North Carolina Department of Transportation

Design Guide for Permeable Interlocking Concrete Pavements For Local Streets

March 2024

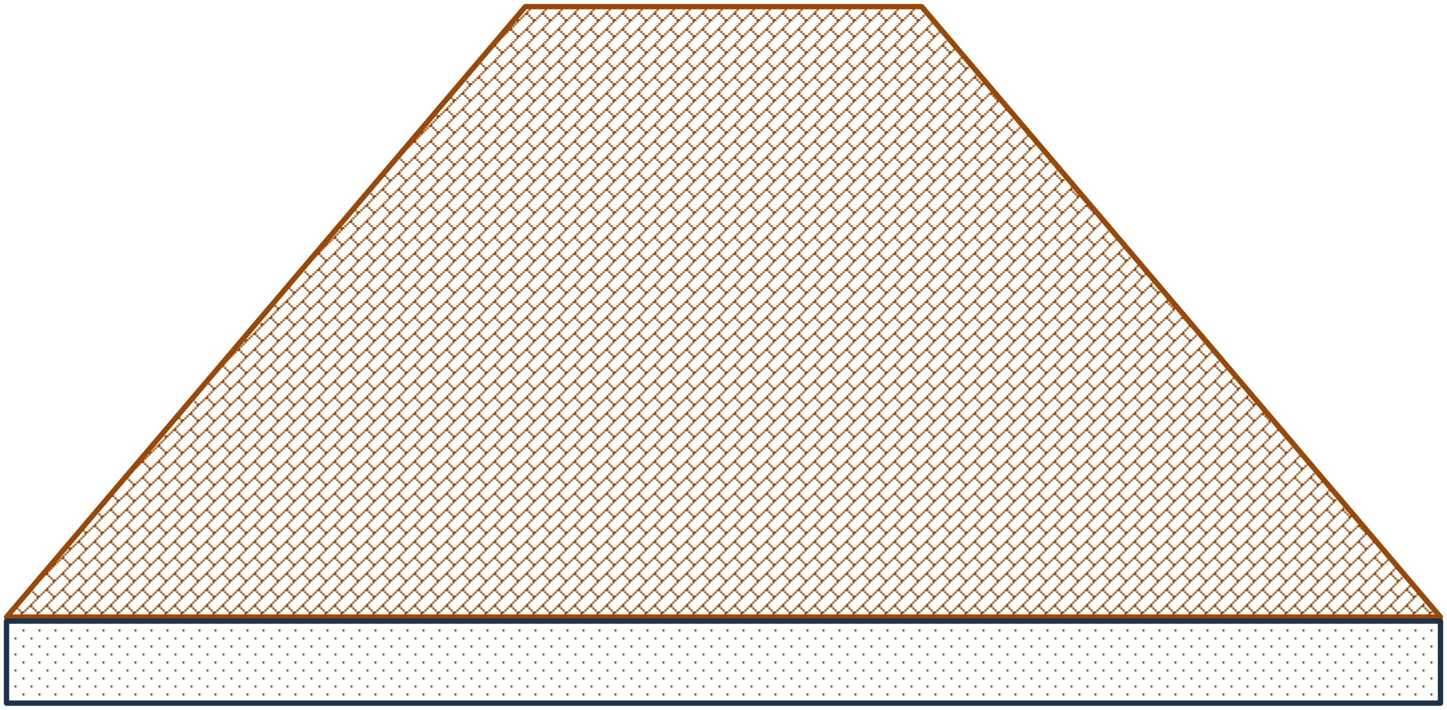


Table of Contents

CONTENTS

EXECUTIVE SUMMARY **3**

OVERVIEW OF THE GUIDE **6**

SITE SELECTION CRITERIA **8**

PICP SYSTEM OPTIONS **9**

PICP DESIGN **156**

DEVELOPMENT OF INPUT VALUES **17**

- Site-Related Design Inputs 24
- Design-Related Variables 25

DESIGN DEVELOPMENT USING THIS GUIDE **26**

- Methodology 26
- Pavement Design Example 1 29
- Pavement Design Example 2 31

MAINTENANCE **34**

SUMMARY **35**

REFERENCES **36**

EXECUTIVE SUMMARY

The Design Guide supports NCDOT *Special Provision for Permeable Interlocking Concrete Pavements* (hereinafter PICP) for use in parking lots, alleys, and residential streets. PICP is a stormwater control measure (SCM) while providing a pavement suitable for vehicular traffic. Besides supporting compliance with national pollutant discharge elimination system (NPDES) permits and total maximum daily (pollutant) load (TMDL) regulations, PICP reduces stormwater runoff volumes via infiltration into the soil subgrade. Volume reduction equates to pollutant reductions.

Given tidal storm surges and gradual sea rise, PICP offers a resilient solution to local flooding in coastal as well as non-coastal regions. Other PICP benefits include reduction or elimination of detention ponds (with related liability and mosquitoes), aquifer recharge, an irrigation water source, energy source for ground source heat pumps, cooler microclimates, and traffic calming. Figure 1 illustrates PICP in Fayetteville, NC.

Figure 1. PICP in Fayetteville, NC. This pavement was cleaned after 6 years of service. The white marks are where infiltration test was conducted to assess cleaning results. The marks will fade with time.

All PICP applications should comply with the NC Department of Environmental Quality (DEQ) *Stormwater Design Manual*. Relevant sections include Section A2 Soils in Part A, Common Site and SCM Elements; Section B, Calculations for hydrologic/hydraulic design; and Section C5, Permeable Pavement of the Minimum Design Criteria and Recommendations for Stormwater Control Measures. A significant incentive to use PICP is that it counts as 100% permeable surface when calculating built upon area per DEQ requirements. While the surface area has 5% to 15% open area, the entire surface is permeable, i.e., capable of passing water. Similarly, pervious concrete and porous asphalt exhibit an approximate open surface area of 20%. For all permeable pavements, the most significant cost savings for municipalities comes from not consuming additional real estate for detention ponds because detention and pavement are built in the same place. Land normally used for detention ponds can be directed to other, more productive purposes or conserved.

Hereafter referred to as “the Guide,” this publication specifically addresses structural design method in ASCE 68-18 *Permeable Interlocking Concrete Pavement*. Structural design is not covered in the DEQ manual. Hence, its treatment in this Guide for municipal vehicular applications. In addition, this Guide is informed by the Interlocking Concrete Pavement Institute (ICPI) guide specifications, ‘Tech Spec’ technical bulletins, contractor and owner experiences representing best practices for constructing and maintaining PICP. These are referenced throughout this Guide.

Design of pavements in continually saturated subgrades is not normally within the scope of civil engineering education and practice. In response, PICP design has introduced concepts that address this design condition. PICP structural design is based on a mechanistic-empirical model and design procedure validated with full-scale load testing in 2014 by the University of California Pavement Research Center (Li 2014). The research resulted in determining an adequate PICP subbase thickness in saturated soil conditions. The design procedure incorporates numerous design elements under the control of the pavement designer and various site condition variables, including traffic and soil type for a specific project. The construction specifications were derived from agency and industry specifications and guidelines.

The structural design process has been simplified to avoid performing multiple design or computer iterations typical to mechanistic designs and analyzing the results to determine a feasible structural design to support traffic. The simplified processes presented in the Guide provide the required pavement subbase thickness based on soil characteristics and anticipated traffic. Several variables, including design life, concrete paver strength properties, and rutting criteria are based on recommended industry practices. Site variables including traffic characterization, soil type, and infiltration rate must be determined for each project. Simultaneously, the need for sound engineering judgment remains a crucial aspect in generating a pavement design with reasonable initial cost and good long-term performance.

The information is presented in graphical and tabular format with specific guidance regarding selection of the most appropriate design to use for a project. Long-lasting PICP pavements are a combination of suitable site selection and design, reasonable specifications, high quality materials, and good construction and maintenance practices. The information presented in this Guide pertains only to design and construction specifications. References are provided with additional insights into construction practices. Maintenance is covered in Section C5, Permeable Pavements, in the DEQ *Stormwater Design Manual*. Additional information is provided at the end of this document.

OVERVIEW OF THE GUIDE

The Guide is intended to standardize the way in which PICP is designed for a range of traffic and site conditions typical to parking lots, alleys, and residential streets. Specifically, the guide covers the structural design of the open-graded PICP subbase to support vehicular traffic. Due to its porosity, the subbase layer is also used for water storage for no longer than 72 hours and infiltration and/or release. Hydrologic and hydraulic design to determine the thickness of subbase for water storage and infiltration are addressed in Section B, Calculations, and Section C5, Permeable Pavement, in the DEQ *Stormwater Design Manual*. This Guide focuses on the structural design process for determining the thickness of the subbase to support traffic. The thicker of the two required subbase thicknesses designed to store water and support traffic is selected for the pavement structure.

The structural design procedure in this Guide is based on a mechanistic model validated and calibrated with full-scale accelerated load testing. Full-scale load testing of PICP was conducted on unsaturated and saturated (very weak) subgrade soil conditions. This methodology is referred to as mechanistic modeling validated with full-scale load testing, i.e., empirical observations and measurements. This represents one of the most up-to-date approaches in designing reliable and long-lasting pavements.

Having to accommodate saturated soil conditions under open-graded aggregate bases and often for a considerable length of time, PICP is conservatively designed to a maximum of 1 million lifetime 18,000 lb equivalent single axle loads or ESALs. The maximum loads this ESAL limit represents are those on most residential collector streets. Lifetime loads exceeding 1 million ESALs can be addressed with stabilized permeable base materials and/or three-dimensional geocells. While tried on a limited bases outside of North Carolina, these alternatives have not been evaluated with accelerated, full-scale load tests.

The primary reference for PICP structural design is ASCE 68-18 *Permeable Interlocking Concrete Pavement.* This is a national standard design guide and should be read by permeable pavement designers. In addition, ICPI provides Tech Spec technical bulletins on www.icpi.org and design software for PICP called Permeable Design Pro on www.permeabledesignpro.com. The program is available at no charge to PICP designers upon email request to ICPI. This software offers subbase design solutions using the validated ASCE 68-18 design method. The software also includes a design method based on the 1993

AASHTO *Guide for Design of Pavement Structures*. The AASHTO design method was originally developed for impervious asphalt and concrete streets and highways. The AASHTO design method has not been validated or calibrated with full-scale load testing on saturated subgrades common to permeable pavements. It is included as a user option in the Permeable Design Pro software program to compare design results to the ASCE 68-18 design method.

All permeable pavements including PICP, porous asphalt, and pervious concrete have yet to evolve for use on urban arterial routes and highway shoulders. That will require increased surface/base/subbase material stiffnesses as well as full-scale load testing to validate and calibrate models that form the basis for design methods.

For PICP, this Guide uses the design method in ASCE 68-18 in which key design variables are determined and then entered to the appropriate tables to arrive at a feasible subbase thickness design. A list of the variables in the ASCE 68-18 and Permeable Design Pro are helpful in characterizing required structural and hydrologic design inputs:

- Pavement structure and infiltration type
- Pavement layout and geometry
    - Contributing drainage area characteristics
- Soil subgrade
    - Classification and gradation
    - Resilient modulus, CBR, or R-value
    - Porosity
    - Slope
- Subbase aggregate layer
    - Pedestrian or vehicular application
    - Gradation
    - Porosity
- Base aggregate
    - Gradation
    - Porosity
- Pavement layer
    - Bedding layer gradation

    - Surface infiltration rate
- Precipitation
    - Geographic location, storm type, intensity, duration in hours and frequency (return period in years expressing storm probability)
    - Water volume from design rainstorm(s)
    - Underdrain design (drainage area per pipe, distance to pipe, pipe diameter, height of outflow above underdrains, pipe slope, roughness coefficients
    - Initial depth of water above the subgrade (from antecedent rain)
    - Maximum allowable depth of water in the subbase
    - Hydrologic subbase thickness required to drain and/or released within 72 hours
    - Number of days per year water stands in the subbase
- Structural Design
    - Subgrade permeability
    - Traffic category, growth, lanes, and lifetime ESALs
    - Subgrade properties.
    - Base properties and resulting thickness to support traffic

Design outputs include the following:

- Volume of inflow into the surface from adjacent surfaces (typically impervious)
- Water standing on the surface (if any)
- Depth of water in the subbase over time
- Underdrain pipe drainage and outflow hydrograph
- Subgrade infiltration
- Concrete paver and bedding material thickness
- Recommended base and subbase materials and thicknesses for managing the stormwater volume and to support anticipated traffic

SITE SELECTION CRITERIA

Section C.5, Permeable Pavements, of the DEQ *Stormwater Design Manual* provides recommendations on suitable sites. A comprehensive list of site selection criteria is found in ASCE 68-18. Another resource that includes a site location checklist is the ASCE book *Permeable Pavements* (ASCE 2015).

PICP SYSTEM OPTIONS

A description of the PICP pavement structure follows. PICP is surfaced with solid concrete paving units capable of being installed by hand or more rapidly with machines via groups or 'clusters' in their final laying pattern. Most unit paver designs are non-proprietary and can be purchased from manufacturers in North Carolina or in adjacent states. The paving units should meet the requirements of ASTM C936 Standard Specification for Solid Concrete Interlocking Paving Units. This standard requires a minimum average compressive strength of 8,000 psi as well as freeze-thaw durability requirements.

The paving units typically have spacers on their sides that create ¼ to ½ in. wide openings in the pavement surface. Some spacers interlock like gear teeth with those on neighboring paving units. This can contribute to lateral stability under concentrated braking and turning tires.

The openings (joints) between the paving units are filled with aggregate gradations that allow water to freely enter the surface. Depending on the joint widths formed when the pavers are installed, the aggregates placed between them are typically washed AASHTO No. 78M and/or 9M. Concrete paver suppliers can recommend gradations appropriate for their products.

When assembled into a pattern, the surface is 100% permeable. The permeable surface allows initial infiltration rates as high as 1,000 in./hr (Borst 2010) but typically between 300 and 800 in./hr. Infiltration rates generally decrease over time and routine surface cleaning is often required to prevent complete clogging. Herringbone patterns installed as in 45º or 90º orientation to the traffic direction are recommended. Pavements subject to vehicular traffic should use a sailor or string courses against a concrete curb shown in Figures 2 and 3.

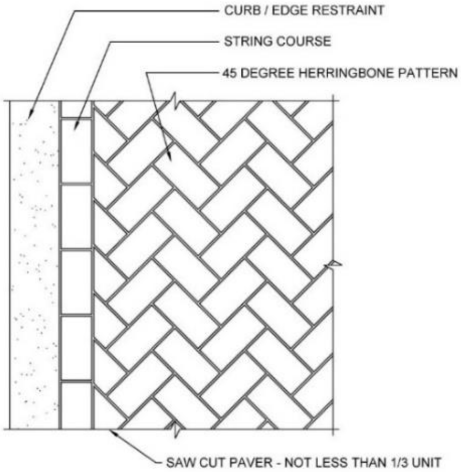


Figure 2. String/sailor course and a 90⁰ herringbone pattern.

Figure 3. String/sailor course and a 45⁰ herringbone pattern.

The paving units rest on a 2 in. thick bedding layer of washed 78M aggregate that also freely passes water. This layer rests on a 4 in. thick base or choke layer of washed AASHTO No. 57 open-graded aggregate and subbase of No. 4, also open-graded. AASHTO No. 2 or 3 can be used as well. The porosity of the base and subbase aggregates (i.e., 35% to 40%) enables water storage and infiltration into the soil subgrade. Perforated plastic underdrains in the base or subbase remove water that does not infiltrate within 72 hours as required by the DEQ. The concrete pavers, bedding and base layers are typically restrained by a concrete curb in vehicular applications. Curb-and-gutter designs typically rest on the subbase. Full-depth curbs are required between impervious and PICP pavements. Examples are illustrated in Figures 4 and 5 below.

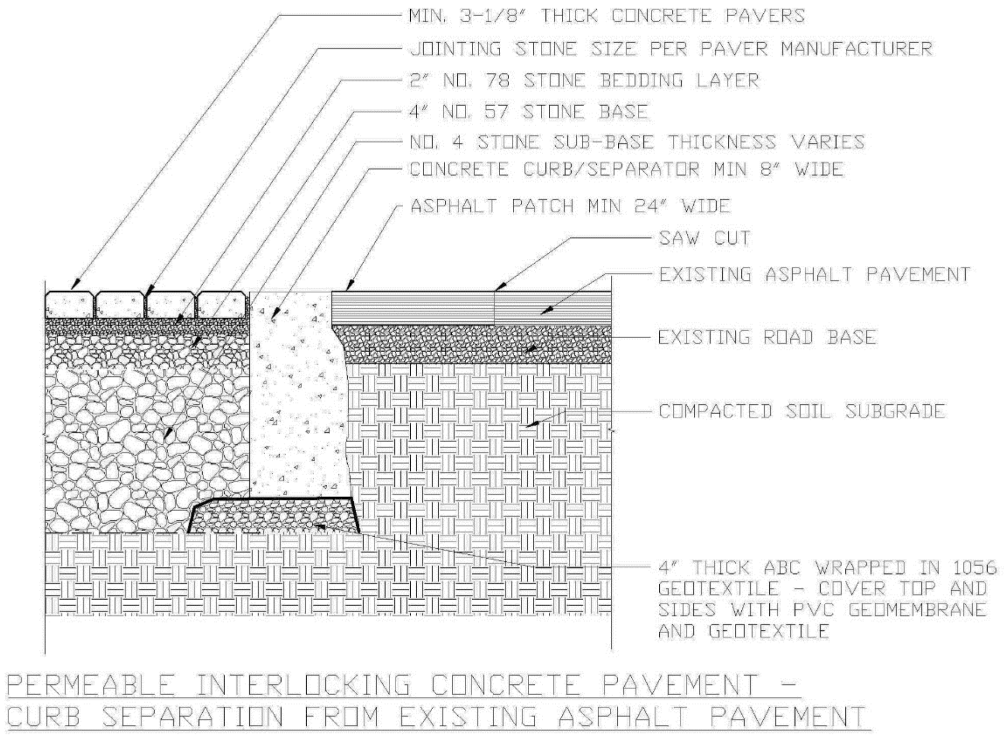


Figure 4. PICP junction with existing asphalt pavement.

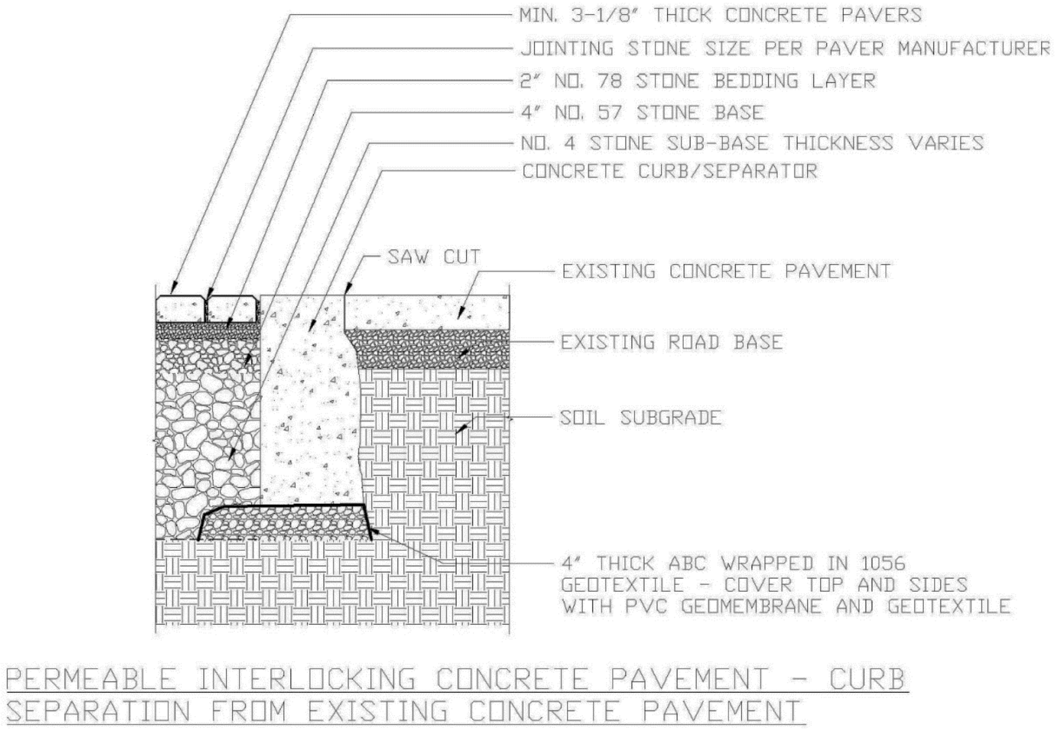


Figure 5. PICP junction with existing concrete pavement.

Geosynthetics such as geotextiles, geogrids, geocells, or geomembranes are applied depending on site conditions as well as hydrologic design objectives. Separation geotextiles are applied to the sides of the base/subbase to prevent entrance of fines (piping) from adjacent soils when curbs or impermeable liners do not cover the soil walls. Geotextiles are typically placed on the soil subgrade to prevent accumulation of fines under them.

Designs on sloped subgrades exceeding 3% often require the use of intermittently spaced check dams constructed with PVC impermeable liners. The dams contain the water within confined areas allowing it to infiltrate rather than flowing downhill. Should that area fill with water, it drains through an orifice (hole) in the impermeable liner or directly over the top of the membrane into the next area. An underdrain in the base layer can allow for outflow of water in overflow conditions. Figure 6 illustrates a cross section of the liners. Additional liners may be required on the sides of the PICP to prevent ingress into downslope areas.

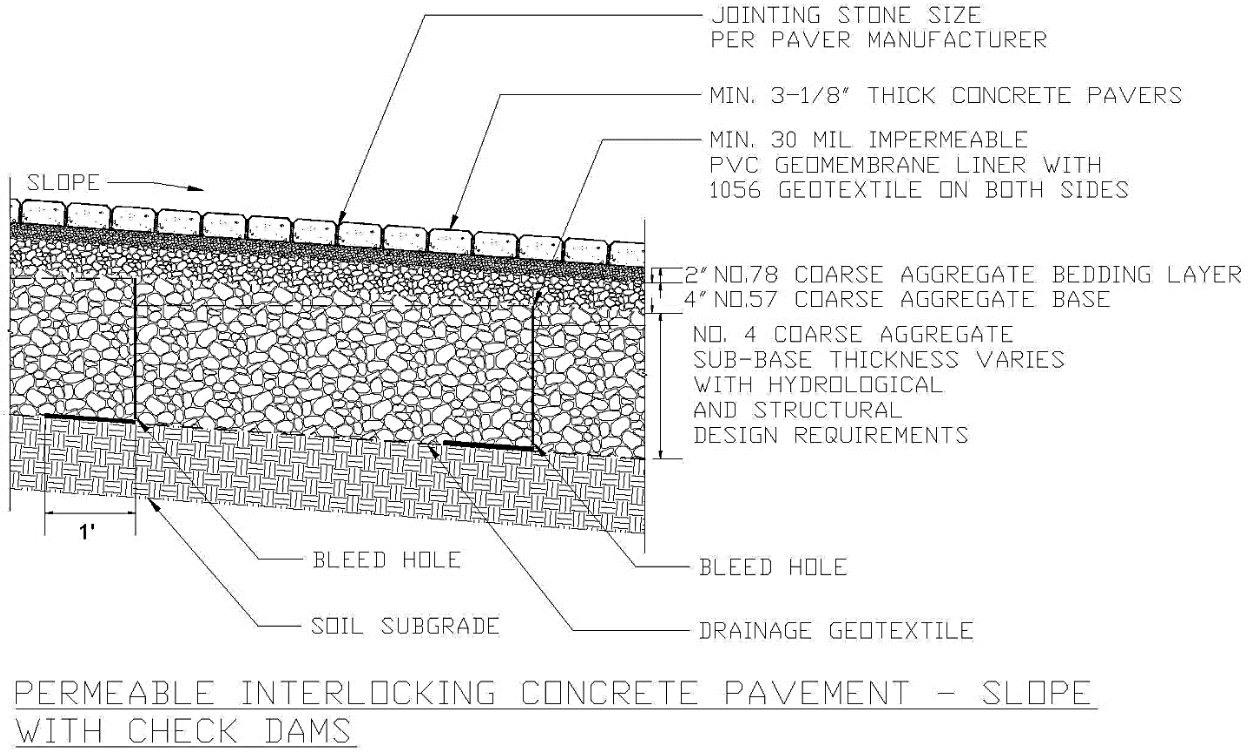


Figure 6. Cross section of impermeable liners as check dams to restrain downslope water flow and encourage infiltration into the soil subgrade.

Figures 7, 8 and 9 illustrate PICP system components whose selection depends on the intended hydrologic design (ASCE 2018). Figure 7, a full infiltration design, is typically used over high infiltration subgrade soils where a perforated underdrain is not required. Figure 8, a partial infiltration design, is typically used over low-infiltration silt and clay soils. This is the most common design. The perforated underdrain pipe shown can be raised or designed to rest on the subgrade with a raised outlet. Either location promotes as much subgrade infiltration as possible while discharging excess water during higher precipitation events.

Figure 9, no infiltration design, is used over expansive or fill soils, or next to buildings. The bottom and sides of the pavement structure are enclosed with a geomembrane (aka impermeable liner). An outlet pipe with flow restriction is used to regulate the outflow rate. During high precipitation events, water exceeding the flow limits of the outlet pipe is temporarily stored in the base and subbase aggregates until such time as it is released through the outlet pipe. This design approach also can be used for water harvesting or as a heat or cooling source for horizontal ground source heat pumps. Figure 10 includes a small diameter bleed pipe at the bottom of the subbase that eventually drains all water.

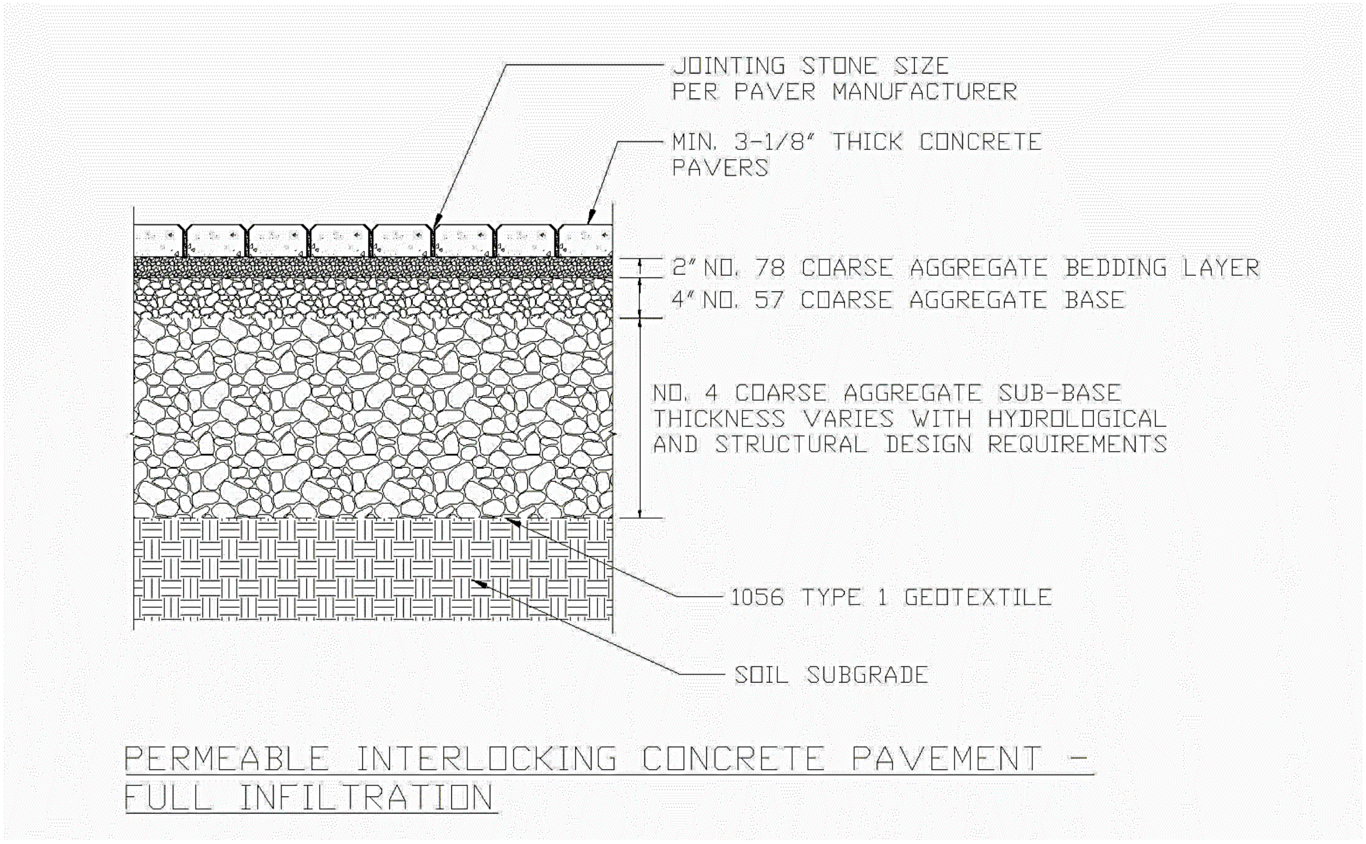


Figure 7. Full infiltration permeable interlocking pavement for vehicular traffic.

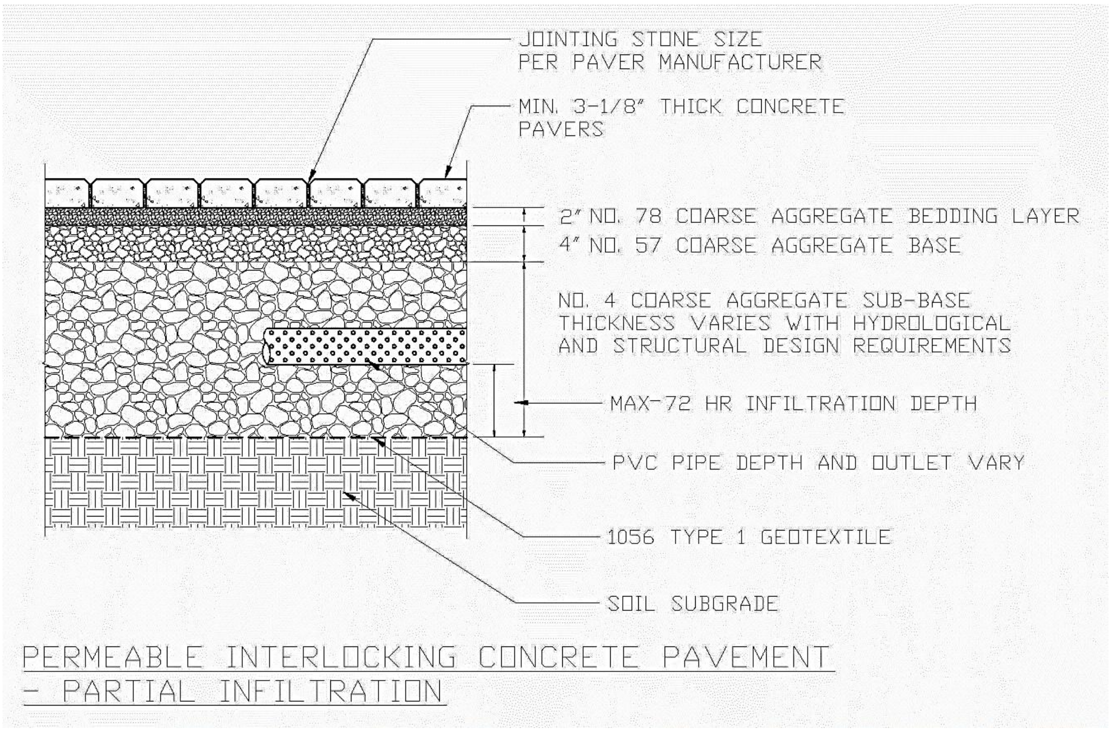


Figure 8. Partial infiltration permeable interlocking pavement for vehicular traffic for detention, infiltration, and release. Perforated underdrain(s) typically includes a raised outlet to a catch basin or watercourse.

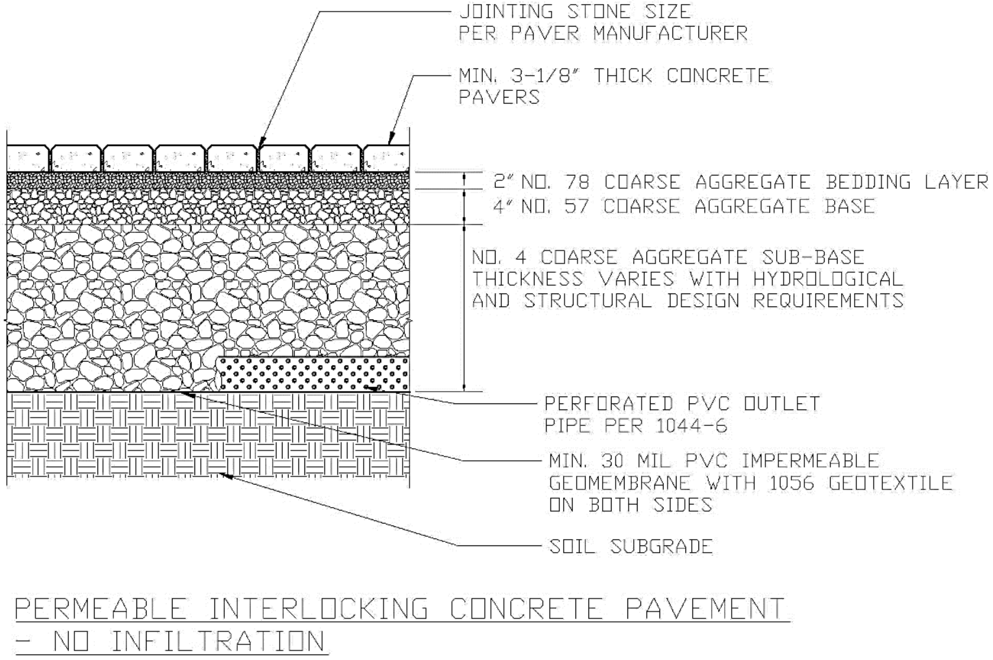
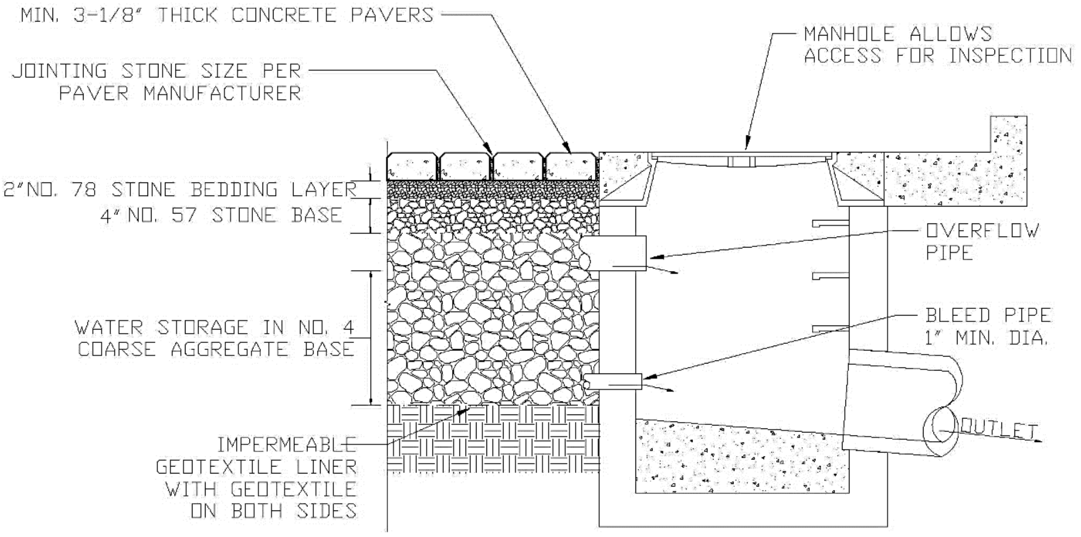


Figure 9. No infiltration permeable interlocking pavement for vehicular traffic. An impermeable liner on the bottom and sides prevents infiltration into the soil subgrade. Perforated underdrains typically include a raised outlet or elevated within the subbase or base.



PERMEABLE INTERLOCKING CONCRETE PAVEMENT
- NO INFILTRATION NEXT TO CATCH BASIN

Figure 10. Some no-infiltration designs may include small diameter bleed holes or pipes exiting near the bottom of the subbase as shown above to slowly drain water. Other cases may have a bleed pipe penetrating an impermeable liner. Hydrologic design follows detention pond procedures.

Plastic geocells can be used to confine on the base and/or subbase aggregate to provide additional stiffness under vehicular traffic. Geocells provide confinement of the aggregate and thereby increase its stiffness. They typically are manufactured to confine 3, 4, 6 or 8 inch heights to confine these compacted aggregate layer thicknesses. Geocell manufacturers should be consulted regarding thickness design and resulting contribution to structural capacity. Geocells are perforated which allows lateral flow of water within open-graded aggregate when required. Figure 11 illustrates an example applying geocells in a 4 inch thick aggregate base layer. This layer can be thicker when confined with geocells.

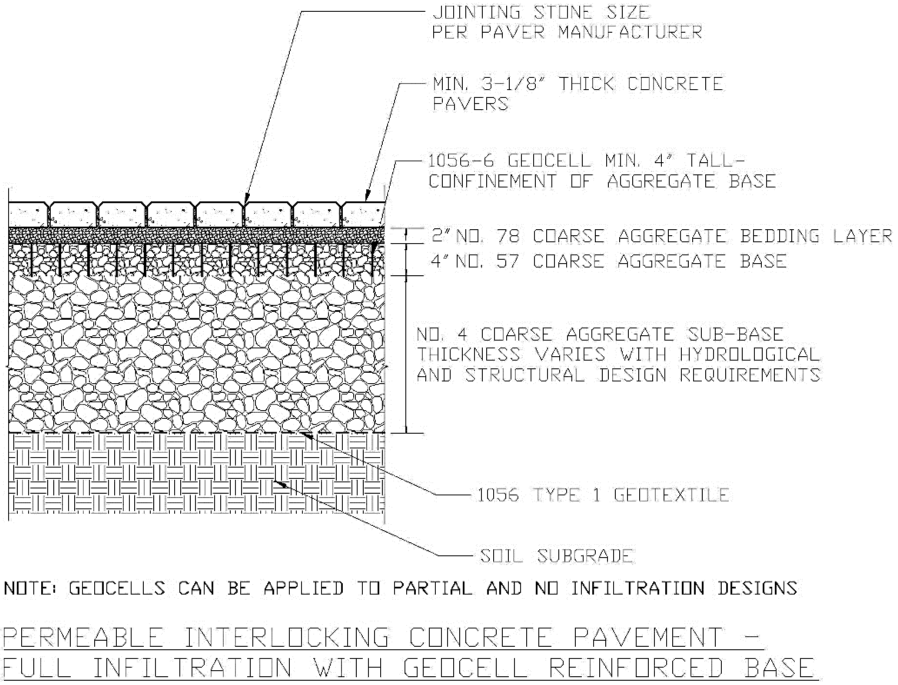


Figure 11. Plastic geocells are shown as providing confinement of the aggregate base layer. This increases the layer stiffness. Geocells should be considered for street applications.

PICP DESIGN

For structural design and hydrologic design inputs, interactive factors that require consideration are illustrated in Figure 12. The structural and hydrologic design approaches require finding the subbase thickness of stone subbase for structural support of anticipated 18,000 lb equivalent single axle loads (ESALs) as well as the thickness required for storage (reservoir) of rainfall. As previously noted, once structural and hydrologic subbase thickness solutions are separately determined, the designer selects the thicker of the two subbases for the design. This is noted at the bottom of Figure 12.

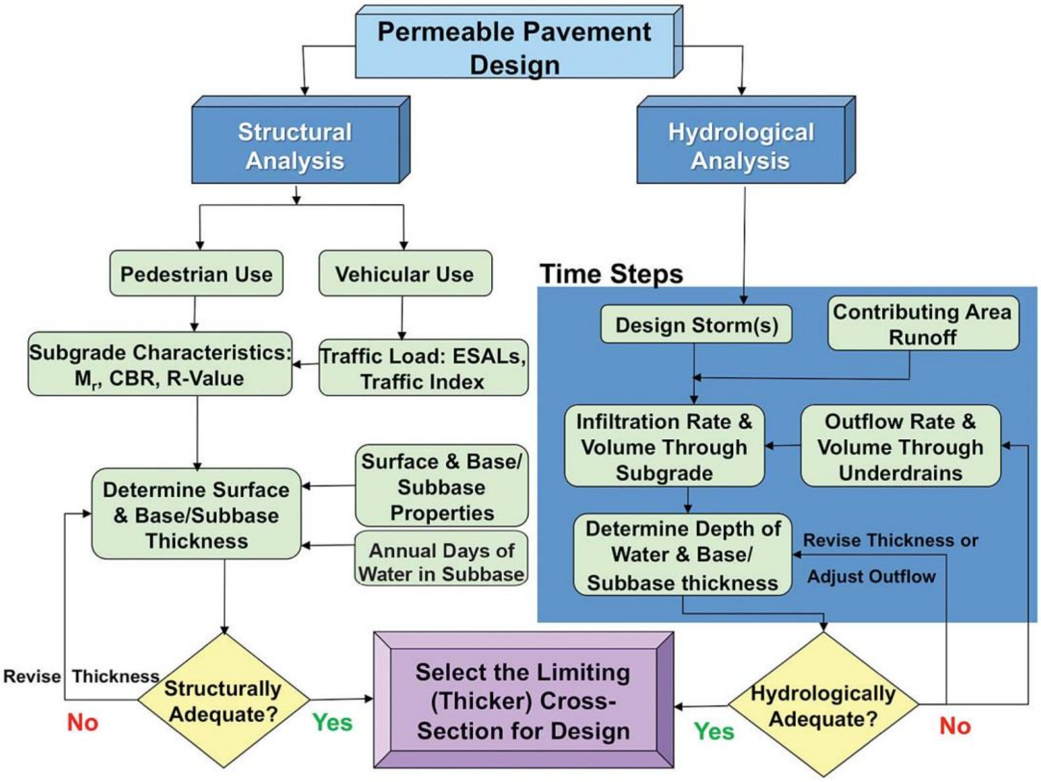


Figure 12. Structural and hydrologic design flow chart for permeable interlocking pavements (Smith 2017).

The hydrologic subbase thickness is determined using the design methods in the DEQ *Stormwater Design Manual.* More sophisticated approaches model a range of rainfall events, infiltration, and outflows as a water balance over an extended period often as long as a year. When storm patterns, soil infiltration, and outflows are modeled continuously over a year, this approach provides the most efficient hydrologic designs with storage and infiltration up to 72 hours and release via perforated pipes as needed.

Runoff into PICP from impervious contributing areas (aka contributing drainage areas or CDA), typically are adjacent impervious pavements and/or roofs with downspouts exiting onto the pavement. The ratio of the CDA to the receiving PICP should be 1:1. The CDA can be increased if runoff is from roofs filters sediment and debris in downspouts prior to entering the PICP.

DEVELOPMENT OF INPUT VALUES

Pedestrian-only areas include a pavement structure with 3⅛ in. thick concrete pavers with joints filled with permeable aggregates, 2 in. of AASHTO No. 78M bedding, a minimum 6 in.

of AASHTO No. 57 or similar open-graded aggregate base. A subbase consisting of No. 4 aggregate is typically not required.

For vehicular areas, the pavement structure includes 3⅛ in. thick concrete pavers, 2 in. of No. 78M stone bedding, 4 in. thick No. 57 choke layer over a subbase of No. 4 stone. The structural design method determines the thickness of the subbase given lifetime design ESALs and the saturated resilient modulus or CBR of the soil subgrade. Given the expense of resilient modulus tests, the 96-hour soaked CBR per AASHTO T 193 may be used as a surrogate. The relationship among resilient modulus, M_R and CBR: M_R in psi $=2{,}555 \times (CBR)^{0.64}$

Surface, base, and subbase properties and reactions to loads as design input values were established with mechanistic modeling validated using full-scale accelerated load testing of PICP. Load testing was done on unsaturated and very weak saturated, compacted subgrade by the University of California Pavement Research Center (UCPRC) (Li 2014). This report notes, “Rut development rate as a function of the shear stress to shear strength to ratios at the top of the subbase and the top of the subgrade was used as the basis for the design approach….The alternative approach of using a vertical strain criterion was considered inappropriate for permeable pavements, given that this is typically used where the shear stresses relative to the shear strains are relatively low, which typically results in low overall rutting.” The research provided a validated design method and easy-to-use tables to determine the subbase thickness based on ESALs, soil strength, and the number of days per year the subgrade is saturated. This is explained below.

As a critical design input, the soil infiltration rate must be established as this is used in the structural design method as well as for hydrologic design. The reader should note that while slightly different, the terms “soil infiltration” and “soil permeability” are used interchangeably in this Guide.

Assumed soil infiltration rates based on soil classifications (e.g., NRCS, ASTM, or AASHTO) provide an estimate for initial computations that can help approximate the pavement structure. These estimates should <u>not</u> be used for the final design. Estimated infiltration rates vary with the soil classification system. For example, stormwater engineers often use the Natural Resource Conservation Service Hydrologic Soil Groups (NRCS 2003) or HSGs to characterize saturated hydraulic conductivity. This classification divides soils into four declining permeability groups labeled A through D. It was originally developed to better characterize soil maps. HSGs are used in the NRCS Curve Number method of calculating runoff from various land uses. Unfortunately, HSGs do not characterize soil permeability in a compacted state which may be required in some PICP applications. Assessing the structural capacity of uncompacted subgrades is covered later.

In contrast, the permeability of 15 soil types defined in ASTM D2487, i.e., the Unified Soil Classification System, were published by FHWA in Highway Subdrainage Design (Moulton 1980). These provide coefficients of permeability, k, originally developed for earthen dam construction, i.e., a highly compacted condition. The k symbol should not be confused with k, modulus of subgrade reaction.

The divergence between these two soil classification systems, NRCS HSGs used by stormwater agencies and USCS often used by transportation agencies, underscores the need to measure soil permeability (infiltration) in the field in a non-compacted or compacted state per the design engineer’s recommendations. This is especially important considering that soil reports may provide HSGs or USCS soil classifications which can include or suggest approximate (unmeasured) permeabilities. This leads to inaccuracies in estimating the infiltration rate at the surface of the soil subgrade. This underscores the need for in-situ soil infiltration testing.

While there are several methods for measuring in-situ soil infiltration described in ASTM D5126 *Standard Guide for Comparison of Field Methods for Determining Hydraulic Conductivity in Vadose Zone*, ASTM D3385 *Standard Test Method for Infiltration Rate of Soils in Field Using Double-Ring Infiltrometer* is commonly used. The device is shown in Figure 13 and is recommended by the NCDEQ. Single-ring test methods (e.g., permeameters) can be used, and results may include adjustments to align more closely with double-ring results. Test holes are dug on the site to the approximate depth of the subbase bottom. Holes or pits are dug, and the subgrade tested during the design stage of the project. If more than one test is required, the average soil infiltration rate is used per ASTM D3385. The average infiltration rate is then divided by 2 as safety factor for hydraulic and structural design.

Figure 13. Double-ring infiltrometer test per ASTM D3385.

If the soil subgrade requires compaction for structural support, augured soil samples from the project site should be tested in the laboratory for density at optimum moisture content. Then a test pit or pits should be dug on the project site to the approximate depth of the bottom of the subbase. The exposed soil subgrade is compacted, and density and moisture content measured. Next, a soil infiltration test is conducted in saturated conditions per ASTM D3385. The number of infiltration tests is recommended in Section A2 Soils, NC DEQ *Stormwater Design Guide*: areas <2,000 sf require only one infiltration test; areas from 2,000 to 20,000 sf require at least two infiltration tests; and areas >20,000 sf require 1 infiltration test every 10,000 sf.

In addition, at least a 2 ft separation is recommended between the top of the subgrade and the seasonal-high water table. This separation does not preclude PICP applications in coastal areas with high water tables as saturated sandy soils can provide sufficient structural support under limited vehicular traffic and subgrade drainage as illustrated in Figure 14.

Figure 14. PICP in Ocean Isle, NC

For structural design, the average soil infiltration rate in inches per hour is multiplied by 24 hours. This rate is divided in half i.e., multiplied by 0.5 as a safety factor. The resulting depth in inches infiltrated in 24 hours is compared to the number of days per year the 24-hour rainfall depth equals or exceeds that amount. Historic daily rainfall depths issued by month for a given year are available from weather sources such as NOAA. Daily rainfall depth data should be used from weather stations as close to the project site as possible.

To find rainfall data, go to www.weather.gov: Click ‘Past Weather’ menu on the home page, click North Carolina on the US map, select the area and nearest city from those listed. Under ‘Product’ click ‘Calendar day summaries.’ Under ‘Options’ fill in the year range, then under Variable select ‘Precipitation’ and under Summary select ‘Daily Maximum’ from the pull-down menus. Then go to ‘View’ and click ‘Go’ to view and print tables indicating the total maximum daily rainfall. Then add the total number of days per year daily rainfall exceeds the infiltration rate of the soil subgrade (infiltration rate safety factor included). If available, maximum daily precipitation data can be used from rain gauges closer to the project site than the nearest city provided by weather.gov.

The total number days that the rainfall depth exceeds the 24-hour infiltration depth of the subgrade varies from year to year. Therefore, depths should be selected from the most recent three years and the average value applied to the tables below for the number of days per year water stands in the subbase.

Keep in mind that run-on depth from any CDA will increase the number of days per year the total depth of the water accumulated in the subbase over 24 hours exceeds the 24-hour rainfall depth coming from the sky and falling directly on the PICP. This run-on depth of water will need to be added to the number of days water is standing in the subbase after 24 hours due to the low soil infiltration rate. The total days water exceeds the rainfall depth per se will likely increase the required subbase depth. Also, any days with the 24-hour rainfall depth twice as great as the 24-hour infiltration rate or greater, must be counted as two or more days water is standing in the subbase.

The subgrade 96-hour soaked CBR is provided from laboratory tests. The subbase thickness design tables are based on compacted soil subgrades. If compaction is not desired to enable increased infiltration, using a 96-hour CBR for soil at a density characterizing a more natural site conditions will be *lower* than that for compacted soil. The lower soaked CBR should be used to select a lower soil CBR on the design tables. This means a thicker subbase will be required over uncompacted soils.

Find the closest value for the number of days per year water stands in the subbase in Table 1. The dry (unsaturated) soil characterizations are provided for comparison only. Then find the closest CBR value, i.e., equal to or less than laboratory test results. CBR values higher than those provided on the Table should default to the highest CBR value indicated on the table. If the soil is uncompacted, use a reduced CBR based on a lower soil density than in a compacted state typical to soils under road pavements.

Table 1. Permeable Interlocking Pavement Structural Design Table (Li 2014). Continued on the next page.

Number of Days per Year Water Stands in Subbase		0				≤10				11 - 30				31 - 50			
Subgrade Resilient Modulus, ksi (CBR)	Dry	5.8	8.7	11.6	14.5	5.8	8.7	11.6	14.5	5.8	8.7	11.6	14.5	5.8	8.7	11.6	14.5
	Wet	3.5 (1.6)	5.2 (3)	6.7 (4.8)	8.7 (6.8)	3.5 (1.6)	5.2 (3)	6.7 (4.8)	8.7 (6.8)	3.5 (1.6)	5.2 (3)	6.7 (4.8)	8.7 (6.8)	3.5 (1.6)	5.2 (3)	6.7 (4.8)	8.7 (6.8)
Lifetime ESALs (Traffic Index)		Minimum Subbase Thickness in inches for ASTM No. 2, 3 or 4 for 1 in. Allowable Rut Depth (All subbases are under 4 in. ASTM No. 57 base, under 2 in. ASTM No. 8 bedding layer under 3 1/8 in. thick concrete pavers.)															
50,000 (6.3)		6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	7.0	6.0	6.0	6.0
100,000 (6.8)		6.0	6.0	6.0	6.0	8.5	6.0	6.0	6.0	10.5	6.0	6.0	6.0	11.5	7.0	6.0	6.0
200,000 (7.4)		9.0	6.0	6.0	6.0	12.5	8.5	6.0	6.0	14.5	10.0	6.5	6.0	16.0	11.5	7.5	6.0
300,000 (7.8)		11.5	7.0	6.0	6.0	15.0	10.5	7.0	6.0	17.0	12.5	8.5	6.0	18.0	13.5	9.5	6.5
400,000 (8.1)		13.0	9.0	6.0	6.0	17.0	12.0	8.5	6.0	19.0	14.0	10.0	7.0	20.0	15.0	11.0	8.0
500,000 (8.3)		14.5	10.0	6.5	6.0	18.0	13.5	9.5	6.5	20.0	15.0	11.0	8.0	21.0	16.5	12.0	9.0
600,000 (8.5)		15.5	11.0	7.5	6.0	19.0	14.5	10.5	7.0	21.0	16.0	12.0	9.0	22.0	17.5	13.0	10.0
700,000 (8.6)		16.5	12.0	8.0	6.0	20.0	15.0	11.0	8.0	22.0	17.0	13.0	10.0	23.0	18.0	14.0	11.0
800,000 (8.8)		17.0	12.5	9.0	6.0	20.5	16.0	12.0	8.5	22.5	17.5	13.5	10.5	24.0	19.0	14.5	11.5
900,000 (8.9)		17.5	13.0	9.5	6.0	21.0	16.5	12.5	9.0	23.5	18.0	14.0	11.0	24.5	19.5	15.0	12.0
1,000,000 (9.0)		18.0	13.5	10.0	6.5	22.0	17.0	13.0	9.5	24.0	19.0	14.5	11.5	25.0	20.0	15.5	12.5

Number of Days per Year Water Stands in Subbase		51 - 70				71 - 90				91 - 110				111 - 130			
Subgrade Resilient Modulus, ksi (CBR)	Dry	5.8	8.7	11.6	14.5	5.8	8.7	11.6	14.5	5.8	8.7	11.6	14.5	5.8	8.7	11.6	14.5
	Wet	3.5 (1.6)	5.2 (3)	6.7 (4.8)	8.7 (6.8)	3.5 (1.6)	5.2 (3)	6.7 (4.8)	8.7 (6.8)	3.5 (1.6)	5.2 (3)	6.7 (4.8)	8.7 (6.8)	3.5 (1.6)	5.2 (3)	6.7 (4.8)	8.7 (6.8)
Lifetime ESALs (Traffic Index)		Minimum Subbase Thickness in inches ASTM No. 2, 3 or 4 for 1 in. Allowable Rut Depth (All subbases are under 4 in. ASTM No. 57 base, under 2 in. ASTM No. 8 bedding layer under 3 1/8 in. concrete pavers.)															
50,000 (6.3)		8.0	6.0	6.0	6.0	8.5	6.0	6.0	6.0	9.0	6.0	6.0	6.0	9.5	6.0	6.0	6.0
100,000 (6.8)		12.0	8.0	6.0	6.0	13.0	8.5	6.0	6.0	13.0	9.0	6.0	6.0	14.0	9.5	6.0	6.0
200,000 (7.4)		16.5	12.0	8.0	6.0	17.0	13.0	8.5	6.0	17.5	13.0	9.0	6.0	18.0	13.5	9.5	6.5
300,000 (7.8)		18.5	14.0	10.0	7.0	20.0	15.0	11.0	8.0	20.0	15.5	11.0	8.5	20.5	15.5	11.5	8.5
400,000 (8.1)		20.5	15.5	11.5	8.5	21.5	16.5	12.5	9.5	21.5	17.0	13.0	9.5	22.0	17.5	13.0	10.0
500,000 (8.3)		21.5	17.0	13.0	9.5	23.0	18.0	13.5	10.5	23.0	18.0	14.0	10.5	23.5	18.5	14.0	11.0
600,000 (8.5)		23.0	18.0	14.0	10.5	24.0	19.0	14.5	11.0	24.0	19.0	15.0	11.5	24.5	19.5	15.0	12.0
700,000 (8.6)		23.5	18.5	14.5	11.0	25.0	19.5	15.0	12.0	25.0	20.0	15.5	12.0	25.5	20.5	16.0	12.5
800,000 (8.8)		24.5	19.5	15.0	12.0	25.5	20.0	16.0	12.5	26.0	20.5	16.0	13.0	26.0	21.0	16.5	13.5
900,000 (8.9)		25.0	20.0	15.5	12.5	26.0	21.0	16.5	13.0	26.5	21.0	16.5	13.5	27.0	21.5	17.0	14.0
1,000,000 (9.0)		25.5	20.5	16.0	13.0	27.0	21.5	17.0	13.5	27.0	21.5	17.0	14.0	27.5	22.0	17.5	14.5

This design method and subbase thickness tables illustrated above are in ASCE 68-18 (ASCE 2018) and were adopted by Caltrans (Caltrans 2016). *Note*: the subbase thicknesses apply to No. 3 and 4 gradations as well as to No. 2 indicated on Table 1.

The AASHTO 1993 *Guide* for flexible pavement design may be used, but the (impermeable) pavement design method may result in thicker subbases than needed in semi-arid or high-infiltration (sandy) soils than would those derived from using the UCPRC design method. If using the AASHTO 1993 *Guide*, special consideration should be given to layer coefficients for open-graded aggregate base/subbases. While not specifically defined in research literature or in any AASHTO publication, layer coefficients are lower (e.g., by 30% to 50%) than those typically used for dense-graded aggregate bases and subbases. For the PICP surface layer, i.e., 3⅛ in. thick pavers with joints filled all placed on 2 in. of No. 78M bedding, this layer is assumed to have an AASHTO layer coefficient of 0.3 per in. or a 1.54 structural number.

Site-Related Design Inputs

Site-related variables include traffic and subgrade support conditions. These values are project specific and cannot be altered significantly by the pavement designer. The exception to this would be removal and replacement of the existing subgrade soil, chemical stabilization of the soil to a substantial depth or mechanical stabilization. Stabilization is rare in permeable pavements because such treatments typically render a practically impermeable subgrade soil.

Traffic Characterization

Besides assessing the soil bearing capacity, traffic characterization is one of the most critical inputs in any pavement design. Reasonably accurate traffic counts, in terms of the number of vehicles (particularly trucks), vehicle weights, number of axles and so on, are necessary for all projects. This baseline value is increased by incorporating a traffic growth factor for the specified design period. Note that the ESALs on Table 1 are lifetime which includes annual growth percentages.

ESALs consider the number and weights of heavy trucks and are relatively unaffected by axle loads from cars and light truck traffic. Due to the expected number of ESALs being low (i.e., 1 million) compared to that sustained on urban thoroughfares or on highways (many millions), the estimated lifetime ESALs are used rather than axle load spectra. Roads within a particular traffic category, i.e., residential, have approximately the same relative proportion of vehicles. Therefore, a traffic count to determine the number of daily trucks converted to ESALs can provide a reasonable traffic input. Designers should focus on the number of trucks, i.e., equal to or greater than FHWA Class 4.

Number of Lanes

The number of lanes refers to all through travel lanes in both directions. In cases where there are 4 design lanes, multiplying the ADTT or ESALs in that direction by 0.90 for 4 lanes will provide a reasonable estimate of the design lane traffic to be used in the design tables.

Directional Distribution

The directional distribution refers to the percentage of traffic travelling in each direction. A directional distribution of 50% assumes an equal number of vehicles travelling in each direction.

Traffic Growth Factor

The traffic growth factor anticipates the annual growth of traffic over the design life of the pavement. This value can vary depending on the traffic category and surrounding economic conditions.

Subgrade Characterization

The soil conditions on which the pavement is to be constructed should be thoroughly evaluated in terms of uniformity, strength, and load bearing characteristics especially when saturated. The soil characteristics may be assessed by material sampling from the project site and laboratory testing. The time and expenditure devoted to soil characterization is based on the scale and importance of the project. Residential streets should rely on laboratory testing to determine the 96-hour soaked CBR since the subgrade will be saturated for extended periods.

Design-Related Variables

Design-related variables include inputs selected by the pavement designer to meet the requirements of a specific project. Decisions regarding these variables have a significant impact on pavement performance, constructability, long-term maintenance and rehabilitation requirements, initial and long-term costs, and related issues.

Design Life

The design life is characterized by ESALS and can be converted to the years required to reach this level of loads and reach a specified level of pavement distress (rutting). The design life is an important parameter since the accumulated damage in the pavement is a function of the initial traffic volume and the specified growth rate per year. Note that the design life does not equate to failure of the pavement, it relates only to the specified level of distress, i.e., rutting. Table 1 was developed for rutting at 1 inch depth. In some applications higher rut depths can be tolerated as long as the surface is infiltrating.

Failure Criteria

There are two realms of failure with PICP, structural and hydrologic. For structural failure (i.e., not meeting the intended service), the percentage of rut depths exceeding 1 in. (at the end of the design life) is a measure of pavement distress due to fatigue damage in the base, subbase and subgrade. This generally occurs when greater than 10% of the pavement has rut depths exceeding 1 in. These are typically in the wheel paths and/or at transitions to other (impervious) pavements.

Hydrologic failure means the surface is not infiltrating or draining. This is generally defined as ponding on the surface such that the water runs off thereby defeating the purpose of the permeable pavement. While ponding is common on older permeable pavements during and immediately after rainstorms, the water from such ponds often moves to an adjacent spot on the pavement where infiltration into the surface occurs. Generally, if there is more than a third of the pavement holding water in ponds across its surface for at least 15 minutes after a rainstorm, the pavement should be cleaned to restore surface infiltration. Cleaning recommendations are found in Section C5 of the DEQ *Stormwater Design Manual*. A lack subsurface drainage is often due to damaged or sediment clogged drainpipes.

Reliability

Design reliability is a measure of the factor of safety against premature failure. Reliability has a significant effect on the design thickness, particularly at very high levels (greater than 95%). Reliability considers the traffic volume and speed, availability of alternate routes, user costs related to roadway maintenance and rehabilitation, as well as alternative means to manage stormwater. The reliability level of 80% used in the Guide for PICP is typical for the residential and collector roadways.

DESIGN DEVELOPMENT USING THE GUIDE

Methodology

For any given project, there are several permeable pavement designs that will meet the specified performance criteria. Selection of realistic and appropriate input values establishes a baseline from which to generate the designs. Designing the most economical pavement section requires sound engineering judgment via sensitivity analyses to gain a thorough understanding of the inter-relationship among design variables.

This Guide presents a stepwise process to generate feasible structural designs after hydrologic design and the required base thickness for managing stormwater has been computed. The site and soil subgrade characteristics determine whether a full, partial, or no infiltration system is selected to manage stormwater. Once the appropriate system and subbase thickness have been determined using Section C5 of the DEQ *Stormwater Design Manual*, the following steps should be taken for all structural designs:

1. Determine the lifetime ESALs that most closely fit the numerical list in the left-hand column presented in Table 1.

2. Determine the saturated subgrade strength by sampling the subgrade at a depth approximating the final pavement system and conduct testing to determine the 96-hour soaked CBR.

3. Conduct subgrade infiltration tests to determine the hydrologic design. This information will be used on structural design. Determine whether such tests were conducted on uncompacted or compacted soil subgrades. Verify compaction with a report or reports. Compacted subgrades should be considered for street traffic subject to trucks over 10,000 lbs gross vehicle weight. Repeated subgrade infiltration tests are only required if infiltration testing was conducted on an uncompacted subgrade and compacting the soil is deemed necessary by the design Engineer for structural stability under the anticipated traffic loads.
4. For compacted subgrades, sample the soil subgrade on the site with an auger at the approximate depth at the top of the excavated elevation. Conduct a laboratory Proctor test (or tests) to determine the Proctor density at 95% compaction and the optimum moisture content. The number of samples should follow the guidelines for infiltration tests.
5. Dig the recommended number of test holes per Section A2 Soils in the DEQ *Stormwater Design Guide*. Establish a similar level of density attained in the laboratory to that in test holes on the project site. Test the compacted soil using a nuclear density gauge. Conduct infiltration tests using ASTM D3385 on the compacted subgrade. Be sure the subgrade is thoroughly saturated prior to measuring the infiltration rate.
6. If there is more than one infiltration test conducted, use the average of the test values in inches per hour and multiply by 24 hours to determine the daily infiltration depth in inches. Divide that depth in half.
7. Use the halved (reduced) infiltration rate to determine the number of days per year rainfall equals or exceeds that depth. As previously noted, this data is available on www.weather.gov. Look up data for at least the three most recent years, typically on tables for each month called ‘Calendar Day Summaries,’ and add the number of days

per year rainfall depth exceeds the 24-hour infiltration rate. Then average the number of days per year for at least three years. The average rainfall depth and greater represents the number of days per year water will be standing in the subbase and on the soil subgrade, i.e., a saturated condition.

This bears repeating: Run-on depth from any CDA will <u>*increase*</u> *the number of days per year the total depth of the water accumulated in the subbase over 24 hours exceeds the 24-hour rainfall depth from the sky and falling directly on the PICP. This run-on depth of water will need to be added to the number of days water is standing in the subbase after 24 hours*. The total days water exceeds the rainfall depth per se will likely increase the required subbase depth. Also, any days with the 24-hour rainfall depth twice as great as the 24-hour infiltration rate or greater, must be counted as two or more days water is standing in the subbase.

8. Find the number of days per year water remains in the base on Table 1.
9. Under that column find the CBR value that is closest to or lower than the laboratory 96-hour soaked CBR.
10. Move down from that CBR column and stop at the row that represents the expected lifetime ESALs. The value on the table is the minimum subbase thickness required for structural design. Round up that thickness to the nearest even number. As a practical construction consideration, odd whole numbers for subbase thicknesses should be rounded up to the next highest even number.
11. Compare that subbase thickness to that for hydrologic design and use the thicker of the two subbases for the final pavement design.
12. Edge supports are typically concrete curbs, either as cast-in-place or precast concrete. These typically are placed on the compacted subbase to contain the pavers, bedding, and base layers. This dimension is 9 inches so that the gutter thickness contains these layers.
13. Exposed soil walls must be covered with geotextile. Adjacent bases for impermeable pavements must be covered with an impermeable liner to prevent ingress of water.

This process results in a design that meets the hydrologic and structural requirements for the project. *Note*: Higher soil strengths with a low number of days per year of water standing in the subbase result in thinner subbases than soils with opposite characteristics. The maximum subbase thickness is 27 in.

Pavement Design Example 1

The following example is based on reconstruction of a two-lane residential street and illustrates the key points involved in the pavement design process using the Guide.

Site Variables.

A visual survey of the existing residential street of 15,000 sf in Wilson, NC shows that the pavement has performed well but is distressed sufficiently to warrant reconstruction. Due to its age and low-lying position in the landscape, the street has been subject to local flooding due to the drainage system being under capacity with almost flat terrain and receiving runoff from adjacent impermeable pavement. It will be less expensive to replace the worn impervious pavement with PICP than to upsize the storm drainage pipes and catch basins. The pavement replacement will include other work on water and sanitary sewer lines which provides economic (as well as environmental) justification to replace the entire street with PICP. The existing distressed impermeable pavement materials will be removed and recycled. Hydrologic modeling has determined that PICP will relieve backed up storm drainage pipes that deposit water on the street causing local flooding. The soil subgrade is silty sand which offers an opportunity for infiltrating some of the stormwater. There is no run-on entering the PICP from adjacent impervious pavements or other surfaces.

Traffic

A recent traffic count indicates that the average two-way daily truck traffic (AADT) is 100 trucks with three or more axles. The expected growth rate is 0% annually. This was confirmed by repeated traffic monitoring. Also, the road is an older, established neighborhood that will not receive increasing traffic from adjacent neighborhoods. Not counting cars, the total ESALs on the road from trucks over 20 years was estimated at 720,000 ESALs. Traffic in both directions was approximately the same. Therefore, the anticipated ESAL is 360,000 in each direction. This is rounded to 400,000 per lane to account for cars.

Subgrade Soil Properties

The existing pavement section was cored in two locations and material samples of the subgrade soil were extracted and tested for their classification: sandy soil with some silt content. The depth to the seasonal high water table was identified at 7 feet. A cursory examination showed the subgrade to be a predominantly sandy soil with moderate silt content. A 96-hour soaked CBR test was conducted indicating 5% CBR. The soil infiltration rate measured with a double-ring infiltrometer indicated an average of 0.1 in./hr. A safety factor is applied to reduce this to 0.05 in./hr. Therefore, 0.05 X 24 hours = 1.2 in. www.weather.gov indicates the following on the number of days per year the 24-hour rainfall depth ≥ 1.2 in. for the past three years:

2019 = 8 days over 1.2 inches rainfall = 13.97 inches/1.2 = 12 days water stands in the subbase for more than 24 hours

2020 = 13 days over 1.2 inches rainfall = 27.11 inches/1.2 = 23 days water stands in the subbase for more than 24 hours

2021 = 7 days over 1.2 inches rainfall = 13.37 inches/1.2 = 11 days water stands in the subbase

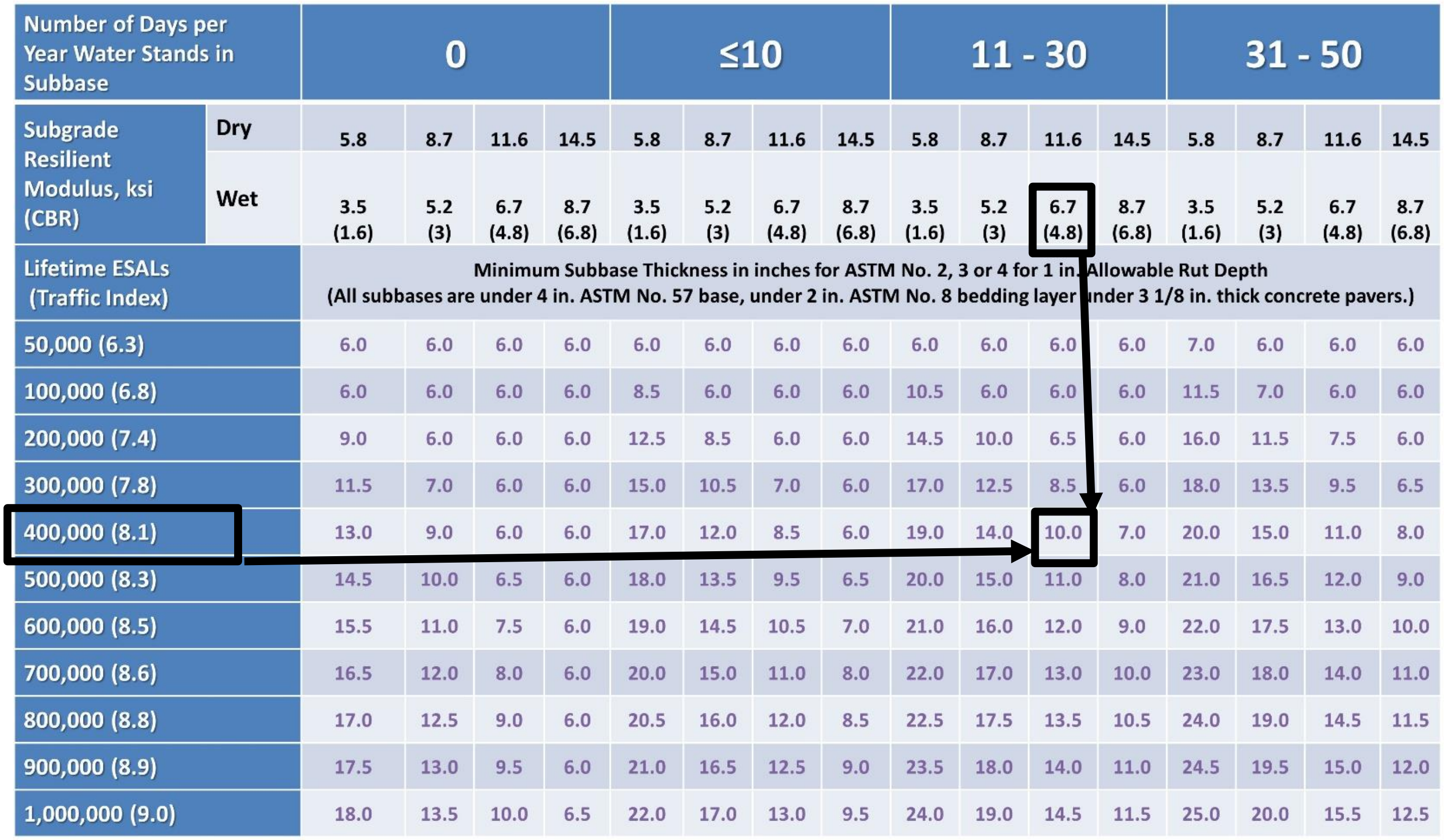
Use the average = 12 + 23 + 11 = 46/3 = 15.3 days

Table 2 below (replicating Table 1) shows the intersection of the number of days per year, 5% the CBR, and the ESALs shown below converge on 10.0 in. for the subbase. Keep in mind that resting on the subbase, there is a 4 in. thick base of No. 57 stone. Above that, there is 2 in. of No. 78M bedding and the 3⅛ in. (80 mm) thick concrete pavers. While 4 in. of the No. 57 base can store about 1.5 in. of water, that is not considered in the hydrologic design. It is a safety reservoir to hold additional water. Therefore, the entire pavement cross section thickness is 19 inches.

Edge Support

The existing street has a curb and gutter in need of replacement. For constructability and pavement performance reasons, a curb and gutter will be used for the new construction.

Table 2. Design solution for Design Example 1.



Number of Days per Year Water Stands in Subbase		0				≤10				11 - 30				31 - 50			
Subgrade Resilient Modulus, ksi (CBR)	Dry	5.8	8.7	11.6	14.5	5.8	8.7	11.6	14.5	5.8	8.7	11.6	14.5	5.8	8.7	11.6	14.5
	Wet	3.5 (1.6)	5.2 (3)	6.7 (4.8)	8.7 (6.8)	3.5 (1.6)	5.2 (3)	6.7 (4.8)	8.7 (6.8)	3.5 (1.6)	5.2 (3)	6.7 (4.8)	8.7 (6.8)	3.5 (1.6)	5.2 (3)	6.7 (4.8)	8.7 (6.8)
Lifetime ESALs (Traffic Index)		Minimum Subbase Thickness in inches for ASTM No. 2, 3 or 4 for 1 in. Allowable Rut Depth (All subbases are under 4 in. ASTM No. 57 base, under 2 in. ASTM No. 8 bedding layer under 3 1/8 in. thick concrete pavers.)															
50,000 (6.3)		6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	6.0	7.0	6.0	6.0	6.0
100,000 (6.8)		6.0	6.0	6.0	6.0	8.5	6.0	6.0	6.0	10.5	6.0	6.0	6.0	11.5	7.0	6.0	6.0
200,000 (7.4)		9.0	6.0	6.0	6.0	12.5	8.5	6.0	6.0	14.5	10.0	6.5	6.0	16.0	11.5	7.5	6.0
300,000 (7.8)		11.5	7.0	6.0	6.0	15.0	10.5	7.0	6.0	17.0	12.5	8.5	6.0	18.0	13.5	9.5	6.5
400,000 (8.1)		13.0	9.0	6.0	6.0	17.0	12.0	8.5	6.0	19.0	14.0	10.0	7.0	20.0	15.0	11.0	8.0
500,000 (8.3)		14.5	10.0	6.5	6.0	18.0	13.5	9.5	6.5	20.0	15.0	11.0	8.0	21.0	16.5	12.0	9.0
600,000 (8.5)		15.5	11.0	7.5	6.0	19.0	14.5	10.5	7.0	21.0	16.0	12.0	9.0	22.0	17.5	13.0	10.0
700,000 (8.6)		16.5	12.0	8.0	6.0	20.0	15.0	11.0	8.0	22.0	17.0	13.0	10.0	23.0	18.0	14.0	11.0
800,000 (8.8)		17.0	12.5	9.0	6.0	20.5	16.0	12.0	8.5	22.5	17.5	13.5	10.5	24.0	19.0	14.5	11.5
900,000 (8.9)		17.5	13.0	9.5	6.0	21.0	16.5	12.5	9.0	23.5	18.0	14.0	11.0	24.5	19.5	15.0	12.0
1,000,000 (9.0)		18.0	13.5	10.0	6.5	22.0	17.0	13.0	9.5	24.0	19.0	14.5	11.5	25.0	20.0	15.5	12.5

In contrast to the structural design requirement of 19 inches, the hydrologic design requires a 22 in. thick subbase with perforated underdrains to remove water exceeding the reservoir storage capacity of the subbase within 72 hours. Therefore, from the hydrologic design perspective, there is sufficient subbase thickness for the structural design. The final design will be 22 inches.

Pavement Design Example 2

An area of cars-only parking lot at a popular rest area along Interstate 40 near Greensboro needs expansion. Additional picnic tables, trash bins, landscaping, and lighting are part of the expansion project. There is no additional capacity in the storm drainage system to receive water from new impervious pavement. Hence, the decision to use PICP.

Site Variables.

Traffic

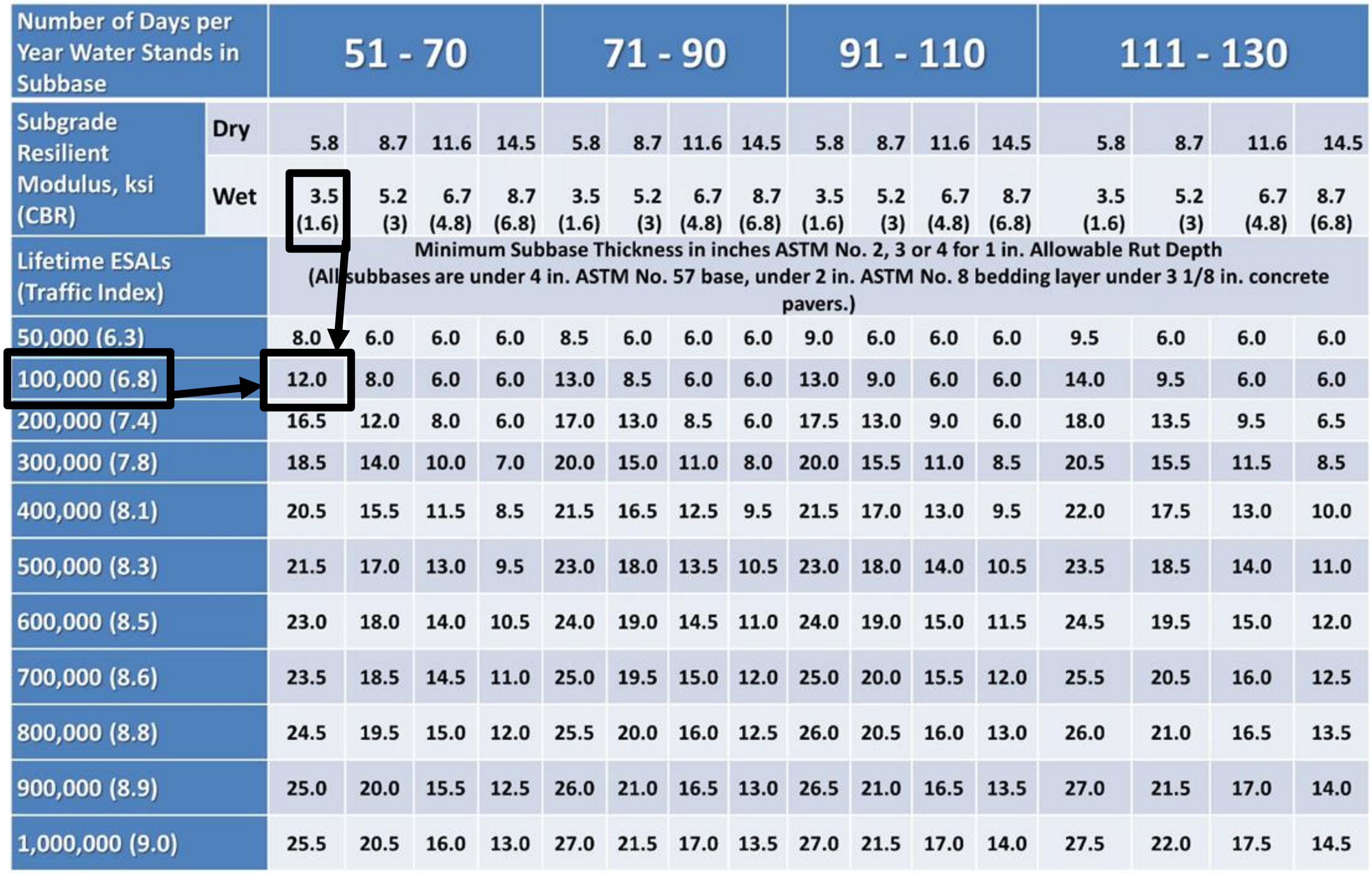
The parking area will accommodate 30 parking spaces and occupy about 20,000 sf including ingress and egress. Since this is a cars-only parking area, the only trucks entering the area will be maintenance and emergency vehicles. Therefore, the anticipated lifetime ESALs are 100,000.

Subgrade Soil Properties

The existing pavement and subgrade soils were cored with an auger and material samples of the subgrade soil were extracted at three locations. The clay soil rendered 2% CBR from conducting a 96-hour CBR test. The soil infiltration rate measured with a double-ring infiltrometer indicated an average of 0.05 in./hr. A safety factor is applied to reduce this to 0.025 in./hr. Therefore, 0.025 in. hr X 24 hours = 0.6 in.

www.weather.gov indicates the following on the number of days per year the 24-hour rainfall depth ≥ 0.6 in. for the past three years. Daily precipitation is provided by each the month in the past three years:
2019 = 30 days over 0.6 inches rainfall = 33.29 inches/0.6 = 55 days water stands in the subbase for more than 24 hours
2020 = 34 days over 0.6 inches rainfall = 47.22 inches/0.6 = 79 days water stands in the subbase for more than 24 hours
2021 = 23 days over 0.6 inches rainfall = 22.27 inches/0.6 = 37 days water stands in the subbase
Use the average = 55 + 79 + 37 = 171/3 = 57 days

Table 3. Design solution for Design Example 2.



Number of Days per Year Water Stands in Subbase		51 - 70				71 - 90				91 - 110				111 - 130			
Subgrade Resilient Modulus, ksi (CBR)	Dry	5.8	8.7	11.6	14.5	5.8	8.7	11.6	14.5	5.8	8.7	11.6	14.5	5.8	8.7	11.6	14.5
	Wet	3.5 (1.6)	5.2 (3)	6.7 (4.8)	8.7 (6.8)	3.5 (1.6)	5.2 (3)	6.7 (4.8)	8.7 (6.8)	3.5 (1.6)	5.2 (3)	6.7 (4.8)	8.7 (6.8)	3.5 (1.6)	5.2 (3)	6.7 (4.8)	8.7 (6.8)
Lifetime ESALs (Traffic Index)		Minimum Subbase Thickness in inches ASTM No. 2, 3 or 4 for 1 in. Allowable Rut Depth (All subbases are under 4 in. ASTM No. 57 base, under 2 in. ASTM No. 8 bedding layer under 3 1/8 in. concrete pavers.)															
50,000 (6.3)		8.0	6.0	6.0	6.0	8.5	6.0	6.0	6.0	9.0	6.0	6.0	6.0	9.5	6.0	6.0	6.0
100,000 (6.8)		12.0	8.0	6.0	6.0	13.0	8.5	6.0	6.0	13.0	9.0	6.0	6.0	14.0	9.5	6.0	6.0
200,000 (7.4)		16.5	12.0	8.0	6.0	17.0	13.0	8.5	6.0	17.5	13.0	9.0	6.0	18.0	13.5	9.5	6.5
300,000 (7.8)		18.5	14.0	10.0	7.0	20.0	15.0	11.0	8.0	20.0	15.5	11.0	8.5	20.5	15.5	11.5	8.5
400,000 (8.1)		20.5	15.5	11.5	8.5	21.5	16.5	12.5	9.5	21.5	17.0	13.0	9.5	22.0	17.5	13.0	10.0
500,000 (8.3)		21.5	17.0	13.0	9.5	23.0	18.0	13.5	10.5	23.0	18.0	14.0	10.5	23.5	18.5	14.0	11.0
600,000 (8.5)		23.0	18.0	14.0	10.5	24.0	19.0	14.5	11.0	24.0	19.0	15.0	11.5	24.5	19.5	15.0	12.0
700,000 (8.6)		23.5	18.5	14.5	11.0	25.0	19.5	15.0	12.0	25.0	20.0	15.5	12.0	25.5	20.5	16.0	12.5
800,000 (8.8)		24.5	19.5	15.0	12.0	25.5	20.0	16.0	12.5	26.0	20.5	16.0	13.0	26.0	21.0	16.5	13.5
900,000 (8.9)		25.0	20.0	15.5	12.5	26.0	21.0	16.5	13.0	26.5	21.0	16.5	13.5	27.0	21.5	17.0	14.0
1,000,000 (9.0)		25.5	20.5	16.0	13.0	27.0	21.5	17.0	13.5	27.0	21.5	17.0	14.0	27.5	22.0	17.5	14.5

Given the days per year the subbase has water in it (saturated subgrade), the CBR, and the lifetime ESALs, Table 3 above marks the required subbase thickness. The result is 12 in. Therefore, the entire pavement structure is ~21 in. thick, i.e., 3⅛ in. thick concrete pavers with joints filled with permeable aggregate, 2 in. of No. 78M stone for the bedding layer under the pavers, and 4 in. thick base layer of No. 57 stone. All these rest on a 12 in. thick subbase of No. 4 stone.

While not the case in this example, the depth from additional run-on from adjacent impervious pavements, roofs, etc. must be added to all the daily rainfall depths obtained from www.weather.gov. Then the number of days depths exceeding 0.6 inches would be identified and divided by 0.6 to obtain the number of days the subbase and subgrade are saturated for 24 or more hours. *Continuous hydrologic modeling is highly recommended* to determine the number of days the water in the subbase exceeds 0.6 inches or other depth that may be infiltrated into the subgrade within 24 hours.

For this example, the hydrologic design requires a 22 in. thick subbase with perforated underdrains that will remove water exceeding the reservoir storage capacity of the subbase. Therefore, from the hydrologic design perspective, there is sufficient subbase thickness for the structural design of 21 in. *Note*: In most cases in the eastern U.S. the subbase required to manage stormwater will be thicker than that required for structural support of traffic. The opposite is true in semi-arid and arid regions often found in the western U.S.

MAINTENANCE

As previously noted, maintenance is covered in Section C5, Permeable Pavements, in the DEQ *Stormwater Design Manual*. When plowed and depending on temperatures and sunlight, the remaining snow may melt and infiltrate into the surface rather than re-freeze as ice on the surface. This suggests a reduction of deicer use with related savings and reduction in liability. Marvin (2021) demonstrated the deicer reductions can be as high as 50% compared to that used on impervious pavements. Sodium chloride and calcium chloride are acceptable deicers. Magnesium chloride is not recommended.

All permeable pavements accumulate sediment in their surfaces over time and this contributes to decreased infiltration. Such decreases do not necessarily mean that the PICP is not infiltrating. Brown (2013) demonstrated that sedimentation of permeable paver joints occurs primarily along the PICP perimeter, areas where vehicles travel from other pavements onto PICP and where contributing run-on with sediment meets the PICP surface. This type of localized clogging does not prohibit the overall effectiveness of the PICP as a system that distributes incoming drainage over a large area in spite ponding at the impervious-permeable pavement junction.

An unacceptable level of infiltration is when water ponds on the surface during and remains within a half an hour after a rainstorm over more than 25% of the entire PICP surface. This translates to such areas having an infiltration rate of 20 inches per hour or lower. The most significant factor affecting decreasing infiltration is the amount of impervious pavement draining into the permeable pavement. Impervious surfaces shed sediment into permeable pavement surfaces. While the Manual allows the drainage area (pervious and impervious) to be a maximum of three times the PICP area, minimizing the contributing drainage area will reduce maintenance and related costs.

The least expensive method to maintaining infiltration rates is routine cleaning with a leaf blower to remove loose leaves, debris, and sediment. Vacuum sweeping with a regenerative air machine is another cleaning method typically done once or twice annually. Neglected maintenance likely means removing sediment and dirty jointing stone from the joints (see Figure 15) and replenishing the joints with clean stone. Additional maintenance information is found in ICPI Tech Spec 23 Maintenance Guide for Permeable Interlocking Concrete Pavements.

Figure 15. Cleaning PICP in Fayetteville, NC. The installation had not received regular cleaning. Equipment was used to remove accumulated sediment from the joints.

SUMMARY

PICP design procedures are dictated by Agency policy, the level of traffic and the type of roadway. The ASCE 68-18 methodology is applicable to a wide range of conditions and selected as the design method for development of the Guide. The intent of the Guide was to simplify and standardize PICP designs for parking lots, alleys, and residential streets. This does not excuse the designer from reading and applying the recommendations in ASCE 68-18.

This Guide is not intended for PICP design on higher traffic volume streets and highways. As previously noted, pavements receiving more than 1 million lifetime ESALs may benefit from the use of three-dimensional geocells in the base or subbase. In addition, permeable stabilized aggregate drainage courses can be considered for base and subbases. Such applications will require the expertise of a pavement engineer familiar with the structural capacity of these bases and with permeable pavement design.

In sum, the Guide is not intended to replace sound engineering judgment in generating feasible pavement designs for the design method provided. The results of the analysis are only as sound as the input values on which they are based. Structural design of pedestrian and car-only parking lots can generally rely on conservatively estimated soil support values and traffic values. However, as traffic volumes, vehicle weights, and speeds increase for residential streets and collectors, it is crucial that soil support and traffic are based on actual site data.

For PICP to fulfill the performance requirements established by the Agency, the specifications, plans and construction operations must be a coordinated effort.

REFERENCES

Note: In 2022, the Interlocking Concrete Pavement Institute (ICPI) merged with the National Masonry Association (NCMA) to form the Concrete Masonry and Hardscapes Association or CMHA. Internet reference searches may require ICPI and CMHA.

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