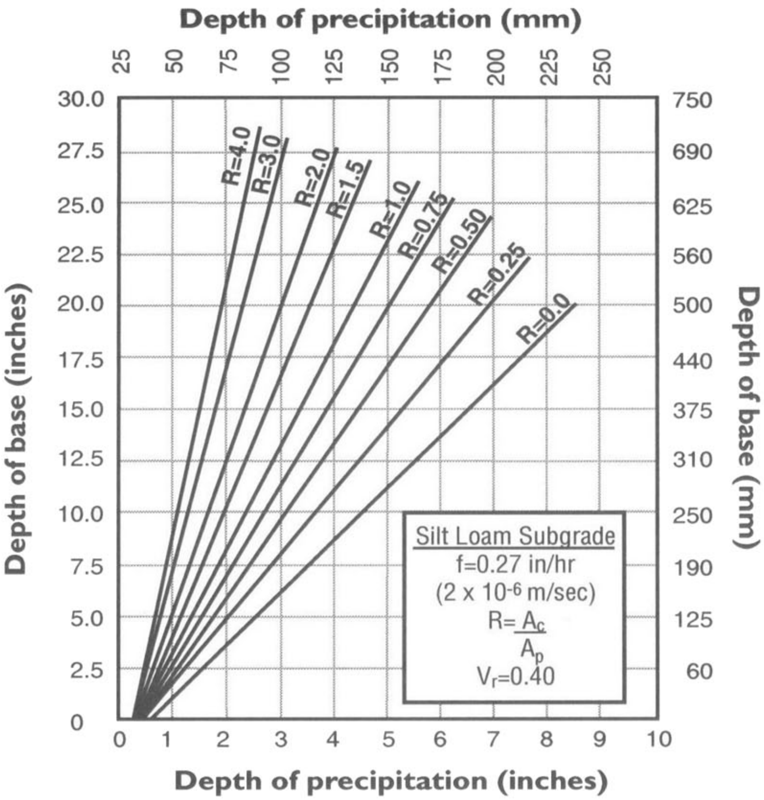


Figure 20. Open-graded base depth for silt loam subgrade.

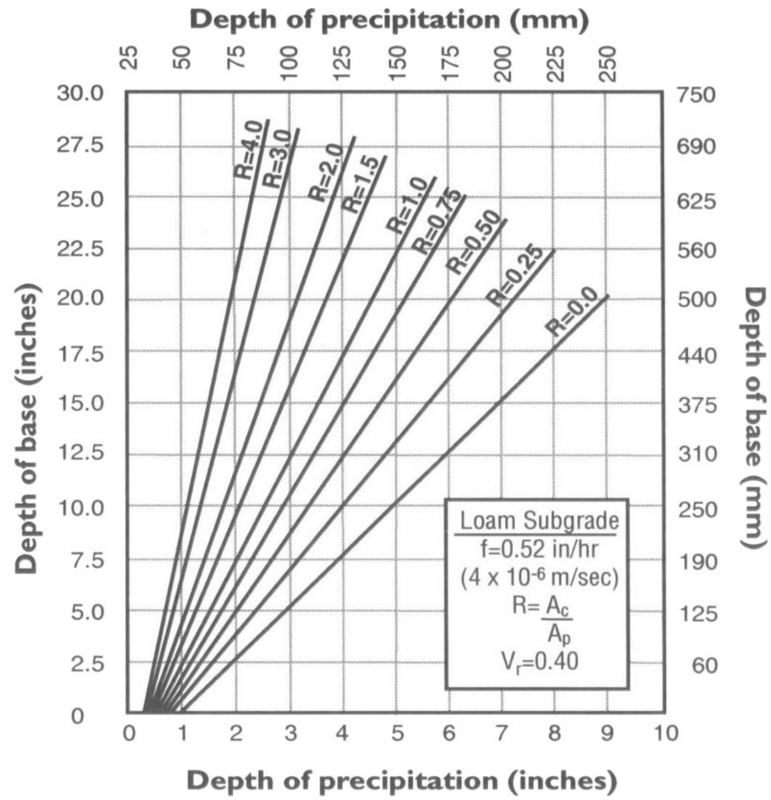


Figure 21. Open-graded base depth for loam subgrade.

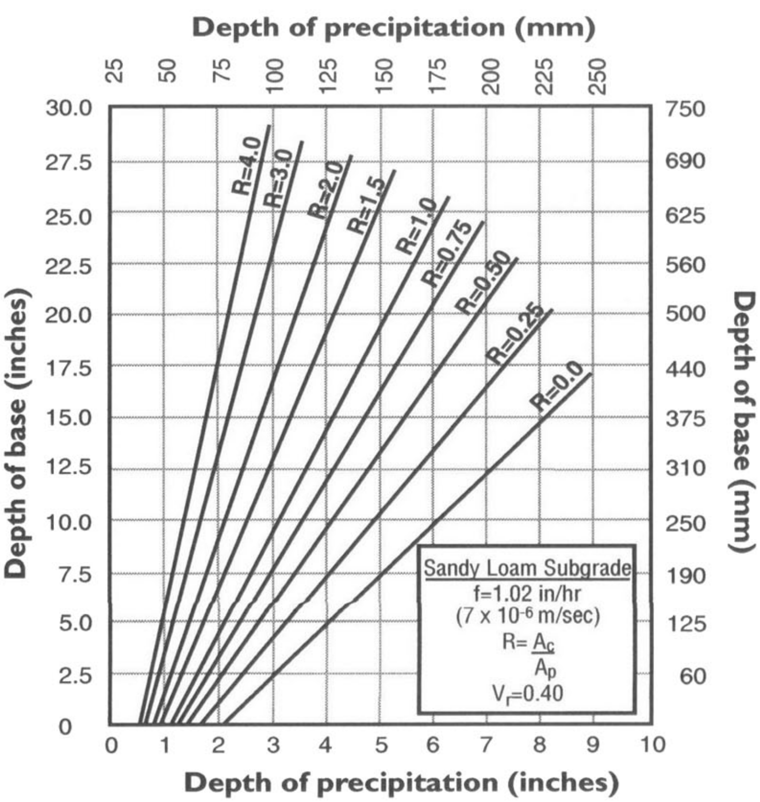


Figure 22. Open-graded base depth in sandy loam subgrade.

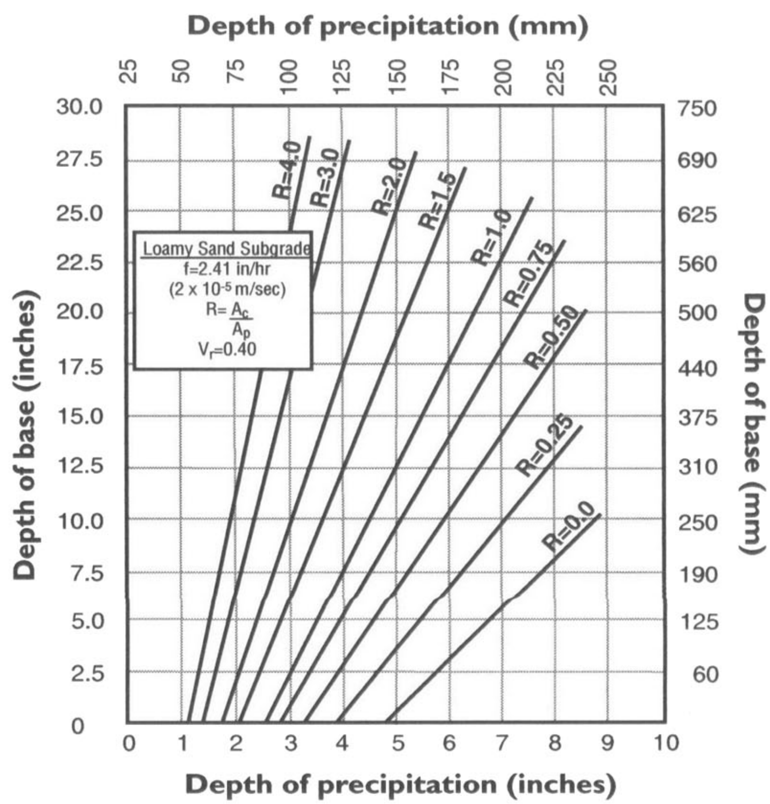


Figure 23. Open-graded base depth for loamy sand subgrade.

Where:

$\mathbf{R}$ = equal to the ratio of the contributing area and the permeable pavement area ($\mathbf{A_c/A_p}$).

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 ($\mathbf{Q_cA_c}$) based on the SCS curve number for an impervious area, CN = 98. The SCS 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.

Minimum Depth Method

1. From the selected design rainfall ($\mathbf{P}$) and the SCS 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 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 by the feasibility formula:

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

   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 SCS 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:

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

   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:

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

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: SCS 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%

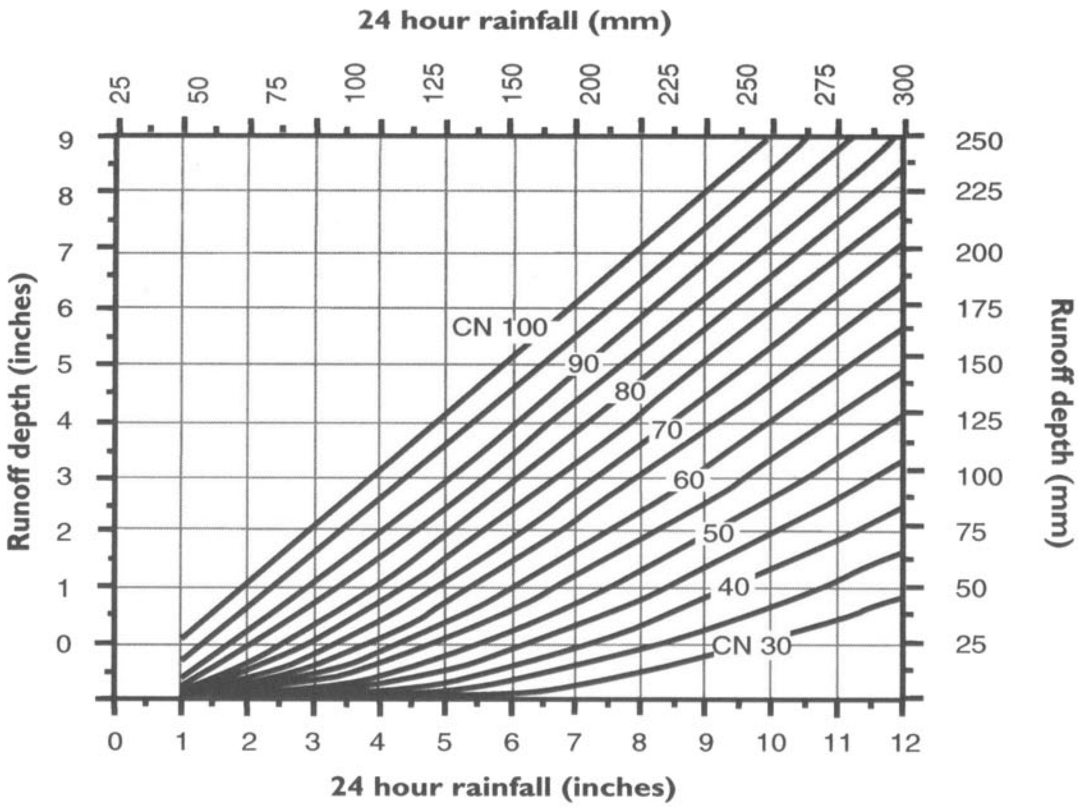


Figure 24. SCS (NRCS) chart for finding runoff depth for various curve numbers.

passing the No. 200 (0.075 mm) sieve. Permeability was tested at 1.02 in./hr (5 x 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 x 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.)

The void space in the No. 57 open-graded, crushed stone base 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 x 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 SCS 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:

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

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 with interpolation yields a thickness close to 17 in. (0.425 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
17 in. (425 mm) No. 57 stone base
Total thickness = 23 in. (580 mm)

Almost 2 ft. (0.6 m) minus 10 ft (3 m) leaves about 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**

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

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

Where:
B = 1 for 2 $\geq C_U \geq$ 8, 3.2 is okay.
B = 0.5 for 2 < C_U < 4, 3.2 is okay.
B = 8/C_U for 4 < 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) $\geq$ k (0.52 in./hr)
Clogging criteria:

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

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

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

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.