2J-1 General Information for Permeable Pavement Systems

A. Introduction

This section provides design guidelines for a group of stormwater management BMPs broadly referred to as permeable pavement systems. In urban watersheds, almost all of the impervious surface area is represented by building rooftops and paved surfaces. In residential areas most of the paved area is represented by the roadway system and residential driveways. Parking lots and paved industrial storage areas represent an even larger portion of the impervious surface in commercial and industrial areas. Impervious pavements can produce two-thirds of the excess runoff in an urban catchment. Runoff from impervious pavements contributes a substantial loading of hydrocarbons and heavy metal pollutants, and contributes greatly to the increased temperature of surface runoff. In most urban jurisdictions, a paved roadway system with a traditional curb and gutter configuration provides a key component of the overall urban drainage system. Surface flow from adjoining tributary watersheds is conveyed directly into catch basin inlets and connected piping systems. In these traditional impervious paved systems, the runoff coefficient (runoff volume) is increased and the time of concentration (T_c) is decreased resulting in increased peak rates of runoff.

Permeable pavement includes a variety of stabilized surfaces that can be used for the movement and parking of vehicles (automobiles, trucks, construction equipment, light aircraft, etc.) and storage of materials and equipment. Compared to conventional pavement, these pavements are designed to infiltrate stormwater runoff instead of shedding it off the surface. Permeable pavement systems reduce the amount of runoff by allowing water to pass through surfaces that would otherwise be impervious. The storm water passes through the load bearing surface and aggregate subbase that are selected based upon the intended application and required infiltration rate. Runoff is stored in the stone aggregate subbase course and storage layer, and allowed to infiltrate into the surrounding soil (functioning like an infiltration basin). For less permeable subsoils, a subdrain system can be placed in the aggregate subbase to collect and convey runoff from larger storm events to the storm sewer system or directly to receiving waters (functioning like a surface sand filter). Water can infiltrate into the ground if soil permeability rates allow, be conveyed to other downstream BMPs, or routed through a subdrain and piped to an adjacent storm water system. Since the pavement surface is permeable these pavement systems can effectively reduce the volume and peak rate of runoff compared to traditional impervious pavement surfaces. The value of permeable pavement systems includes:

- *Runoff volume reduction* is achieved when permeable pavements are placed over permeable soils and a defined volume of the water passing through the pavement is infiltrated into the soil subgrade below.
- *Peak runoff rate reduction* is achieved when the volume of water passing through the pavement surface is “detained” for a defined period of time within the pavement cross-section and the open-graded aggregate subbase beneath the pavement. The effective infiltration rate for the watershed is increased by trapping the water in the permeable surfaces and effectively increasing the time of concentration in the catchment area. The depth of the aggregate subbase can be designed to meet varying degrees of stormwater detention from the Water Quality Volume (WQv) up to the Channel Protection Volume (CPv). For sites using underground detention for peak discharge control (Qp), a permeable pavement system can provide an efficient method to move water into the underground storage.

- Water quality is improved by capturing pollutants in the open matrix of the pavement structure. Removal of soluble pollutants is achieved by moving a portion of the water into the subsoil though infiltration.

B. General description

Permeable pavements offer the advantage of decreasing the effective imperviousness (I_A) of a new urbanizing area or redevelopment site, thereby reducing runoff and pollutant loads leaving the site. Permeable pavements can be designed with and without underdrains. When underdrains are used, infiltrated water will behave similarly to interflow and will surface at a much reduced rate over extended periods of time. All types of permeable pavement help return stormwater runoff hydrology to more closely resemble pre-developed conditions. The designer needs to consider the development site and soil conditions to ensure the suitability of each type of permeable pavement for the loads and traffic it will support and carry, as well as the geologic conditions the pavement will rest upon. What follows is a description of five types of permeable pavement and defines their acronyms. These will be used throughout the remainder of this section of the manual:

Permeable pavements can be divided into the following general categories.

- **Pervious concrete:** Open graded portland cement concrete surface. (See Section 2J-2).
- **Porous asphalt:** Uniformly graded hot mix asphalt. (See Section 2J-3).
- **Permeable pavers:** Two types are included in this category. The first type is monolithic units that do not have void areas incorporated in the pavers. The second type includes manufactured paving units with incorporated void areas that are filled with pervious materials such as gravel or grass turf. (See Section 2J-4).

Permeable pavement systems can replace traditional pavement allowing rainfall and runoff from adjacent contributing areas to infiltrate directly through the pavement surface and receive water quality treatment. Unlike traditional concrete pavement, pervious concrete pavement contains little or no "fine" aggregate materials. Removing the fine aggregate from the concrete mix creates voids that encourage infiltration. Porous asphalt pavement consists of an open-graded coarse aggregate, bonded together by asphalt cement, with sufficient interconnected voids to make it highly permeable to water. Pervious concrete typically consists of specially formulated mixtures of cementitious materials, a uniform open-graded coarse aggregate, and water. Pervious concrete and porous asphalt have enough void space (approximately 15% to 18%) to allow rapid percolation of water through the pavement. Permeable pavers and modular pavements, including concrete and brick pavers, geowebs, and manufactured concrete and plastic units, have void areas that are filled with sand, gravel, or grass to allow infiltration. Other alternative paving surfaces can help reduce runoff from paved areas, but do not incorporate an aggregate subbase layer or trench for temporary storage below the pavement. While permeable pavement can be a highly effective treatment practice, maintenance and proper installation are necessary to ensure its long-term effectiveness.

1. **Advantages/disadvantages.** Aside from the potential for high particulate pollutant removal and the removal of other constituents similar to what a sand filter would provide, permeable pavements of all types can dramatically reduce the surface runoff from most rainstorms and snowmelt events and virtually eliminate surface runoff from smaller storms. These reductions in runoff volumes translate directly to proportional reductions in pollutant loads leaving the site. The use of permeable pavements can result in stormwater surface runoff conditions that approximate the predevelopment site conditions. These BMPs can be used in selecting surface retention and infiltration parameters that are close to pre-developed conditions when using stormwater runoff hydrologic models. Even when underdrains are used, the response time of runoff is significantly delayed and approaches the characteristics of what is sometimes called interflow. As a result, drainage and downstream flooding problems can be significantly reduced.

This can translate in savings since the downstream facilities needed to address site runoff rate and volume, such as detention volumes and conveyance facilities, can be smaller.

Another advantage is creative selection by land planners and landscape architects of materials, patterns and colors to provide aesthetic enhancements to what are often are very plain surfaces.

The primary disadvantage of permeable pavements is that they cost more to install and maintain than conventional concrete or asphalt pavement. These added costs can be somewhat offset by the cost savings in the downsizing of on-site and downstream drainage systems and facilities such as detention basins, numbers of inlets, storm sewers and channels. Other disadvantages can include a somewhat rougher surface texture for walking and other activities.

2. **Physical site suitability and need for underdrains.** All types of permeable pavements can be installed over low permeability subsoils by providing underdrain piping systems. An underdrain insures that the aggregate subbase is drained when the subsoils or site conditions do not allow infiltration. In the case where the installation is located on top of expansive soils, the installation of an impermeable liner along with underdrains is strongly recommended. The liner is needed to prevent wetting the underlying expansive clays. In addition, permeable pavements installed over expansive soils should not be located adjacent to structure foundations in order to reduce the potential for damages to structures.

   A continuous impermeable liner with underdrains should also be used whenever a commercial or industrial site may have activities, or processes, that could result in the storage and/or handling of toxic or caustic chemicals, fertilizers, petroleum products, fats, or greases. The impermeable liner is designed to prevent groundwater and soil contamination should such products or materials come into contact with stormwater and could infiltrate into the ground. If the site is expected to have contaminants mentioned above, the underdrains are directed or connected to runoff capture and treatment facilities.

3. **Pollutant removal.** Specific field data on the reductions of pollutant concentrations by various permeable pavements are limited. However, reductions in the concentrations of total suspended solids and associated constituents, such as metals, oils, and greases appear to be relatively high. The fact that all permeable pavements significantly reduce the average annual runoff volume makes them very effective in reducing pollutant loads reaching the receiving waters. Infiltration of stormwater runoff through the pavement surface will provide a degree of suspended solids removal followed by additional removal of colloidal solids and soluble pollutants in the aggregate subbase and subsoils. Sorption of metals to colloidal solids and within the pavement void matrix is another removal function. Soluble organic pollutants adsorbed within the pavement void matrix and the open graded aggregate subbase will be exposed to biodegradation over time. Adsorption and ion exchange occur as stormwater travels through the unsaturated (vadose) zone below the aggregate base and reduce the particulate and dissolved pollutant loading to the groundwater (saturated zone).

   Permeable pavement can be used to provide ground water recharge. Some data suggest that as much as 70% to 80% of annual rainfall will go toward ground water recharge (Gburek and Urban, 1980). This data will vary depending on design characteristics and underlying soils. Two studies have been conducted on the long-term pollutant removal of permeable pavement, both in the Washington, DC area. They suggest high pollutant removal, although it is difficult to extrapolate these results to all applications of the practice. The results of the studies are presented in Table 1.

Table 1: Effectiveness of permeable pavement pollutant removal

Study	Pollutant Removal (%)				
	TSS	**TP**	**TN**	**COD**	**Metals**
Prince William, VA	82	65	80	-	-
Rockville, MD	95	65	85	82	98-99
Source: Schueler, 1987					

A third study by Brattebo and Booth (2003) indicates that many trademarked permeable paver systems effectively reduced concentrations of motor oil, copper, and zinc. Furthermore, the study found that almost all precipitation that fell on the permeable pavers infiltrated even after 6 years of daily use as a parking area.

4. **Reduction in effective site imperviousness and stormwater runoff volume.** When using permeable pavements the site designer can take advantage of the fact that it reduces the effective surface runoff rates and volumes. All of the three main types of permeable pavement (pervious concrete, porous asphalt, permeable pavers) have very high initial surface infiltration rates and all can immediately infiltrate and store rainfall and runoff from high intensity rainstorms. In many cases, direct runoff is completely eliminated. The surface infiltration rates for these pavements will in most cases exceed 200-250 inches/hour. This is several orders of magnitude higher than all the rainfall intensities encountered in the upper Midwest. These high infiltration rates are also 2-3 orders of magnitude higher than most soil infiltration rates. Permeable pavements rely on the ability of the void space within the surface material and the subbase to receive, store, and infiltrate water into the underlying subsoils. The aggregate subbase provides a temporary "reservoir", receiving the inflow from the surface pavement layer and providing temporary storage while the water is discharged to the subgrade through infiltration or released to surface discharge through a subdrain system. The reduction in runoff volume is achieved by infiltrating all or a portion of the "collected" rainfall or runoff. The primary limitations to the reduction in volume will be the infiltration rate of the subgrade soils and the depth to the seasonal high water table. The infiltration rate and the area under the pavement will control the "drain-down" time for the accumulated water in the subbase. The goal is to "empty" the aggregate reservoir before the next rainfall event occurs. A maximum time of 72 hours is typical, while a 48 hour drain-down represents a more conservative approach. Sites with soil infiltration rates $\geq$ 0.5 inches/hour will, in most cases, be able to infiltrate the WQv from the site drainage area within a 24-48 hour time period. For larger storm events (i.e. Cpv for the 1 year, 24 hour storm or the 2 year storm) a perforated subdrain placed in the aggregate layer can be placed and configured to release the water from the aggregate "reservoir" at a controlled rate.

   Like all BMPs, permeable pavement can and should be combined with other practices to capitalize on each technology's benefits and to allow protection in case of BMP failure. However, construction using pervious materials may not require as much treatment as other BMP approaches. For instance, a small facility using permeable pavement may only need several bioretention basins or a grass swale, rather than a full dry detention basin. This combined approach might prove less land intensive and more cost effective. It may increase the amount of open space for public or tenant use. It may also lead to an increase in environmental benefits.

5. **Applications.** Medium traffic areas are the ideal application for permeable pavement. It may also have some application on highways, where it is currently used to reduce hydroplaning. In some areas, such as truck loading docks and areas of high commercial traffic, the permeable pavement design will need to include consideration of vehicle traffic loads (ESALs), soil classification (USCS), and strength (CBR) for determining required base thickness for structural

support. In these instances, the aggregate base material provides both strength and storage function for the pavement system.

6. **Regional applicability.** Permeable pavement is suitable for most regions of the country, but cold climates present special challenges. Road salt contains chlorides that may migrate through the permeable pavement into ground water. Plowing may present a challenge to block pavers, because snow plow blades can catch the block's edge and damage its surface. Infiltrating runoff may freeze below the pavement causing frost heave, though design modifications can reduce this risk. These potential problems do not mean that permeable pavement cannot be used in cold climates. For the cold wet-freeze conditions encountered in Iowa and the upper Midwest, the site design must consider a reliable drainage system for the aggregate and upper portion of the subgrade. A common site design includes a perimeter drain installed below the typical frost line as a conservative method to prevent possible frost action. Research at a full-scale pervious concrete parking facility at Iowa State University has shown temperatures in the pervious pavement, aggregate, and subsoil remain above freezing for all but the very coldest of winter conditions. The open void space in the pavement and aggregate allows for convection movement of warmer air from the underlying soils. Additionally, the open void space allows for expansion of any water that may freeze within the aggregate or the pavement surface during wet-freezing rain events. A pervious concrete mix design has been developed at Iowa State University that provides a durable and freeze-thaw resistant material (Section 2J-2).

7. **Stormwater hot spots.** Stormwater hot spots are areas where land use or activities generate highly contaminated runoff. Hot spot runoff frequently contains pollutant concentrations exceeding those typically found in stormwater. Hot spots include commercial nurseries, auto recycle facilities, fueling stations, storage areas, industrial rooftops, marinas, outdoor container storage of liquids, outdoor loading and unloading facilities, public works storage areas, hazardous materials generators (if containers are exposed to rainfall), vehicle service and maintenance areas, and vehicle and equipment washing and steam cleaning facilities. Since permeable pavement is an infiltration practice, it should not be applied at stormwater hot spots due to the potential for ground water contamination (see exception for no exfiltration systems with liners).

8. **Stormwater retrofit.** A stormwater retrofit is a stormwater management practice (usually structural) installed post development to improve water quality, protect downstream channels, reduce flooding, or to meet other specific objectives. The best retrofit application for permeable pavement is parking lot replacement on individual sites. If many impervious lots are replaced with pervious concrete, permeable interlocking concrete pavers, or porous asphalt, then overall stormwater peak flows can be reduced.

9. **Cold water streams.** Permeable pavement can help lower high stormwater runoff temperatures commonly associated with impervious surfaces. Stormwater pools on the surface of conventional pavement, where it is heated by the sun and the hot pavement surface. By rapidly infiltrating rainfall, permeable pavement reduces stormwater exposure to sun and heat.

10. **Siting and design considerations.** A preliminary assessment of the site should be conducted prior to detailed design and hydrologic evaluation. This initial assessment is similar to the procedures presented in Part 2E - Infiltration Practices and includes a review of the following:
    - Underlying geology and soil maps
    - Preliminary identification of the NRCS soil classifications for the site: texture classification and hydrologic soil grouping (HSG_A/B/C/D)
    - Preliminary assessment of engineering, physical, and chemical properties can be obtained from the NRCS/USDA soil survey data
    - Determining evidence of fill soil or previous disturbance or compaction

- Determination of local topography and drainage patterns for the site and contributing catchment area
- Determining absence of stormwater hotspots in the contributing catchment area
- Identification of existing and proposed land use in the contributing catchment area

11. Rainfall and traffic data.

The design of the pavement system will require the following data:

- The total contributing catchment area and percent of impervious surface draining to the permeable pavement system.
- The design storm used for the project. The typical and minimum design for permeable pavement systems is the Water Quality Volume (WQv). As discussed in Section 2B, the WQv design storm event for Iowa is a depth of 1.25 inches.
- Permeable pavement systems can be designed for larger and less frequent events such as the 1 year, 24 hour duration rainfall for Channel Protection Volume (CPv), or possibly 2 year up to 5 year recurrence interval storms.
- The design of permeable pavement systems is a volume-based design. While the Rational method can be used to determine the peak runoff rate (cfs), the recommended approach is to use the simplified methodology for WQv or the NRCS CN method for larger storms. The NRCS WINTR55 computational method will provide a runoff volume in inches for any desired storm up through the 100 year reoccurrence interval event. (See Part 2B and Sections 2C-5, 2C-6, and 2C-9).
- An estimate of the vehicle traffic loading expressed as 18,000 kip (80kN) equivalent single axle load (ESALs) over the design life of the pavement (typically 20 years).

Permeable pavement has the same site design considerations as other infiltration practices (see Part 2E). The site needs to meet the following criteria:

- Soils should have a permeability of at least 0.5 inches per hour. An acceptable alternative design for soils with low permeability would be the installation of a subdrain system within the aggregate subbase and a connection to the traditional storm sewer system (with approval from the local jurisdiction). This modified design allows the treatment of stormwater from small to medium stormwater events while allowing a bypass for large events, which will help prevent flooding.
- The configuration and condition of adjacent catchment area contributing direct runoff onto the permeable pavement. Uncontrolled sediment loading from these areas can cause premature failure of the pavement system.
- The bottom of the stone reservoir should be flat, so that runoff can infiltrate through the entire surface.
- If permeable pavement is used near an industrial site or similar area, the pavement should be sited at least 2 to 5 feet above the seasonally high ground water table and at least 100 feet away from drinking water wells.
- Permeable pavement should be sited on low to medium traffic areas such as recreational trails, walkways, parking lots, and possibly residential roads. The use of permeable pavements for roadways in the upper Midwest should consider the additional potential for increased sediment loading from the adjacent right-of-way area and the traditional use of sand and de-icing chemicals in the winter. A detailed plan for increased annual maintenance should be considered in this case.
- Slopes should be flat or gentle (0.5 to 1.0%) to facilitate infiltration versus runoff.

12. Exfiltration

a. **Full or partial exfiltration.** A design for *full exfiltration* means the water infiltrates directly into the base and exfiltrates to the subsoil. This is the most common application where the site soils have high to moderate permeability. Overflows from larger, infrequent storm events are managed with perimeter conveyance to swales, bioretention areas or storm sewer intakes. *Partial exfiltration* does not rely completely on exfiltration of the base reservoir for release of all the captured runoff. Some of the water may infiltrate into the subgrade soil profile while the remainder is conveyed out of the system through perforated underdrain piping. The underdrain piping can discharge to a surface outfall at a swale or bioretention area, or can be connected directly to an adjacent stormsewer structure. For some applications, the depth of the aggregate subbase can be increased to handle larger storms to manage the Channel Protection Volume (CPv), which is based on releasing the runoff from a 1 year, 24 hour storm. Figures 1 and 2 illustrate the configurations for full and partial exfiltration, respectively.

b. **No exfiltration.** When the site soils have very low permeability and low strength, or there are other site limitations, a system with no exfiltration can be used. For sites where pollutant loads may exceed the capacity of the soil base to provide treatment, an impermeable liner may be used. Examples of liner materials are polyethylene (HDPE), ethylene diene monomer (EPDM), rubber asphalt, or asphalt-based materials. While an infiltration based practice is not generally recommended where there is a stormwater hotspot, a permeable pavement system with a liner could be a feasible solution. The permeable surface reduces the direct runoff potential and the liner system provides a final capture system to allow the pollutants to be retained and removed for off-site disposal. Figure 3 illustrates a no exfiltration system. The permeable pavement surface in the following illustrated systems can be any of the three general types of permeable pavements.

Figure 1: Full exfiltration through the soil subgrade surface

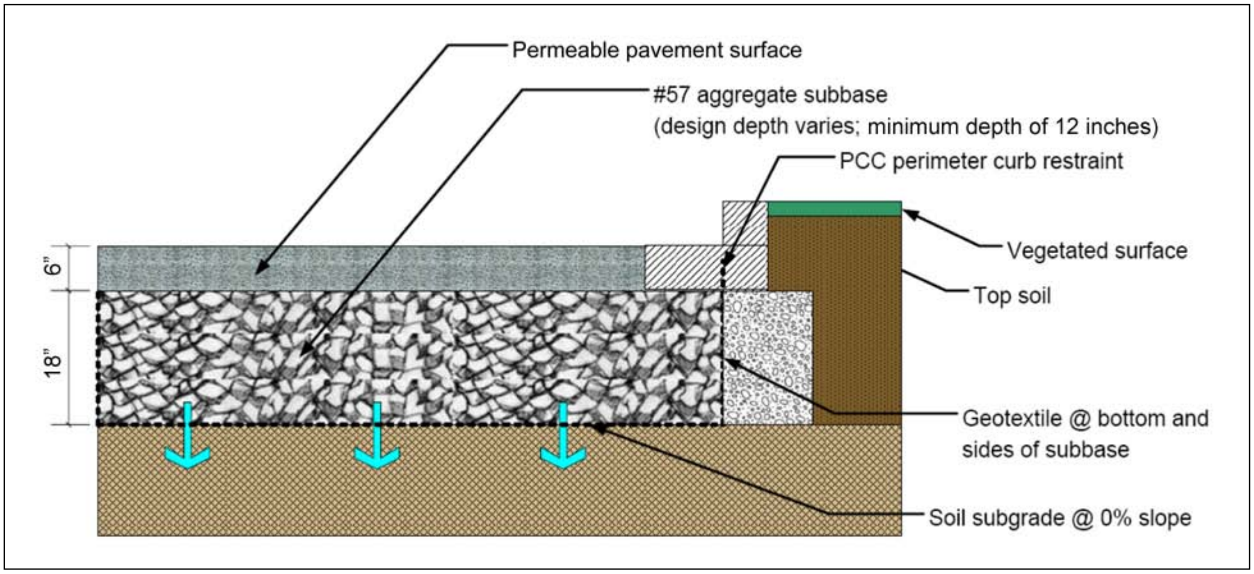


Figure 2: Partial exfiltration through the soil subgrade surface

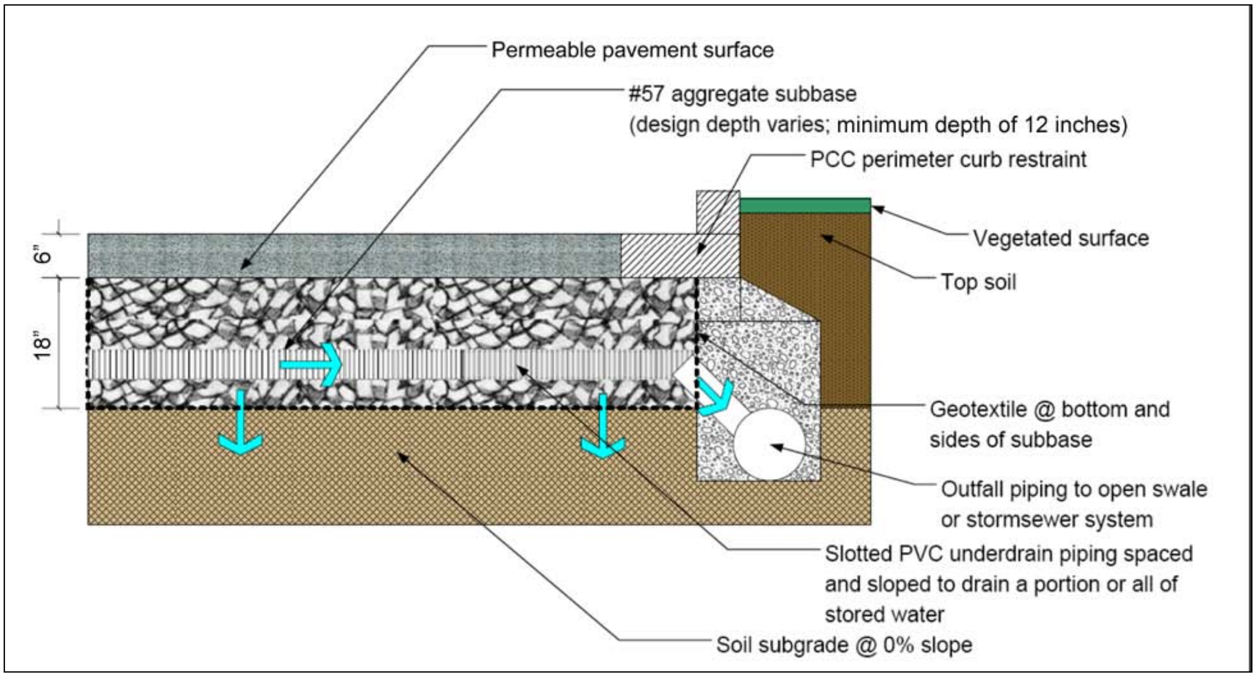
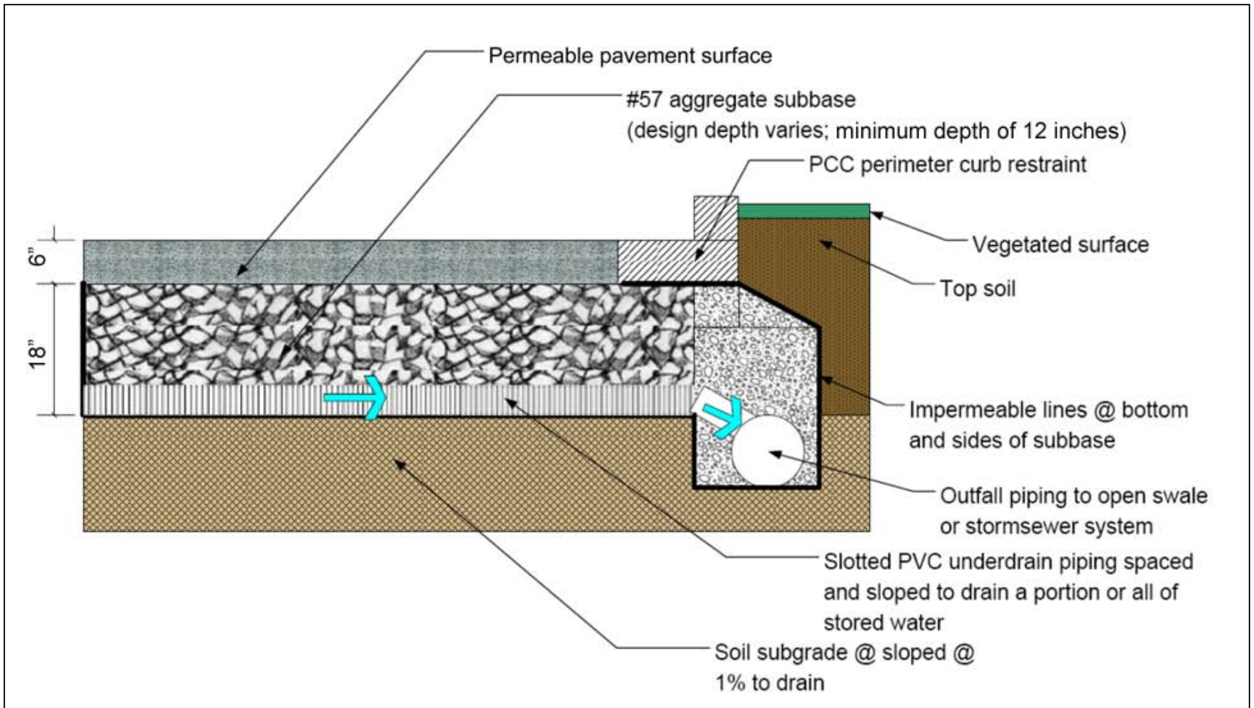


Figure 3: No exfiltration through the soil subgrade surface



13. **Soil subgrade sampling and analysis.** The site soils characterization should be supervised by a licensed professional engineer with experience in soil sampling procedures. The assessment should include soil borings and/or test pits and other testing as required to determine design strength, permeability, soil density, and depth to water table.

    Test pits (dug with a backhoe) or soil borings (Shelby tubes) are recommended for every 7,000 square feet of pavement with a minimum of two holes per site. The depth of all pits or samples should be at least 5 feet deep with soil logs recorded to at least 4 feet below the proposed bottom of the pavement subbase material. Additional holes at varying depth may be required in areas where soil types are variable, near shallow bedrock, in low-lying areas or where the water table is likely to be within 8 to 10 feet of the surface. Confirmation of a high water table, impermeable soil layers, expansive clays, or fractured bedrock may require a pavement design with no exfiltration.

    The following tests are recommended to determine the suitability of the site soils in supporting traffic loads under saturated conditions:

    - Unified Soil Classification System (USCS) using ASTM D 2487 (17).
    - Sieve analysis and gradation of the subgrade soils.
    - Sampled moisture content in percent.
    - Onsite tests for the infiltration rate of the soils. Several test methods are described in Section 2E-7 for initial determination of soil permeability and for final confirmation of the design infiltration rate for the soils. All tests for infiltration should be done at the elevation corresponding to the bottom of pavement subbase (i.e. interface of the subbase and uncompacted soil subgrade). The recommended test method for determining the design infiltration rate is ASTM D 3385 (19) Test Method for Infiltration Rate of Soils in the Field Using a Double-Ring Infiltrometer. For soils with an expected infiltration rate of 1.4×10^{-2} inches/hour to 1.4×10^{-5} inches/hour, ASTM D 5093 (20) Test Method for Field Measurement of Infiltration Rate Using a Double-Ring Infiltrometer with a sealed Inner Ring

is used. The typical percolation tests for the design of wastewater soil adsorption fields are not recommended for design of stormwater infiltration systems.

- As discussed in Part 2E, Infiltration Practices, a factor of safety of 2.0 is recommended in the determination of the final design infiltration rate. Application of the safety factor will compensate for decreases in infiltration rate during construction and over the life of the permeable pavement system.

Soils with a tested permeability equal to or greater than 0.50 inches/hour will usually be gravel, sand, loamy sand, sandy loam, loam and silt loam (See Section 2E-1). These soils will usually have no more than 10-12% passing the No. 200 sieve. These soils would be characteristic of NRCS Hydrologic Soil Groups A and B. Silt and clay soils will likely have lower permeability and not be suitable for full exfiltration from the open-graded subbase. For the cold wet-freeze climate in Iowa and the Upper Midwest the lowest recommended design infiltration rate for the soil subgrade is 0.25 inches/hour.

For optimum infiltration the subgrade would have less than 5% passing the No. 200 sieve. Soils with up to 25% passing the No. 200 may provide adequate infiltration depending on site conditions, degree of compaction, and other characteristics. Soils with a permeability less than 0.50 inches/hour can be used for infiltration as long as the soil remains stable while saturated, particularly when loaded by vehicles. Under these conditions, a subdrain system will be required. Table 1 summarizes the permeability of soils using the USCS as well as typical ranges of the California Bearing Ratio (CBR) for the classifications. These are general guidelines and additional field and laboratory testing may be warranted for sites with variable soil conditions.

To qualify for use under vehicular traffic loads, a typical pavement design would call for a soil CBR (minimum 96 hours soaked per ASTM S 1883) of at least 5%. The compaction required to achieve this will likely reduce the infiltration rate of the soil. Therefore, the permeability or infiltration rate of the soil should be assessed at the density required to achieve 5% CBR. Soils with a lower soaked CBR or expansive soils can be treated to raise the CBR above 5%. Treatment can be accomplished with cement, lime or lime/flyash (expansive soils) to raise the CBR. For most applications, the subbase placed under the permeable pavement will raise the subgrade CBR to over 5%. The subbase layer should have a minimum soaked CBR of 20% and be a minimum of 8 inches in depth. A geotextile is also recommended as a separation layer between the subgrade and subbase.

14. **Soil compaction.** Soil compaction will decrease the soil infiltration rate. Compaction and decreased infiltration will shorten the design life of the permeable pavement system. Use and diligent site control of tracked construction equipment moving across the excavated subgrade will minimize additional compaction. Wheeled construction equipment should be kept off the excavated subgrade. Pedestrian applications such as recreational trails should not require soil subgrade compaction and it should be avoided if possible for vehicular applications. Most permeable pavement applications will be constructed on undisturbed native soils. A common exception would be redevelopment of an existing traditional paved parking structure with a new permeable pavement. Soil excavations will typically be 2-3 feet in depth and cut into consolidated soil horizons that provide some stability when wet. In most cases, the exposed soil layer will not require compaction except for static rolling after grading to provide a smooth subgrade surface for checking final grade, installation of the geotextile and subdrain piping, and placement of the open-graded subbase. Some heavier clays will require compaction to provide stability when wet. These will likely be soils with a low CBR ($< 4\%$) and will already have low infiltration rates prior to compaction. In this case, the compaction will make little difference in the infiltration rate and the design will be based on partial exfiltration by using slotted underdrain piping to remove existing water at the bottom of the subbase reservoir.

Table 2: Suitability of soils (Unified Soils Classification System) for infiltration of stormwater and bearing capacity

USCS Soil Classification	Range of typical Permeability coefficient, k (inches/hr)	Relative permeability when compacted and saturated	Shear strength when compacted	Compressibility	Typical range of CBR values
GW-well graded gravels	1.3 to 137	Pervious	Excellent	Negligible	30 - 80
GP-poorly graded gravels	6.8 to 137	Very pervious	Good	Negligible	20 – 60
GM-silty gravels	1.3 x 10^{-4} to 13.5	Semi-pervious to impervious	Good	Negligible	20 – 60
GC-clayey gravels	1.3 x 10^{-4} to 1.3 x 10^{-2}	Impervious	Good to fair	Very low	20 – 40
SW-well graded sands	0.7 to 68	Pervious	Excellent	Negligible	10 – 40
SP-poorly graded sands	0.07 to 0.7	Pervious to semi-pervious	Good	Very low	10 – 40
SM-silty sands	1.3 x 10^{-4} to 0.7	Semi-pervious to impervious	Good	Low	10 – 40
SC-clayey sands	1.3 x 10^{-5} to 0.7	Impervious	Good to fair	Low	5 – 20
ML-inorganic silts of low plasticity	1.3 x 10^{-5} to 0.07	Impervious	Fair	Medium	2 – 15
CL-inorganic clays of low plasticity	1.3 x 10^{-5} to 1.3 x 10^{-3}	Impervious	Fair	Medium	2 – 5
OL-organic silts	1.3 x 10^{-5} to 1.3 x 10^{-2}	Impervious	Poor	Medium	2 – 5
MH-inorganic silts of high plasticity	1.3 x 10^{-6} to 1.3 x 10^{-5}	Very impervious	Fair to poor	High	2 -10
CH-inorganic clays of high plasticity	1.3 x 10^{-7} to 1.3 x 10^{-5}	Very impervious	Poor	High	2 – 5
OH-organic clays	Not appropriate under permeable pavements				
PT-peat, mulch, soils w/high organic content	Not appropriate under permeable pavements				

Source: (10), (11), (12)

C. Design considerations

Some basic features should be incorporated into all permeable pavement practices. These design features can be divided into four basic categories: pretreatment, treatment, conveyance, and landscaping.

- ***Pretreatment.*** Protect the permeable pavement surface from excessive sediment loading caused by poor erosion control in the contributing drainage area. The single largest contributing factor for premature failure of permeable pavements is clogging with sediment. The most critical time is during initial construction or re-development of a site when the permeable pavement is placed before the remainder of the site drainage area is stabilized for erosion and sediment control. The preferred option would be to complete the stabilization of the contributing drainage area with vegetation and/or "effective" erosion and sediment control prior to placing the new permeable pavement. In permeable pavement designs, the pavement itself acts as pretreatment to the stone reservoir below. Periodic maintenance of the surface, such as sweeping, is critical to prevent clogging. Permeable pavements will not need to be sanded in the winter for ice control. In fact, the application of sand can lead to premature clogging of the voids in the pavement. If ice control is needed, then a conservative application of de-icing chemical is recommended. Portland cement pervious concrete pavements should not receive any salt for the first winter of operation.

- ***Treatment.*** The stone reservoir is composed of layers of small stone or open-graded aggregate placed directly below the pavement surface. The aggregate subbase below the permeable surface should be sized to attenuate storm flows for the storm event to be treated. Typically, permeable pavement is sized to treat a small event, such as a water quality storm (i.e., the storms that will be treated for pollutant removal). The water quality design storm in Iowa is 1.25 inches (see Section 2B). As in infiltration trenches, water can be stored in the voids of the stone reservoir. During storage in the aggregate layer, pollutants can be removed through adsorption within the material, biological degradation, fine sediment removal, and filtration of pollutants in the upper layer of the soil vadose zone. Oils and greases will generally be trapped in the pavement profile and within the aggregate matrix.
- ***Conveyance.*** Water conveyed to the stone subbase though the pavement surface infiltrates into the ground below. A geotextile fabric liner and/or a sand layer are placed below the stone reservoir to prevent preferential flow paths and to maintain a flat bottom. The geotextile filter material can also prevent the movement of fine silts and clays into the aggregate layer from the surrounding soils and cause premature blinding of the aggregate/soil interface. If used, the geotextile material should meet the following general criteria: a non-woven fabric meeting ASTM D 4833 (puncture strength - 125 pounds); ASTM D-3786 (Mullen burst strength – 350 psi); ASTM D 4632 (Tensile strength – 200 LB); Fabric shall have 0.08 inch thick Apparent Opening Size (AOS) of #80 sieve, and maintain a minimum flow rate of 90 gpm/ft^2 flow rate. The design also requires a means to convey larger amounts of stormwater to the storm drain system. This can be accomplished with a subdrain system placed up in the aggregate subbase to convey the accumulated water directly to an adjacent open swale or to the stormsewer system. Storm drain inlets set slightly above the pavement surface is another option. This allows for some ponding above the surface, but bypasses flows too large to be treated by the system or when the surface clogs.
- ***Landscaping.*** For permeable pavement, the most important landscaping feature is a fully stabilized upland drainage area. Reducing sediment loads entering the pavement will reduce the rate of clogging and prolong the life of the pavement system.

1. **Geotextiles and filter layers.** Fine and colloidal particles suspended in stormwater runoff will be deposited in the pores of adjacent material surfaces. In the case of permeable pavements, particles will be deposited in and on the downstream soil matrix, the aggregate subbase, the bedding course under permeable pavers, the aggregate in permeable paver joint openings, in the pervious concrete and porous asphalt pore spaces, and in the geotextile. The build up of fines eventually clogs and reduces the permeability of these materials. To reduce the clogging, filter criteria must be met whenever there is change in materials. While aggregate materials can be used as filters, the use of geotextiles more common and often more cost effective. Figure 4 provides geotextile filter criteria from the FHWA (14) and AASHTO (15).

Figure 4: Geotextile Filter Criteria

U.S. Federal Highway Administration (FHWA)
For fine grained soils with more than 50% passing the No. 200 sieve:
Woven geotextiles: Apparent Opening Size (AOS) $\leq D_{85}$
Non-woven geotextiles: $AOS_{geotextile} \leq 1.8\ D_{85}$
AOS $\leq$ 0.3 mm or $\geq$ No. 50 sieve

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

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

Clogging criteria
Woven: Percent of open area $\geq$ 4%
Non-woven Porosity $\geq$ 30%

American Association of State Highway and Transportation Officials (AASHTO)
For soils $\leq$ 50% passing the No. 200 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 the gradation curve. i.e. D_{10} is the size particle of soil or aggregate gradation for which 10% of the particles are smaller and 90% are larger.
2. O_x is geotextile size corresponding to x particle size based on dry glass bead sieving. i.e. O_{95} is the geotextile size opening for which 95% of the holes are smaller.
3. Apparent opening size (AOS) 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).
4. Permeability, K, of the soil and geotextile (non-woven only) are designated k_s and k_G respectively.

Source: (14), (15)

2. **Subbase and bedding materials.** The following data are required for materials used for the subbase (pervious concrete, porous asphalt, permeable pavers) and for the bedding and aggregate in the openings between the permeable pavers.
   - Sieve analysis, including washed gradations IAW ASTM C 136.
   - Void space in percent for the open graded base IAW ASTM C 29.

a. Crushed stone, open-graded subbase. This material should be a hard durable rock with 90% fractured faces and a LA Abrasion of < 40. A minimum effective porosity of 0.32 and a design CBR of at least 80% are recommended (12, 13).The water storage capacity of the open-graded subbase will vary with depth and the percent of void space. The material supplier can provide the nominal porosity and gradation or independent testing can be called out in the materials specifications.

Crushed aggregate meeting ASTM No. 57 is commonly used for open-graded subbases along with ASTM No. 2 to No. 4. These materials are widely available and they are recommended for most permeable pavement applications. These materials will have a nominal porosity (volume of voids/total volume of base) over 0.32 and a storage capacity in the void space (volume of voids/volume of aggregate) approaching 40%. A 40% void space provides 0.4 cubic feet of storage capacity for each cubic foot of aggregate (the volume of the base will need to be 2.5 times the volume of water to be stored).

For permeable paver applications, the large size of the No. 57 aggregates creates an uneven surface when compacted. To provide a smooth and level surface for the placement of the pavers, a bedding course of ASTM No. 8 crushed aggregate is placed and compacted into the No. 57 open-graded base. The No. 8 bedding material is commonly called choke stone since it stabilizes and partially closes the surface of the open-graded base. The thickness of the No. 8 bedding layer should not exceed 2 inches prior to compaction. The No. 8 aggregate should be similar in hardness and shape to the No. 57. All of the materials need to be clean, washed material with less than 1 to 2% passing the No. 200 sieve. The No. 8 material stabilizes the surface of the No. 57 and provides some filtering of water.

If the bedding material cannot meet this filter criteria (i.e. the bedding aggregate is smaller or the subbase material is larger), a layer of geotextile can be used between the bedding and subbase course. This will add some stability to the structure. Standard aggregate gradations (ASTM D 448) are provided in Table 3 and Table 4. Supplemental information on using Iowa DOT standard aggregate gradations is also included. For permeable pavers, the No. 8 crushed stone aggregate is also recommended for fill material in the paver joint openings. Some additional filter criteria for aggregate layers are also provided by Ferguson (23).

b. Material descriptions for permeable pavement aggregate subbase

- Open graded; Uniformity coefficient (UC) ≤ 2.0
- Material: clean, bank-run river gravel or clean washed limestone or crushed granite – less than 0-1.5% passing a #200 sieve
  (*Note: Bank-run gravel will be more rounded and will be difficult to compact; this may cause problems with trucks backing onto the subbase. In this case, a choker layer of smaller, clean crushed aggregate can be placed and lightly compacted providing a smoother and firm surface*).
- Standard gradation - ASTM #5 and #57 (ASTM D 448) is widely available in Iowa and is the recommended subbase material for permeable pavement
- Flexible pavements like porous asphalt and permeable pavers may require a larger subbase material such as ASTM # 2 or Iowa DOT Macadam (Iowa DOT #13) to provide a stiffer base on fine-grained soils

Table 3: ASTM Gradations for Aggregate Materials
(ASTM D 448; Iowa DOT Section 4109)

Sieve	Size (inches)	Percent Passing					
		ASTM #2	ASTM #4	ASTM #5	ASTM #57	Iowa DOT #3 (PCC CA)	Iowa DOT #29 (Permeable Backfill)
3 inch	3.0	100	--------	--------	--------	--------	--------
2 1/2 inch	2.5	90 to 100	--------	--------	--------	--------	--------
2 inch	2.0	35 to 70	100	--------	--------	--------	--------
1 1/2 inch	1.5	0 to 15	90 to 100	100	100	100	--------
1 inch	1.0	--------	20 to 55	90 to 100	95 to 100	95 to 100	--------
3/4 inch	0.75	0 to 5	0 to 15	20 to 55	--------	--------	100
1/2 inch	0.5	--------		0 to 10	25 to 60	25 to 60	95 to 100
3/8 inch	0.375	--------	0 to 5	0 to 5	--------	--------	50 to 100
No. 4	0.187	--------	--------	--------	0 to 10	0 to 10	10 to 50
No. 8	0.0937	--------	--------	--------	0 to 5	0 to 5	0 to 8
No. 200		--------	--------	--------	--------	0 to 1.5	--------

- Iowa DOT Macadam Crushed Stone (Gradation #13) with a nominal maximum size of 3 inches, screened over a 3/4 or 1 inch screen can be used as larger subbase material for porous asphalt and permeable paver subbase material

- The filter ("choke") layer of smaller aggregate on top of the coarse aggregate subbase is used as a setting bed for permeable paver construction. This layer would be about 2 inches in depth. An ASTM # 8 gradation would meet the criteria listed above when placed over a #57 gradation.

Table 4: ASTM Gradations for Filter ("Choke") Layer (ASTM D 448)

Sieve	Size (inches)	Percent Passing	
		ASTM #8	ASTM #78
2 inch	2.0	--------	--------
1 1/2 inch	1.5	--------	--------
1 inch	1.0	--------	--------
3/4 inch	0.75	--------	100
1/2 inch	0.5	100	90 to 100
3/8 inch	0.375	85 to 100	40 to 75
No. 4	0.187	10 to 30	5 to 25
No. 8	0.0937	0 to 10	0 to 10
No. 16	0.0469	0 to 5	0 to 5
No. 50	0.0118	--------	--------
No. 100	0.0059	--------	--------

- Check local availability of what is called a "clean" 1/2 inch chip limestone; this would be close to the ASTM #78 or even a #8. Confirm that it is a washed material free of fines (i.e. #200 clay, silt and limestone dust).
- All aggregate used for the subbase should be washed clean to remove silt and fines.

3. **Sizing the open-graded base for stormwater infiltration and storage.** The design and sizing of the open-graded aggregate subbase for a permeable pavement system is similar to the sizing of an infiltration trench (Section 2E-2). Permeable pavement systems rely on an open-graded aggregate subbase into which water rapidly infiltrates for temporary storage. The pavement subbase essentially functions as an underground detention structure. The aggregate subbase storage can be designed with the same procedure used for conventional or extended detention basins. For a full exfiltration system, the rate of flow into the subgrade functions as the outflow function in performing the detention routing. For partial exfiltration systems, the subbase exfiltration flow functions as the first stage outlet, while the perforated underdrain piping performs the second stage outflow control for larger storm events. The design method presented below assumes full exfiltration of the stored water by infiltration into the subgrade soil.

   The catchment area for permeable pavement systems consists of the pavement surface area and the adjacent contributing surface area. The contributing area may be additional impervious area draining to the permeable pavement system (i.e. traditional pavement, roof drainage, etc) or runoff from adjacent vegetated pervious areas. If the contributing area has been disturbed by excavation and grading operations and is not fully stabilized with vegetation, installation of effective erosion and sediment control must be accomplished. The leading cause of permeable pavement failure is uncontrolled sediment loading during and just after construction. The runoff analysis for the contributing area can be completed using the NRCS CN method (Section 2C-5) using the manual methods or WINTR55. WINTR55 analysis will provide determination of the contributing runoff volume required for design of the pavement subbase volume.

   The main design constraint for the permeable pavement subbase storage is the textural class or USCS soil classification and nominal infiltration rate of the soils underlying the subbase. Soils with infiltration rates greater than 0.3 inches/hour are generally silt loam, loam, sandy loam, loamy sand, and sand. Soils with lower permeability ($\leq$0.25 inches/hour) will limit the exfiltration into the soil subgrade and will require a high ratio of bottom surface area to storage volume. For low permeability soils a partial exfiltration system will typically be used with perforated underdrain piping to convey the excess water. The following design method does not include guidance on design of the underdrain pipe system. Additional design guidance can be found in references (24) and (25).

   The following method finds the maximum allowable depth for the pavement subbase ($\mathbf{d_{max}}$) for a maximum storage time of 72 hours. Shorter storage times can be used to provide a conservative design and provide a factor of safety to minimize risk from continually saturates and potentially weakened subgrade in areas subject to heavier traffic loadings. Calculations for 24, 48 and 72 hours provide a comparison and range of base thicknesses. In some cases, the calculated depth of the subbase for storage may be too shallow to support vehicular traffic. In this case, the minimum subase thickness would be that required to accommodate traffic.

   The NRCS CN method uses a 24 hour duration storm (Section 2C-5) as the basis of design so this method is based on controlling the runoff for a specific 24 hour storm. When considering a permeable pavement application, the minimum design would be based on the WQv and the corresponding rainfall depth of 1.25 inches for Iowa (Section 2B). Based on site soil infiltration rates and other site constraints (i.e. depth to water table) a larger storm depth may be accommodated (i.e. extended detention for Cpv, and detention for peak flow attenuation from 5 year through 25 year recurrence interval storms.

Table 5: Recommended minimum open-graded base and subbase thicknesses for permeable pavements (inches)

Climate	**No Frost**	**No Frost**	**No Frost**	**No Frost**	**Frost**	**Frost**	**Frost**	**Frost**
	Soaked CBR	>15	10 - 14	5 - 9	Gravelly Soils	Clayey Gravels, Plastic Sandy Clays	Silty Gravel, Sand, Sandy Clays	Silts, Silty Gravel, Silty Clays
ESALs *	Layers of subbase	inches	inches	inches	inches	inches	inches	inches
Pedestrian	No. 57 No. 2	4 6	4 6	4 6	4 6	4 6	4 6	4 6
50,000	No. 57 No. 2	4 8	4 8	4 8	4 8	4 8	4 8	4 8
150,000	No. 57 No. 2	4 8	4 8	4 8	4 8	4 8	4 10	****
600,000	No. 57 No. 2	4 8	4 8	4 10	4 8	4 14	4 18	****

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

**** Strengthen subgrade with aggregate subbase to full frost depth

1. All thicknesses are after compaction and apply to full, partial, and no exfiltration systems.
2. Pedestrian applications should use a minimum base thickness of 10 inches.
3. Thicknesses do not include the No. 8 bedding course (2 inches) plus the paver unit thickness (typical 3.125 inches) for permeable paver systems; a standard pervious concrete thickness of 6-inches and 5 to 6 inches of porous asphalt surface would be similar in thickness to the permeable paver bedding course and pavers.
4. Geotextile over the subgrade is recommended.
5. Silty soils or others with more than 3% of particles smaller than 0.02 mm are considered susceptible to frost action.
6. All soils have a minimum CBR of 5%.

Source: (26), (27)

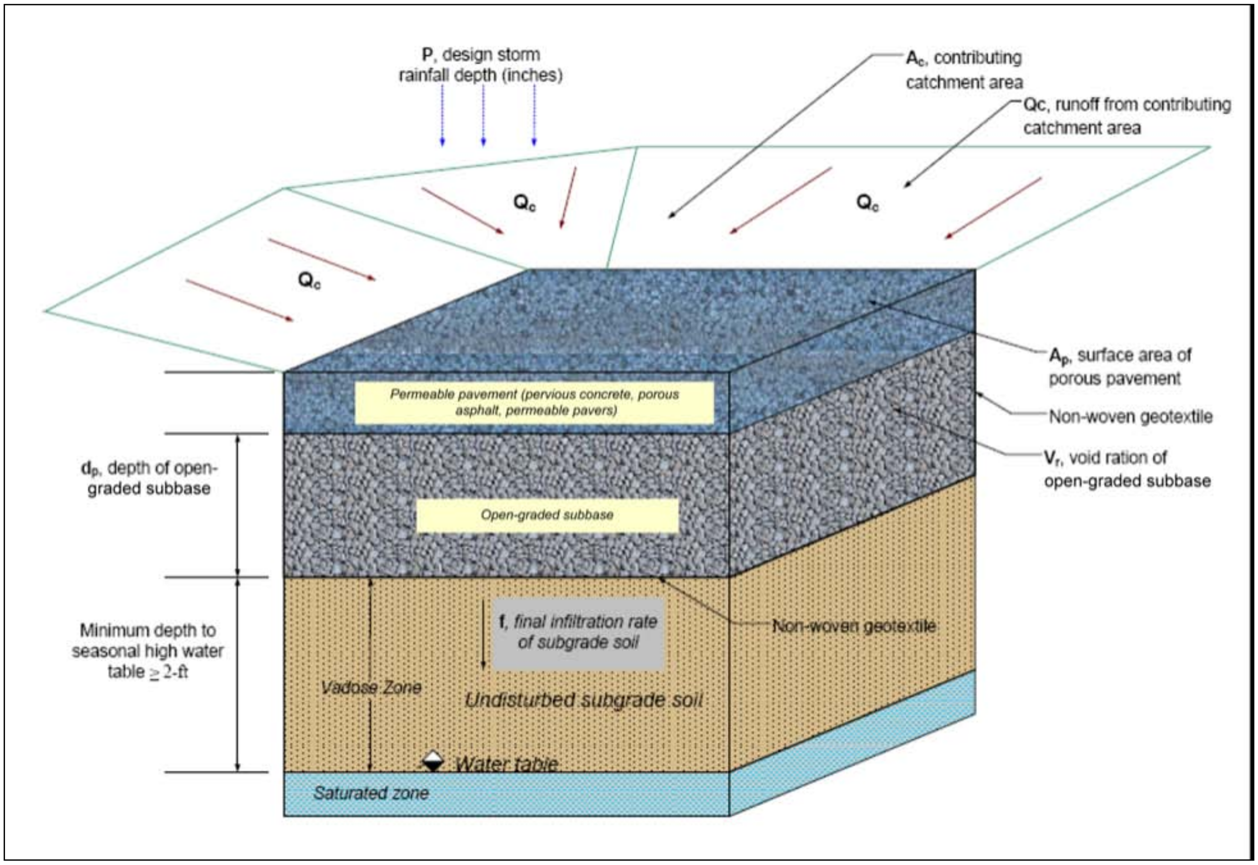
Table 6: Maximum allowable depths, inches of storage for selected maximum storage times (T_s, hrs), and minimum infiltration rates, inches/hr. (Ref: Sections 2E-1, 2E-2)

		Soil Subgrade Texture/Infiltration Rate (inches/hr)										
		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	2.41	1.02	0.52	0.27	0.17	0.09	0.06	0.05	0.04	0.02
fT_s / V_r *for* $V_r = 0.4$	24	496	145	61	31	16	10	5	4	3	2	1
	48	992	290	122	62	32	20	11	7	6	2	2
	72	1489	434	183	93	49	31	16	11	9	7	4

f = infiltration rate (in/hr) Ts = maximum allowable storage time Vr = voids ratio

Supplement subbase exfiltration with underdrain piping

Figure 5: Schematic of permeable pavement system with design parameters



Parameter definitions:

f = the final design infiltration rate in inches per hour of the soil under the pavement subbase aggregate layer

T_s = the maximum allowable storage time (hrs) (≤ 72 hours)

V_r = void ratio of the aggregate subbase (minimum ≥ 0.32, typical ≈ 0.4)

A_c = contributing runoff catchment area (ft^2)

Q_c = runoff volume from contributing catchment area (NRCS CN method/WINTR55) (ft^3)

A_p = area of pavement surface (ft^2)

P = design rainfall depth (1.25 inch for WQv; 1 year 24 hour event for CPv (in) (in/12 = ft)

d_p = depth of open-graded aggregate layer subbase (ft)

T = effective filling time of the aggregate subbase (hrs) (2 hours is typical)

As in the procedure for infiltration trenches (Section 2E-2), the design of the pavement subbase is also based on the maximum allowable depth of the subbase layer (d_{max} - inches). A schematic of a permeable pavement system with contributing catchment area and parameter definitions is provided in Figure 5.

The maximum allowable depth should meet the following criteria:

$d_{max} = (fT_s / n) = (fT_s / V_r)$ (inches) **Equation 1**

- Where *f* is the final infiltration rate of the soil subgrade area in inches per hour, T_s is the maximum allowable storage time in hours, and *n* is the porosity, volume voids/total volume (*Vv/Vt*) of the aggregate reservoir. *Also termed the void ratio,* V_r *.* A nominal value for *n* of 0.32-0.35 is typical. This can be adjusted based on specific measurement for the aggregate specified. The maximum allowable storage time should be no greater than 72 hours. The maximum allowable depth for a site may also be limited by the depth to the water table.
- The subbase aggregate layer is sized to accept the design volume that enters the pavement system from the contributing catchment area (V_C) plus the volume of rain that falls on the surface of the permeable pavement (PA_p) minus the exfiltration volume (fTA_p) out of the bottom of the subbase into the soil subgrade. Based on NRCS hydrograph analysis, the effective filling time for the aggregate subbase (T) will generally be less than two hours. The volume of water that must be stored in the permeable pavement subbase (V_W) is defined as:

  $V_W = V_C + (P/12)(A_p) – (f/12)TA_p$ **Equation 2**

  Where:
  V_W = Water Quality Volume (WQv) or total runoff volume to be infiltrated (ft^3)
  V_C = Volume of runoff from contributing catchment area (ft^3)
  P = design rainfall event (in)
  A_p = pavement surface area (ft^2)
  f = infiltration rate (in/hr)
  T = fill time (hr)

For a site configuration where an adjacent area contributes runoff to the pavement system, V_C is equal to the runoff in inches (Q_c) times the contributing catchment area (A_c) in ft^2. Equation 2 in Section 2E-2 then becomes:

$V_W = (Q_c)(A_c)/12 + (P/12)(A_p) – fTA_p$ **Equation 3**

Where:
Q_c = Runoff from contributing catchment area (in) (from NRCS CN method)
A_c = Contributing catchment area (ft^2)
P = design rainfall event (in)
A_p = pavement surface area (ft^2)
f = infiltration rate (in/hr)
T = fill time (hr)

For sites where there is no contributing runoff, the volume of water due to rainfall on the surface area of the pavement (PA_p) will define the design volume (V_W) of the aggregate subbase layer. The volume of rainfall entering the pavement system can be defined in terms of pavement and subbase geometry. The gross volume of the subbase layer (V_P) is equal to the ratio of the volume of water that must be stored (V_W) to the porosity (*n*) of the aggregate in the subbase layer; V_P is also equal to the product of the aggregate depth, d_p, (ft) and the surface area, A_p, (ft^2):

$$V_P = V_W/V_r = d_p \text{ x } A_p \text{ x } V_r \qquad \textbf{Equation 4}$$

Combining Equations 3 and 4 provides the following expression:

$$d_p \text{ x } A_p \text{ x } Vr = (Q_c)(A_c)/12 + (P/12)(A_p) - (f/12)TA_p \qquad \textbf{Equation 5}$$

The surface area of the pavement, A_p (ft^2) and the depth of the subbase, d_p (inches), can be defined from Equation 5 as follows:

$$A_p\ (ft^2) = \frac{(Q_C/12)(A_C)}{(V_r)(d_p/12) - P/12 + (f/12)T} \qquad \textbf{Equation 6}$$

and

$$d_p\ (\text{inches}) = \frac{(Q_C)\ (A_C/A_P) + P - fT}{V_r} \qquad \textbf{Equation 7}$$

Where:

- d_p = depth of subbase layer (in)
- Q_c = Runoff from contributing catchment area (in) (from NRCS CN method)
- A_c = Contributing catchment area (ft^2)
- P = design rainfall event (in)
- A_p = pavement surface area (ft^2)
- f = infiltration rate (in/hr)
- T = fill time (hr)
- V_r = void ration of aggregate base (typical value of 0.32 – 0.4)

Equation 7 will be used most often since the surface area of the pavement is normally defined by the project configuration (i.e. parking area) and depth of base is to be determined.

The NRCS CN method can be used to determine the value of Q_C (runoff volume) from either a graphical solution using CN and rainfall depth (See Figure 2, Section 2C-5) or using the WINTR55 computer model.

4. **Design procedures.** The design of the subbase storage area is completed through one of two methods:
   - ***Minimum depth method.*** Compute the minimum depth of the subbase given the area of the permeable structure.
   - ***Minimum area method.*** Compute the minimum surface area of the permeable pavement given the required design depth of the subbase.

a. Minimum depth method

1) Select the design rainfall event, P, and determine the CN for the contributing catchment area. Compute the runoff volume, Q_C from the contributing area. The Water Quality volume (WQv) can be used as a minimum design volume.
2) Compute the depth of the aggregate subbase (d_p) using Equation 7.
3) Compute the maximum allowable depth (d_{max}) of the aggregate base using Equation 1.
4) Check the feasibility of the computed depth, d_p.
   a) The depth d_p must be less than or equal to d_{max}.
   b) Based on the computed depth for d_p, the bottom of the aggregate must be a minimum of 2 feet above the seasonal high water table at the site.
   c) If d_p does not meet the above criteria, the surface area of the permeable pavement must be increased or the design storm depth must be reduced.

b. Minimum area method

1) Select the design rainfall event, P, and determine the CN for the contributing catchment area. Compute the runoff volume, Q_C from the contributing area. The Water Quality volume (WQv) can be used as a minimum design volume.
2) Compute the maximum allowable depth (d_{max}) of the aggregate subbase using Equation 1.
3) Select a design depth for the aggregate subbase, d_p less than or equal to the computed d_{max} or a depth that places the bottom of the aggregate subbase at least 2 feet above the seasonal high water table.
4) Compute the minimum required surface area for the permeable pavement (A_p) using Equation 6.

5. Additional considerations

a. Performance. In addition to the siting requirements of permeable pavement, keys to the success of a permeable pavement system include selection of appropriate materials, construction specifications, and installation by a qualified contractor. A limitation to the practice is the poor success rate it has experienced in the field; however, recent installations have shown improved performance and service life due to innovations in knowledge, materials, equipment, and contractor experience. Several studies indicate that with proper maintenance permeable pavement can retain its permeability (e.g., Goforth et al., 1983; Gburek and Urban, 1980; Hossain and Scofield, 1991). Dated studies indicate that when permeable pavement was implemented in communities, the failure rate was as high as 75% over 2 years (Galli, 1992). However, newer studies, particularly with permeable pavers and pervious concrete, indicate that success rates can be substantially higher when the paving medium is properly installed (Brattebo and Booth, 2003).

b. Maintenance. Owners should be aware of a site's permeable pavement because failure to perform maintenance is a primary reason for failure of this practice. One nonstructural component that can help ensure proper maintenance of permeable pavement is a carefully worded maintenance plan providing specific guidance, including how to conduct routine maintenance and how the surface should be maintained. Ideally, signs should be posted on the site identifying permeable pavement areas. Typical requirements are shown in Table 7.

One design option incorporates an "overflow edge," which is a trench surrounding the edge of the pavement. The trench connects to the stone reservoir below the pavement surface. Although this feature does not in itself reduce maintenance requirements, it acts as a backup in case the surface clogs. If the surface clogs, stormwater will flow over the surface and into the trench where some infiltration and treatment will occur.

Table 7: Typical maintenance activities for permeable pavement

Activity	Schedule
• Do not seal or repave with non-permeable materials.	N/A
• Ensure that paving area is clean of debris. • Ensure that paving dewaters between storms. • Ensure that the area is clean of sediments.	Semi-annually
• Mow upland and adjacent areas, and seed bare areas. • Vacuum sweep frequently to keep the surface free of sediment.	As needed (typically three to four times per year).
• Inspect the surface for deterioration.	Annual
Source: WMI, 1997	

c. Cost. Permeable pavement systems will be more expensive than traditional PCC or AC pavement. While traditional asphalt and concrete costs between $1.50 to $3.00 per square foot, permeable pavement can range from $2.00 to $8.00 per square foot, depending on the design and type of surface materials (pervious concrete, porous asphalt, permeable pavers). There will be additional costs for the aggregate subbase not traditionally used for parking lot design and construction. When compared to most traditional parking lot construction (pavement placed directly on a compacted subgrade) an increased durability and life span of a properly constructed permeable pavement with an open-graded subbase layer will be attained. Permeable pavement, when used in combination with other techniques such as bioretention cells, vegetated swales, or vegetated filter strips, may eliminate or reduce the need for land intensive BMPs, such as dry extended detention or wet retention ponds. The use of permeable pavement systems will reduce the impervious area of the project site, increase the time of concentration for runoff, and decrease the peak runoff rate from the site. Permeable pavement systems can be an effective BMP for Low Impact Development designs and provide a design option for projects seeking LEED accreditation for sustainable design. In areas where land prices are high, the savings associated with decreased land consumption should be considered. The cost of vacuum sweeping may be substantial if a community does not already perform vacuum sweeping operations. Finally, if not designed and maintained properly, the effective lifespan of permeable pavement may be short because of the potential high risks of clogging.

D. Permeable pavement design example

Figure 6: Site plan
Widget Manufacturing Company, Bucketsville, IA (Marshall County)

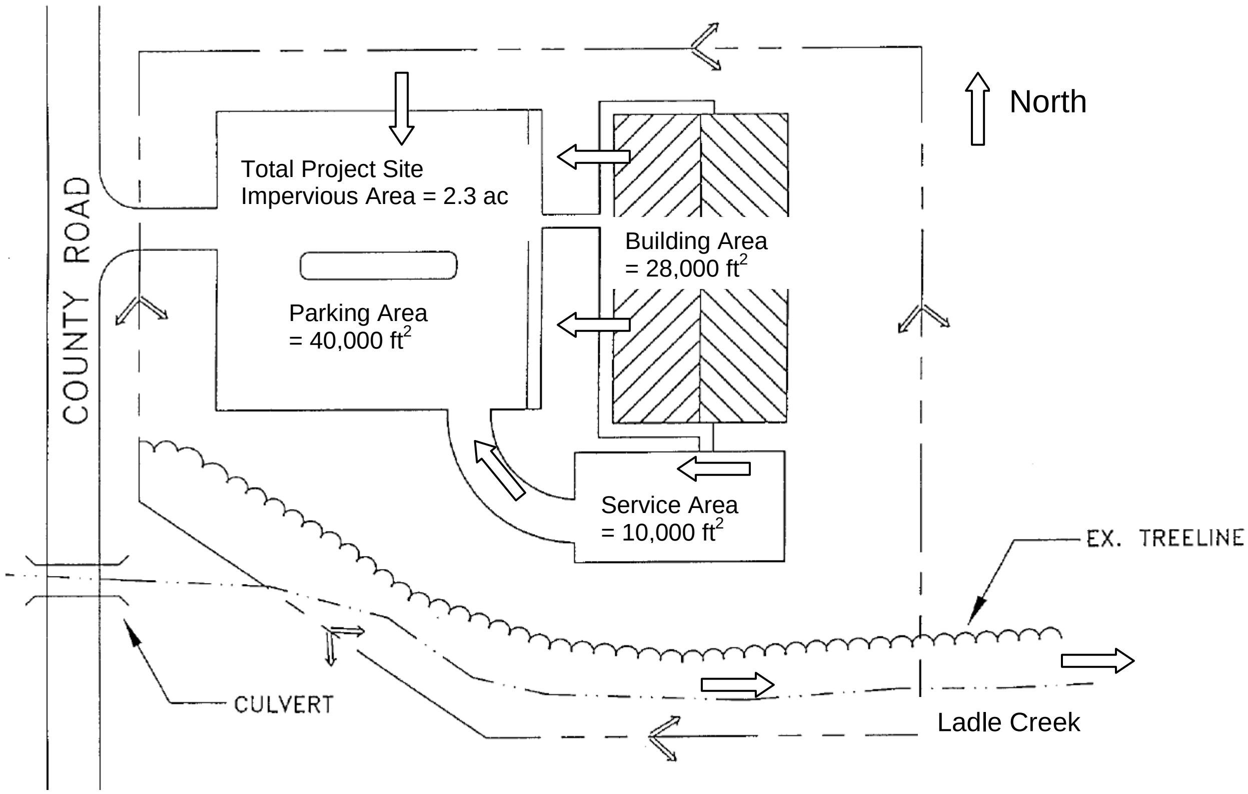


Table 8: Hydrologic site data for existing and proposed conditions

Base Site Data	Hydrologic Data			
Total Site Drainage Area (A) = 4.0 ac		Pre Development	Post Development w/traditional intakes and piping	Post Development w/impervious disconnected
Impervious Area = 2.3ac; I = 2.3/4.0 = 57.5%	CN	68	85	74
Soils: HSG B (Loam) ~50%; HSG C (Silt loam) ~ 50%	t_c	.29	.10	0.10

Existing conditions:

- Undeveloped - pasture/grassland in fair condition
- Land slope is ± 2% to 3% to the south to Ladle Creek
- Soil textures in north half of site are loam and silt loam (south half).
- Soil borings at the site indicate soils in the north half of site are SP and transition to SM and SC in the direction of the creek.
- Borings indicate depth to seasonal high water table at approximately 8 feet.
- Two tests with double-ring infiltrometer at the proposed location of parking area indicated infiltration rates at 0.88 in/hr (north) and 0.48 in/hr (south). A nominal rate of 0.32 in/hr will be used for design (0.68 in/hr / 2 = 0.32in/hr). Design safety factor = 2.

Proposed site structures and development:

- Commercial building: 38,000 ft^2
- Main parking lot: 50,000 ft^2
- Service road and service dock/loading area: 11,000 ft^2
- Additional entrance drive and sidewalks: 1,000 ft^2

Total impervious area ± 100,000 ft^2

This example is focused on the design of a permeable pavement system to meet the water quality treatment requirements (WQv) for the site. Analysis for CPv and Qp will be completed to determine preliminary storage volume and peak discharge requirements. The feasibility of providing CPv storage and Qp requirements will be examined. This example demonstrates the procedural steps and calculations for sizing the permeable pavement subbase and the minimum and maximum depth of aggregate.

Step 1: Compute runoff control volumes from Unified Sizing Criteria

a. Compute WQv
   - Rv = 0.05 + (57.5)(0.009) = 0.57
   - WQv = (1.25-in)(Rv)(A)/12
     = (1.25)(0.57)(4.0)(1-ft/12-in)(43,560-ft^2/ac) = 10,345 ft^3 = 0.237 ac-ft

b. Compute Stream Channel Protection Volume, (CPv):
   - Use WINTR-55 to compute the pre and post development peak runoff rates for the 1-yr, 24-hr duration storm. (See Table 9)
   - Use modified CN of 89 for 1-yr storm event. See Section 2C-6; P = 2.38-in and Q = 1.36 in.
   - Use WINTR-55 to compute channel protection storage volume: (See Section 2C-6)

     q_u = 994 csm/in   qo/qi = 0.02   Qa = 1.34-in

     $Vs/Vr = 0.683-1.43(qo/qi)+1.64(qo/qi)^2 -0.804(qo/qi)^3$

     Vs/Vr = 0.64

     Vs = CPv and Vr = Qa = 1.34 volume of runoff in inches

     Vs = CPv = 0.64(1.34-in)(1/12)(4.0-ac) = 0.29 ac-ft = 12,726 ft^3

   CPv of 12,726 ft^3 to be released over 24 hours or stored in aggregate subbase and infiltrated over design storage time (i.e. 48 to 72 hours):

     12,726 ft^3 / (24-hrs x 3600 sec/hr) = 0.15 cfs (average release rate for CPv)

c. Determine Overbank Protection Flood Protection Volume (Q_p)
   - Use WINTR-55 for analysis of Q5 to Q100 runoff volume in inches and respective peak rates. (See Section 2C-9).
   - Using data in Table 10 for pre and post development runoff rates for the 5 year, 10 year, and 25 year storm events. The criterion is control of the post-development peak runoff rate to no more than the predevelopment peak rate.
   - For a q_{in} of 21.29 cfs and an allowable q_{out} of 9.19 cfs, the volume of storage (V_{st}) necessary for 25-yr control is 0.36 ac-ft or 15,529 ft^3 under a developed CN of 85.
   - For control of post-development rates to no more than the similar *pre-development rate*, the storage requirements (V_{st}) are summarized in Table 11.

Table 9: Storage requirements for attenuation of post-development peak rates to pre-development rates

Recurrence Interval	q_{pb} (cfs)	q_{pa} (cfs)	a	R_v	Q_a (inches)	Vs (inches)	Am (ac)	V_{st} (ac-ft)	V_{st} (ft^3)
5	4.28	13.16	0.33	0.36	2.13	0.77	4.00	0.26	11,217
10	6.23	16.54	0.38	0.33	2.69	0.90	4.00	0.30	13,008
25	9.19	21.29	0.43	0.31	3.50	1.07	4.00	0.36	15,529
100	14.56	29.20	0.50	0.28	4.87	1.35	4.00	0.45	19,581

- For control of post-development rates to no more than the 5 year pre-development rate, the storage requirements (V_{st}) are summarized in Table 9.
- For a q_{in} of 21.29 cfs and an allowable q_{out} of 4.28 cfs, the volume of storage (V_{st}) necessary for 25 year control is 0.53 ac-ft or 23,086 ft^3 under a developed CN of 85.

Table 10: Storage requirements for attenuation of post-development peak rates to pre-development 5 year rate

Recurrence Interval	q_{pb} (cfs)	q_{pa} (cfs)	a	R_v	Q_a (inches)	Vs (inches)	Am (ac)	V_{st} (ac-ft)	V_{st} (ft^3)
5	4.28	13.16	0.33	0.36	2.13	0.77	4.00	0.26	11,217
10	6.23	16.54	0.26	0.41	2.69	1.10	4.00	0.37	15,929
25	9.19	21.29	0.20	0.45	3.50	1.59	4.00	0.53	23,086
100	14.56	29.20	0.15	0.51	4.87	2.46	4.00	0.82	35,717

d. Compute WQv Peak discharge (Q_{wq}): From Section 2C-6 and Modified NRCS WINTR55 procedure.

WQv = <u>10,345 ft^3 = 0.237 ac-ft</u>

$CN = 1000/[10+5P+10Q_a-10(Q_a^2 + 1.25Q_aP)^{0.5}]$

- P = rainfall depth for Water Quality storm – 1.25 inches
- Q_a = runoff volume, inches (equal to P x Rv) = (1.25)(0.57) = 0.712-in

$CN = 1000 / [10 + 5(1.25") + 10(.71") – 10[(.71")^2 + 1.25(0.71")(1.25")]^{0.5}$

CN = 93.8 Use CN = 94 Use t_c = 0.10 hour

Compute Q_{WQ} using WINTR55 using modified CN and t_c :
WINTR55 results for *modified* CN = 94 and t_c = 0.10-hr:

For 1.25-inch rainfall q_u = 622.89 csm/in

Q_{WQ} = <u>3.89 ft^3/sec</u>

Step 2: Compute runoff volume and peak runoff rate for existing and proposed development conditions.

a. Hydrologic assessment conditions (See Table 7)
- Predevelopment (existing) condition
- Post development – runoff from impervious area conveyed via standard surface intakes and piping directly to Ladle Creek
- Post development – impervious area runoff disconnected and conveyed to Ladle Creek across vegetated pervious area

b. Compute 1 year, 2 year, 5 year, 10 year, 25 year, and 100 year peak discharge using *conventional* WINTR55 procedure:
At 57.5% impervious, HSG B and C soils, CN=98 for Imp and CN=64 for open space, composite CN = 85
Use t_c = 0.1-hr
WINTR55 results:

c. Summary of runoff volume and peak runoff rate listed in Table 10.

Table 11: Runoff volume and peak discharge summary for existing and post development conditions

Condition	CN	Q_1		Q_2		Q_5		Q_{10}		Q_{25}	Q_{100}
		in	cfs	in	cfs	in	cfs	in	cfs	cfs	cfs
Pre-developed	68	0.54	2.25	.85	3.78	1.33	6.15	1.79	8.38	11.68	17.42
Post-Dev (57.5% impervious) w/standard direct connected intakes and piping	85	1.08	6.66	1.5	9.33	2.13	13.16	2.69	16.54	21.29	29.20
Post-Dev (57.5% impervious) w/disconnected impervious area	74	.54	2.97	.85	4.96	1.33	8.07	1.79	10.98	15.30	22.84

Step 3: Determine if the development site and conditions are appropriate for using an infiltration trench

Site Specific Data	
Criteria	**Value**
Soil (NRCS texture)	Loam and Silt Loam
Soils (USCS)	SP; SM; SC
Infiltration Rate (onsite testing)	0.32 in/hr
Ground Elevation at BMP	1020
Seasonally high water table	1012
Stream Invert	1006
Soil Slopes	2.0 – 4.0 %

Step 4: Confirm design criteria and applicability

Infiltration Feasibility	
Criteria	**Status**
Infiltration rate (f) greater than or equal to 0.5 inches/hour.	Nominal infiltration rate 0.88 to 0.48 in/hr; nominal design rate of used will be 0.32. Soil type indicates moderate permeability; use underdrain piping for partial exfiltration from pavement base. OK.
Soils have a clay content of less than 20% and a silt/clay content of less than 40%.	Loam and silt loam soils at this site meets both criteria. SP/SM/SC soils. Soil gradation indicated 58% sand, 12% clay, and 18% silt. Soaked CBR of 15
Infiltration cannot be located on slopes greater than 6% or in fill soils.	Slope is 2-4%; not fill soils. OK.
Hotspot runoff should not be infiltrated.	Not a hotspot land use. OK.
Infiltration is prohibited in karst topography.	Not in karst. OK.
The bottom of the aggregate base must be separated by at least 2 feet vertically from the seasonally high water table.	Elevation of seasonally high water table: 1008 feet Elevation of BMP location: 1020 feet The difference is 12 feet The aggregate base can be up to 4 feet in depth and meet these criteria. OK.
Infiltration facilities must be located 100 feet horizontally from any water supply well.	No water supply wells nearby. OK.
Maximum contributing area generally less than 5 acres. (Optional)	4-acres. OK.
Setback 25 feet down-gradient from structures.	240 feet straight-line distance between the parking lot and the tree line. OK

Step 5: Size the aggregate base

a. Use the minimum depth method. Equation 7.

b. Design goal is to capture runoff from building roof, service area pavement, and access road and convey to permeable pavement system at main parking facility.

c. Contributing catchment area, A_C = 38,000 ft^2 (CN=98).

d. Permeable pavement area, A_P = 50,000 ft^2.

e. Design vehicle load on parking load is estimated at 250,000 ESALs over the 20 year life-cycle.

f. The minimum design will be for WQv; storage feasibility for the Cpv, as well as the 2 year and 5 year requirements to be checked.

g. Select the design rainfall event, P, and determine the CN for the contributing catchment area. Compute the runoff volume, Q_C from the contributing area.

h. The Water Quality volume (WQv) can be used as a minimum design volume. The WQV for the contributing area plus the parking area will based on P=1.25 inches.

- Solve for minimum depth of base, d_p using Equation 7:

  d_p (inches) = [(Q_C) (A_C/A_P) + P – fT] / V_r

  A_c = 38,000 ft^2
  A_p = 50,000 ft^2
  For P= 1.25 inch and CN =98 Qc = 0.674 inch (WINTR55 analysis)
  f = 0.32 in/hr (design infiltration rate
  T = 2 hours (nominal fill time for pavement)
  V_r = 0.4 (tested void ratio in #57/#4 subbase was 40%)

  d_p = [(0.647 inch) (38,000 ft^2/50,000 ft^2) + 1.25 inch – (0.32 in/hr)(2 hours)] / 0.4

  d_p = 2.75 inches (required depth for WQv)

  Other depth and storage options:

  CPv: Capture and release the 1 year, 24 hour runoff. P = 2.38 inches Qc = 1.70 inches
  d_p = [(1.70 inches) (38,000 ft^2/50,000 ft^2) + 2.38 inches – (0.32 in/hr)(2 hours)] / 0.4
  d_p = 7.58 inches (required depth for Cpv)

  2 year, 24 hour rainfall: P = 2.91 inches Qc = 2.23 inches
  d_p = [(2.23 inches) (38,000 ft^2/50,000 ft^2) + 2.91 inches – (0.32 in/hr)(2 hours)] / 0.4
  d_p = 9.91 inches (required depth for 2 year, 24 hour storm)

  5 year, 24 hour rainfall: P = 3.64 inches Qc = 3.02 inches
  d_p = [(3.02 inches) (38,000 ft^2/50,000 ft^2) + 3.64 inches – (0.32 in/hr)(2 hours)] / 0.4
  d_p = 13.24 inches (required depth for 5 year, 24 hour storm)

  10 year, 24 hour rainfall: P = 4.27 inches Qc = 3.69 inches
  d_p = [(3.69 inches) (38,000 ft^2/50,000 ft^2) + 4.27 inches – (0.32 in/hr)(2 hours)] / 0.4
  d_p = 16.1 inches (required depth for 10 year, 24 hour storm)

- Determine the maximum depth (d_{max}) using Equation 1:
  (Criterion is drain-down time of 48 hours).

  d_{max} = (fT_s / n) = (fT_s / V_r) (inches)

  Ts = 48 hours
  f = 0.32 in/hr
  Vr = 0.4

  d_{max} = (0.32 in/hr)(48 hours) / 0.4 (inches)
  d_{max} = 38-in

Step 6: Determine the minimum required subbase thickness for structural support

a. Must meet minimum depth for storage requirement plus also provide support for the expected vehicle loading (250,000 ESALs)

b. Table 5 provides guidance on aggregate subbase depth as a function of traffic load (ESALs), soil type, and presence of frost (cold climate conditions)

c. For the expected traffic load and the sandy/silty soil, a subbase depth of 16 to 18 inches is indicated for structural support

d. This depth is equal to the subbase depth for storing the 10 year, 24 hour storm

Step 7: Check for minimum separation of bottom of subbase aggregate from seasonal high water table

a. Existing ground elevation at site is 1,020 feet

b. Proposed finished floor elevation of building is 1,020 feet

c. Top of pavement for parking lot will be 1,018.7 feet

d. Thickness of permeable pavement surface is 6 inches

e. Top of aggregate subbase will ± 1,018 feet

f. For an aggregate subbase depth of 18 inches, the bottom of subbase will be at 1,016.5 feet

g. Measured water table elevation from soils investigation was ± 1,012 feet (8 feet)

h. At 18-in aggregate depth, the separation from water table will be ≈ 4.5 feet

Step 8: Check criteria for geotextile separation layer at base and sides of aggregate subbase

a. The sieve analysis of the subgrade soils showed a 6% passing the No. 200 sieve.

b. The gradation analysis results showed the following:

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

c. Use FHWA geotextile filter criteria from Figure 4.

d. For granular soils (i.e. SP/SM/SC) with less than 50% passing the No. 200 sieve the following criteria would apply (Figure 4):

All geotextiles: $AOS_{geotextile} \leq B \times D_{85soil}$

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

Where :
$B = 1$ for $2 \geq C_u \geq 8$ 3.2 OK

B = 0.5 for $2 < C_u < 4$ 3.2 OK
B = 8/Cu for 4 < Cu < 8 8/3.2 = 2.5 does not meet criteria for 4 < Cu < 8 (Do not use for B).

e. Select a geotextile with AOS between 0.5 x 0.63 = 0.32-mm and 1.0 x 0.63 = 0.63-mm

f. Permeability criteria: k (fabric) ≥ k (soil) ≥ 0.32 in/hr

g. Use non-woven fabric with porosity ≥ 30%

Step 9: Design of underdrain piping

a. For this design, a 4 inch diameter perforated PVC underdrain will be installed with a flow line depth of 16 inches above the bottom of aggregate.

b. The final design depth for the subbase aggregate will be 24 inches.

c. This places the flow-line of the underdrain piping at the top of the storage depth for the 10-yr, 24-hr storm. This also allows a 4 inch aggregate cover over the top of the piping.

d. A 24 inch base depth still provides the minimum 2 feet separation from the water table.

e. The total storage capacity of the base below the underdrain piping is 26,600 ft^3. This storage volume would meet the detention requirements for reducing the 25 year runoff to the pre-development 5 year runoff rate.

f. The storage provided in the permeable pavement system will also provide complete capture and infiltration for up the 5 year storm and will more than meet the WQv and CPv requirements.

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