Permeable Interlocking Concrete Pavements, 5th Edition

David R. Smith

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Permeable Interlocking Concrete Pavements

Design • Specifications • Construction • Maintenance

Fifth Edition

David R. Smith

icpi
Interlocking Concrete Pavement Institute®

Interlocking Concrete Pavement Institute
14801 Murdock Street, Suite 230
Chantilly, VA 20151
Tel: 703.657.6900
Fax: 703.657.6901
E-mail: ICPI@icpi.org
Web: www.icpi.org

In Canada
P.O. Box 1150
Uxbridge, ON L9P 1N4

The Interlocking Concrete Pavement Institute (ICPI), founded in 1993, is the North American trade association representing the interlocking concrete paving industry. ICPI is considered by peer associations around the world as the leader in development and dissemination of technical information for design professionals and contractors. Our leadership position is due to years of commitment and energy from more than 1,000 members. ICPI engages in a broad range of technical, marketing, educational, government relations and communications activities. Membership consists of interlocking paver manufacturers, design professionals, paver installation contractors and suppliers of products and services related to the industry.

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By David R. Smith

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Interlocking Concrete Pavement Institute
14801 Murdock Street, Suite 230
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Tel: 703.657.6900
Fax: 703.657.6901
E-mail: ICPI@icpi.org
Web: www.icpi.org

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- Industry and public agency funded research and technical reports;
- Experience by consulting civil engineers and agency representatives; plus
- Agency/owner/user experiences.

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David R. Smith
Chantilly, Virginia
2017

Introduction

The environmental impacts of impervious, monolithic pavements are well known and documented. It is seldom said that such pavements are beautiful. For at least a century, the blandness of monolithic pavements also has numbed the human mind and soul to such impacts.

This manual is about deploying pavements that don't do that. Instead, it's about PICP that visually delights and inspires the human soul simply by looking at it, especially during or just after a rainstorm. Delight comes from PICP giving back to nature by integrating these functions: runoff and flooding reduction, pollution reduction, cooler surfaces, reduced energy consumption, traffic calming, and increased property values, among others.

This manual is support for civil engineers as well as for landscape architects, urban planners, contractors, stormwater and transportation agencies. Those who use it should be familiar with stormwater management concepts and calculation methods. This fifth edition includes revised subbase thickness design tables developed via full-scale load testing and mechanistic modeling in 2014 by the University of California Pavement Research Center. The revised tables, selected figures, and ideas from this manual are also included in the ASCE/ANSI national standard on PICP now in its final stages at this writing. So be on the lookout for it. That standard gives more in-depth information on PICP hydrologic and hydraulic design. This manual has comprehensive reading on construction and maintenance. The two should be read together.

As with the previous edition, this fifth edition is divided into five sections. Section 1 provides an overview on PICP. Section 2 provides criteria for selecting appropriate sites and systems. Section 3 includes basics for sizing storage and selecting base and subbase thicknesses. Detailed inflow and outflow calculations can be examined using ICPI's Permeable Design Pro software or other stormwater models. Calculations must be done by qualified engineers familiar with hydrology and hydraulics, as well as pavement structural design using flexible pavement design concepts articulated by the University of California Pavement Research Center and by the American Association of State Highway and Transportation Officials (AASHTO).

Updated construction methods and guide specifications are included in Section 4. Much has been learned about maintenance, so Section 5 is completely revised. There are construction and maintenance checklists, as well as a model ordinance for use by municipal governments. There is a Glossary of Terms and References at the end that provides a wealth of information beyond this manual.

While synonyms, the words porous, pervious, and permeable differentiate surfacing materials with underlying base configurations, i.e. porous asphalt, pervious concrete, and PICP. These terms have been designated by their respective industries.

Etymology is instructive. The Latin root for permeable (*permeare*) means capable of passing something such as air or water. The Latin root for pervious (*pervius*) means capable of *accepting* something such as air, water, or even ideas. The Latin root for porous (*porus*) means full of holes. When referring to runoff-reducing pavements collectively, all pass water through them making all permeable.

As readers use this manual, it should always be applied within the context of broader site designs and community goals that encompass integrated stormwater management. Finally, I trust that this manual's use improves the mental health and well-being of people, as well as of nature and the built environment. PICP does this more elegantly than any other pavement, porous, pervious or impervious.

Section 1. Overview

Impacts from Impervious Surfaces

Urbanization brings an increasing concentration of pavements, buildings, and other impervious surfaces. They generate additional runoff and pollutants during rainstorms, causing streambank erosion, as well as degenerating lakes and polluting sources of drinking water. Increased runoff deprives ground water from being recharged, decreasing the amount of available water in many communities. Figure 1-1 summarizes the impacts of impervious surfaces.

Increased Imperviousness leads to:	RESULTING IMPACTS				
	Flooding	Habitat Loss	Erosion	Streambed alteration	Channel widening
Increased volume	*	*	*	*	*
Increased peak flow	*	*	*	*	*
Increased peak flow duration	*	*	*	*	*
Increased stream temperature		*			
Decreased base flow	*	*			
Changes in sediment loadings	*	*	*	*	*

Figure 1-1. Impacts from increases to impervious surfaces (USEPA 1997).

Stormwater generates intermittent discharges of pollutants into water courses. Since the pollutants in stormwater runoff are not generated by a single, identifiable point source such as a factory, but from many different and spatially separated sources within a watershed, they are called nonpoint sources of water pollution. During and after rainstorms, nonpoint sources of runoff pollution flow in huge quantities that render them untreatable by conventional wastewater treatment plants. In many cases, the receiving water (e.g., a stream, lake, river, estuary, or beach) cannot process the overwhelming amount of pollutants either. Even worse, in older areas combined storm and sanitary sewers can discharge even higher flows and pollutants that bypass wastewater treatment plants, further damaging receiving waters. Therefore, the breadth of pollutants is difficult to control, as well as the extent to which they can be treated through nature's processes in a lake, stream, or river.

While impervious surfaces provide buildings and transportation networks, they have environmental costs beyond those from hydrologic and pollutant impacts. Other environmental impacts from impervious surfaces, especially impervious pavements, include (USEPA 2008):

- Urban heat island and increased air conditioning costs
- Air emissions from asphalt and cement plants
- Air emissions from pavement construction and maintenance
- Decrease in green space
- Opportunity costs (i.e., forfeiting higher value uses)
- Degradation of community and neighborhood character
- Thermal pollution of runoff resulting in aquatic ecosystem damage

Best Management Practices (BMPs)

US federal law (USEPA 2005) has mandated that states control nonpoint source water pollution through the National Pollution Discharge Elimination System (NPDES) program. The law requires, among many things, that states identify and require best management practices, or BMPs, to control nonpoint source pollution from new development. BMPs are implemented typically through regional and local governments charged with water quality management, planning, and regulation. (BMPs are more recently called stormwater control measures or SCMs. The two terms are interchangable.)

BMPs include many technologies and land management practices for reducing the quantity of pollutants in stormwater. They are used in combination at the site, development and watershed scales to attain the maximum benefits to the stormwater drainage system. BMPs are divided into structural and non-structural practices. Structural BMPs capture runoff and rely on gravitational settling and/or infiltration through a porous medium plus chemical and biological processes for pollutant reduction. They include detention dry ponds, wet (retention) ponds, infiltration trenches, sand filtration systems, bio-retention and permeable pavements. These are often used to offset increases in pollutants caused by new development or decrease those from redevelopment.

Nonstructural BMPs involve a wider scope of practices. They can be public awareness programs about preventing nonpoint water pollution, street sweeping or the use of planning techniques such as riparian vegetative buffers. Many non-structural practices involve more efficient site planning. For example, these can include reducing the overall size of parking lots by reducing parking demand ratios, increasing shared parking, and use of mass transit. Many examples of nonstructural and structural practices can be found in *Better Site Design: A Handbook for Changing Development Rules in your Community* (CWP 1998).

In Canada, the Canadian Environmental Protection Act regulates many of the substances that have a deleterious effect on the environment including water pollutants in runoff. Recognizing the need for better environmental management, the Canadian federal government passed the Canada Water Act in 1970 and created the Department of the Environment in 1971, entrusting the Inland Waters Directorate with providing national leadership for freshwater management. Under the Constitution Act (1867), the provinces are "owners" of the water resources and have wide responsibilities in their day-to-day management.

The federal government has certain specific responsibilities relating to water, such as fisheries and navigation. While providing national leadership to ensure that Canada's freshwater management is in the national interest, Environment Canada also actively promotes a partnership approach among the various levels of government and private sector interests that contribute to, and benefit from, the wise management and sustainable use of this resource.

All of these interests were extensively consulted during the 1984–85 Inquiry on Federal Water Policy, which conducted Canada-wide hearings toward the development of a federal water policy. Guided by the findings of the inquiry, the government released its Federal Water Policy in 1987 and it has given focus to all federal departments' water-related activities and provides a framework for future action as they evolve in light of new issues and concerns. Stormwater management is a growing concern at the federal, provincial and municipal levels. Infiltration practices and low impact development tools such as permeable interlocking concrete pavement (PICP) are increasing in use across Canada as a means to address those concerns.

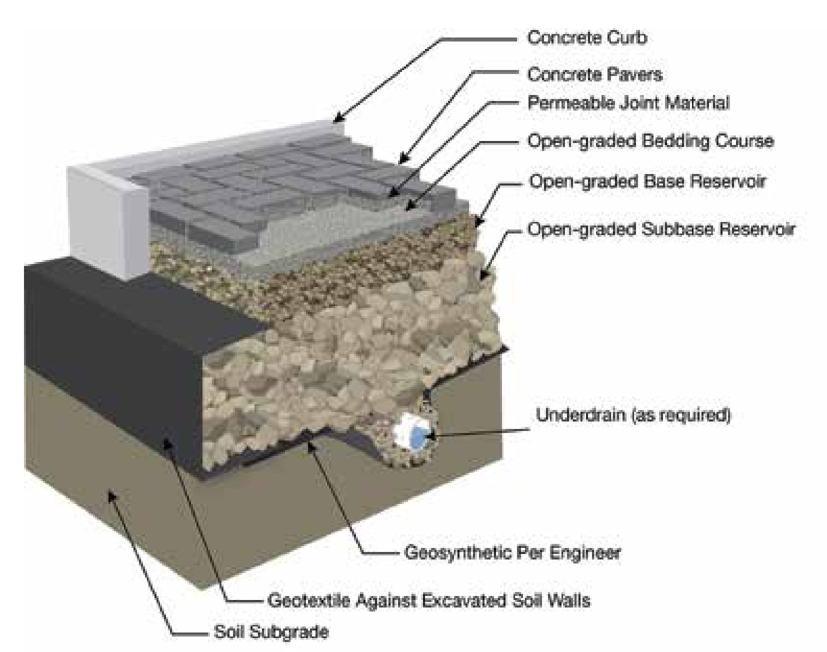


Figure 1-2. PICP typical cross section. A description of each component is provided below.

PICP System Description

PICP is recognized by federal, provincial, state and municipal stormwater and transportation agencies as a BMP and low impact development (LID) tool to reduce runoff and water pollution. In addition, PICP offers unique design opportunities for creating green streets, green alleys and parking lots as well as for reducing the urban heat island.

Figure 1-3. Various types of paving units used in PICP

Traditional stormwater management solutions focus on collecting, concentrating and centralizing the disposal of stormwater. As a key BMP and LID tool, PICP helps disconnect, decentralize and more widely distribute runoff through infiltration, detention, filtering and treatment.

Figure 1-2 illustrates a typical PICP cross section. Solid (impermeable) concrete pavers with molded joints and/or openings create openings across the pavement surface. Filled with permeable aggregate joint material, the openings/joints allow water from storm events to freely enter them. Figure 1-3 provides a sample of various paver configurations.

Concrete Pavers—Concrete pavers should conform to American Society for Testing and Materials, ASTM C936 (ASTM 2016) in the US or Canadian Standards Association, CSA A231.2 (CSA 2014) in Canada. Pavers are typically a minimum of 3⅛ in. (80 mm) thick for vehicular areas, and pedestrian areas may use 2⅜ in. (60 mm) thick units. Pavers are manufactured in a range of shapes and colors. Lighter colored pavers can meet a minimum solar reflectance of 0.33 per ASTM C1549 (ASTM 2014). The units may include photocatalytic cement or pigment materials containing titanium oxide on their surface to reduce nitrous oxide air pollutants (Beeldens 2006). The traditional approach is that joints and/or openings comprise 5% to 15% of the paver surface to provide sufficient drainage. However, research has shown that the jointing aggregate size as well as joint widths have a much greater impact on surface infiltration rates (Kevern 2016) (Kim 2007). Therefore, ICPI recommends that the surface infiltration rate be defined by measuring the interaction of these two variables via surface infiltration testing. (This is covered in Section 2.)

Permeable Joint Material—PICP surface infiltration relies on highly permeable, washed, small-sized aggregates such as ASTM No. 8, 89 or 9 stone.[1] The permeable joints allow stormwater to enter a crushed stone, open-graded aggregate bedding course. Sand is not used in the joints or bedding layer.

Concrete Grid Pavements—PICP should not be confused with concrete grid pavements, concrete units with cells that typically contain topsoil and grass. See Figure 1-4. These paving units can infiltrate water, but at substantially lower rates than PICP, usually similar to that of a grassed surface. Unlike PICP, concrete grid pavements are typically designed with a dense-graded, crushed stone base rather than an open-graded base for water storage. Moreover, grids are for light-duty use, i.e., intermittently trafficked areas such as overflow parking areas and emergency fire lanes for fire trucks with a design limit of no greater than 7,500 18,000 lb (80 kN) equivalent single axle loads. Grid pavements are not intended for regularly used parking lots or roads, whereas PICP is well-suited for these applications. Grids with grass offer substantial cooling compared to hard surfaces and qualify for LEED credits. Grid pavement design and construction requirements differ substantially from PICP. See *ICPI Tech Spec 8–Concrete Grid Pavements* which provides detailed information on www.icpi.org.

Figure 1-4. Concrete grid pavements are a permeable pavement but are used in intermittently trafficked areas.

Open-graded bedding course—This permeable layer is typically 2 in. (50 mm) thick and provides a level bed upon which pavers can be installed. It consists of small-sized, open-graded aggregate, typically ASTM No. 8 stone or similar sized material.

Open-graded base reservoir—This is an aggregate layer 4 in. (100 mm) thick and made of crushed stones primarily 1 in. down to 1/2 in. (25 mm down to 13 mm). Besides storing water, this high infiltration rate layer provides a gradational transition between the bedding and subbase layers. The stone size is typically ASTM No. 57 or similar sized material.

Open-graded subbase reservoir—The stone sizes are larger than the base, primarily 3 in. down to 2 in. (75 mm down to 50 mm), typically ASTM No. 2, 3 or 4 stone. Like the base layer, water can be stored in the spaces among the stones. The subbase layer thickness depends on water storage requirements and traffic loads (covered in Section 3). A subbase layer may not be required in pedestrian or residential driveway applications. In such instances, the base layer thickness is increased a minimum of 6 in. (150 mm) to provide water storage and support.

Underdrain (as required)—In sites where PICP is installed over low-infiltration soils, underdrains facilitate water removal from the base and subbase. The underdrains are perforated pipes that "daylight" to a swale or stream, or connect to an outlet structure. Pipe elevation, spacing, diameter and slope will impact water detention times, outflow volumes and rates from PICP bases/subbases. Another design option to which underdrains connect underground are plastic or concrete vaults or plastic crates. These can store significant amounts of runoff.

Geosynthetic (design option per engineer)— Typically, a geotextile separates the subbase from the subgrade and prevents migration of soil into the aggregate subbase or base. For this reason,

[1]Numeric designations for jointing, bedding, open-graded base and subbase aggregate gradations used throughout this manual are found in ASTM D448 *Standard Classification for Sizes of Aggregate for Road and Bridge Construction.* The same gradations can be found in ASTM C33 *Standard Specification for Concrete Aggregates* or AASHTO M-43 *Sizes of Aggregate for Road and Bridge Construction.* Many of the referenced numeric designations for aggregates or similar ones are supplied by local quarries. Similar aggregate sizes in Canada can be found in CSA A23.1 *Concrete Materials and Methods of Construction.*

Figure 1-5. Ferdinand Street in Chicago is paved with PICP as part of a city redevelopment project.

Figure 1-6. Approximately 4 miles (6.4 km) of PICP in SE Atlanta, Georgia, is used for flood mitigation for a more resilient infrastructure.

Figure 1-7. Elmhurst College, Elmhurst, Illinois, uses PICP parking lots for runoff control and water harvesting.

Figure 1-8. Allston Way in Berkeley, California, reduces runoff volumes and pollutants in a highly urbanized setting. (Photo courtesy of AECOM)

geotextile is required against the vertical soil left from excavation when no curb is present. However, it may be an option for horizontal placement on the soil subgrade. A detailed discussion on this geotextile is presented in Section 3. The geosynthetic can also be a geomembrane to prevent water movement into the soil subgrade.

Subgrade—This is the layer of soil immediately beneath the aggregate base or subbase. The infiltration rate of the (hydraulically) saturated subgrade determines how much water can exfiltrate from the aggregate into the underlying soils. For no-infiltration systems, the subgrade is compacted per standard construction practices. For full and partial infiltration systems, the subgrade soil is generally not compacted as this can substantially reduce soil infiltration. However, some poorly draining clay soils are often compacted to help ensure structural stability especially while saturated. Since compaction reduces infiltration, managing the excess water must be considered in the hydrologic design via the base/subbase thickness and use of perforated pipe underdrains. This is covered in Sections 2 and 3.

PICP Applications

PICP is used as a standard pavement (replacing impervious pavements) by municipalities for stormwater management programs and by private developers. The runoff volume, rate and pollutant reductions allow municipalities to meet federal, provincial, state and local regulatory water quality criteria. Municipal initiatives such as the City of Chicago Stormwater Infrastructure Strategy, City of Atlanta Green Infrastructure Action Plan and City of Toronto Green Streets Initiative, promote the use of PICP to reduce combined sewer overflows (CSO) and minimize localized flooding by infiltrating and treating stormwater on site. Green alley projects by the City of Richmond, Virginia, Dubuque, Iowa, St. Louis, Missouri, Los Angeles, California,

Figure 1-9. Park 542, also known as Mary Bartelme Park, located in Chicago's West Loop, includes PICP with a white titanium oxide cement to help reduce air pollutants.

Figure 1-10. Autumn Trails in Moline, Illinois used 39,000 sf (3,900 m^2) of PICP without storm sewers, making it cost-competitive with conventional paving with drainage.

Philadelphia, Pennsylvania and Washington, DC store and slowly release water to reduce peak flows, as well as filter pollutants, as a CSO reduction tool. There are several examples around the continent of PICP used for low-volume streets in residential and redeveloped industrial areas. Figures 1-5 and 1-6 illustrate these projects.

Public projects such as universities, colleges (Figure 1-7), schools, fire stations, libraries, museums and stadiums use PICP to reduce runoff and achieve sustainable site design objectives. Figure 1-8 illustrates a busy municipal PICP street in downtown Berkeley, California. This is one of many examples of municipalities using PICP to replace traditional impervious pavement for pedestrian and vehicular applications except for high-volume/high-speed roadways. PICP has performed successfully in pedestrian walkways, sidewalks, driveways, parking lots, and low-volume roadways subject to truck traffic. The environmental benefits from PICP allow it to be incorporated into municipal green infrastructure and low impact development (LID) programs. PICP is a key element in the LID "treatment train" approach that seeks to maximize on-site infiltration.

Figure 1-11. Unlike other permeable pavement surfaces, PICP in the Peoplestown neighborhood in Atlanta, Georgia, provides a distinctive visual character.

In addition to providing stormwater volume and quality management, light colored pavers are cooler than conventional asphalt. This helps reduce urban summer temperatures and improve air quality by using photocatalytic materials made with titanium dioxide. An example is shown in Figure 1-9. The textured surface of PICP also provides traffic calming, and supports neighborhood character that helps provide a visually unifying appearance. Figures 1-10 and 1-11 provide examples of PICP supporting neighborhood character while potentially providing traffic calming.

Ground Source Horizontal Heat Pumps—An innovative use of PICP combines it with a horizontal ground source heat pump (HGSHP). This requires water retention using a waterproof geomembrane around the PICP that contains heat exchange pipes within the aggregate subbase directed to building heat pumps. The exchange pipes and heat pumps provide supplementary heating and cooling to an adjacent building. An example of this is an office building in Bedford, England, where an adjacent 70,000 sf (6,500 m^2) PICP parking lot incorporates a HGSHP system energized by stored water. Figures 1-12, 1-13 and 1-14 illustrate this project built in 2008. (Photos are courtesy of Formpave.)

Figure 1-12. Coiled pipes within a PICP aggregate subbase provide heat and cooling exchange for a horizontal ground source heat pump.

Figure 1-13. The pipes are under a 70,000 sf (6,500 m^2) PICP parking lot just completing construction.

Figure 1-14. The collection system and heat pump provide 520 kW of heating and 200 kW of cooling.

Economics—Private commercial and residential development projects use PICP to meet post-construction stormwater quantity and quality regulations and low impact development ordinances. In many cases, PICP can be cost-effective in new development and redevelopment. Cost savings in new projects arise from on-site infiltration that reduces or eliminates storm sewers and detention/retention ponds, making more land available for buildings. An example of cost savings in residential roads is Autumn Trails community in Moline, Illinois. About 39,000 sf (3,900 m^2) in PICP eliminated the need for storm sewer inlets and pipes. Figure 1-10 illustrates the project.

According to developer estimates, PICP without storm sewer drainage was cost-competitive with conventional pavements using standard drainage systems (2006 prices). Cost comparisons include identical curbing for all pavements and appropriate base materials and thicknesses.

Pavement System	PICP no sewers	Concrete w/ sewers	Asphalt w/ sewers
Cost/sf (m^2)	\$10.95 (\$117.82)	\$15.00 (\$161.40)	\$11.50 (\$123.74)

Another source of savings emerges from local regulations that limit the total amount of impervious cover. Savings comes from permeable pavement counted as pervious land cover, which can enable a larger building footprint on the site and greater sales or rental income. The higher cost of PICP compared to conventional paving may be recovered from increased income from more buildings or from more rentable space in buildings. Sites should be evaluated for these economic trade-offs of pavement system choices, stormwater management options, and building space.

Within existing urban redevelopment projects, PICP is particularly cost-effective for parking areas with no space for detention ponds or existing ponds that cannot be expanded. In some projects, low-slope building

Figure 1-15. The parking lot at this retail center in Burnaby, British Columbia, provides the retention and filtering of water from the adjacent roofs as well as from the parking lot.

roofs (or vegetated roofs) can serve as detention and transfer the water into the permeable pavement. This is the case in a shopping center in Burnaby, British Columbia, as shown in Figure 1-15. The water from the roofs is directed into the base under the 350,000 sf (35,000 m^2) PICP surface, which covers the entire parking lot. There are no storm sewer inlets in the parking lot since the entire surface functions as one.

Life-cycle and pollutant removal costs for PICP can be lower than other practices. While the initial cost of asphalt is lower, maintenance costs accrue from crack sealing, seal coating, milling and resurfacing. PICP has none of these maintenance items and this can yield lower projected life-cycle costs over the pavement life. This was the case for a 500-car PICP parking lot in Morton Arboretum in Lisle, Illinois. PICP had a lower maintenance after year 23 compared to asphalt due to accumulating crack filling and seal coating (ICPI 2011).

The Toronto and Region Conservation Authority conducted a theoretical assessment of PICP and asphalt life-cycle costs compared to equivalent area parking lots. The report says while PICP initial costs were higher, "The present value cost differences narrowed considerably over the 50 year evaluation period. This is due to the impact of asphalt maintenance costs accumulating over time, particularly compared to lower PICP maintenance." Other factors such as reduced land and drainage infrastructure costs, and avoided pollutant wastewater treatment costs, reduce PICP life-cycle costs to lower than those for impermeable pavements. The TRCA report further demonstrated that life-cycle costs per kilogram of total suspended solids removed was lowest for PICP compared to other stormwater BMPs (TRCA 2013).

Many urban areas suffer from storm sewers operating at capacity and flooding in high rainfall events. An increasing number of local governments require PICP for new or rebuilt residential and commercial pavements. Some local governments provide financial incentives to residential and commercial property owners to convert impervious pavement to permeable pavement. Examples include Washington, DC, Montgomery County, Maryland, and Palo Alto, California. These municipalities offer rebates to land owners for installing a range of methods to reduce stormwater runoff including PICP. In these jurisdictions, replacing existing storm sewers with larger ones to reduce flooding was not economical. Therefore, providing financial incentives to land owners that help transform impervious surfaces to PICP presents a less expensive solution for the municipality.

Impervious Cover Restrictions, Stormwater Utilities and PICP

An increasing number of municipalities regulate the amount of impervious cover on a range of land uses. Restrictions can be based on not exceeding the maximum capacity of storm sewers and streams to handle runoff from existing impervious surfaces without flooding and property damage. In other cases, severe restrictions (e.g., <15% impervious cover) are enacted to preserve fish habitats or nearby natural resources (e.g., natural area next to a stream, estuary or bay) or to stop local flooding from worsening.

Since runoff from impervious surfaces are the primary cause of drainage system damage, impervious cover restrictions are the most effective means to reduce runoff volumes and pollutants. In such cases, provincial/state and municipal regulations often credit PICP as a permeable or pervious surface when some or all of the water for a given design storm is infiltrated into soil subgrade. Reduction or elimination of impervious pavement using PICP has a two-fold benefit depending on local development objectives. PICP can facilitate conservation of existing natural areas or enable larger building/roof area. Roofs can be designed to sustain vegetation (green roof), capture water for irrigating site vegetation or simply detain and slowly release water in PICP. Additional houses or commercial buildings can readily offset the additional expense for PICP.

Another approach that establishes a legal, technical and municipal administrative framework for managing municipal drainage infrastructure is the stormwater utility. Almost 1,600 US and Canadian municipalities have created stormwater utilities similar to existing water and sewer utilities (Campbell 2016). The legal rationale for a stormwater utility is rain that falls on private property belongs to the property owner. Therefore, removal of runoff from private property through a publicly-owned municipal drainage system should be paid as a user fee by the property owner to the local municipal utility (similar to sanitary waste or trash removal). The fee charged by the municipality for this service depends on how much runoff is discharged from each property. The fee is often based on the percent of impervious cover, land use (i.e., zoning), or the local government's need to capitalize and maintain a storm drainage system. A residential property owner pays a lower fee, while a shopping center owner pays a higher one due to generating more runoff from a greater area of roofs and parking lots.

In most cases, the fees go specifically to managing stormwater. Therefore, the charge to property owners is not considered a tax which pays for a wider range of municipal services. Typically, stormwater utility fees are used by the municipality for maintaining and expanding the municipal drainage system. In some instances, fees are also used to restore damaged streams and riparian habitats, thereby reinstating lost or damaged riparian property and natural or recreational amenities.

Some stormwater utility fee structures offer a discount or credit to land owners that reduce runoff entering the municipal drainage system. An owner's fee may be reduced if there is reduction of impermeable surfaces using permeable pavement or if the water is stored on the owner's site. Since PICP offers storage and infiltration, a strong rationale exists for reduction of stormwater utility fees. Reese (Reese 2007) offers additional rationale for credits to stormwater utility fees.

Some regulatory agencies achieve volume and pollutant reductions through comprehensive stormwater management operation and maintenance plan funded and administered through stormwater utilities. Larger municipalities or those with stormwater utilities can operate computational models to forecast development impacts and costs on the publicly owned drainage system.

While the Rational Method persists in many places due to its simplicity in calculating peak flows, some governments and design consultants use more sophisticated stormwater modeling and field calibration of watersheds to forecast impacts. Models can range from NRCS TR-55 (USDA 1986) to other event-based models customized for permeable pavements such as ICPI's *Permeable Design Pro* software. Highly sophisticated continuous simulation models include HEC or EPA SWMM, WINSLAM, DRAINMOD specifically for PICP (Smolek 2015), or agency-specific models. Modeled results inform drainage guidelines for specific site development proposals. Sophisticated modeling can also simulate downstream impacts (i.e., stream bank erosion and flooding) from a specific development proposal. Chapter 2 provides PICP site selection criteria design options that can impact hydrologic modeling inputs.

PICP Benefits

Construction

- Supports SWPPP and reduces construction costs to meet SWPPP requirements
- Immediately ready for traffic upon completion, no time needed for curing
- Can be installed in cold weather if subgrade and aggregates remain unfrozen
- Capable of wet weather (light rain) installation
- No time-sensitive pavement materials that require site forming and management for curing
- Contractor training and credentials available through ICPI
- Machine installation of paving products and equipment accelerate installation

Reduced Runoff

- Up to 100% surface runoff reduction (subject to design requirements)
- Up to 100% infiltration depending on the design and soil subgrade infiltration rate
- Capable of installation over or next to concrete or plastic underground storage vaults or crates
- Can be designed with water harvesting systems for site irrigation and gray water uses

Improved Water Quality

- Reduces total suspended solids 80% or higher compared to that from impervious pavements
- Reduces nutrients, metals and oils
- Does not raise runoff temperature which can damage aquatic life
- Can be used to achieve water quality capture volume
- Can be used to achieve total maximum daily load (TMDL) limits for a range of pollutants

Site Utilization

- Reduces or eliminates unsightly detention/retention ponds
- Increased site and building utilization
- Conservation of space on the site and reduction of impervious cover
- Preserves woods and open space that would have been destroyed for detention ponds
- Promotes tree survival by providing air and water to roots (roots do not heave pavement)

Drainage System

- Reduced downstream flows and stream bank erosion due to decreased peak flows and volumes
- Increased recharge of groundwater
- Decreases risk of salt water incursion and drinking water well pollution in coastal areas
- Reduced peak discharges and stress on storm sewers
- Reduces combined sanitary/storm sewer overflows

Reduced Operating Costs

- Reduced overall project costs due to reducing or eliminating storm sewers and drainage appurtenances
- Lower life-cycle costs than conventional pavements
- Capable of integration with horizontal ground source heat pumps to reduce building heating and cooling energy costs
- Enables landowner credits on stormwater utility fees
- Does not require sealing, which lowers maintenance costs

Paver Surface/Units

- 40-year-plus design life based on proven field performance
- Most products meet ADA or other national guidelines; many products meet ASME A112.6.3 Floor and Trench Drains, Section 5.3 on Heel-Resistant Grates
- Colored units can delineate parking stalls and driving lanes; light colors can reduce night time lighting needs

- Eliminates puddles on parking lots, walkways, entrances, etc.
- Capable of plowing with municipal snow removal equipment
- Durable, high-strength, low-absorption concrete units resist freeze-thaw, heaving and degradation from deicing materials
- Most products provide a slip resistant surface in accordance with ANSI A137.1 and ANSI B101.3 Dynamic Coefficient of Friction Test
- Reduced ice and deicing material use/costs due to rapid ice melt and surface infiltration
- Reduced liability from slipping on ice due to rapid ice melt and surface infiltration
- Provides traffic calming
- Paver surface can include photocatalytic materials to reduce air pollution
- High solar reflectance surface helps reduce micro-climatic temperatures and contributes to urban heat island reduction
- Units manufactured with recycled materials and cement substitutes to reduce greenhouse gas emissions

Ease of Maintenance & Repairs

- Paving units and base materials can be removed and reinstated
- Utility cuts into the pavement do not damage the surface and decrease pavement life
- Capable of winter repairs
- No unsightly patches from utility cuts
- Surface cleaning with standard equipment
- Clogged surfaces may be restored with high-powered vacuum equipment to reinstate infiltration rates

LEED version 4 Credits

Initiated in 1998 by the US Green Building Council, Leadership in Energy and Environmental Design or LEED® supports an ethos of energy and material conservation in building and site design, construction and operation. LEED® evolved through several updates to version 4 (v4) released in late 2013. LEED® supports creating environments that enhance human existence and natural processes (e.g., PICP functions). One of the primary motivations of LEED is to influence building and site design and codes toward zero environmental impacts, particularly carbon emissions. Among many things, LEED® helps achieve project design goals via product/system selection that supports cost-effectiveness, environmental friendliness and social responsibility.

For the site, pavement can be a significant investment with positive or negative economic, environmental and social impacts. In support of positive impacts, PICP can help earn LEED® v4 credits from three credit categories: Sustainable Sites, Materials and Resources, and Water Efficiency. Open space, rainwater management, and heat island mitigation credits are under Sustainable Sites. Materials and Resources credits have shifted emphasis from recycling to reducing impacts during a product's entire life cycle, i.e., manufacture, construction, use, and end-of-life phases. These and other credits are listed in Table 1-1 that can be earned using PICP. For additional information, the reader is referred to *ICPI Tech Spec 16 Achieving LEED Credits with Segmental Concrete Pavement*.

Table 1-1. Summary of potential points earned with support from using PICP in the LEED BD+C rating system.

LEED Credit Category	Available	Potential Points Using PICP
Integrative Process	1 – 5	1 – 5
Sustainable Sites	10	
Open Space		1
Rainwater Management		3
Heat Island Reduction		2
Water Efficiency	11	
Outdoor water use		Prerequisite (no points)
Materials & Resources	13	
Building Product Disclosure and Optimization–Environmental Product Declarations		1
Building Product Disclosure and Optimization–Sourcing of Raw Materials		1
Building Product Disclosure and Optimization–Material Ingredients		3
Construction and Demolition Waste Management		2
Innovation	6	6
Regional priority	4	4
Range of potential points	45 – 50	25 – 30

Other Sustainable Design Evaluation Systems for PICP

Besides LEED®, there are other environmental assessment and sustainability rating programs favorable to PICP. These include the following:

Green Globes www.greenglobes.com

Sustainable Sites Initiative www.sustainablesites.org

Greenroads www.greenroads.org

Envision www.sustainableinfrastructure.org

Invest www.sustainablehighways.org

Sustainable Sites has a structure similar to LEED® v4 with a sites-only focus rather than on building evaluations. According to Sustainable Sites, its central message is (and credits recognize) that, "…any project… holds the potential to protect, improve, and regenerate the benefits and services provided by healthy ecosystems." PICP participates in this regenerative process.

The latter three frameworks listed evaluate roads and/or urban infrastructure, and recognize permeable pavement use via credits. The frameworks include rating systems for design, construction and use of roadways. These provide transportation agencies with checklists and encourage more substantive environmental impact evaluations using life cycle assessment (LCA) that includes quantifying impacts listed below. Pavement industries and material suppliers often can provide LCAs, typically expressed as environmental product declarations or EPDs, for their materials that include manufacturing impacts on:

- Global warming (from greenhouse gases)
- Acidification (typically from acid rain)
- Eutrophication (accelerated aging of water bodies through excess nutrient intake)
- Fossil fuel depletion

- Habitat alteration
- Water intake
- Air pollutants and smog
- Ecological toxicity
- Ozone depletion
- Human health

Moving past LCAs for pavement materials, LCA for their construction, use and end-of-life phases is in early development stages. This full life cycle analysis will grow as more transportation agencies include LCA in construction and maintenance bids, and particularly when funding depends on such analyses. In the meantime, local, state and federal transportation agencies, as well as private sector project owners, view LCA as a means to reduce costs by reducing waste, pollutants and social impacts from projects to the wider society. Fortunately, PICP offers a range of environmental, economic and social benefits that can reduce the above impacts during:

- Manufacture due to cement substitutes, recycled materials, and carbonization processes
- Construction due to simple, fast mechanized installation (compared to alternative pavements)
- Use by reducing runoff and pollutants, and
- End-of-life/re-use as a completely recyclable material

For the present, a growing number of road agencies are placing greater emphasis on evaluating environmental and social impacts from roads. They are using roadway sustainability rating systems that typically consider and rate the following environmental and economic aspects:

- Environmental review including LCA and environmental product declarations (EPD)
- Life cycle energy use inventory (as input to LCA) for materials, construction, use and end-of-life phases
- Life cycle cost analysis or LCCA (construction costs plus present value of future maintenance costs and user delay costs due to maintenance)

For additional information on pavement LCA and LCCA, see the US Federal Highway Administration's *Sustainable Pavements Reference Document* and *Pavement Life Cycle Assessment Framework*. Both publications can be downloaded from www.fhwa.dot.gov/pavement/sustainability/.

Section 2. Design Objectives, Selection Criteria and Guidelines

Municipal Stormwater Management Objectives

Municipal drainage and low-impact development ordinances vary widely. Factors influencing them include geomorphology, water supply needs, water laws, rainfall patterns, development and redevelopment pressures, capacity of the natural drainage or man-made storm sewer system, as well as the receiving water capacity to process pollutants and excessive water volumes. Many regional authorities, drainage districts, counties, cities and towns aim at preserving natural drainage and treatment systems or limit flows to drainage systems, especially if they are working at capacity. Integration of low-impact development principles into many state/provincial and municipal regulations has increased focus on reducing runoff volumes which results in pollutant reductions.

A well-structured municipal stormwater management strategy will use a range of post-construction BMPs that address runoff reduction and water quality improvement. Regulatory approaches implement BMPs that incorporate some or all of the following water quality and water quantity goals.

1. Reduce generation of additional stormwater and pollutants by restricting the growth of impervious surfaces. This approach can embrace one or more goals that include:
    - Reduce runoff volumes to control local flooding from the natural drainage system or from storm sewers operating at capacity
    - Recharge groundwater for maintaining stream base flows
    - Recharge aquifers used for drinking water
    - Relieve combined sewer overflows in older urban areas
    - Protect nearby high-value (drinking water supply, recreation or fishing) body of water from pollution
2. Treat (i.e., detain and infiltrate) runoff from commonly recurring storms to remove a given percentage of pollutants from the average annual post-development load. This approach is sometimes called "water quality volume capture." Target pollutant reductions typically include total suspended solids (TSS), total phosphorous (TP) and/or total nitrogen (TN), as these are primary indicators of water quality. Pollutant levels are measured in sewers, streams and other natural water bodies on the basis of mass reduced or reduced (rainfall) event mean concentrations.
3. Reduce specific pollutants to lower levels (concentrations or mass loads) for processing by a receiving body of water. Pollutant emissions are sometimes reduced to levels a receiving body of water (e.g., stream, lake, estuary, bay, etc.) can process without incurring permanent damage to the aquatic ecosystem and especially to the receiving water's economic value. This approach to limiting pollutants from a watershed is often called total maximum daily load or TMDL restrictions. There is an increasing number of US watersheds subject to such restrictions. This approach can rely on documented relationships between land uses and pollutant loads in runoff from them.

    Other regulatory approaches manage stormwater in a hierarchy of rainfall events according to recurrence level with strategies to manage increasing depths, volumes, flows and resulting environmental impacts. The hierarchy manages runoff volumes and flow criteria based on their potential for pollution and flooding. The approach is typically structured in ascending order of storm depths as follows:

(a) Capture and treat a specific water quality volume defined as the initial depth of rainfall on a site (usually ranging from 0.75 in to 1.5 in. or 19 to 40 mm). The depth also can be expressed as a percentage of all storms that can range between 75% and 95%. This approach often controls runoff from commonly recurring storms (up to one year recurrence) since they generally contain the highest concentration of pollutants, similar to number 2 above.

(b) Enhance stream channel protection through extended detention and infiltration of runoff volumes from a given storm event, e.g., a 1- or 2-year 24-hour storm. The difference in volumes between pre- and post development is often detained, infiltrated and/or slowly released. Sometimes there is agency-developer debate on what type of land cover and resulting runoff constitutes a "pre-development" condition. Streambank protection is regulated through techniques that dissipate water energy and velocity in streams and through preservation of vegetative buffers along streams.

(c) Reduce overbank flooding in streams through reducing the post-development peak discharge rate to the pre-development rate for larger storms such as a 25-year, 24-hour event.

(d) Reduce the risk of extreme flooding by controlling and/or safely conveying the 100-year, 24-hour return frequency storm event. This goal is also supported by preserving existing and future floodplain areas from development or restricting it in them as much as possible.

Figure 2-1 schematically illustrates how PICP can help address the above regulatory goals. PICP is most effective in managing runoff from commonly recurring storms and can be designed to help manage less frequent, higher depth storms. In most parts of North America, commonly recurring storms comprise 75% to 95% of all rain events. If designed to store less frequent, bigger storms, runoff volumes and/or discharge rates, these can be decreased with PICP to help reduce erosion of drainage channels. PICP with deep water storage reservoirs can significantly contribute to reduced local flooding. In such instances, PICP roads can become the means for flood storage, infiltration and conveyence.

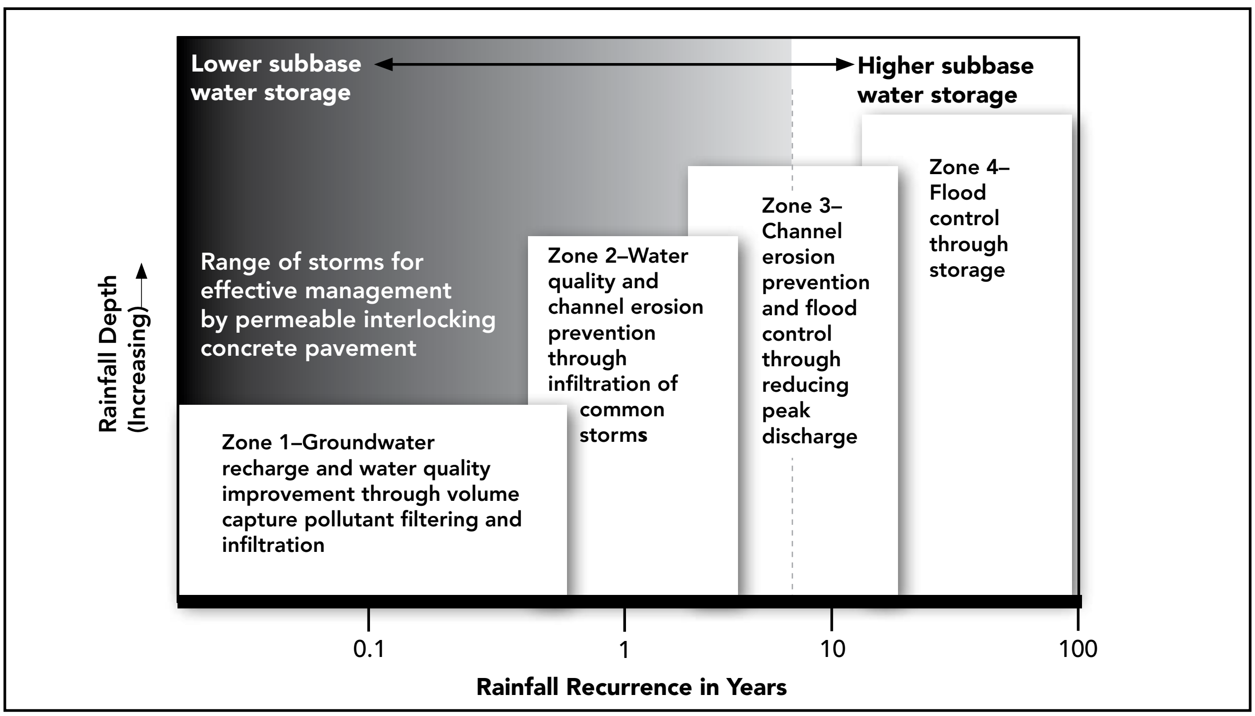


Figure 2-1. Various stormwater management objectives related to the spectrum of storms can be met with PICP (after Claytor 1996).

Site Selection Criteria

PICP is recommended in areas with the following site characteristics:

- Regulatory acceptance
- Residential patios, walks and driveways
- Walks, parking lots, main and service driveways around commercial, institutional, recreational and cultural buildings
- Low speed (<35 mph or 50 kph) residential roads, road shoulders, and on-street parking lanes
- Where traffic calming is needed as well as reduced ice formation for driver and pedestrian safety
- Boat landings and marinas
- Industrial sites that do not receive hazardous materials, i.e., where there is no risk to groundwater or soils from spills
- Storage areas for shipping containers with non-hazardous contents
- Runoff from contributing at-grade impervious drainage areas does not exceed five times the area of the PICP receiving the runoff
- The estimated depth from the bottom of the pavement base to the seasonal high level of the water table is greater than 2 feet (0.6 m). Greater depths may be required to obtain additional filtering of pollutants through the soil. High groundwater does not categorically exclude PICP use, but storage and infiltration will be impacted.
- Sites without potential for sinkholes (often karst formations) or high shrink-swell potential when water infiltrates; no-infiltration designs are an option
- Downslope from waterproofed building foundations and the foundations have piped drainage at the footers
- The slope of the permeable pavement surface is at least 1% and no greater than 12%. Figure 2-2 illustrates a large PICP parking lot near Atlanta, Georgia, with a slope of 12% across the site. While slopes as high as 12% have been built, PICP surface slopes are typically 5% or less. Subgrade slopes typically 3% or greater will require engineered baffles or berms to slow downslope flows and increase infiltration. There should be a minimum 1% surface slope to enable removal of water in the extreme case of the entire system filling with water such that it emerges from the surface.
- Land surrounding and draining into the PICP does not exceed 20% slope
- At least 100 ft (30 m) should be maintained between PICP and municipal water supply wells. (Local jurisdictions may provide additional guidance or regulations.) No-infiltration designs may be an option.
- Sites where the owner executes maintenance requirements (see Section 5 on maintenance)
- Sites where runoff draining onto PICP surface is not from soil erosion, exposed topsoil or mulch
- Sites where there will not be an increase in impervious cover draining into the PICP (unless the pavement is designed to infiltrate and store runoff from future increases in impervious cover due to future development)
- Sites where space constraints, high land prices, tree/green space conservation, land used by detention facilities, and/or runoff from additional development make PICP a cost-effective solution initially or life-cycle costs are lower compared to other pavements
- Sites outside permafrost regions

Figure 2-2. A large PICP parking lot manages an overall site slope of 12% using terraced areas.

PICP is not recommended on any site classified as a stormwater hotspot, i.e., if there is any risk that stormwater can infiltrate and contaminate groundwater. These land uses and activities may require no-infiltration designs (i.e., use of an impermeable liner discharging into a storage tank) or avoiding permeable pavement use:

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

PICP can be designed with full, partial or no infiltration through the open-graded stone base into the soil subgrade. Details on each follow.

Full Infiltration—Full infiltration directs water through the base/subbase and into the soil subgrade. This is commonly used over high infiltration soils such as gravels and sands. Overflows are often managed via perimeter drains to swales, bio-retention areas or storm sewer inlets. Figure 2-3 illustrates

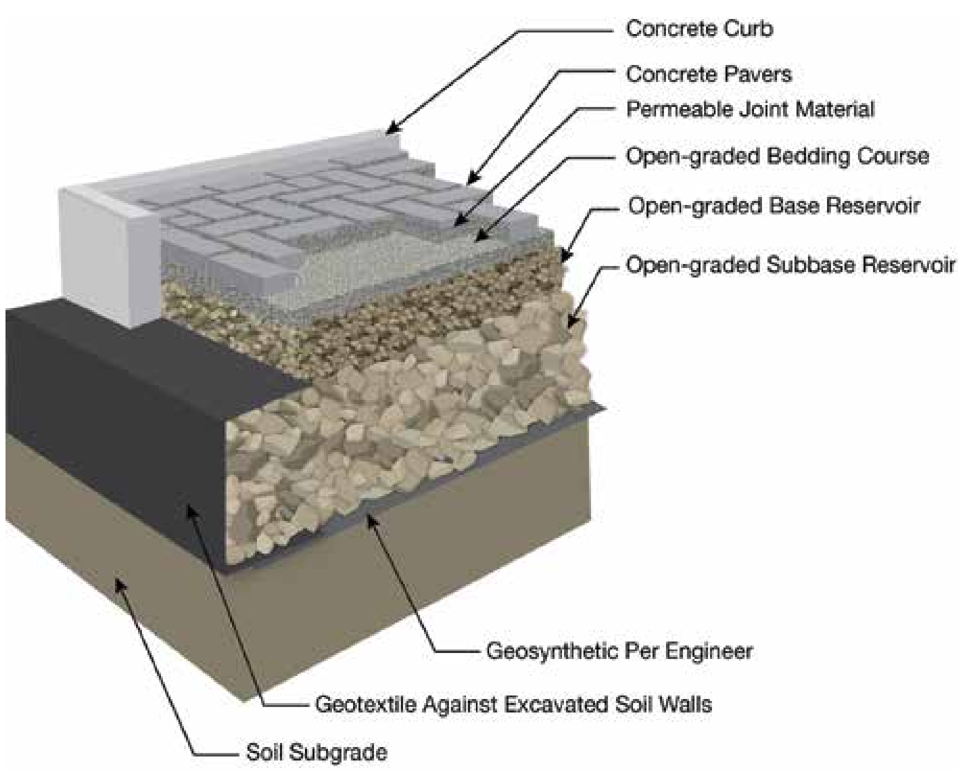


Figure 2-3. Full infiltration cross section allows storage and infiltration. Overflows are managed via perimeter drainage to swales, bio-retention areas or storm sewer inlets.

Figure 2-4. Elmhurst College, Elmhurst, Illinois, parking lots use full infiltration through the soil subgrade with overflows directed through curb inlets into bio-retention areas and overflow drains to manage extreme rain events.

schematic cross section of a full infiltration PICP. Overflow drainage can exit from the surface but is better managed via large drainpipes from within the base layer. Subsurface drainage can help prevent mobilization of sediment trapped in the PICP openings from a surface overflow. Figure 2-4 illustrates an example of handling PICP overflows via curb inlets to bioswales.

Partial infiltration also relies on drainage of the base/subbase into the subgrade, but includes drainage pipes

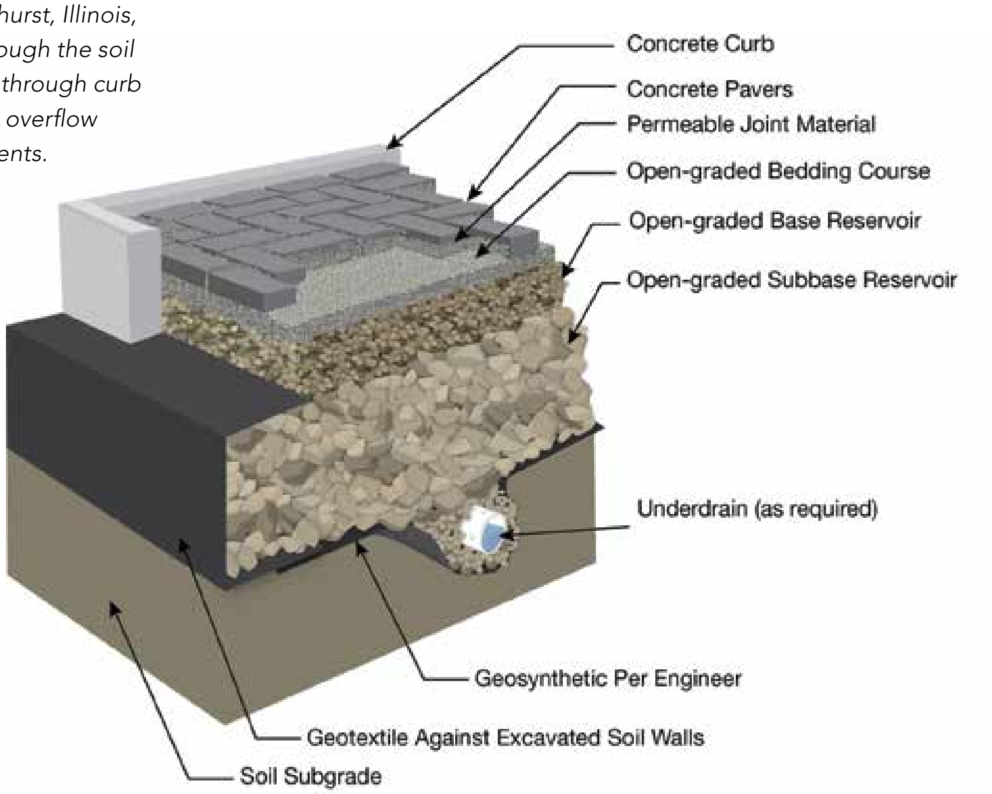


Figure 2-5. Partial infiltration through the soil subgrade. Perforated pipes or their outlets can be raised above the soil subgrade to drain water from higher depth rainstorms. Smaller storms which often contain higher pollutant concentrations can be captured below the perforated pipes, stored and infiltrated.

Figure 2-6. Partial infiltration designs typically use perforated pipes raised above the soil subgrade. This enables capture and infiltration of some runoff.

Figure 2-7. A non-perforated, raised outlet pipe is another way to achieve detention and partial infiltration. The pipe positioned on the soil is perforated.

to discharge excess water during extreme storm events to a sewer or a stream. This design is common to lower infiltration rate soils such as silts and some clays. The storage depth of the system is controlled using raised pipes (Figure 2-6), raised elbows (Figure 2-7) or outlet control devices. After the water level in the system reaches the storage depth, excess water drains away through them. The storage depth is based on the amount of time the subgrade can remain saturated, which typically ranges from 24 to 72 hours. This detention time enables nutrient reduction through de-nitrification (Smolek 2015). Soils with infiltration rates as low as 0.01 in./hr (7×10^{-6} cm/sec) can infiltrate about 0.5 in. (13 mm) over 48 hours. Therefore, this design approach can be used in some clay soils and in some compacted soils. Figure 2-5 illustrates a schematic cross-section of partial infiltration design, and Figure 2-6 shows a perforated pipe raised over the soil subgrade. Figure 2-7 shows a raised outlet pipe, sometimes called a sump or upturned elbow pipe.

Partial infiltration designs have also been successfully used in coastal areas and islands where the depth to the water table is close to the surface with little slope to drain bases. PICP structures have been designed with sufficiently thick bases to support vehicular traffic while water continually occupies the lower portion of the aggregate subbase over a sandy subgrade. The sandy soil remains stable while saturated and the base/subbase mitigates stresses from loads to the soil. Drain pipes provided at higher elevations within the base remove excess water when the water table rises from rainfall and tidal surges. Drain pipes are usually connected to a storm sewer. This design approach can address salt water incursion in coastal areas by maintaining needed fresh water in groundwater aquifers, which blocks incursion of less dense salt water. A mounding analysis may be required to assess the impacts of a raised water table to adjacent buildings and structures.

In the US, the Safe Drinking Water Act regulates the infiltration of stormwater in certain situations pursuant to the Underground Injection Control (UIC) Program administered by the US EPA or a delegated state groundwater protection agency. This program divides wells into five classes depending on their design and use. According to EPA, "Class V wells are shallow disposal systems that depend on gravity to drain fluids directly in the ground…Most of these Class V wells are unsophisticated shallow disposal systems that include storm water drainage wells, cesspools, and

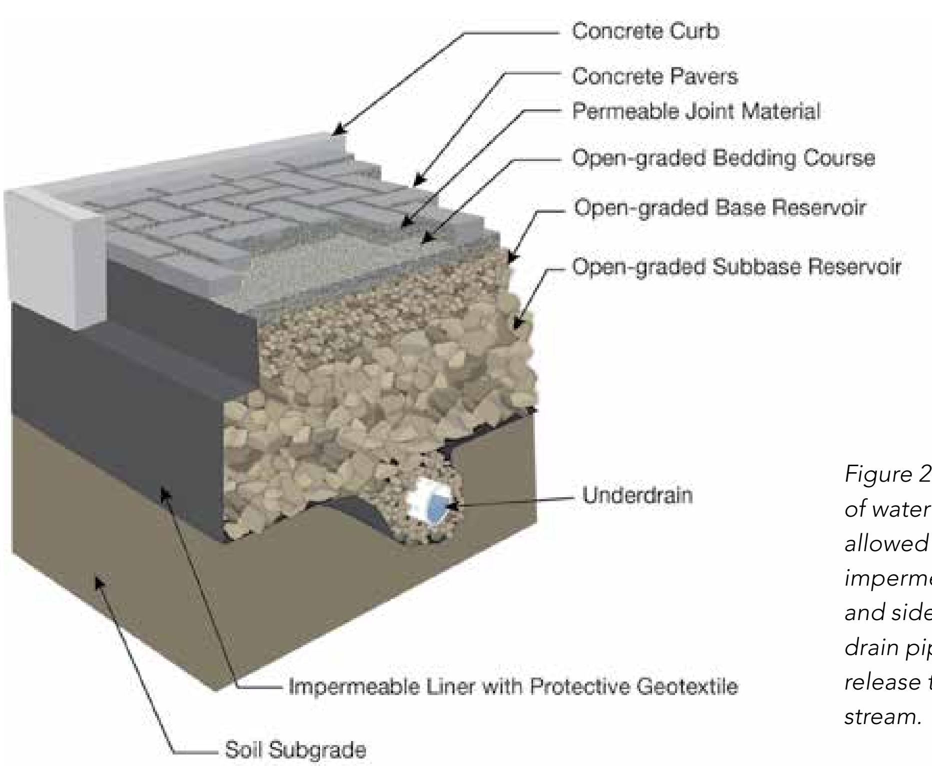


Figure 2-8. No exfiltration of water from the base is allowed into the soil due to an impermeable liner at the bottom and sides of the base. Perforated drain pipes are sized to slowly release the water into a sewer or stream.

septic system leach fields. However, the Class V well category also includes more complex wells that are typically deeper and often used at commercial or industrial facilities." The EPA (USEPA 2008) determined that permeable pavement installations are not classified as Class V injection wells, since they are always wider than they are deep.

No Infiltration

No infiltration is required when the soil has very low permeability and low strength, or there are other site limitations. The assembly typically includes a liner that creates a detention pond with an outlet. Figure 2-8 illustrates a cross-section design for no-infiltration into the soil subgrade. The outlet often consists of a small bleed drainpipe (orifice) at the bottom of the subbase that enables a continuous discharge rate, and a higher, large diameter drain pipe for emergency overflow. The liner can be high density polyethylene (HDPE), ethylene propylene diene monomer (EPDM) or polyvinyl chloride (PVC). Manufacturers of these materials should be consulted for appropriate applications, thicknesses, specifications and field construction guidance including seam welding, and how to render a tight fit against penetrating drain pipes. Liners typically require non-woven geotextile over them for additional protection during aggregate filling and compaction. Figure 2-9 shows an impermeable liner with geotextile around a PICP subbase. No infiltration designs are also used for creating a reservoir for water harvesting or horizontal ground source heat pumps that augment nearby building heating and cooling needs.

Figure 2-9. The bottom and sides of this PICP subbase are enclosed with an EPDM impermeable liner and geotextile to capture, filter and eventually drain runoff through the subbase via an underdrain.

A minimum 1 ft (0.3 m) clearance is recommended between the bottom of the impermeable liner and the seasonal high water table. (A minimum of 2 ft (0.6 m) clearance is recommended for full or partial infiltration designs.) In some cases, the soil may be stabilized to render improved support for vehicular loads.

No-infiltration designs with impermeable liners are recommended in the following sites:

- Over aquifers with insufficient soil depth to filter the pollutants before entering the ground water
- Shallow bedrock or karst terrain
- Over fill soils whose behavior when exposed to infiltrating water may cause unacceptable settling and movement. These might include expansive soils such as loess, gypsiferous soils, etc.

In rare cases, soil directly below the subbase may be low-infiltration clay while soils further down may offer increased infiltration. It may be cost-effective to drain the water via a vertical French drain or pipes through the impermeable layer of soil into the lower soil layer with greater permeability.

Handling Sloped Sites

Soil subgrades can be bermed and piped to control downslope flows and encourage infiltration. Figures 2-10, 2-11 and 2-12 illustrate options for sloped PICP applications using concrete or impermeable liner-wrapped aggregate berms; stepped and sloped installations. More recent designs use an impermeable liner folded into the aggregate subbase. Figure 2-13 illustrates this approach. Figure 2-14 illustrates a way to maximize storage capacity by creating almost flat areas for infiltration.

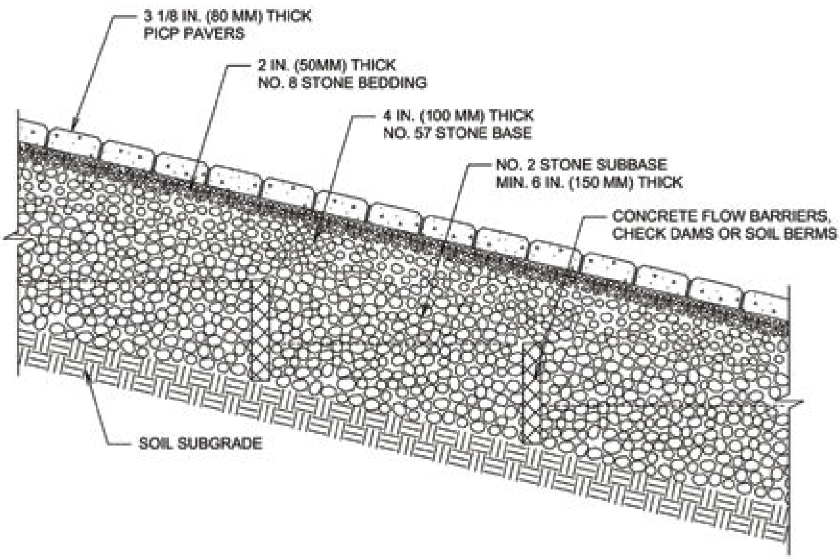


Figure 2-10. PICP with stepped check dams for slowing flows and promoting infiltration. Check dams can be concrete or geomembrane. Subgrade slopes generally over 3% should consider using check dams to slow flows and promote infiltration.

Figure 2-11. Concrete check dams are used to slow flows in this alley in Richmond, Virginia. Subbase and base compaction are critical to minimizing differential settlement.

Figure 2-12. Check dams are formed with open-graded aggregate wrapped in an impermeable liner in this parking lot project.

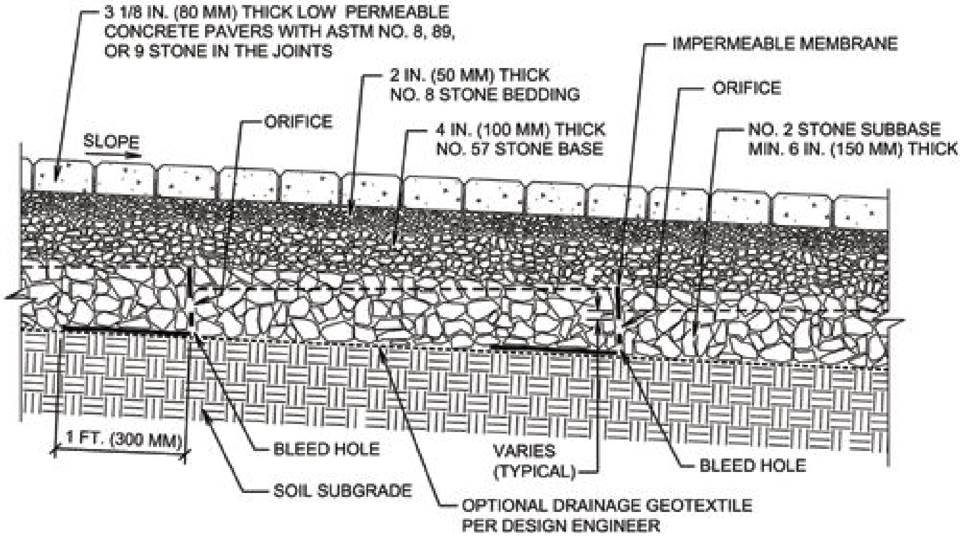


Figure 2-13. Impermeable liners are used as check dams with a bleed hole and a higher drain hole. (Courtesy of the City of Atlanta Department of Watershed Management)

Formulas are provided to estimate water storage between barriers or soil berms:

$V = P \times \frac{D\,A}{2}$ This applies where the subgrade is sloped between barriers or berms shown on Figure 2-10 and 2-13.

V = Volume available in the reservoir (cf)
P = Porosity of the aggregate base/subbase (e.g., 0.4)
D = Maximum depth of the reservoir at the barrier (ft)
A = Horizontal surface area of the PICP between barriers (sf) or L x pavement width

V = P D A This applies where the subgrade is relatively flat between barriers or berms as shown on Figure 2-14.

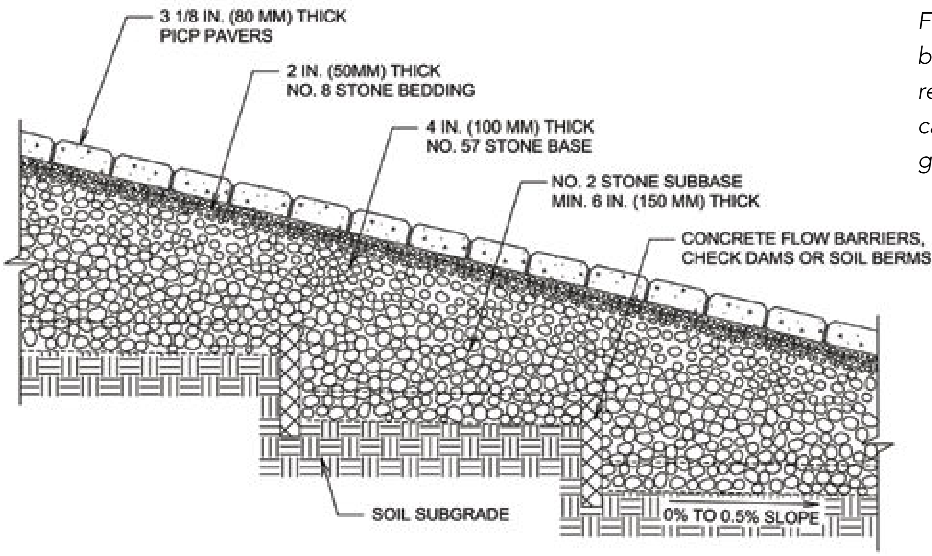


Figure 2-14. PICP with barriers that form stepped reservoirs. Barriers can be constructed of geomembrane or concrete.

Design Considerations for Disabled Persons

PICP complies with the Americans with Disabilities Act (ADA) design guidelines, provided that surfaces within accessible paths of travel meet the following criteria (DOJ 2010):

- Firm, stable and slip resistant
- Openings that cannot receive insertion of a ½ in. (13 mm) steel sphere. PICP openings filled with small aggregate (typically to the bottom of the paver chamfers) comply with this design guideline.
- Vertical changes in elevations among pavers do not exceed ¼ in. (6 mm). Changes between ¼ and ½ in. (6 and 13 mm) require a bevel and those over ½ in. (13 mm) require a ramp. PICP guide specification provided in Section 4 Construction limits vertical differences among pavers to ⅛ in. or 3 mm. Correctly installed concrete pavers have little or no vertical differences among them. Wheelchair user comfort can be increased by using pavers with small chamfers.

Pedestrian paths of travel through PICP parking lots should be studied and defined in the design stage. Vehicle lanes, parking spaces, pedestrian paths, and parking spaces for disabled persons can be delineated with different colored PICP or solid concrete pavers. See Figure 2-15. Likewise, parking spaces accessible to disabled persons can be paved with solid pavers and use a color contrasting with the PICP pavers.

Surface, Base/subbase and Soil Subgrade Infiltration Rates

PICP Surface Infiltration Rates—A common misunderstanding in PICP design is assuming that the percent of open surface area is equal to the percent of perviousness. For example, a 15% open PICP surface

Figure 2-15. Various examples of pavement markings using PICP.

area is incorrectly assumed to be 15% pervious or 85% impervious. This suggests that 85% of the rain that falls on the PICP surface runs off, which of course is not the case. All of the rain falling on the impervious paving units runs into the openings between them, which makes their surface 100% pervious.

While PICP has less than 100% open surface area, the entire surface is considered 100% pervious since all water enters through it. Like all permeable pavements, water will not enter PICP if the surface is completely clogged with sediment. Avoiding this condition is covered in Section 5 Maintenance. The initial surface infiltration rate depends on the joint filling material, paver joint widths and slope, not the percentage of surface open area.

Initial surface infiltration rates on PICP are high. This is due to the joint filling material, typically ASTM No. 8, 89 or 9 stone. Wider joints accommodate No. 8 stone whereas narrower joints often use No. 89 or 9 stone. No. 10 stone is not recommended in PICP joints as it most easily clogs with sediment. The US EPA measured surface infiltration rates (USEPA 2010) over the first six months of a PICP parking lot with ASTM No. 8 stone in the openings and bedding. Infiltration rates varied between 984 in./hr and 1,377 in./hr (2,500 and 3,500 cm/hr) using ASTM C1701 (ASTM 2017), a single-ring infiltrometer test method that provides results comparable to ASTM C1781 *Standard Test Method for Surface Infiltration Rate of Permeable Unit Pavement Systems* developed after C1701 (ASTM 2015).

Long-term Surface Infiltration Rates—There have been several other researchers who have investigated surface infiltration rates in new and older PICP. An extensive list follows. Bean (Bean 2007) found an average of 787 in./hr (2,000 cm/hr) on nine parking lots in Maryland, Delaware and North Carolina using a single-ring infiltrometer. He also found significantly lower rates on PICP that received an extraordinary amount of fines deposited on the pavement surface. The most severely clogged surfaces showed infiltration rates similar to that of the soils in the openings, suggesting that some water may infiltrate if regular surface cleaning isn't conducted or if the surface is not exposed to traffic that might compact such soils on the surface. A low-infiltration condition (i.e., below that of the design rainstorm intensity) from lack of routine cleaning can be restored to a higher infiltration rate. This process is covered in Section 5 Maintenance.

Studies by Beecham (Beecham 2009) in Australia also confirmed that continuously unmaintained PICP surfaces provide some infiltration. His research used a double-ring infiltrometer and measured between 0.5 and 37.5 in./hr (1.3 to 952 cm/hr) on unmaintained, eight- to ten-year old roads, parking lots and pedestrian areas in New South Wales and Victoria.

Collins (Collins 2007) measured surface infiltration rates on fairly new PICP test sites in North Carolina with 12.9% and 8.5% surface open areas using a double ring infiltrometer. Significantly higher infiltration rates were found on PICP with the higher percentage of open area. However, both PICP surfaces demonstrated 97% to 99% infiltration of rainfall from 40 events monitored.

In a laboratory study in Australia, Yong et al. (Yong 2008) compared surface and base infiltration rates of PICP and porous asphalt via accelerated simulation of over 17 years of stormwater for Melbourne and over 8 years for Brisbane. Selected PICP demonstrated no surface clogging after simulated polluted stormwater was poured onto these surfaces at rates equivalent to those periods for Brisbane and Melbourne. Total suspended solid removals were also high with lower nutrient reductions.

Shahin (Shahin 1994) constructed a laboratory installation of two PICP pavements (both with 12.2% open surface area), regular interlocking concrete pavers with sand jonts, impervious asphalt and examined pollutant reductions. The test apparatus enabled sloping of the installations up to 10% under a rainfall simulator. All pavements were tested with rainfall intensities up to 3.5 in./hr (90 mm/hr). While the study focused on pollutant reduction, Shahin's data indicates that at a 10% slope under 3.5 in./hr (90 mm/hr) of rainfall, approximately 2.5% of the rainfall converted to surface runoff on the two PICP surfaces tested. He observed that water ponding in joints and openings directed it inside the PICP. He also provides data that indicates little difference in water collected from the surface and subsurface when testing the two PICPs at 5% and 10% at a rainfall intensity of 3.5 in./hr (90 mm/hr).

Borgwardt (Borgwardt 1994, 1995, 1997, 2006) monitored infiltration rates of many new and older PICP in Germany and concluded that PICP surfaces lose 75% to 90% of their surface infiltration rate over the initial years of use if not maintained with vacuum cleaning of the surface to remove sediment. Infiltration rates then level off in the seventh or eighth year of service. This conclusion fits with broader experience with infiltration practices decreasing infiltration capacity over time due to sedimentation. This condition has been observed in pervious concrete (Chopra 2010) and porous asphalt (Ballestero 2009). While all unmaintained permeable pavements clog over time, PICP is the easiest surface to increase and restore higher surface infiltration rates. Restorative surface cleaning is covered in Section 5 Maintenance.

Borgwardt (Borgwardt 2006) found limited correlation between the surface infiltration performance and the percentage of paver surface open area. Instead, he emphasized the selection of highly permeable aggregates for the joint filling as a more important consideration. Borgwardt also observed that smaller joint stone sizes render somewhat lower surface infiltration rates, but he noted that such differences make little difference in the ability of the PICP surface to take in water. He notes that sand provides the lowest infiltration. For that reason, as well as its high clogging potential, ICPI recommends against using sand in PICP joints and the bedding layer.

Two additional studies examined the relationship among sediment deposition, joint width and jointing stone gradation. Kim (2007) conducted infiltration tests on PICP with similar joint widths (0.55 in. or 14 mm wide yielding a 9% open surface area) using ASTM No. 8, 9 and 10 stone. A sandy-silt sediment mix was introduced into the water and repeatedly applied to simulate 20 years of sediment loading on level PICP surfaces. Additionally, winter sand (coarse gradation) was applied to the joints. Surface infiltration rates were measured to track reductions over the accelerated 20-year dosing period.

Not surprisingly, this study demonstrated that the larger size No. 8 stone saw the slowest decrease in infiltration rates and No. 10 saw the highest. The study also demonstrated the essential role of the jointing stone in reducing total suspended solids (TSS) and noted that while one sediment gradation was tested, particle size distribution will impact trapping rates. For testing with this particular type of sediment, the study recommended using No. 9 stone, as it balanced sediment trapping with the rate of reduction in surface infiltration over the 20 years of simulated deposition.

A second study by Kevern (2016) examined relationships among surface flow, infiltration into PICP with 6, 10 and 12.5 mm joint widths, and No. 8 and 9 stone in them. Laboratory tests were conducted in a 12 ft (3.6 m) long flume with clean flowing water and while dosing flowing water with sediment having a particle size distribution very similar to that in the previously described study by Kim. The down-flow end of the flume was fitted with 4 sf (0.37 m^2) of PICP having 6 mm wide joints with No. 9 stone in them. This area was also tested with No. 8 stone in 10 and 12.5 mm wide joints. Vertical and horizontal infiltration rates into all three assemblies were measured. All were tested as separate installations under identical flow conditions.

High surface flows yielded surface overflows as well as horizontal and vertical infiltration. Flows and infiltrations were measured at 0%, 1%, 2%, 5% and 10% slopes, with and without a high concentration of sediment in the water. The 6 mm wide joints could infiltrate up to 2% slope without hindrance and the 10 and the 12.5 mm wide joints could handle flows to 10% slope. Units with 6 mm wide joints filled with No. 9 stone clogged about seven times faster than the 10 mm wide joints filled with No. 8 stone. The results suggest that PICP with narrow joints adjacent to a sediment-contributing impervious area may require more frequent vacuuming in order to maintain infiltration. While the slope of most PICP surfaces is 2% or less, wider joints are better suited for PICP surfaces over 2% if there is sediment in run-on from adjacent contributing impervious pavement.

Research by Winston (Winston 2015) identified contributing impervious drainage area as a key factor in sediment deposition from run-on with sediment. The junction between impervious pavements and PICP typically clogs first due to sediment deposition, often exhibited by ponding during storms. Winston (2016) also provides a review of the literature on clogging studies as well as examining the effectiveness of various surface cleaning methods. From a water quality improvement perspective, jointing stone has an essential role in trapping sediment at the surface so it can more easily and economically be removed by vacuuming. For that reason (as well as providing interlock), open-graded aggregates are recommended in the joints in PICP, thereby meeting the definition of a permeable unit pavement system per ASTM C1232.

While the sources and amounts of sediment deposition can vary from site to site, the application of Borgwardt's suggested reductions (Borgwardt 2006) of initial surface infiltration of 75% to 90% still yields rates that will receive practically all storms. For example, if a PICP has an initial surface infiltration rate of 500 in./hr (1270 cm/hr) a 90% reduction over several years yields a surface infiltration rate of 50 in./hr (127 cm/hr). The expectation, however, is that PICP surfaces require periodic cleaning to maintain infiltration over their entire service life, typically 30 or more years. *For design purposes, a conservative lowest surface infiltration for maintained PICP is 10 in./hr (25 cm/hr) as measured using ASTM C1781 test method.* This infiltration rate represents a surface drainage time of 60 minutes using this test method.

Base/subbase infiltration—The initial and long-term infiltration rates of PICP base and subbase materials are very high, typically in the thousands of inches (cm) per hour. They are not considered an obstacle to water moving vertically through the pavement cross section. Designers may consider reduced flows from increasing levels or heads of water within a base as well as from horizontal movement of water through base and subbase materials. They will delay horizontal movement, and the extensive amount of stone surfaces and mass help reduce flow rates. Models such as Darcy's Law to estimate horizontal flow rates and time of concentration within the stone materials are approximate.

More than surface infiltration, a key design consideration is the *lifetime* infiltration of soil subgrade. There can be short-term variations from a saturated soil subgrade and long-term reductions of infiltration from deposition of sediments. Studies by Gerrits (Gerrits 2002) and Bean (Bean 2007) demonstrated that much inbound sediment is trapped within the joints and bedding aggregates at the PICP surface. They also showed that removal of surface sediment increases surface infiltration rates. Sediment trapping and eventual removal (cleaning) helps slow the deposition of sediment onto the soil subgrade. However, deposition rates on the soil subgrade are almost impossible to predict. Therefore, a conservative approach should always be taken when establishing the design infiltration rate of the soil subgrade.

Soil subgrade infiltration—For this reason, ICPI recommends measuring the soil infiltration rate on the site and applying a safety factor of 2 for hydrologic design. For example, if the measured infiltration rate of a soil subgrade is 1 in./hr (25 mm/hr), then ½ in./hr (13 mm/hr) is the recommended design infiltration rate for calculations. This helps compensate for unpredictable decreases in infiltration due to construction and sediment deposition over time. A higher factor of safety may be appropriate for sites with highly variable infiltration rates due to different soils or soil horizons. Recommended sampling and testing procedures for determining soil infiltration rates are provided in Section 3.

Some agency guidelines prohibit permeable pavements over soils with an infiltration rate less than 0.5 in./hr (3.5×10^{-4} cm/sec) and sometimes require underdrains. As previously noted, soils with infiltration rates as low as 0.01 in./hr (7×10^{-6} cm/sec) can infiltrate about 0.5 in. (13 mm) over 48 hours. So there is almost always an opportunity to infiltrate water, the most effective means to reducing pollutants. The effectiveness of PICP infiltrating in low-infiltration clay soils has been documented by Fassman (2010) and in another study by Smolek (2016). Additionally, the California Department of Transportation (Caltrans 2016) allows permeable pavements in soils with infiltration rates as low as 0.01 in./hr (7×10^{-6} cm/sec). Therefore, not restricting PICP to soils having a 0.5 in./hr (3.5×10^{-4} cm/sec) infiltration rate or greater and designing PICP to capture and infiltrate as much water as economically possible presents a more effective approach to volume and pollutant reductions.

Cold Climate Design Considerations

Experience with PICP in cold climates in the U.S. and Canada has demonstrated no heaving after many winters. Should water freeze within an open-graded base, there is sufficient space between the aggregates to allow for water to expand (9%) as it freezes without their movement. Air in the spaces among aggregates and heat from the earth and water retained in the soil can extend thaw periods. This extension means PICP can provide additional water quantity reductions and quality improvement compared to other exposed control measures. This has been demonstrated by Roseen, first evaluating testing gravel filters (2009), then PICP (2013), as well as by Drake (2012).

When frozen, the soil subgrade generally does not heave because it had sufficient time to drain to an unsaturated condition prior to freezing. Research in Chicago, Illinois, demonstrated the ability of the PICP base to not freeze in the winter. The City of Chicago Department of Transportation monitored ambient air and in the upper, middle, and lower portions of the Maxwell Street Market Plaza PICP parking lot from September 2008 to February 2009. See Figure 2-16. Temperature data indicated that none

Figure 2-16. Maxwell Street Market Plaza winter temperature monitoring by the City of Chicago demonstrated the insulating effect of the aggregate. This condition precluded heaving.

of the PICP layers reached freezing temperatures. The coldest day, January 16, 2009, was -7° F (-21.7° C) not including the wind chill factor. The coldest Fahrenheit temperatures were as follows: upper area 33.4° (0.7° C), middle 34.1° (1.2° C) and lower base at 38.6° (3.7° C) (Attarian 2010).

Research on other permeable pavements in cold climates using open-graded bases (similar to that in PICP) provide further explanations for an absence of heaving and not needing a frost protection layer. Kevern (Kevern 2009) studied temperatures in open-graded bases under pervious concrete during the winter and concluded that, "Air in the aggregate base…acts as an insulating layer that, coupled with the higher latent heat associated with the higher soil moisture content, delays or eliminates the formation of a frost layer…while maintaining permeability." He also noted faster thawing than traditional concrete pavement.

Houle (Houle 2009) at the University of New Hampshire Stormwater Center measured air and base temperatures in an installation there of porous asphalt base. His findings agreed with Bäckström's (Bäckström 2000) study on porous asphalt bases that yielded greater resistance to freezing, decreased frost penetration and provided more rapid thawing than conventional pavement due to higher water content in the underlying soil which increased the latent heat in the ground.

This heat-holding characteristic of open-graded bases enables permeable surfaces on them to use lower doses of deicing materials with commensurate cost savings. Substantial reductions also have been observed on porous asphalt (UNHSC 2008). PICP can expect similar reductions when sunlight exposure and temperatures melt snow, and it immediately infiltrates into the surface. Figure 2-17 illustrates this melting, which can also reduce slipping hazards from ice and related liability.

An unacceptably high concentration of deicing salts and sand in snowmelt, from impervious surfaces into PICP as well as those placed directly on it, requires some design considerations. The considerations apply in climates with extended winters having large, rapid volumes of snow melt in the late winter and early spring. Such areas are mostly in the northern US and Canada (Caraco 1997). There is no BMP

Figure 2-17. Upon plowing with standard plowing equipment, remaining snow can melt with water immediately entering the PICP surface. This reduces deicing and sand materials use as well as reducing liability hazards from slipping on ice.

including PICP that removes chlorides in deicing materials. Studies by Van Seters (2007) on PICP suggests that potential for deicing salts to mobilize heavy metals may warrant an increase in the depth of soil to the seasonally high ground water table 6.7 ft (2 m) or more below the PICP subbase for filtering purposes. In a subsequent report on a second PICP parking lot monitored by Van Seters (2015), he found no evidence of mobilized metals likely due to low salt use during the five-year monitoring period.

Sand applied for traction can reduce the surface infiltration rate of PICP and will require removal in the spring. Plowed and piled snow with chlorides and/or sand should be located on parking lot islands or other vegetated areas. As an alternative to sand for traction, PICP joint filling stone can be used (i.e., ASTM No. 8, 9 or 89 stone). Maintenance should include annual inspection in the spring and vacuum removal of sand and surface sediment, as well as monitoring of groundwater for chlorides. This is paramount to continued infiltration performance and is covered in Section 5.

Managing salts and sand on a PICP site is a better option than collecting them on an impervious pavement and sending them in high concentrations to streams, lakes and rivers. If salts are used for deicing PICP and build up is a concern, then the soil and/or groundwater should be monitored. The amount of salts that locate in the soil and are transferred out of the PICP will vary, and monitoring can be done through sampling water in observation wells located in the pavement base and soil. Chloride levels in the samples should be compared to local or national criteria for the particular use of the water in the receiving lake, stream, or river (e.g., drinking water, recreation, fishing, etc.).

If unacceptably high chloride concentrations in the runoff and groundwater are anticipated, then consideration should be given to using one or two design options below:

(a) Runoff from snowmelt can be diverted from the pavement during the winter. Diverting runoff away from the pavement is typically done through pipes in base/subbase. Pipe valves must be operated each winter and spring. Snowmelt, however, cannot be treated but is diverted elsewhere.

(b) Oversized drainage pipes can be used to remove the runoff during snowmelt, and then be closed for the remainder of the year. The owner of the pavement must take responsibility for operating pipe valves that divert snowmelt. This may not be realistic with some designs.

When the local frost depth exceeds 3 ft (1 m), PICP should be set back from the subgrade of adjacent roads by at least 20 ft (6 m). This will reduce the potential for ice lenses and heaving of soil under the roadway. If this is not practical, another approach is using a vertical impermeable liner and perforated underdrains along the side of the PICP closest to a conventional roadbase to help block movement of water into the soil subgrade under the road. Additional guidance on permeable pavements for road shoulders is provided in an AASHTO report by Hein (2013).

Finally, concrete pavers in freezing climates exposed to deicers should meet the freeze-thaw durability requirements in ASTM C936 or CSA A231.2. Both standards reference methods with similar procedures for freeze-thaw testing while immersed in a 3% saline solution. Based on the geographic project location in the U.S., ASTM C936 provides an optional lower temperature (-15°C) for freeze-thaw durability testing according to test method ASTM C1645. This test method with the optional lower temperature is identical to the lowest temperature in CSA A231.2 test method, as well as the number of freeze-thaw cycles and mass lost criteria. Meeting or exceeding these criteria does not guarantee absolute durability in winter conditions. No freeze-thaw durability test can do so, because they cannot replicate site conditions. Instead, they are surrogate, accelerated tests whose results may be correlated to long-term in-situ durability performance. Meeting or exceeding the freeze-thaw durability criteria in the ASTM (optional -15°C) and CSA product standards helps provide a greater assurance of durability performance in winter conditions.

An advantage of PICP is its ability to drain snowmelt and icemelt into it. This avoids surface refreezing and related slipping hazards on ice. On some sites, there can be subfreezing temperatures and solar exposure that don't allow melting and infiltration to occur. If that's the case, sometimes deicers will be required. A key to successfully using deicing materials on PICP is using only as much as needed to do the job. Do not over apply deicing chemicals; follow the recommended dosage. This will maximize their benefits while minimizing any damage to the concrete pavers and to the surrounding environment. The following guidelines can help limit deicing chemical use while maintaining a safe environment:

- Do not use deicing chemicals in place of snow removal, but reserve them for melting ice formed by freezing precipitation or freezing snow melt.
- Rock salt (sodium chloride or NaCl) is the least damaging to concrete materials and should be used whenever possible.
- If a more effective, quicker acting deicer is necessary, consider the judicial use of calcium chloride.
- The use of magnesium chloride and calcium magnesium acetate (CMA) are not recommended, because they can chemically degrade all types of concrete, significantly increasing potential damage.
- The potential for concrete damage from CMA increases with the amount of magnesium in the formulation.
- Limit the use of deicing chemicals by combining them with a traction aid such as jointing stone.
- Avoid using sand for traction. If used, it will need to be vacuumed from the surface in the spring.

Additional guidance on deicer use is provided in Section 5 Maintenance on page 104.

Section 3. PICP Design

Desktop Assessment

A preliminary assessment is an essential prerequisite to detailed site, hydrological and structural design. This assessment includes a review of the following:

- Rainfall data including daily rainfall depths
- Underlying geology and soils maps
- Identifying the NRCS hydrologic soil groups (A, B, C, D)
- Verifying history of fill soil, previous disturbances or compaction
- Review of topographical maps and identifying drainage patterns
- Identifying streams, wetlands, wells and structures
- Confirming absence of stormwater hotspots
- Identifying current and future land uses draining onto the site
- Identify potential receptors for underdrains (if used)

PICP design follows paths for structural and hydrological analyses as noted in Figure 3-1. PICP design merges these two previously disconnected spheres of civil engineering and design. The base/subbase

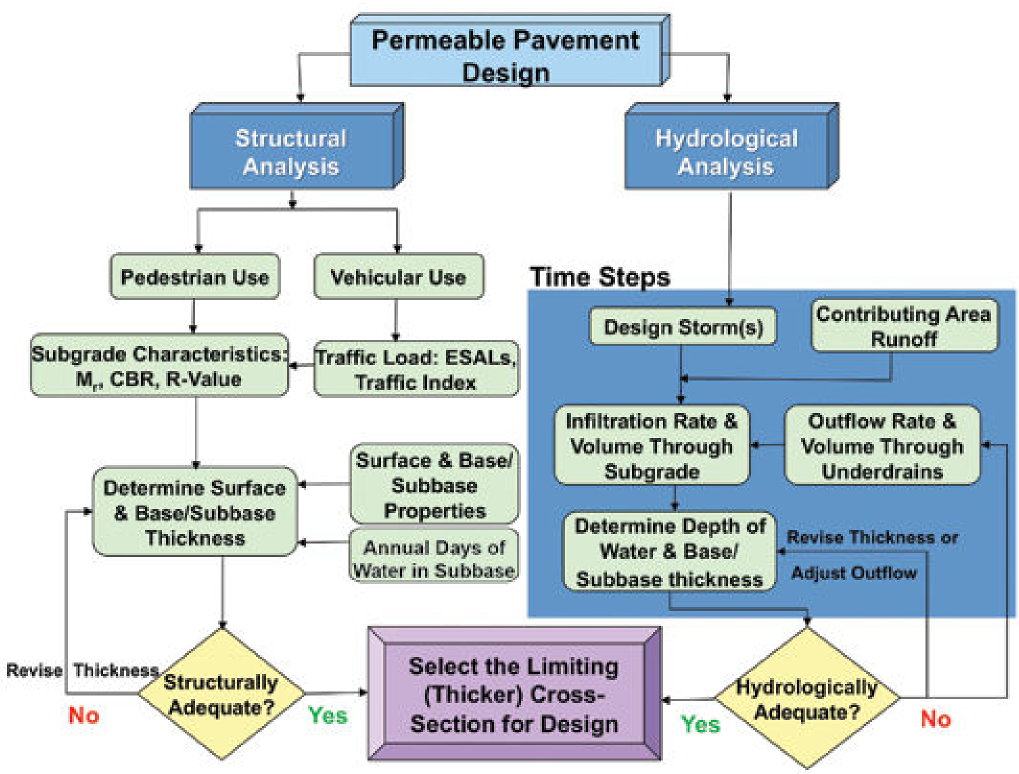


Figure 3-1. PICP design flow chart. See accompanying text that explains each step.

thickness is determined for hydrological and structural (vehicular traffic loading) needs, and the thicker section is selected for drawings, specifications and construction. In many cases, the hydrologic requirements will require a thicker base than that required for supporting traffic. The following explains the design process by following the Figure 3-1 flow chart.

Structural Analysis

Pedestrian Use—These use only the ASTM No. 57 stone base with a minimum thickness of 6 in. (150 mm). Thicker bases can be used for additional water storage.

Residential driveways have a minimum 6 in. (150 mm) ASTM No. 2 subbase under a 4 in. (100 mm) thick ASTM No. 57 base. Some designs may use ASTM No. 57 stone for the entire driveway base and subbase. This makes one less aggregate to install on typically small areas with minimal vehicular loads. Section 4 illustrates one of several possible designs for a residential driveway.

Vehicular Use Traffic Load: ESALs, Traffic Index—This requires an estimate of the vehicular traffic loads expressed as 18,000 kip (80 kN) equivalent single axle loads (ESALs) or Caltrans Traffic Index (TI) over the design life of the pavement, typically 20 years. The ESAL concept recognizes that when a vehicle passes over a pavement, it damages it. The cumulative effects of many passes (ESALs) eventually causes ruts or cracks making any pavement unserviceable and needing rehabilitation. For PICP, rutting is the primary damage, so structural design aims to minimize this.

Vehicles passing over a pavement exert a wide range of axle loads. Trucks and busses do the most damage to pavements because their loads and tire pressures are much higher than automobiles. One pass of a fully loaded truck will do more damage to pavement than several thousand automobiles passing over it.

The 18,000 lb (80 kN) emerged as a convenient basis for characterizing loads from trucks as part of the American Association of State Highway Officials (AASHO) road tests conducted in the 1950s (more recently called AASHTO; the T stands for Transportation). The number of ESALs is determined by the weight of each axle and dividing them by a standard ESAL of 18,000 lbs or 80 kN. For example, a five axle trailer-truck has two rear axles on the trailer each exerting 18,000 lbs (80 kN); two on the back of the truck at 15,800 lbs (70 kN); and one in the front (steering) of the truck at 11,000 lbs (50 kN).

AASHTO uses "load equivalency factors" or LEFs for each axle to estimate ESALs from vehicles. LEFs equalize all loads to 18,000 lbs (80 kN) and raise them to the fourth power as AASHTO established this relationship in their road tests. LEFs and resulting ESALs for one pass of this truck over a pavement are calculated as follows (in kN):

Trailer: $(80/80)^4 = 1$ (x 2 axles) = 2 ESALs
Truck rear: $(70/80)^4 = 0.6$ (x 2 axles) = 1.2 ESALs
Truck front: $(50/80)^4 = 0.15$ ESALs
When added together LEFs = 2 + 1.2 + 0.15 = 3.35 ESALs.

In other words, for every pass across a pavement, the trailer-truck in this example exerts 3.35 18,000 lbs (80 kN) ESALs. For all projects, ESALs are estimated for a range of truck configurations expected to use a pavement over its lifetime. To put automobile axle loads into perspective, the two axle loads from one passenger automobile placed into the formula yields about 0.0002 ESALs. As previously noted, pavement design primarily considers trucks because they exert the highest loads and tire pressures, thereby rendering

PICP can support an AASHTO H-20 truck load. This characterization of one truck axle loading was developed for bridge design and not pavement design. AASHTO H-20 loading is defined in the AASHTO publication, *Standard Specifications for Highway Bridges* and is one front axle load of 8,000 lbs (36 kN) and a single rear axle (tandem wheels) of 32,000 lbs (142 kN). H-20 loading is mistakenly construed as a basis for pavement design which typically characterizes ESALs as 18,000 lb (80 kN) repetitions and not as a single load. Incidentally, one H-20 load is 10 ESALs. H-20 loads require characterization as ESAL *repetitions* in order to be used in pavement design.

the most damage. In contrast, thousands of automobiles are required to apply the same loading and damage as one passage of a truck.

The recommended ESAL limit for PICP is 1,000,000 using non-stabilized open-graded aggregate bases and subbases. This means PICP can support truck loads for a parking lot, alley, residential collector streets as well as on-street parking lanes along busier roads with commercial truck traffic. This has been verified with full-scale load testing of PICP (Li 2014) as well as use in fire stations and commercial parking lots that experience truck traffic. Table 3-1 provides a range of road classifications and typical lifetime ESALs.

Table 3-1. Road Classification, Description and Traffic (after BIA 2003)

<table>
<tr><th>Road Class</th><th>Description</th><th>Design ESALs*</th><th>Design TI**</th><th></th><th></th></tr>
<tr><td>Arterial</td><td>Through traffic with access to high-density, regional, commercial and office developments or downtown streets. General traffic mix.</td><td>9,000,000</td><td>11.5</td><td rowspan="2"></td><td rowspan="9">***Potential Design Range for PICP with Stabilized Bases</td></tr>
<tr><td>Major Collector</td><td>Traffic with access to low-density, local, commercial and office development or high density, residential sub-divisions. General traffic mix.</td><td>3,000,000</td><td>10</td></tr>
<tr><td>Minor Collector</td><td>Through traffic with access to low-density, neighborhood, commercial development or low-density, residential sub-divisions. General traffic mix.</td><td>1,000,000</td><td>9</td><td rowspan="7">Design Range for PICP on Non-stabilized, Open-Graded Aggregate Bases</td></tr>
<tr><td>Bus Passenger Drop-off</td><td>Public transport centralized facility for buses to pick up passengers from other modes of transport, or for parking of city or school buses.</td><td>500,000</td><td>8.5</td></tr>
<tr><td>Local Commercial</td><td>Commercial and limited through traffic with access to commercial premises and multi-family and single-family residential roads. Used by automobiles, service vehicles and heavy delivery trucks This category includes large parking lots at commercial retail facilities.</td><td>330,000</td><td>8</td></tr>
<tr><td>Residential</td><td>No through traffic with access to multi-family and single-family residential properties. Used by automobiles, service vehicles and light delivery trucks, including limited construction traffic.</td><td>110,000</td><td>7</td></tr>
<tr><td>Facility Parking and Alleys</td><td>Parking areas for automobiles at large facilities with access for emergency vehicles and occasional use by service vehicles or heavy delivery trucks.</td><td>90,000</td><td>7</td></tr>
<tr><td>Commercial Parking</td><td>Restricted parking and drop-off areas associated with business premises, mostly used by automobiles and occasional light delivery trucks. No construction traffic over finished surfaces.</td><td>30,000</td><td>6</td></tr>
<tr><td>Commercial Plaza</td><td>Predominantly pedestrian traffic, but with access for occasional heavy maintenance and emergency vehicles. No construction traffic over finished surfaces.</td><td>10,000</td><td>5</td></tr>
</table>

*ESAL = 18,000 lb (80 kN) equivalent single axle load
**TI = Caltrans Traffic Index TI = 9 X $(\text{ESALs}/1{,}000{,}000)^{0.119}$
***Consult a pavement engineer

Subgrade Characteristics: M_r, CBR, R-value—Soil stability under traffic should be carefully reviewed for each application by a qualified geotechnical or civil engineer and lowest anticipated soil strength or stiffness values used for design. The structural design procedure explained below relies on soil characterized using resilient modulus (M_r), California Bearing Ratio (CBR), or resistance (R-value). Transportation agencies and design engineers use one or more of these to characterize the ability of soil to withstand traffic loads. Correlations among M_r, CBR and R-value are as follows:

M_r in psi = $2{,}555 * (\text{CBR})^{0.64}$ (Equation 3-1)
M_r in MPa = $17.61 \times \text{CBR}^{0.64}$ (Equation 3-2)
M_r in psi = $1{,}155 + 555 \times R$ (Equation 3-3)

M_r in MPa = (1,155 + 555 x R)/145 (Equation 3-4)

PICP structural design for vehicular applications recommends a minimum soil CBR (96-hour soaked per ASTM D 1883 or AASHTO T-193) of 2%, or a minimum R-value = 4 per ASTM D2844 or AASHTO T-190, or a minimum M_r of 3,500 psi (24 MPa) per AASHTO T-307 to qualify for use under vehicular traffic. Soil compaction required to achieve this will reduce the infiltration rate of the soil. Therefore, the permeability or infiltration rate of soil should be assessed at the density required to achieve at least 2% soaked CBR. Soils with such low CBRs will have very low infiltration rates.

If soils have a soaked CBR<2% or are expansive when wet, one option is treatment to raise the CBR above 2% by stabilizing them. Treatment can be with cement, lime or lime/flyash. Guidelines on the amount and depth of cement required for soil stabilization can be found in publications by the Portland Cement Association (PCA 2003). Soil stabilization will render essentially no infiltration, and this should be reflected in the hydrologic analysis. Cement- or asphalt-stablized base/subbase aggregates including pervious concrete are another option. Stabilized bases are covered below under "Base/subbase Properties."

Surface Properties—Many accelerated traffic studies and non-destructive testing have defined the AASHTO layer coefficient of (non-permeable) interlocking concrete pavements and the bedding sand layer equal to or higher than an equivalent thickness of asphalt, typically 0.44 per inch (or 25 mm) of thickness (ASCE 2016). Many of these studies are summarized by Rollings (Rollings 1992). Some studies have measured AASHTO layer coefficients higher than 0.44 due to progressive stiffening of the paver and bedding sand layers.

In contrast, testing to characterize the layer coefficient of the pavers and bedding in PICP has been minimal. PICP layer coefficients are estimated between 0.20 to 0.40 with 0.3 as an average value. This value includes a 3 1/8 in. (80 mm) thick units with joints filled with ASTM No. 8, 9 or 89 stone, and a 2 in. (50 mm) thick bedding layer of typical ASTM No. 8 bedding stone under PICP units. This value considers wider joints in PICP and filled with aggregate with a lower contact area with the adjacent paver sides and bottoms than those in interlocking concrete pavement with sand-filled joints. Manufacturers of pavers used in PICP may have additional information and test results that characterize the layer coefficient for their pavers, using specific jointing and bedding materials. They may also have additional information that characterizes benefits of specific paver shapes on structural and hydrologic design, installation and maintenance.

Base/subbase Properties—Dense-graded road base consists of crushed stone and fines (material passing the No. 100 and 200 or 0.150 and 0.075 mm sieves) with densities from approximately 120 to 145 pcf (1,922 to 2,322 kg/m^3) with porosities less than 15%. In contrast, open-graded aggregates for PICP have no fines (≤2% passing the No. 200 sieve) and are typically 95 to 120 pcf (1,522 to 1,922 kg/m^3). Porosities should be at least 30% for water storage. Porosity can be approximated using ASTM C29 Standard Test Method for Bulk Density ("Unit Weight") and Voids in Aggregate. Sieve analysis of washed gradations should be per ASTM C136 Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates. Porosity is the volume of voids divided by the total volume of the open-graded aggregate. This measurement is different than void ratio which is the volume of voids around the aggregate divided by the volume of solids, i.e., the aggregate itself. Jointing, bedding, base and subbase aggregates used in vehicular PICP applications should be crushed with minimum 90% fractured faces and a minimum Los Angeles (LA) abrasion <40 per ASTM C131 Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine and C535 Standard Test Method for Resistance to Degradation of Large-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine.

The resilient modulus or stiffness of open-graded materials in permeable pavements are generally recognized as being lower than dense-graded materials (typically 0.12 to 0.14). Consequently, AASHTO layer coefficients are 0.09 per inch (25 mm) for the No. 57 stone base and 0.06 for the subbase. These low coefficients recognize that the aggregate will be saturated at least part of each year. In addition, laboratory tests by Jones (2010) and Raad (1994) noted lower resilient modulus values than those typical to dense-graded bases. Raad noted that No. 57 material remained more stable in saturated conditions than dense-graded base. Hein (2006) and Salem (2006) also conducted laboratory tests that demonstrated the structural contribution of open-graded bases when not saturated.

Some state transportation agencies specify well-graded aggregates as permeable bases (drainage layers) under conventional pavements (either unstabilized, or stabilized with asphalt or cement). Such bases have lower porosity than open-graded bases, often under 20%. These lower porosity aggregates can be used in PICP for their pollutant-filtering capacity as long as they meet certain gradations, and only under certain conditions, as detailed below.

These bases can have a higher percentage of material passing the No. 4 (4.75 mm) sieve than those described in this manual, but are limited to 2% passing the No. 200 (0.075 mm) sieve. Using such bases for PICP can be a design option when water storage is not the primary objective, for example, when smaller rainfall depths are captured, treated and released. This may be the design case over low- or no-infiltration rate soils. Stability is increased by using underdrains that prevent saturation of the aggregates, and related pore pressures. Such underdrains are recommended in all applications to prevent this condition.

Other aggregate bases may also be used if they are deemed to meet the hydrological and structural requirements of the projects by the engineer/designer of record. Due to its variable quality, and friability during compaction and service, recycled concrete aggregate (RCA) is not recommended in PICP vehicular applications. RCA can be used in pedestrian only areas. It should be mixed with non-recycled aggregates to no greater than 50% RCA content. Caution should be exercised in using RCA, as excessive fines risk clogging soil subgrade surfaces and underdrains.

Transportation agencies often have specifications for stabilized open-graded bases using cement or asphalt. These can be used to increase the structural capacity of PICP while offering permeability and water storage, albeit less volume within unstabilized, open-graded aggregates. Stabilized bases including pervious concrete can be used under the bedding layer or applied directly to the subgrade to increase the base stiffness and strength over weak soils. As a type of stabilized, permeable base, the use of pervious concrete directly under permeable pavers has been used in the Chicago area. See Figure 3-2. There is also a design method for heavy duty permeable pavement covered by Knapton (2008). Another approach is using impervious road asphalt with 3 in. (75 mm) diameter holes placed on a 3 ft (750 mm) orthogonal grid per UK recommendations (Interpave 2010). Finally, geogrids and three-dimensional geocells filled with open-graded aggregate have been used in a few PICP projects in the U.S. to offer additional structural support. See Figure 3-3. Suppliers of geogrids and geocells should be consulted for design guidance.

Figure 3-2. Pervious concrete is used as a base under PICP paving units in a Chicago, Illinois, restaurant parking lot. The pavers provide a durable winter surface while the pervious concrete provides improved structural support for heavy trucks. The underdrains lead to the Chicago River.

Figure 3-3. Geogrids and geocells are combined for additional PICP support while protecting tree root zones. Geocells were also applied at the bottom of the subbase layer for this street project built on clay soils and subject to substantial traffic.

Table 3-2. PICP subbase thicknesses (US units)

Number of Days in a 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
Subgrade Resilient Modulus, ksi (CBR) — 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 mm ASTM No. 2 for 1 in. Allowable Rut Depth (All subbases are under 4 in. thick ASTM No. 57 base, under 2 in. ASTM No. 8 bedding layer, under 3.125 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

Note: Subbase thickness is calculated by dividing metric thicknesses in Table 3-3 by 25 and rounding to the nearest 0.5 in. Designers should round up to the nearest inch.

Table 3-2. PICP subbase thicknesses (US units) (continued)

Number of Days in a 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
Subgrade Resilient Modulus, ksi (CBR) — 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 mm ASTM No. 2 for 1 in. Allowable Rut Depth (All subbases are under 4 in. thick ASTM No. 57 base, under 2 in. ASTM No. 8 bedding layer, under 3.125 in. thick 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

Note: Subbase thickness is calculated by dividing metric thicknesses in Table 3-3 by 25 and rounding to the nearest 0.5 in. Designers should round up to the nearest inch.

Table 3-3. PICP subbase thicknesses (metric units)

Number of Days in a Year Water Stands in Subbase		0				≤10				11 - 30				31 - 50			
Subgrade Resilient Modulus, MPa (CBR)	Dry	40	60	80	100	40	60	80	100	40	60	80	100	40	60	80	100
	Wet	24 (1.6)	36 (3)	48 (4.8)	60 (6.8)	24 (1.6)	36 (3)	48 (4.8)	60 (6.8)	24 (1.6)	36 (3)	48 (4.8)	60 (6.8)	24 (1.6)	36 (3)	48 (4.8)	60 (6.8)
Lifetime ESALs (Traffic Index)		Minimum Subbase Thickness in mm ASTM No. 2 for 25 mm Allowable Rut Depth (All subbases are under 100 mm thick ASTM No. 57 base, under 50 mm ASTM No. 8 bedding layer, under 80 mm thick concrete pavers.)															
50,000 (6.3)		150	150	150	150	150	150	150	150	150	150	150	150	175	150	150	150
100,000 (6.8)		150	150	150	150	210	150	150	150	260	150	150	150	285	180	150	150
200,000 (7.4)		230	150	150	150	315	210	150	150	365	255	160	150	395	285	185	150
300,000 (7.8)		290	180	150	150	375	265	170	150	425	315	215	150	455	340	240	160
400,000 (8.1)		330	220	150	150	420	305	210	150	470	350	255	175	500	380	280	200
500,000 (8.3)		360	250	160	150	450	335	240	160	500	380	280	205	530	410	305	230
600,000 (8.5)		385	275	185	150	475	360	260	180	525	405	305	225	555	435	330	250
700,000 (8.6)		410	295	205	150	495	380	280	200	550	425	325	245	580	455	350	270
800,000 (8.8)		425	310	220	150	515	395	295	215	565	440	340	260	600	470	365	285
900,000 (8.9)		440	325	235	155	530	410	310	230	585	455	355	270	615	485	380	295
1,000,000 (9.0)		455	340	250	165	545	425	325	240	600	470	365	285	630	500	390	310

Table 3-3. PICP subbase thicknesses (metric units) (continued)

Number of Days in a Year Water Stands in Subbase		51 - 70				71 - 90				91 - 110				111 - 130			
Subgrade Resilient Modulus, MPa (CBR)	Dry	40	60	80	100	40	60	80	100	40	60	80	100	40	60	80	100
	Wet	24 (1.6)	36 (3)	48 (4.8)	60 (6.8)	24 (1.6)	36 (3)	48 (4.8)	60 (6.8)	24 (1.6)	36 (3)	48 (4.8)	60 (6.8)	24 (1.6)	36 (3)	48 (4.8)	60 (6.8)
Lifetime ESALs (Traffic Index)		Minimum Subbase Thickness in mm ASTM No. 2 for 25 mm Allowable Rut Depth (All subbases are under 100 mm thick ASTM No. 57 base, under 50 mm ASTM No. 8 bedding layer, under 80 mm thick concrete pavers.)															
50,000 (6.3)		195	150	150	150	210	150	150	150	225	150	150	150	235	150	150	150
100,000 (6.8)		310	200	150	150	325	215	150	150	335	230	150	150	350	240	150	150
200,000 (7.4)		415	305	205	150	430	320	215	150	445	330	230	150	455	340	240	160
300,000 (7.8)		475	360	260	180	495	375	275	195	505	390	285	210	520	400	295	220
400,000 (8.1)		520	400	295	220	535	415	310	235	550	430	325	245	565	440	335	255
500,000 (8.3)		550	430	325	245	570	445	340	260	585	460	350	270	595	470	360	280
600,000 (8.5)		580	455	350	270	595	470	360	280	610	485	375	295	625	495	385	305
700,000 (8.6)		600	475	365	285	620	490	380	300	635	505	395	310	645	515	405	320
800,000 (8.8)		620	490	385	300	640	505	395	315	655	520	410	330	665	535	420	340
900,000 (8.9)		635	505	395	315	655	525	410	330	670	535	425	340	685	550	435	350
1,000,000 (9.0)		650	520	410	325	670	535	425	340	685	550	435	355	700	560	445	365

For the purposes of this manual, only designs using non-stabilized bases and subbases are covered. Experience using stabilized bases or subbase in PICP for high ESAL applications (i.e., over 1 million ESALs) is limited and requires expertise of an experienced pavement engineer as noted in Table 3-1.

Annual Days of Water in the Subbase—Following the flow chart in Figure 3-1, the number of days in a year when the subbase has standing water in it can be conservatively estimated as follows:

1. Determine the infiltration rate of the underlying soils. Applying a safety factor that reduces the measured infiltration rate is recommended to account for potential subgrade compaction during construction and sediment settling on it over time.
2. Using daily rainfall data, determine the average number of days per year that have a greater rainfall than the 24-hour infiltration rate of the subgrade.

Determine Surface and Base/Subbase Thickness—PICP surfaces for vehicular traffic are minimum 3 1/8 in. (80 mm) thick over 2 in. (50 mm) layer of ASTM No. 8 stone or similar aggregate. All bases for vehicular traffic are 4 in. (100 mm) thick ASTM No. 57 stone or similar sized aggregate. Tables 3-2 and 3-3 provide recommended subbase thickness. The tables provide subbase thickness solutions using ASTM No. 2 stone given ESALs or Caltrans Traffic Index (TI) and soil characterizations. ASTM No. 3 or 4 stone subbases are applicable.

The previous (4th) edition of this manual applied the AASHTO 1993 flexible pavement design method to determine the PICP subbase thickness. Research by the University of California (Davis) Pavement Research Center in 2014 (Li 2014) with mechanistic modeling and full-scale load testing validated the design tables published in the 4th edition of this manual. Therefore, 0.09 for the base and 0.06 for the subbase are realistic layer coefficients. The research clarified relationships between the number of days per year water stands in the subbase, soil properties, loads and resulting subbase thickness. The outcomes from the research are modified subbase thicknesses in Tables 3-2 (English units) and 3-3 (metric units). One outcome of the UC Davis research was that the tables allow for thinner subbases in semi-arid and arid climates that do not see many days per year with water in the subbase with saturated soil subgrades. The tables also allow for thinner subbases in high infiltration soils. UC Davis also developed a mechanistic computational model using Open Pave software (Li 2014). Input values and instructions for accessing this free software program is provided on www.icpi.org. Tables 3-2 and 3-3 were developed from this software program validated by full-scale load testing.

Research previously referenced in Section 2 and experience has shown that a frost protection layer of additional base is not required provided that the soil subgrade drains water prior to freezing and/or through perforated pipes. The minimal fines and high porosity of the base and subbase help prevent accumulation and freezing of water that creates frost heaving.

Hydrological Analysis

The first step in the hydrologic analysis is verifying hydrologic goals for the project. Several common water quality and quantity goals are listed in Section 2. Consult with the local regulatory agency to determine which goals apply to the project site.

Design Storm—The design storm(s) with the return period and intensity in inches or millimeters per hour is typically supplied by the municipality or other regulatory agency. While local data from the past 20 years is preferred, rainfall intensity-duration-frequency maps or databases can be referenced to establish the design storm for the eastern half of the U.S. (Hershfield 1961), western half (west of the 105th meridian) (Miller 1973), or Canada (Environment Canada 2010).

Contributing Drainage Area (CDA) Runoff—Some PICP designs may receive runoff from roofs, adjacent impervious pavement and pervious areas. The total area and CDA runoff from it (if applicable) should be estimated using the design storm(s). The total impervious area draining into the PICP should not exceed five times the area of the PICP. State or local regulations may require lower ratios. Since sediment deposition and PICP clogging rates are directly proportional to the amount of impervious CDA, careful consideration is required in deciding this ratio for each project. For some sites, impervious CDA may be cleaned regularly which can faciliate higher ratios. Other sites may not enjoy this service, and may require lower or no impervious CDAs. The designer should also consider the amount and cleanliness of runoff from roofs that drains onto PICP.

Figure 3-4. A double-ring infiltrometer applied to a test pit measures the soil infiltration rate in preparation for a retrofit PICP street.

The movement of water from impervious pavements into PICP is typically received as sheet flow. The inlet capacity of new or consistently vaccuumed PICP is assumed to be practically infinite and is generally not considered a design factor. Design relationships among an impervious contributing drainage area, its slope, sediment load and characteristics of the receiving PICP surface have been modeled by Kevern (2016). These provide some guidelines for determining the limits of adjacent impervious cover contributing runoff to PICP.

Infiltration Rate & Volume Through the Subgrade—Subsequent to the desktop assessment is an in-depth investigation of the site. This includes tests for soil infiltration that inform a decision on the design soil infiltration rate. The soil sampling and testing should be designed and supervised by a licensed professional geotechnical or civil engineer knowledgeable about local soils. Besides infiltration test results, this engineer should provide a soils report that includes assessment of design strength, compaction requirements as needed, and other appropriate site assessment information. Some guidelines follow on sampling and testing procedures to help determine the design soil infiltration rate.

Test pits dug with a backhoe are recommended for every 7,000 sf (700 m^2) of paving with a minimum of two holes per site. All pits should be dug at least 5 ft (1.5 m) deep with soil logs recorded to at least 3 ft (1 m) below the bottom of the base. More test pits at various depths (horizons) may be required by the engineer in areas where soil types may change, near rock outcroppings, in low lying areas or where the water table is likely to be within 6 ft (1.8 m) of the surface. Evidence of a high water table, impermeable soil layers, rock or dissimilar layers may require a no infiltration design.

The following tests are recommended on soils in test pits, especially if the soil has clay content. Besides assessing infiltration potential, the tests can assist in evaluating the soil's suitability for supporting traffic in a saturated condition. Other tests may be required by the design engineer. AASHTO tests equivalent to ASTM methods may be used.

1. Unified (USCS) soil classification per ASTM D2487 Standard Practice for Classification of Soils for Engineering Purposes.
2. Sampled moisture content in percent.
3. Onsite tests of the infiltration rate of the soil. Use local, state or provincial recommendations for test methods and frequency if they exist. All tests for infiltration should be done at the approximate elevation corresponding to the bottom of the subbase and in a saturated state. If there are no requirements for infiltration test methods, ASTM D3385 Test Method for Infiltration Rate of Soils in Field Using a Double-Ring Infiltrometer is recommended. Figure 3-4 illustrates a test pit with this double-ring infiltrometer on soil subgrade under an existing asphalt street pavement to be converted to PICP.

Table 3-4. Permeability of Hydrologic Soil Groups (HSG) (NRCS 2009)

Depth to water impermeablelayer[1]	Depth to high water table[2]	K_{sat} of least transmissive layerin depth range	K_{sat} depth range	HSG[3]
<20 in. (<50 cm)	—	—	—	D
20 to 40 in. (50 to 100 cm)	<24 in. (<60 cm)	>5.67 in./hr (>40.0 µm/s)	0 to 24 in. (0 to 60 cm)	A/D
		>1.42 to ≤5.67 in./hr (>10.0 to ≤40.0 µm/s)	0 to 24 in. (0 to 60 cm)	B/D
		>0.14 to ≤1.42 in./hr (>1.0 to ≤10.0 µm/s)	0 to 24 in. (0 to 60 cm)	C/D
		≤0.14 in./hr (≤1.0 µm/s)	0 to 24 in. (0 to 60 cm)	D
	≥24 in. (≥60 cm)	>5.67 in./hr (>40.0 µm/s)	0 to 20 in. (0 to 50 cm)	A
		>1.42 to ≤5.67 in./hr (>10.0 to ≤40.0 µm/s)	0 to 20 in. (0 to 50 cm)	B
		>0.14 to ≤1.42 in./hr (>1.0 to ≤10.0 µm/s)	0 to 20 in. (0 to 50 cm)	C
		≤0.14 in./hr (≤1.0 µm/s)	0 to 20 in. (0 to 50 cm)	D
>40 in. (>100 cm)	<60 cm (<24 in.)	>1.42 in./hr (>10.0 µm/s)	0 to 40 in. (0 to 100 cm)	A/D
		>0.57 to ≤1.42 in./hr (>4.0 to ≤10.0 µm/s)	0 to 40 in. (0 to 100 cm)	B/D
		>0.06 to ≤0.57 in./hr (>0.40 to ≤4.0 µm/s)	0 to 40 in. (0 to 100 cm)	C/D
		≤0.06 in./hr (≤0.40 µm/s)	0 to 40 in. (0 to 100 cm)	D
	24 to 40 in. (60 to 100 cm)	>5.67 in./hr (>40.0 µm/s)	0 to 20 in. (0 to 50 cm)	A
		>1.42 to ≤5.67 in./hr (>10.0 to ≤40.0 µm/s)	0 to 20 in. (0 to 50 cm)	B
		>0.14 to ≤1.42 in./hr (>1.0 to ≤10.0 µm/s)	0 to 20 in. (0 to 50 cm)	C
		≤0.14 in./hr (≤1.0 µm/s)	0 to 20 in. (0 to 50 cm)	D
	>40 in. (>100 cm)	>1.42 in./hr (>10.0 µm/s)	0 to 40 in. (0 to 100 cm)	A
		>0.57 to ≤1.42 in./hr (>4.0 to ≤ 10.0 µm/s)	0 to 40 in. (0 to 100 cm)	B
		>0.06 to ≤0.57 in./hr (>0.40 to ≤4.0 µm/s)	0 to 40 in. (0 to 100 cm)	C
		≤0.06 in./hr (≤0.40 µm/s)	0 to 40 in. (0 to 100 cm)	D

[1]An impermeable layer has a K_{sat} less than 0.0014 in./hr (0.01 µm/s) or a component restriction of fragipan; duripan; petrocalcic; orstein; petrogypsic; cemented horizon; densic material; placic; bedrock, paralithic; bedrock, lithic; bedrock, densic; or permafrost.

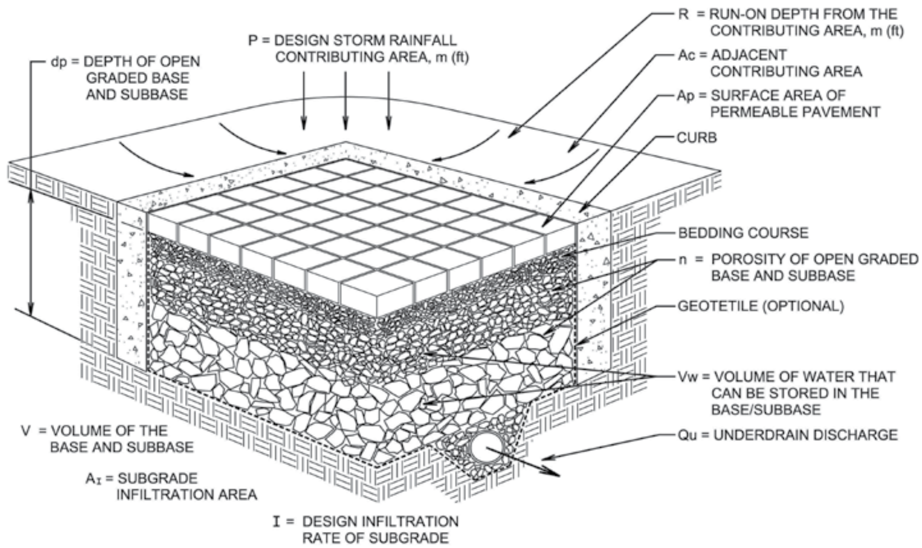
[2]High water table during any month during the year.

[3]Dual HSG classes are applied only for wet soils (water table less than 24 in. or 60 cm). If these soils can be drained, a less restrictive HSG can be assigned, depending on the K_{sat}.

Table 3-5. Approximate correlations between permeability and compacted soils per the Unified Soil Classification (Moulton 1980)

USCS Soil Classification Per ASTM D2487	Coefficient of Permeability, k, Approximate inches/hour (µm/s)
GW–well graded gravels	1.3 to 127 (9.12 to 896)
GP–poorly graded gravels	6.8 to 13,700 (50 to 96,661)
GM-silty gravels	1.3×10^{-4} to 13.5 (0.00092 to 95)
GC-clayey gravel	1.3×10^{-5} to 1.3×10^{-2} (9.17×10^{-5} to 0.0917)
SW-well graded sands	0.7 to 68 (5 to 480)
SP-poorly graded sands	0.07 to 0.7 (0.49 to 4.9)
SM-silty sands	1.3×10^{-4} to 0.7 (0.00091 to 4.9)
SC-clayey sands	1.3×10^{-5} to 0.7 (9.17×10^{-5} to 4.9)
ML-inorganic silts of low plasticity	1.3×10^{-5} to 0.7 (9.17×10^{-5} to 4.9)
CL-inorganic clays of low plasticity	1.3×10^{-5} to 1.3×10^{-3} (9.17×10^{-5} to 0.00917)
OL-organic silts of low plasticity	1.3×10^{-5} to 1.3×10^{-2} (9.17×10^{-5} to 0.0917)
MH-inorganic silts of high plasticity	1.3×10^{-6} to 1.3×10^{-4} (9.17×10^{-6} to 9.17×10^{-4})
CH-inorganic clays of high plasticity	1.3×10^{-7} to 1.3×10^{-5} (9.17×10^{-7} to 9.17×10^{-5})
OH-organic clays of high plasticity	Not recommended under full and partial infiltration PICP
PT-Peat, mulch, soils with high organic content	Not recommended under full and partial infiltration PICP

Note: These values characterizing the permeability of rolled-earth embankments with moisture-density control are from FHWA *Highway Subdrainage Design* (Moulton 1980). The table was originally published in *Earth and Earth-Rock Dams*, by Sherard, J.L. et alia, published by John Wiley & Sons, Inc., in 1963. These can be compared to the values in Table 3-4 to better understand the impact of compaction on soil permeability.



A_c = Surface area of the adjacent contributing drainage area (CDA), sf (m^2)

A_p = Surface area of the permeable interlocking concrete pavement, sf (m^2)

A_I = Area of subgrade infiltration, sf (m^2). Commonly $A_P \approx A_I$. In situations where a portion of the subgrade is either lined (e.g., a PICP area adjacent to a building) or is not conducive to infiltration (e.g., highly sloped), the reduced subgrade infiltration area is adjusted. Alternately, where the subbase extends beyond the curb line an increased subgrade infiltration area can be used.

C = Runoff Coefficient for the contributing drainage area, which represents the ratio of runoff to rainfall. C is between 0 and 1.

d_p = Depth of open graded stone base/subbase reservoir, ft (m). The depth does not include the bedding layer or pavers. This depth should be compared to the base/subbase thickness determined from the structural analysis.

I = Design infiltration rate in ft/hr (m/hr) of the subgrade soil under the pavement. Design infiltration rates are based on in-situ infiltration tests and reduced per engineering judgment.

n = Porosity of the base and subbase aggregates (typically 0.3 to 0.4).

P = Design storm rainfall depth, ft (m)

Q_U = Outflow rate through the underdrain(s), cf/hr (m^3/hr). Cubic feet per second is multiplied by 3,600 to convert to cf/hr per hour.

R = Run-on depth from the contributing drainage area, ft (m), which is the design storm rainfall depth (P) multiplied by the runoff coefficient (C) of the contributing drainage area. $R \le P$.

T_D = The maximum post-storm drawdown time for the base/subbase (hr). The recommended maximum time for the base/subbase drawdown is typically defined by the local stormwater agency, generally no more than 72 hours including the rainstorm.

T_s = Duration of the design storm (hr) that fills the subbase reservoir. Typically, a 24-hour design storm is used for sizing, but it can range from a 2-hour to a 24-hour event.

V = Volume of the base/subbase reservoir, cf (m^3)

V_w = Volume of water that can be stored in the base/subbase reservoir, cf (m^3)

Z = Elevation factor (dimensionless). When the underdrain is raised above the subgrade, Z represents the percentage of time when underdrain flow exists.

Figure 3-5 Design parameters for calculating the subbase depth for water storage for full and partial infiltration systems

Caution: Laboratory infiltration (permeability) tests are not recommended as soil samples have a high risk of structure and porosity changes. Results from field tests can be better approximations because the structure and porosity of soils are not as easily changed. However, caution is still required in conducting field tests on least-disturbed soil as a result of excavation. On-site tests do not account for loss of the soil's conductivity from construction, compaction and clogging from sediment. Nor do they account for lateral drainage of water from the soil into the sides of the base. Individual test results should not be considered absolute values directly representative of expected drawdown of water from the open-graded aggregate. Instead, the test results should be interpreted with permeability estimates based on soil texture, structure, pore geometry and consistency (Fairfax 1991). As previously noted, for design purposes, a safety factor of 2 should be applied to the average or typical measured site soil infiltration rate.

The term 'infiltration rate' pertains to movement of water into a surface, and in the context of this manual, a saturated surface. The term 'permeability' (K_{SAT}) pertains to movement of water through a medium such as saturated aggregate or soil. For this manual, the two terms, infiltration rate and permeability, are used interchangeably.

Table 3-4 presents representative permeabilities for NRCS hydrologic soil groups (HSG) A, B, C or D according to the depth to the impermeable layer and the depth to high water table (USDA 2009). Table 3-5 provides guidance on the permeability of soils classified using the Unified Soils Classification System (USCS). The values represent compacted soils. For uncompacted and generally undisturbed soils, Table 3-4 can be used to assess soil infiltration rates based on the hydrologic soil group. The permeability rates of uncompacted soils in Table 3-4 can be compared to rates for compacted soils in Table 3-5. Soils with a tested permeability equal to or greater than 0.5 in./hr (3.5×10^{-4} m/sec) usually will be gravel, sand, loamy sand, sandy loam, loam, and silt loam. These are usually soils with no more than 10-12% passing the No. 200 (0.075 mm) sieve. While informative for obtaining initial estimates, percolation test results for the design of septic drain fields are not recommended for the design of stormwater infiltration systems as they can overestimate soil infiltration rates (Fairfax 1991) (Oram 2003).

On-site soil infiltration testing is expensive, and residential and some small commercial PICP projects may not justify the expense. In such cases, a soil classification can be used to estimate permeability by selecting conservative (lower) values from the ranges provided in Tables 3-4 or 3-5. Again, conservative values should be selected from one of these tables based on the presence or absence of specified soil subgrade compaction for estimating soil subgrade permeability. Silt and clay soils with lower permeability often require perforated drain pipes per a partial infiltration design.

Design Calculations—Full Infiltration Design—The following procedure calculates the base and subbase thickness for full infiltration designs, i.e., no underdrains. Figure 3-3 provides a summary of symbols used in PICP calculations.

To ensure the system is accommodating maximum water storage requirements, the volume of water stored in the pavement subbase (V_w) needs to accommodate the rainfall amount at the end of the design storm (T_S), as there has been no opportunity for post-storm drawdown.

Identify the inputs and outputs (water balance)—The following water balance characterizes the inputs and outputs for a full infiltration system during the design storm.

Full Infiltration Design Calculations

Rainfall volume falling directly on the permeable pavement	Plus	Run-on volume from the adjacent contributing drainage area	Minus	Infiltration volume into the underlying soil
PA_p	+	RA_c	–	$I(T_S)A_I$

It may be possible that the results of the water balance analysis will be less than or equal to zero, particularly over soils with high infiltration rates, in which case the pavement thickness required for structural capacity will govern the design.

When the results of the water balance analysis is greater than zero, then the required volume of water that needs to be stored in the pavement base (Vw) can be calculated using Equation 3-5.

$\mathbf{V_W = P(A_P) + R(A_C) - I(T_S)A_I}$ (Equation 3-5)

The hydraulic depth, or the depth of water within the base/subbase at the end of the design storm, can be calculated using Equation 3-6.

Hydraulic depth $\mathbf{= V_W/A_P * n}$ (Equation 3-6)

To ensure the subgrade does not remain saturated for longer than the maximum allowable post-rainfall storage time (TD), which is usually between 24 and 72 hours, Equation 3-7 needs to be satisfied.

$\mathbf{T_D > V_W/A_I * I}$ (Equation 3-7)

When this condition is met, a full-infiltration design is acceptable. When this condition is not met, then a partial-infiltration design is required.

Full Infiltration Calculations

Step 1 – Assess site conditions. A busy parking lot in Durham, New Hampshire, is being designed in an urbanized area where storm sewers have limited capacity to convey runoff from an increase in existing impervious surfaces. Runoff from a 2 acre (8,094 m^2) asphalt parking lot (assume 100% imperviousness) is to be captured by a 1 acre (4,047 m^2) PICP area over an open-graded base. In other words, $A_P = A_I = 1$ acre, $A_C = 2$ acres. The project is not close to building foundations nor are there any wells in the area.

Soil borings revealed that the seasonal high water is 10 ft (3 m) below grade. The soil borings and testing indicated a USCS classification of GM (silty gravel) with 18% passing the No. 200 (0.075 mm) sieve. Infiltration was field tested at 0.48 in./hr (0.04 ft/hr or 3.4×10^{-6} m/sec). While this was the tested rate, the designer is taking a conservative position on design infiltration by assuming it at half or I = 0.24 in./hr (0.08 ft/hr or 1.7×10^{-6} m/sec). This approach recognizes a loss of permeability from construction, soil compaction and the soil subgrade clogging over time. The 96-hour soaked CBR of the soil is 6%. Using the CBR to resilient modulus conversion per Equation 3-1, an equivalent resilient modulus is 8,000 psi or 55 MPa. An estimated 600,000 ESALs will traffic this parking lot over 20 years.

Local regulations require this site to capture and when possible infiltrate all rainfall and runoff from a 2-year, 24-hour storm, which is 3 in. (0.25 ft or 0.076 m) based on rainfall maps. In other words, P=3 in., $T_s = 24$ hrs. The porosity of the ASTM No. 2 subbase provided by the local quarry is 40% or 0.40. A one-day drainage of the base/subbase (or 24-hour drawdown) is a design criterion provided by the local municipal stormwater agency ($T_D = 24$ hrs). Since the PICP area is established at one acre, the depth of the base and subbase needs to be determined.

Step 2 – Calculate the water volume requirements. Using Equation 3-5, the volume of water that needs to be stored in the pavement base (V_W) is:

$$
\begin{aligned}
V_W &= P(A_P) + R(A_C) - I(T_S)A_I \\
&= 0.25 \text{ ft} * 43{,}560 \text{ ft}^2 + 0.25 \text{ ft} * 87{,}120 \text{ ft}^2 - 0.02 \text{ ft/hr} * 24 \text{ hr} * 43{,}560 \text{ ft}^2 \\
&= 10{,}890 \text{ ft}^3 + 21{,}780 \text{ ft}^3 - 20{,}909 \text{ ft}^3 \\
&= 11{,}761 \text{ ft}^3
\end{aligned}
$$

Step 3 – Calculate the hydraulic depth. Using Equation 3-6, the hydraulic depth is:

$\mathbf{V_W / (A_P * n) = 11{,}761 \text{ ft}^3 / (43{,}560 \text{ ft}^2 * 0.4) = 0.67}$ **feet (8 in.)**

Assuming the base and subbase both store water, this is within the recommended minimum design thickness of 10 in. (4 in. of base and 6 in. of subbase). If only the subbase thickness is being used for water storage, then the depth of the subbase should be 8 in.

Step 4 – Ensure the post-storm infiltration period is acceptable. Using Equation 3-7, the required time to drain is:

$$V_W / (A_I * I) = 11{,}761 \text{ ft}^3 / (43{,}560 \text{ ft}^2 * 0.02 \text{ ft/hr}) = 13.5 \text{ hr}$$

This is within the acceptable time frame of 24 hours.

Step 5 – Find the subbase thickness required to support traffic given soil characteristics and ESALs. The first item required is determining the number of days per year water stands in the subbase thereby creating saturated soil conditions. The design soil infiltration rate is 0.02 in./hr (0.24 ft/hr or 1.7 x 10^{-6} m/sec) with a safety factor applied. Using daily rainfall data, determine the average number of days per year that have a greater rainfall than the design infiltration rate of the subgrade.

Daily rainfall data for the U.S. can be found on www.usclimatedata.com for the past few years. The user should review data from at least three previous years, as annual rainfall patterns vary. Each month should be reviewed and the number of days totaled with rainfall exceeding the design infiltration rate to estimate the annual number of days water stands in the subbase. Obviously, low infiltration rate soils will yield a higher number of annual days with water standing in the subbase.

Snow depth can be reckoned one of two ways depending on site conditions. The first way assumes that snow will be plowed from the PICP surface prior to melting and infiltrating. If that is the case, then snow depths can be ignored. The second approach assumes that snow will not be plowed and will be allowed to melt and infiltrate into the PICP. If that is the case, then the depth of snow should be divided by 10 to obtain a water depth. This is a conservative estimate because the depth ratio of 10 snow to 1 rain applies to temperatures near freezing. Colder freezing temperatures produce higher ratios.

For this example in Durham, New Hampshire, snow will be plowed from the PICP. For rainfall, there are less than 10 days per year it exceeds 5.76 in./day (0.24 in./hr x 24 hrs). Using Table 3-2, find the resilient modulus value closest to 8000 psi or 55 MPa and then move down to the 600,000 ESALs row. Since there is no exact depth corresponding to the soil modulus, extrapolation yields 8.5 in. (215 mm) of subbase required. The subbase requirements for hydraulic design (8 in.) and structural design (8.5 in.) are nearly identical.

Step 6—Check that the bottom of the subbase is the recommended 2 ft (0.6 m) from the seasonal high water table. The total thickness of the pavement will be:
3 1/8 in. (80 mm) thick concrete pavers
2 in. (50 mm) ASTM No. 8 stone bedding course
4 in. (100 mm) ASTM No. 57 base
8 in. (300 mm) ASTM No. 2 subbase
Total thickness = 17 in. (430 mm)

Approximately 17 in. leaves a sufficient distance to the top of the seasonal high water table. A consideration is the storage capacity of the layer of ASTM No. 8 and No. 57 crushed stone. As a factor of safety (noted in Step 3), the void space in these two layers is not part of the storage calculations. Overflow drain pipes at the perimeter of the ASTM No. 57 stone layer should be designed to remove excess water before it rises into the bedding layer and to the PICP surface.

Step 7—Check geotextile filter criteria. If geotextile is specified between the subbase and subgrade soil, it will be necessary to check the geotextile filter criteria. Sieve analysis of the soil subgrade showed that 18% passed the No. 200 (0.075 mm) sieve. Tables 3-6 and 3-7 provide guidance on specifications for selecting geotextile. The designer is considering use of a geotextile that meets AASHTO M-288 Class II for average construction conditions. The product is a 6 oz/ft^2 (1.8 kg/m^2) non-woven fabric with

Table 3-6. AASHTO M-288 Geotextile strength property requirements

Characteristic	Test Methods	Elongation < 50% per ASTM D4632		Elongation ≥ 50% per ASTM D4632	
		Class 1	Class 2	Class 1	Class 2
Grab strength	ASTM D4632	315 lb (1400 N)	247 lb (1100 N)	202 lb (900 N)	157 lb (700 N)
Sewn strength	ASTM D4632	283 lb (1260 N)	223 lb (990N)	182 lb (810 N)	142 lb (630N)
Tear strength	ASTM D4533	112 lb (500 N)	90 lb (400 N)	79 lb (350 N)	56 lb (250 N)
Puncture strength	ASTM D6241	618 lb (2750 N)	495 lb (2200 N)	433 lb (1925 N)	309 (1375 N)

Table 3-7. AASHTO M-288 Subsurface drainage geotextile requirements

		Percent In Situ Soil Passing 0.075 mm Sieve per AASHTO T-88		
Characteristic	Test Methods	<15	15 to 50	>50
Permittivity* (1) max. avg. roll value	ASTM D4491	0.5/sec	0.2/second	0.1/second
Apparent opening size (1) max. avg. roll value	ASTM D4751	No. 40 sieve (0.43 mm)	No. 60 sieve (0.25 mm)	No. 70 sieve (0.22 mm)
Ultraviolet stability (retained strength)	ASTM D4355	Maximum average roll value: 50% after 500 hours of exposure		

*Geotextile permeability = permittivity x geotextile thickness; e.g. 0.1/sec x 1.2 mm = 0.12 mm/sec (17 in./hr). The permeability of the geotextile should conservatively exceed an order of magnitude higher than the soil subgrade permeability.

(1) These default filtration property values are based on the predominant particle sizes of in situ soil. In addition to the default permittivity value, the engineer may require geotextile permeability and/or performance testing based on engineering design for drainage systems in problematic soil environments. Site-specific geotextile design should be performed, especially if one or more of the following problematic soil environments is encountered: unstable or highly erodible soils such as non-cohesive silts; gap-graded soils; alternating sand/silt laminated soils; dispersive clays; and/or rock flour.

From M 288-17 (Geotextile Specifications for Highway Applications) in Standard Specifications for Transportation Materials and Methods of Sampling and Testing, 2017, by the American Association of State Highway and Transportation Officials, Washington, D.C. Used by permission.

an elongation equal to or greater than 50%, a permittivity of 1.4/sec, apparent opening size of 0.212 mm (No. 70 sieve) and grab strength of 712 N (160 lbf). This meets the AASHTO M-288 criteria in Tables 3-6 and 3-7. The geotextile manufacturer specification sheet states that the fabric has a permittivity of 1.4/sec and a thickness of 1.2 mm. Therefore, estimated permeability is 1.4/sec x 1.2 mm = 1.68 mm/s = 238 in./hr. This fulfills the AASHTO M-288 requirement that geotextile permeability exceed that of the soil and the practice that the geotextile permeability is ten times that of the soil being filtered. (Giroud, 1988, 1996)

Partial Infiltration Calculations—The following procedure calculates the total base and subbase thickness for no infiltration systems, i.e., an impermeable liner encapsulating the base/subbase with underdrains. As noted earlier, no infiltration systems are required when native soils have an extremely low infiltration rate, or infiltration into the subgrade soils is discouraged, proximity to wells, karst terrain, etc.

The following water balance equation outlines the inputs and outputs for a no infiltration system during the design storm.

No Infiltration Design Calculations

Rainfall volume falling directly on the permeable pavement	Plus	Run-on volume from the adjacent contributing drainage area	Minus	Outflow volume through the underdrains
PA_p	+	RA_c	-	$Q_U(T_S)$

Although pipe flow is subject to the head pressure above the underdrain, assuming a constant flow is necessary to conduct this analysis. Using the maximum flow rate out of the pipe for Q_U, be it based on an arbitrarily set discharge pipe diameter or pipe flow per the local stormwater criteria controlled by an orifice or similar device, would overestimate the actual pipe discharge in all but extreme conditions. A representative percentage of the maximum flow rate based on engineering judgment should be used to represent the average discharge rate over the duration of the design storm. The required volume of water that needs to be stored in the pavement base (V_w) can be calculated using equation 3-8.

$\mathbf{V_W = P(A_P) + R(A_C) - Q_U(T_S)}$ (Equation 3-8)

The hydraulic depth can be calculated using Equation 3-6 above. The hydraulic depth of the subbase required to store water is then compared to the structural depth. The greater of the two is the design depth. The design engineer decides if the hydraulic depth includes the base and subbase, or the sub-base only.

Partial Infiltration Calculations—The following procedure calculates the total base and subbase thickness for partial infiltration systems, i.e., underdrains are required when the design infiltration rate of the subgrade soil is not sufficient to remove the maximum water storage requirements within a designated time period.

The following water balance outlines the inputs and outputs for a partial infiltration system during the design storm.

Partial Infiltration Design Calculations

Rainfall volume falling directly on the permeable pavement	Plus	Run-on volume from the adjacent contributing drainage area	Minus	Infiltration volume into the underlying soil	Minus	Outflow volume through the underdrains
PAp	+	RA_c	–	$I(T_S)A_I$	–	$Q_U(T_S)Z$

The required volume of water that needs to be stored in the pavement base (V_w) can be calculated using equation 3-9.

$\mathbf{V_W = P(A_P) + R(A_C) - I(T_S)A_I - Q(T_S)Z}$ (Equation 3-9)

With partial exfiltration systems, the outlet for the underdrain is raised so there are four stages of discharge; infiltration during the design storm; infiltration and pipe discharge during the design storm; infiltration and pipe discharge post design storm; and, infiltration post design storm. In Equation 3-8, the underdrain elevation factor (Z) is used to represent the percentage of time that pipe discharge occurs, and is calculated through an iterative process based on the pipe elevation. Partial infiltration designs should use computational models that simulate inflows and outflows over a period of time steps. To assist in modeling water movement over time, ICPI offers a software program for PICP called *Permeable Design Pro*. It can provide a more accurate solution of underdrain peak discharge and required storage volume. It can also calculate subsurface flows via placement of underdrains at a specified diameter, horizontal spacing, slope and distance above the soil subgrade. This enables more efficient partial exfiltration designs in low infiltration clay soils. The model uses a non-proprietary water balance model called Drainage Requirements in Pavements (DRIP) developed by US Federal Highway Administration (FHWA 2002).

Permeable Design Pro also provides structural design calculations for the subbase using the AASHTO 1993 flexible pavement design method. *Permeable Design Pro* is available on a 30-day free trial basis from **www.permeabledesignpro.com**. The program also creates CAD cross sections of design solutions. The model enables sensitivity analyses among rainfall, subgrade infiltration and outflow via underdrains to determine the subbase thickness for water storage. Full, partial and no infiltration designs can also be developed. No infiltration designs should consider using a bleed pipe or pipes that slowly drain the subbase as well as pipes to handle outflows.

Permeable Design Pro does rainfall event-based modeling. More complex, continuous rainfall simulation models may yield further efficiencies in subbase thickness for water storage. Such models can include USEPA Stormwater Management Model (SWMM), the Hydrologic Engineering Center Hydrologic Modeling System (HEC-HMS), Computational Hydraulics International (CHI-PCSWMM), Source Loading and Management Model for Windows (WinSLAMM), and the Integrated Design Evaluation and Assessment of Loadings (IDEAL) model. Some of these models also characterize pollutant loadings and transport.

Other Design Considerations

Soil Compaction

Soil compaction decreases the infiltration rate of the soil. Infiltration reduction depends on the soil type and density. Clay soils will experience the highest reductions. However, Pitt (Pitt 2002) demonstrates that such reductions in compacted clay soils are variable and such variations allow for some infiltration. Jones (Jones 2010) also demonstrated that selected compacted clay soils in Northern California still provided a modest amount of infiltration in laboratory tests.

Soil subgrade compaction is based on designer preferences. The decrease in soil infiltration from compaction must be factored into the design infiltration rate of the soil. If the soil is not compacted in an effort to maintain higher infiltration rates, diligent control of tracked construction equipment that rides on placed aggregate rather than traversing excavated soil subgrade helps minimize inadvertent compaction. Wheeled construction equipment should be kept from the excavated soil, as these tend to concentrate loads, stress and compaction. Pedestrian applications shouldn't require deliberate soil subgrade compaction.

Many PICP installations will be over undisturbed native soils. Soil excavations typically will be 2 to 3 ft (0.6 to 0.9 m) deep and cut into consolidated soil horizons. For vehicular applications, the subgrade layer should be evaluated by a qualified civil or geotechnical engineer for the need for compaction. The following provides some insights on not compacting or compacting the soil subgrade.

In some PICP projects, the soil subgrade was not compacted in order to promote infiltration. These projects were designed with fairly thick base/subbases for water storage, saw moderate traffic loads, and had adequate subgrade infiltration that reduced risks from rutting and deformation. In some cases, the PICP base is overdesigned from a structural standpoint in order to store water. Thicker bases used in PICP work in favor of not compacting the native soil subgrade.

Heavier traffic loads that include truck traffic may require soil subgrade compaction. If soil subgrade compaction is required by the design engineer, then prior to construction, soil samples should be taken from the site at the approximate elevation of the bottom of the pavement structure and compacted at a minimum of 95% Proctor Density per ASTM D698. This laboratory density (or lower, if desired) should be achieved and measured on compacted subgrade typically within a test pit or pits on the site. Once compacted and density measured, then infiltration testing should be conducted per ASTM D3385. An appropriate safety factor should be applied to the infiltration rate selected for hydrologic design in expectation of sediment collecting on the subgrade surface over time.

There are other factors on sites not specifically covered in the manual that influence design decisions. The guidance of an experienced civil or geotechnical engineer familiar with local site conditions and stormwater management should be sought to confirm the suitability of the soil characteristics, the need for compaction, plus many other considerations for structural and hydrologic design solutions.

Geotextiles

Geotextiles are recommended on the sides of all PICP excavations in the absence of a full-depth concrete curb to restrain the base/subbase aggregates. Vertical placement of geotextiles helps prevent erosion of adjacent soil into the base and subbase layers. Geotextiles applied vertically against the walls of the excavation should have at least 1 ft (0.3 m) lying horizontally on the soil subgrade. The use of geotextiles placed horizontally over the entire soil subgrade is the option of the design engineer.

As previously noted, geotextiles selected for use in PICP should conform to subsurface drainage requirements in AASHTO M-288, Geotextiles for Highway Applications (AASHTO 2017). These are provided in Tables 3-6 and 3-7. Class 2 geotextiles are typically used in PICP which often has less severe installation conditions. Geotextile strength properties should conform to Class 1 (highest strength) if exposed to severe installation conditions with greater potential for geotextile damage.

Choke Criteria for the Bedding, Base and Subbase

Ferguson (2005) provides criteria for all aggregate layers and these are noted in Table 3-8 below. D_x is the particle size at which x percent of the particles are finer. For example, D_{15} is the particle size of the aggregate for which 15% of the particles are smaller and 85% are larger. This data is obtained from the sieve analysis. The criteria are also presented as an option for the user to evaluate bedding/base/subbase layer gradations in *Permeable Design Pro* software.

Table 3-8. Choke criteria for PICP bedding, base and subbase aggregates

D_{50} Base/D_{50} Bedding layer ≤ 25
D_{15} Base/D_{85} Bedding layer ≤ 5

D_{50} Subbase/D_{50} Base ≤ 25
D_{15} Subbase/D_{85} Base ≤ 5

North American PICP experience over the past 15 years indicates that the ASTM No. 8 bedding stone chokes well into ASTM No. 57 base, and this material chokes well into ASTM No. 2, 3 or 4 subbase material. When compacted together, water easily moves through each layer to the soil subgrade. Therefore, these gradations offer high permeability while choked into each other. Salient factors that contribute to structural stability of the system under vehicular traffic include using crushed stone, each layer choked or meshed into the next, hard aggregates, appropriate thicknesses, and compaction.

The above choke criteria do not mean absolute stability of the pavement layers. When combined as layers, open-graded aggregates meeting these criteria settle into each other. For this reason it is often necessary to refill the jointing stone after the first six months of service. In addition, all PICP surfaces will settle 5 to 6 mm from consolidation of the compacted open-graded aggregate layers. This settlement should be compensated by setting the finished (compacted) pavement surface slightly higher than adjacent curbs and other pavements. This is covered in Section 4 on Construction.

NRCS Curve Number Calculations

Like most structural BMPs, the hydrological and pollution abatement characteristics of PICP should be incorporated into managing runoff within the larger catchment, sub-watershed or watershed. The U.S. Department of Agriculture, Natural Resource Conservation Service (NRCS) National Engineering Handbook 630 Hydrology (NRCS 2004) method is well-established and used by many agencies. The NRCS characterizes runoff from sites based on the hydrologic soil group (A – D) per Table 3-4 plus land use/cover using a "curve number" or CN. The CN ranges from 0 to 100 to characterize the interaction of rainfall, retention and runoff from a site or watershed. CNs range from 0 meaning no runoff to 100 percent meaning all rainfall runs off.

A key variable in determining the CN for PICP is the soil infiltration capacity. The higher the expected infiltration rate, the lower the volume of rainfall available for runoff, and in turn the lower the CN. Some caution should be exercised in applying the NRCS method to calculating runoff in catchments smaller than 5 acres (2 ha). This method is intended to calculate runoff from larger storms (2-, 10-, and 100-year return periods) with 24-hour durations and from larger catchments or watersheds. Therefore, the NRCS procedure tends to underestimate runoff from smaller storms in small drainage areas.

Development, assumptions and critique of the NRCS method can be found in *Curve Number Hydrology* (Hawkins 2009). Claytor and Schueler (Claytor 1996) suggest methods to calculate runoff from small areas from smaller storms especially when water quality needs to be controlled. Schwartz (Schwartz 2010) provides guidance for applying curve numbers to pervious pavement as well as for runoff into PICP from contributing impervious areas. Ballestero (Stormcon 2010) presented methods to determine CNs based on the pre- and post-development peak flows, lag time, or from runoff depths from simple comparisons of rainfall versus runoff. The following method follows Schwartz's rationale and is the simplest assessment.

$$\mathbf{Q} = \frac{(\mathbf{P} - \mathbf{I_a})^2}{\mathbf{P} - \mathbf{I_a} + \mathbf{S}} \qquad \text{(Equation 3-10)}$$

Where:
Q = Total runoff depth (in.)
P = Total precipitation depth (in.)
$\mathbf{I_a}$ = Initial abstraction (in.) or initial rainfall prior to runoff starting
S = Storage parameter (in.) or the total stored in the PICP base/subbase reservoir that does not become runoff

$$\mathbf{S} = \frac{\mathbf{1000 - 10}}{\mathbf{CN}} \quad \text{or} \quad \mathbf{CN} = \frac{\mathbf{1000}}{\mathbf{S + 10}} \qquad \text{(Equation 3-11)}$$

For impervious parking lots, streets, etc., the CN is 98 regardless of soil type. For all but minor rainfall events, most precipitation ends up as runoff. The slight reduction (compared to CN = 100) in runoff can be attributed to initial evaporation and then wetting of the pavement surface. For PICP, water enters the joints and open-graded aggregate beneath, retaining rainfall in the aggregate reservoir and infiltrating it into the subgrade. This process is analogous to placing a catch basin leading to an infiltration gallery. The entire PICP surface acts like a catch basin with an infiltration gallery located directly below the pavement.

An approximate approach accounting for the combined reduction in runoff volumes and peak surface flows from PICP is calculating an "effective SCS curve number" (CN_{adj}). This yields a lower value than the actual CN because it accounts for infiltration. CN_{adj} can then be used in hydrologic calculations and in routing (Nashville 2016).

$$\mathbf{Q_{adj} = Q - T_s - T_i} \qquad \text{(Equation 3-12)}$$

Where:

T_s = depth of water storage within the aggregate reservoir (in.)
T_i = depth of water infiltrating into the subgrade over the duration of the design storm (in.)

$$\mathbf{CN_{adj} = 1000/(10 + 5P + 10Q_{adj} - 10(Q_{adj}^2 + 1.25Q_{adj}P)^{1/2})} \quad \text{(Equation 3-13)}$$

The following examples demonstrate the effect of an adjusted CN. For example, the 24-hour design storm for a site is 8 in. (200 mm); P=8. From TR-55 (USDA 1986), the runoff coefficient for the parking lot is 98, therefore S= 0.204 using Equation 3-11, and Q = 7.76 in. using Equation 3-10.

If a no infiltration PICP system with a 15 in. (375 mm) thick aggregate reservoir is used for stormwater runoff mitigation, 6 in. (150 mm) of reservoir storage is provided, assuming a 40% porosity within the aggregates; T_s = 6 in. There is no infiltration into the subgrade; T_i = 0. From Equation 3-12, Q_{adj} = 7.76-6 = 1.76 in (44 mm), and the corresponding CN_{adj} using Equation 3-13 is 45.2 (round to 45).

Using the same example, a partial infiltration system with a 12 in. (300 mm) deep aggregate reservoir is used, 4.8 inches (120 mm) of reservoir storage is provided; T_s = 4.8 in. The subgrade soil exhibits an infiltration rate of 0.1 in./hr (2.5 mm/hr) or 2.4 in./day (60 mm/day); T_i = 2.4. The resulting total rainfall depth (Q_{adj}) using Equation 3-12 is 0.56 in. (14 mm), and the corresponding CN_{adj} using Equation 3-13 is 31.9 (round to 32).

Rational Method Calculations

The Rational Method is useful for estimating only peak runoff discharges for sizing storm sewers in watersheds up to 200 acres (80 ha). Peak discharge is found using the formula:

$$\mathbf{Q} = \mathbf{CIA} \quad \text{(Equation 3-14)}$$

Where:
Q = Peak discharge in ft³/second
I = Design rainfall intensity, in./hour
A = Drainage area, acres
C = Coefficient of runoff

Permeable Design Pro software calculates the CN and runoff coefficient C for user inputs on the site, specific design storms and soil infiltration rate, among others. The program enables the user to conduct sensitivity analysis by changing PICP design variables that impact CN and C values.

The "C" value, or coefficient of runoff, is a generalized value which characterizes the percentage of runoff generated from all storms or a specific set of design storms. Since a PICP is typically designed to minimize surface runoff by storing and infiltrating water into the soil subgrade (in the case of full or partial infiltration systems), or store water for controlled discharge like a detention pond in no infiltration systems, a traditional C value cannot be realistically applied. Some agencies calculate an "equivalent C value", which converts the estimated discharge volume from the underdrain into an equivalent runoff per unit area based on the surface area of the permeable pavement. For example, a 1,000 sf parking lot received 6 in. of rain. The total volume of water is 500 cubic feet. If the estimated discharge from the underdrain is 100 cubic feet, then the "equivalent C value" is 0.2 (100/500). This approach works well for showing the benefits of infiltration into the subgrade, but does not account for any time delay resulting from storage and controlled discharge of water.

Design for Water Quality Improvement

Since urbanization significantly alters the land's capacity to absorb and process water pollutants, most localities are regulating the amount of pollutants in stormwater. This is particularly the case when drinking-water supplies and fishing industries need protection. Urban stormwater pollutants and their sources are shown in Table 3-9. Total maximum daily loads or TMDLs are seeing increased use by states and cities to protect such assets. PICP is an important tool in addressing TMDLs at the site scale. The following section summarizes PICP water quality research and can assist in assigning pollutant reduction credits to PICP.

Table 3-9. Common sources of pollution in urban stormwater runoff (NVPDC 1999)

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

PAHs = polynuclear aromatic hydrocarbons SOCs = synthetic organic compounds

PICP reduces pollutant concentrations and mass loads through filtration within the joint material, sedimentation in the base/subbase, adsorption, volatilization, biological degradation, and infiltration into the subgrade, with infiltration into the subgrade being the primary means to reduce water volumes and pollutant loading to receiving water. Sandy subgrade soils will infiltrate more stormwater, but have less metals treatment capability. Clay soils have a high cation exchange capacity and will capture adsorb metals (assuming moderate water pH), but will infiltrate less. Debo and Reese (Debo 1995) recommend that for controling runoff quality, the stormwater should infiltrate through at least 18 in. (0.45 m) of soil which has a minimum cation exchange capacity of 5 milliequivalents per 100 grams of dry soil.

PICP is seeing increased use in water quality volume capture because the subbase can easily store the 1 to 1.5 in. (25 to 40 mm) of water required, which often accounts for 85% to 90% of all rainstorms in most locations. Many soils can infiltrate this depth within 24 to 48 hours. Additional base storage can be designed to capture 95% of all rainstorms as required for U.S. federal government facilities per Section 438 of the Energy Investment and Security Act, as well as for local regulations and sustainable urban drainage design guidelines.

Studies have found that PICP encourages treatment via bacteria in the soils, and beneficial bacteria growth has been found on established aggregate bases (Newman 2002). In addition, PICP can process oil drippings from vehicles (Pratt 1999).

Table 3-10 provides measured pollutant removals from in-situ permeable pavement studies. These include studies on pervious concrete and porous asphalt as well as PICP since the storage, infiltration and pollutant removal mechanisms are similar. Pollutant concentration removals are based on event mean concentrations.

Table 3-10 indicates increases in nitrate and nitrites from traditionally designed PICP systems. Nitrate and nitrite reductions can be achieved by detaining water in the subbase for over 24 hours for de-nitrification provided there is a carbon source (e.g. mulch) within the subbase. Any infiltration will of course reduce the water volumes and mass outflow of nutrients and should be accounted for in pollutant credit programs from provincial/state and local agencies.

Table 3-10. A research summary of pollutant reductions using permeable pavements (after Drake 2013 and Eisenberg 2015)

Study	Type	Site Location	Sampled Events	Concentration (C) or Mass (M)	% Average Removal Efficiency											
					NH3	NO3,2	TKN	TN	OP	TP	TSS	Cd	Pb	Zn	Cu	TPH-D
Bean 2007	PICP	Goldsboro, NC	6-14	C	84	-47	60	42	42	63	33			88	62	
Boving 2008	PA	Kingston, RI	14	C				27		27				90	90	
Brattebo 2003	PICP	Renton, WA	9	C										69	89	
Collins 2010	PC	Kinston, NC	20	C	85	-152	42	-2								
Collins 2010	PICP	Kinston, NC	19	C	85	-331	50	-40								
Collins 2010	PICP	Kinston, NC	19	C	85	-210	50	-11								
Gilbert 2006	PICP	Waterford, CT	1 year	C	72	50	91			34	67		67	71	65	
Dierks 2010	PICP	Ann Arbor, MI	5	C					31	56	12			6	0	
Fassman 2011	PICP	Auckland, NZ	3-13	C							49			93	57	
Pagatto 2000	PA	Nantes, France	25	C	73	69	43				81	69	78	66	35	
Rankin 2004	PICP	Port Adelaide, Australia	9	C			59			43	40		22	43	8	
Roseen 2009	PA	Durham, NH	24 mos.	C						25	96			80		99
Roseen 2011	PA	Durham, NH	13-16	C		-87				20	89			75		92
Roseen 2013	PICP	Durham, NH	18	C	95	95	95	95	95	95	95			95		95
Rushton 2001	PC	Tampa, FL	12-30	C	0	48		28	55	56	31		58	36	58	
Rushton 2001	PC	Tampa, FL	12-30	C	0	36		26	32	39	62		69	53	67	
Smolek 2016	PICP	Durham, NC	19 - 29	C	37			68		96	98		93	90	79	
Van Seters 2007	PICP	North York, ON	27-40	C		-68	53			53	81			73	13	
Drake 2012	PICP	Vaughan, ON	31-45	C	90	-4	89		82	86	89		27		75	
Drake 2012	PICP	Vaughan, ON	45	C	90	-18	87		82	86	87		-20	78	71	
Drake 2012	PC	Vaughan, ON	30-45	C	90	21	78		38	52	79		-5	87	49	
Fassman 2011	PICP	Auckland, NZ	3-13	M							65			93	79	
Legret 1999	PA	Reze, France	11	M							59	77	84	73		
Pagatto 2000	PA	Nantes, France	25	M							77	62	74	59	21	
Rushton 2001	PC	Tampa, FL	12-30	M							91		85	75	81	
Winston 2015	PICP	Willoughby Hills, OH	18	M		-23	42	23	1	30	#		-55	37	13	
Winston 2015	PICP	Willoughby Hills, OH	12	M		42	56	52	22	40	##		-47	53	30	
Winston 2017	PICP	Huron, OH	16	M			67	63	-56	82	100		15	40	14	
Average Concentration Removal					80.7	-42.7	66.3	25.9	57.0	55.4	68.1	69.0	43.1	70.1	58.4	95.3
Average Mass Removal						9.5	55.0	46.1	-10.9	50.5	78.3	69.5	26.1	61.5	39.7	

NH3: Ammonium; NO3, 2: Nitrate & Nitrite; TKN: Total Kjehldal Nitrogen; OP: Ortho-phosphate; TP: Total Phosphate; TSS: Total Suspended Solids; Cd: Cadmium; Pb: Lead; Zn: Zinc; Cu: Copper; TPH-D: Total Petroleum Hydrocarbons as Diesel

-525% and ## -328% due to sediment export from reservoir

Table 3-11. Permeable pavement volume reductions from various research papers (after Drake 2013 and Eisenberg 2015).

Author	Type	Location	Events	CDA Ratio, %	Soil	Underdrains	Mean Volume Reduction, %
Bean 2007	PICP	Goldsboro, NC	14	0	sand	No	100
Bean 2007*	PICP	Swansboro, NC	16	0	sand	No	100
Boving	PA	Kingston, RI	14	0	gravel	No	100
Brattebo 2003*	PICP	Renton, WA	15	0	NR	No	100
Booth 1996*	PICP	Renton, WA	3	0	NR	No	100
Collins 2010	PC	Kinston, NC	51	0	sandy clay	Yes	13
Collins 2010	PICP	Kinston, NC	50	0	loam	Yes	48
Collins 2010	PICP	Kinston, NC	46	0	sandy clay	Yes	3
Gilbert 2006	PICP	Waterford, CT	1 year	Varied	sandy clay	No	72
Dierks 2010*	PICP	Ann Arbor, MI	14	300	NR	Yes	80
Fassman 2010	PICP	Auckland, NZ	44	100	silty clay	Yes	28
Rankin 2002*	PICP	Port Adelaide, Australia	22	45	sandy	No	93
James 1997	PICP	Guelph, ON	9	0	NR	NR	38
James 1997	PICP	Guelph, ON	9	0	NR	NR	61
Legret 1999	PA	Reze, France	40	37	NR	Yes	97
Roseen 2013	PICP	Durham, NH	18	0	sandy clay	Yes	100
Roseen 2012	PA	Durham, NH	17	0	HSG C	No	25
Rushton 2001	PC	Tampa, FL	30	0	sandy	No	29
Rushton 2001	PC	Tampa, FL	30	0	sandy	No	32
Smolek 2016	PICP	Durham, NC	29	300	HSG D	Yes	22
Van Seters 2008	PICP	North York, ON	71	0	clay loam	Yes	90
Drake 2012	PICP	Vaughan, ON	185	0	silty clay	Yes	45
Drake 2012	PICP	Vaughan, ON	185	0	silty clay	Yes	45
Drake 2012	PC	Vaughan, ON	185	0	silty clay	Yes	45
Winston 2015*	PICP	Willoughby Hills, OH	77	220	silt loam HSG D	Yes	32
Winston 2015*	PICP	Willoughby Hills, OH	77	720	silt loam HSG D	Yes	16
Winston 2015*	PICP	Orange Village, OH	77	0	silt loam HSG D	Yes	99
Winston 2015*	PC	Perkins Township, OH	87	60	silty clay HSG C/D	Yes	53
Winston 2017*	PICP	Huron, OH	59	170	silt loam HSG D	Yes**	18

NR = Not reported

*Not paired impervious/permeable pavement studies; instead compared rainfall to runoff/infiltration/outflow

**Cistern collection under 10% of the PICP area

Some agencies encourage the use of sand filters under PICP as a means to reduce nutrients. The addition of iron filings can provide significant dissolved phosphorous reductions (Erickson 2010). Sand filter effectiveness, initial and maintenance costs should be weighed against other design options for nutrient reductions. Sand filters will incur additional construction expense and this can be reduced by placing the sand in the subbase aggregate prior to compacting the combined materials rather than installing a layer beneath the subbase on the subgrade. Combining materials eliminates the need for (and potential clogging of) a separation geotextile between such layers and open-graded aggregate above or below it. The disadvantage of sand filter installed as a layer is that it will eventually require removal and replacement. Locating them in the down slope areas of the site can help reduce future maintenance costs and site disruptions.

An alternative to sand filters for nutrient reduction is using a "treatment train" approach where PICP initially filters runoff and remaining water is directed to bio-retention areas or rain gardens adjacent to the PICP for additional processing and nutrient reduction. There may be additional BMPs used to remove nutrients as the water moves through the watershed. Finally, another technique for nutrient reduction is using jointing and bedding aggregates coated with chemicals. The coated aggregates have an effective life of seven to ten years.

Ecologically, increased runoff temperatures are another form of water pollution. During warmer months, urban environments introduce heat into stormwater. Heat from hot rooftops and pavements is transferred to runoff and conveyed to streams, rivers, lakes, etc. This process can create acute, rapid, and sometimes toxic increases in water temperature to aquatic organisms. Water retained in PICP reservoir layers is often cooled prior to its discharge. Water that infiltrates will become part of the groundwater supply in the water cycle, further promoting temperature reduction.

Since PICP reduces volumes in many applications, stormwater agencies should include pollutant reduction concomitant with volume reduction credits. The range of volume reductions is shown in Table 3-11. Obviously, volume reduction depends on the soil infiltration rate. PICP on clay soils demonstrate some volume reduction capacity and PICP should not be excluded from consideration on such subgrades. In addition to volume reductions, PICP offers peak flow reductions due to infiltration and controlled release via raised outlets.

Some state BMP manuals include volume reduction in recognizing pollutant credits for PICP. Table 3-12 summarizes these credits for four states as examples. This approach recognizes the full pollutant-reduction performance of PICP and further incentivizes its use due to volume reduction plus biological, and chemical processes.

Table 3-12. Permeable pavement pollutant credits from various states (MIDS 2011)

Design	Volume Reduction	Total Phosphorous EMC Reduction				Total Suspended Solids EMC Reduction		
	VA	VA	NH	PA	MN	VA	NH	PA
No underdrains	75%	25%	65%		80%	75%	90%	
With underdrains	45%	25%	45%	85%	80%	75%	90%	85%

EMC = Event mean concentration

VA = Virginia; NH = New Hampshire; PA = Pennsylvania; MN = Minnesota

Note: The Virginia Department of Conservation and Recreation offers 25% total nitrogen removal credit on an EMC (event mean concentration) basis. In addition, credits are given for mass load removal of total phosphorous and total nitrogen. These are 59% and 81% for no underdrain and underdrain designs, respectively.

Section 4. Construction

Construction Overview

Figure 4-1. Special attention to many details makes PICP construction successful. This mechanically installed project is one of the largest PICP parking lots—about 7.5 acres (3 ha)—at a car dealership in Vancouver, Washington.

PICP construction for parking lots and roads involves the steps listed below. This section provides details on them and explains some variations depending on the application. The end of this section includes US and Canadian guide construction specifications. They are available on www.icpi.org and can be downloaded and edited to project conditions. Construction steps follow:

- Attend the pre-construction meeting
- Plan site access and keep PICP materials free from sediment
- Excavate soil or an existing pavement
- Avoid soil compaction unless required in the plans and specifications
- Install geotextiles, impermeable liners and drains pipes if required in the plans and specifications
- Place and compact the aggregate subbase
- Install curbs or other edge restraints
- Place and compact the aggregate base
- Place and screed the bedding layer
- Install pavers manually or with mechanical installation equipment
- Fill the paver joints and sweep the surface clean
- Compact the pavers
- Top up joints with joint filling stone as needed and sweep the surface clean

Attend the pre-construction meeting—For commercial and municipal projects, the specifications should include a pre-construction meeting. The pre-construction meeting is held to discuss methods of accomplishing all phases of the construction operation, contingency planning, and standards of workmanship. The general contractor typically provides the meeting facility, meeting date and time. Representatives from the following entities should be present:

1. Contractor superintendent
2. PICP subcontractor foreman
3. Concrete paving unit manufacturer's representative
4. Testing laboratory (ies) representative(s)
5. Engineer or representative
6. Inspector, if one is maintained on site
7. Other affected trades or representatives who will access PICP area

The following items should be discussed and determined:

1. Verify that site plans are representative of actual site layout.
2. When PICP is being built in the overall construction sequence

3. Security, safety and public access requirements
4. Erosion and sediment control plan, and stormwater pollution prevention plan
5. Test panel (mock-up) location and dimensions
6. Methods for keeping all materials free from sediment during storage, placement, and on completed areas
7. Methods for checking slopes, surface tolerances, and elevations
8. Concrete paving unit delivery method(s), timing, storage location(s) on the site, staging, paving start point(s) and direction(s)
9. Anticipated daily paving production and actual record
10. Diagrams of paving laying/layer pattern and joining layers as indicated on the drawings
11. Monitoring/verifying paver dimensional tolerances in the manufacturing facility and on-site if the concrete paving units are mechanically installed
12. Testing intervals for sieve analyses of aggregates and for the concrete paving units
13. Method(s) for tagging and numbering concrete unit paving packages delivered to the site
14. Testing lab location, test methods, report delivery, contents and timing
15. Engineer inspection intervals and procedures for correcting work that does not conform to the project specifications
16. Procedure for testing and written approval of subgrade, subbase and base
17. Curb type and installation schedule
18. Clearly define who is responsible for repairs prior to final release

Plan site access and keep PICP materials free from sediment—Preventing and diverting sediment from entering the aggregates and pavement surface during construction ***must be the highest priority***. Extra care must be applied to keeping sediment completely away from aggregates stored on site as well as the PICP. In some cases, it may be necessary to construct PICP before other soil-disturbing construction is completed. The options below are for ensuring that the PICP does not become contaminated with sediment from construction vehicles. The options below are in ascending cost order. One or more of these options should be decided in the project planning stages and included in the specifications and drawings.

(1) Install the PICP first and allow construction traffic to use the finished PICP surface. When construction traffic has ceased and adjacent soils are stabilized with vegetation or erosion control mats, clean the PICP surface and joints with a vacuum machine capable of removing an inch (25 mm) of the stone from the joints. Vacuum a test area and inspect the joints when stone is removed to be sure there are no visible traces of sediment on the stone remaining in the joints. If it is visible, then vacuum out jointing stones until no sediment is present. Fill the joints with clean stones and sweep the PICP surface clean.

(2) Protect the finished PICP system by covering the surface with a woven geotextile and a minimum 2 in. (50 mm) thick ASTM No. 8, 89 or 9 open-graded aggregate layer (as specified for the jointing stone). This aggregate layer and geotextile are removed upon project completion and when adjacent soils are stabilized with vegetation or erosion control mats. The PICP surface is swept clean.

(3) Construct the aggregate subbase and protect the surface with geotextile and an additional thick layer of the same aggregate over the geotextile. Thicken this layer at transitions to match elevations of adjacent pavement surfaces subject to vehicular traffic. When construction traffic has ceased and adjacent soils are vegetated or stabilized with erosion control mats, remove geotextile and soiled aggregate and install the remainder of the PICP system per the project specifications.

(4) Establish a temporary road or roads for site access that do not allow construction vehicle traffic to ride over and contaminate the PICP base materials and/or surface with mud and sediment. Other trades on the jobsite need to be informed on using temporary road(s) and staying off the PICP. The temporary road is removed upon completion of construction and opening of the PICP surface to traffic.

Other practices such as keeping muddy construction equipment away from the PICP, installing silt fences, staged excavation, and temporary drainage swales that divert runoff away from the area will make the difference between a pavement that infiltrates well or poorly. A simple technology that may be more effective than silt fences can help block sediment eroding from bare soil. This technology consists of plastic temporary curbs with fabric in them to block the movement of sediment from bare soil. Figure 4-2 illustrates this device.

Another more involved practice is a washing station for truck tires. Larger PICP projects may require this level of cleanliness as trucks enter a muddy PICP site. Figure 4-3 illustrates truck washing equipment which requires disposal of dewatered sediment.

Excavate soil or an existing pavement—In some cases, the excavated area for base and PICP can be used as a sediment trap if there is time between the excavation and aggregate base installation. This is done by excavating within 6 in. (150 mm) of the final bottom elevation. This area can contain water during storms over the construction period with excess water exiting via temporary drain pipes. Heavy equipment should be kept from this area to prevent compaction. If equipment needs to traverse the bottom of the excavation, tracked vehicles can reduce the risk of soil compaction. As the project progresses, sediment and the remaining soil depth can be excavated to the final grade immediately before installing the aggregate subbase and base. Depending on the project design, this technique might eliminate the need for a separate sediment basin during construction.

Avoid soil compaction unless required in the plans and specifications—As discussed previously, soil compaction as part of the design is the engineer's decision and should be executed according to the project specifications. If compaction is not specified, the initial undisturbed soil should be carefully maintained during excavation and construction as this will enable the base/subbase to drain as designed. If the soil is inadvertently compacted by equipment during construction, there will be substantial loss of infiltration. A loss may be acceptable if the infiltration rate of the soil when compacted was initially considered in drainage calculations.

Compacted soil can be remedied by scarifying to increase its infiltration. This is done by back-dragging bucket loader teeth across the soil prior to placing the aggregate subbase. While this method may increase subgrade infiltration, it can create conditions for later settlement due to creating a loose layer of uncompacted soil that eventually settles. If this approach is used to increase subgrade infiltration, special attention to subbase and base aggregate compaction will be required. Compaction measurement methods are noted later in this section. If another contractor is responsible for the excavation, subgrade preparation and compaction, they should provide the paver contractor with written assurance that the subgrade has been prepared to the specifications.

Figure 4-2. This temporary permeable edging around bare soil replaces silt fencing because it restrains sediment while allowing water to pass.

Figure 4-3. Larger PICP projects may require tire washing equipment for trucks to keep mud from contaminating PICP aggregates.

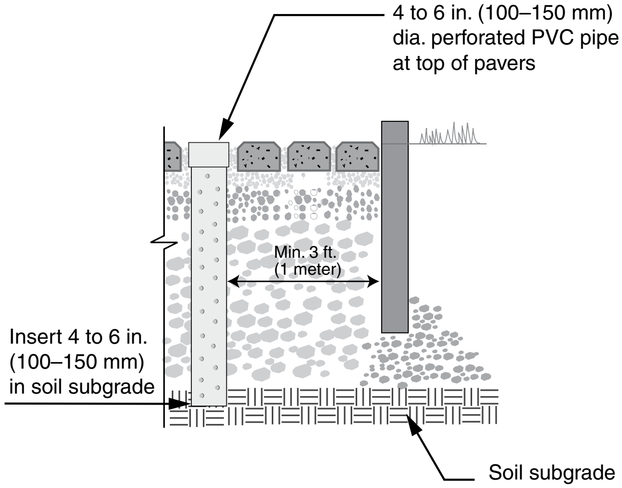


Figure 4-4. Observation well into PICP base and subbase with top accessible directly from the surface to observe drain-down rate.

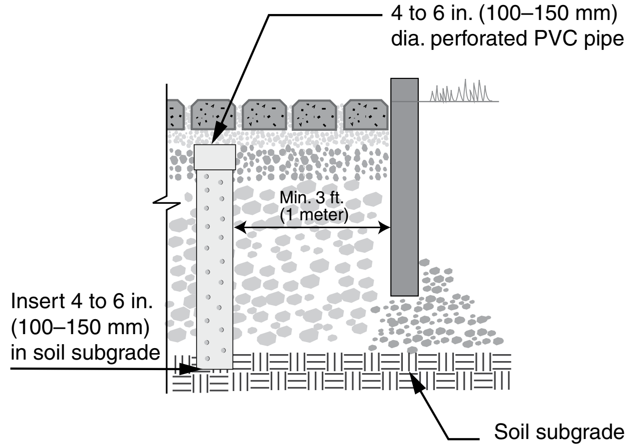


Figure 4-5. Observation well with top hidden under pavers and bedding to obscure from vandals.

Scarifying compacted subgrades emerged from an experiment by Tyner (2009), who demonstrated a substantial increase in soil infiltration rates after various treatments with construction equipment on clay soils. He compared infiltration rates on an untreated area to soil trenched and backfilled with stone aggregate; soil ripped with a subsoiler; and placement of shallow boreholes backfilled with sand. The average exfiltration rates were 0.3 in. (0.8 cm) per day (control), 1.8 in. (4.6 cm) per day (borehole), 3.8 in. (10.0 cm) per day (ripped), and 10.8 in. (25.8 cm) per day (trenched).

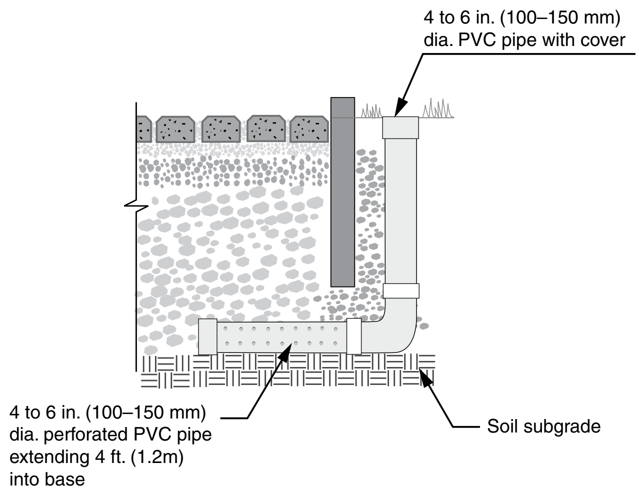


Figure 4-6. Observation well installed outside of pavement area.

Install geotextiles, impermeable liners and drain pipes if required in the plans and specifications—Geotextiles are used in some permeable pavement applications per the design engineer. When soil is restraining the sides of the base/subbase at its perimeter, geotextile should be applied to prevent erosion of soil into the base/subbase aggregates. Geotextile is applied vertically against the soil with at least 1 ft (0.3 m) extending horizontally under the subbase and resting on the soil subgrade. Geotextile specifications were covered in Section 3. A minimum 1 ft (0.3 m) overlap is recommended in well-drained soils and 2 ft (0.6 m) overlap on poor-draining weaker soils (CBR<5%).

When specified, impermeable liners require assembly per manufacturer's instructions at the job site. Once assembled, they should be tested for leaks with special attention to seams and pipe penetrations. Geotextiles are typically installed to protect liners from damage during aggregate placement and compaction. There should be extra fabric and liner material placed on the sides of the excavation to account for movement of each during aggregate placement.

Drain pipes are installed according to plans and specifications. Designs should have curb cut-outs or drain pipes from the PICP entering swales or storm sewer catch basins to handle overflow conditions. Plastic pipes in bases subject to traffic should withstand repeated vehicular loads. A minimum of 12 in. (300 mm) aggregate cover is recommended over drain pipes to protect them from damage during subbase or base compaction.

Figure 4-7. A 10 ton (9 T) vibratory roller compactor settles ASTM No. 2 stone subbase for a large shopping center parking lot.

Pipes are generally rigid Schedule 40 PVC. Verify anticipated loads to determine the proper pipe rating. If there is a risk of drain pipe damage, consider using a heavier gauge pipe or test the pipe and base in a trial area with compaction equipment prior to placing and compacting a large area. Perforations in pipes should terminate 1 ft (0.3 m) short of the sides of the opening for the base. When corrugated metal drain pipes are used, they should be aluminized, and aluminized pipe in contact with concrete should be coated to prevent corrosion. Perforated drain pipes should have caps fastened to the upslope ends. Daylighted drain pipes require wire mesh over the openings to keep out debris and animals.

Observation Wells —A 4 to 6 in. (100 to 150 mm) diameter vertical perforated pipe that serves as an observation well is recommended in PICP subject to vehicular traffic. The pipe should be kept vertical during filling of the excavated area with open-graded aggregate and during compaction. The bottom of the pipe can be forced into the soil subgrade and kept in place during base/subbase filling and compaction. The pipe should be located in the lowest elevation and a minimum of 3 ft (1 m) from the PICP side. Figures 4-4 and 4-5 illustrate a well accessible from the surface and another with the pipe under the pavers to prevent damage from vandals. Figure 4-6 locates access outside the pavement. In this figure, a vertical pipe absent from within the pavement structure can expedite subbase/base construction.

Place and compact the aggregate subbase—ASTM No. 2, 3 or 4 subbase material should be spread in maximum 8 in. (200 mm) lifts. Equipment should ride on the placed aggregates and not the soil subgrade. For large areas, efficient compaction is typically done with a 10 ton (9 T) steel vibratory roller or a 13,500 lbf (60 kN) plate compactor. Lift thicknesses up to 12 in. (300 mm) are normal (i.e., 12 in. or a 0.3 m) when using either of these compactors. When using a roller, the first two passes are in vibratory mode and the last two are in static mode. Compaction is completed when no visible movement can be seen in the aggregate when rolled by the compactor. Plate compactors with compaction indicators should be used to determine when compaction is completed. Plate compactors can reach into corners inaccessible by roller compactors. Aggregates will compact more completely if moistened during compaction. Aggregates should not be crushed by compactors. Figure 4-7 illustrates a vibratory roller compacting ASTM No. 2 stone subbase.

Figure 4-8. A 10 ton (9 T) roller compacts the ASTM No. 57 base.

Figure 4-9. A 13,500 (60 kN) vibratory plate compactor is used on this ASTM No. 57 stone base.

Surface tolerance of the compacted ASTM No. 2 should be no more than ± 2 in. (50 mm) over a 10 ft (3 m) straightedge.

Place and compact the aggregate base—The ASTM No. 57 base layer is spread and compacted as one 4 in. (100 mm) lift. Again, stone materials should be moist during compaction for better consolidation. Like the subbase aggregate, the initial passes with the roller can be with vibration to consolidate the base material as shown in Figure 4-8. The final passes should be without vibration. A 13,500 lbf (60 kN) plate compactor (Figure 4-9) also can be used to compact the ASTM No. 57 base layer. The base surface should be $\pm 1/2$ in. (13 mm) over a 10 ft (3 m) straightedge.

Figure 4-10. Lightweight deflectometer (LWD) testing on a PICP subbase. The device can be used to identify places where compaction was inconsistent.

Figure 4-11. An LWD testing a compacted No. 57 base layer. This should be done on a base with a minimum 10 in. (250 mm) thick compacted subbase under it.

Equipment drivers should avoid rapid acceleration, hard braking, or sharp turning when driving on the compacted subbase and on the base. Tracked equipment is recommended. If the subbase or base surfaces are disturbed, they should be re-leveled and re-compacted.

A test section of the subbase and base should be constructed initially for compaction monitoring. The section will indicate settlement of the pavement section, and be used to monitor and prevent crushing of the aggregate. The area should be used to train inexperienced construction personnel on compaction techniques.

Some designers prefer field measurement of subbase and base aggregates after compaction. The guide construction specification in this section includes a testing method for the compacted ASTM No. 57 base layer using a lightweight deflectometer or LWD. Figures 4-10 and 4-11 show an LWD testing the deflection of a compacted PICP subbase and base. This device is used according to ASTM E2835 *Standard Test Method for Measuring Deflections using a Portable Impulse Plate Load Test Device*. This includes dropping a weight down a shaft on to a plate with an accelerometer. The device immediately calculates a deflection in millimeters and resilient modulus in megapascals. ASTM E2835 requires the user to take three hits to seat the plate and then an additional three hits from which the device provides an average deflection and modulus.

ICPI recommends testing the compacted No. 57 layer to achieve an average deflection no greater than 0.5 mm. To achieve this, the subbase under the base should be at least 10 in. (250 mm) thick. An LWD can be used to check variations in deflections on a compacted subbase. ICPI, however, has not published acceptance criteria. When LWD-testing the subbase, it should be at least 12 in. (300 mm) thick and the soil subgrade should not be saturated.

The PICP guide construction specification provides recommended testing intervals depending on the amount of installed aggregate. An LWD can collect data from many locations very quickly. The device is especially useful in identifying where base or subbase aggregate compaction was inconsistent and may require re-compaction. Deflections will be lower on aggregates confined by curbs, foundations, and utility structures.

Stabilized Bases—While not common, open-graded bases can be stabilized with asphalt or cement, placed, and compacted. Stabilized bases (and subbases) can increase the structural design life of PICP. Asphalt or cement coating the open-graded aggregate will likely reduce a modest amount of its water storage capacity. However, stabilization can increase its structural capacity to extend pavement life or be used in areas subject to concentrated wheel loads. Pervious concrete also can provide a base under the pavers or a subbase option applied over weak, slow draining soils. As previously mentioned, a pavement engineer experienced in stabilized base design and practice should be consulted for PICP designs with stabilized bases.

Install curbs or other edge restraints—The selection of edge restraints depends on whether the PICP is for pedestrian, residential driveways or vehicular use. Table 4-1 summarizes recommended edge restraint type based on the application.

Table 4-1. Recommended edge restraints for PICP

Edge Restraint Type	Pedestrian Only	Residential Driveway	Parking Lot or Street
Cast-in-place concrete curb	Yes	Yes	Yes
Precast concrete curb	Yes	Yes	Yes
Cut stone curb	Yes	Yes	Yes
Geogrid fastened to metal or plastic restraints	Yes	Yes	No
Compacted, dense-graded berms around PICP base perimeter with spiked metal or plastic edging to restrain pavers	Yes	Yes	No
Troweled concrete toe	Yes	Yes	No

Cast-in-place concrete, precast concrete and cut stone curbs are typically a minimum of 9 in. (225 mm) high and rest on the compacted ASTM No. 2 stone subbase. Consideration should be given to installing a concrete haunch under precast concrete or stone curbs. Curbs may be higher than 9 in. (225 mm) if they hold back grass, a sidewalk, bioswale or other structure. Figure 4-12 illustrates a typical raised curb cross section. The drain pipe is raised to create a sump, i.e., detention and infiltration.

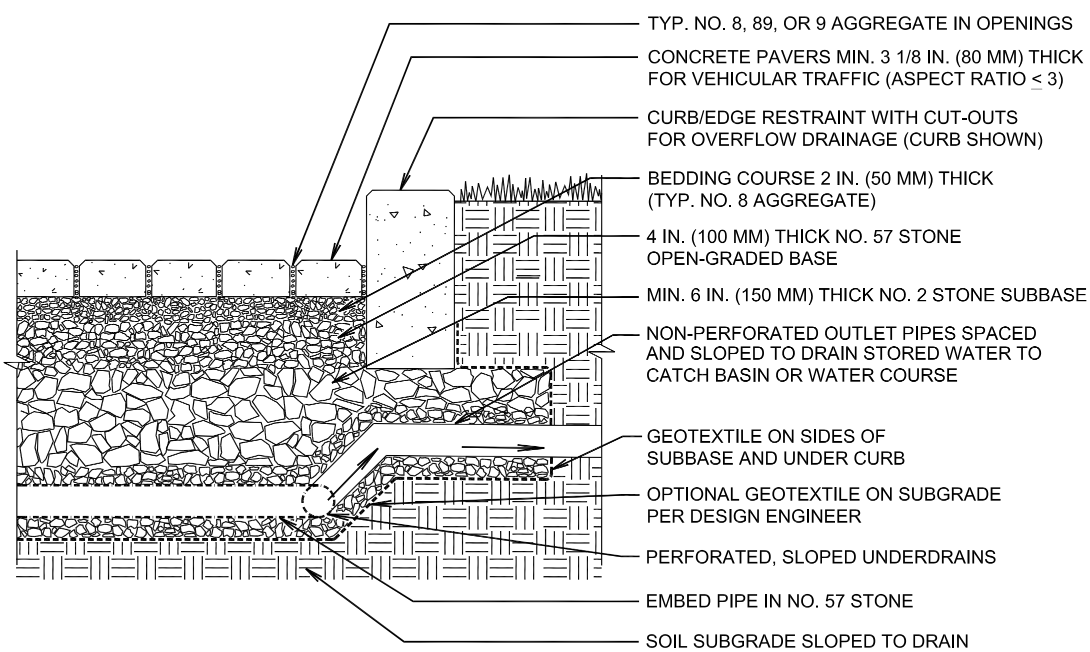


Figure 4-12. Typical cast-in-place concrete curb sits on the ASTM No. 2 stone subbase. Note that the ASTM No. 2 stone requires geotextile along its sides to prevent migration of soil into it.

If PICP is adjacent to existing impervious asphalt or concrete pavement, curbs level with the permeable and impervious surfaces are used. The curb should extend to the deeper of the two bases. Figures 4-13 and 4-14 show a full-depth concrete curb between impervious pavements and PICP. Another option is to separate the two bases with an impermeable liner.

The risk of water weakening the base under the impervious pavement can be substantially decreased by sloping the soil subgrade under the PICP away from the impervious pavement base and by using perforated drain pipes to remove water before it collects next to the base supporting the impervious pavement. Curbs installed against existing impervious pavement and base may cause erosion and weakening of the base from excavation due to installing the PICP. Eroded spaces can be filled with concrete to support the asphalt or concrete surface and base next to the curb.

For pedestrian areas and residential driveways, an edge restraint option involves compacted, dense-graded berms around the PICP base perimeter with plastic or metal edging fastened to their surface. The dense-graded base is a foundation for metal or plastic edging secured with steel spikes. These edge restraints are installed on the dense-graded berms in a manner identical to those on interlocking concrete pavement driveways. Figure 4-15 shows a typical cross section of this construction, and Figure 4-16 illustrates the berms in place prior to filling the driveway with open-graded aggregate. Figure 4-17 shows compaction of both types of bases. Edge restraints are then spiked into the dense-graded base berms, bedding material screeded and pavers installed. Figure 4-18 shows the pavers in place against a plastic edge restraint spiked or nailed into the dense-graded base. The edge restraint contains some of the bedding layer such that at least the bottom 1/2 in. (13 mm) of the pavers is also contained by the edging.

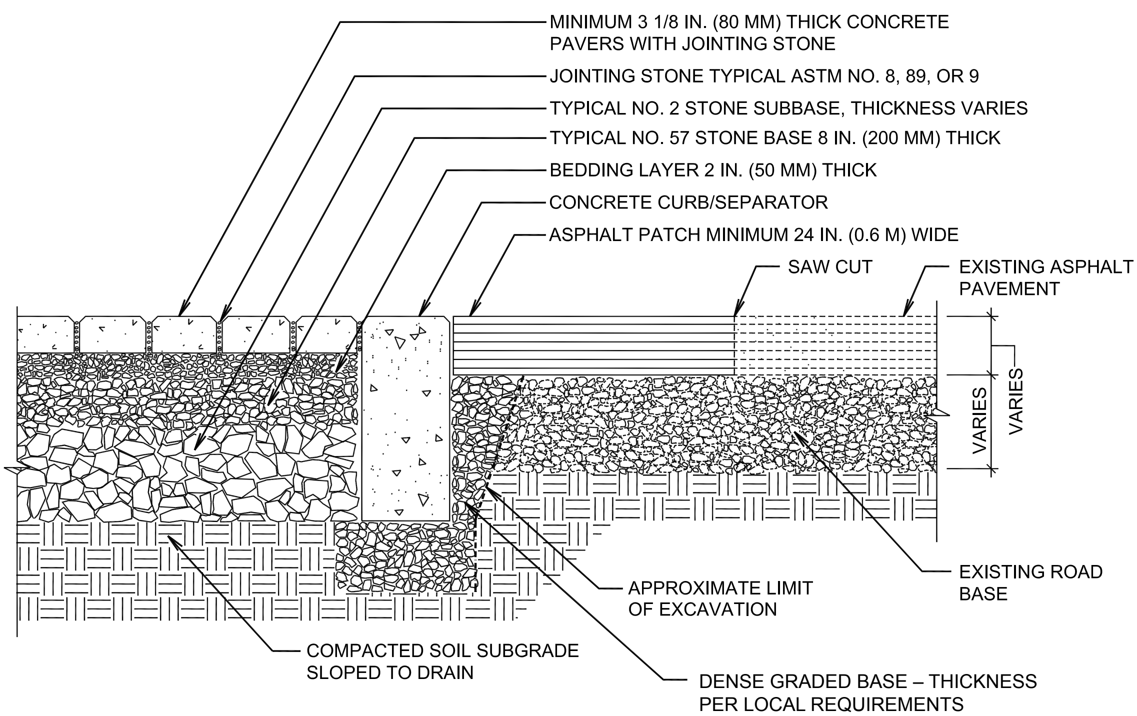


Figure 4-13. Typical cast-in-place concrete curb separates PICP from an adjacent asphalt pavement.

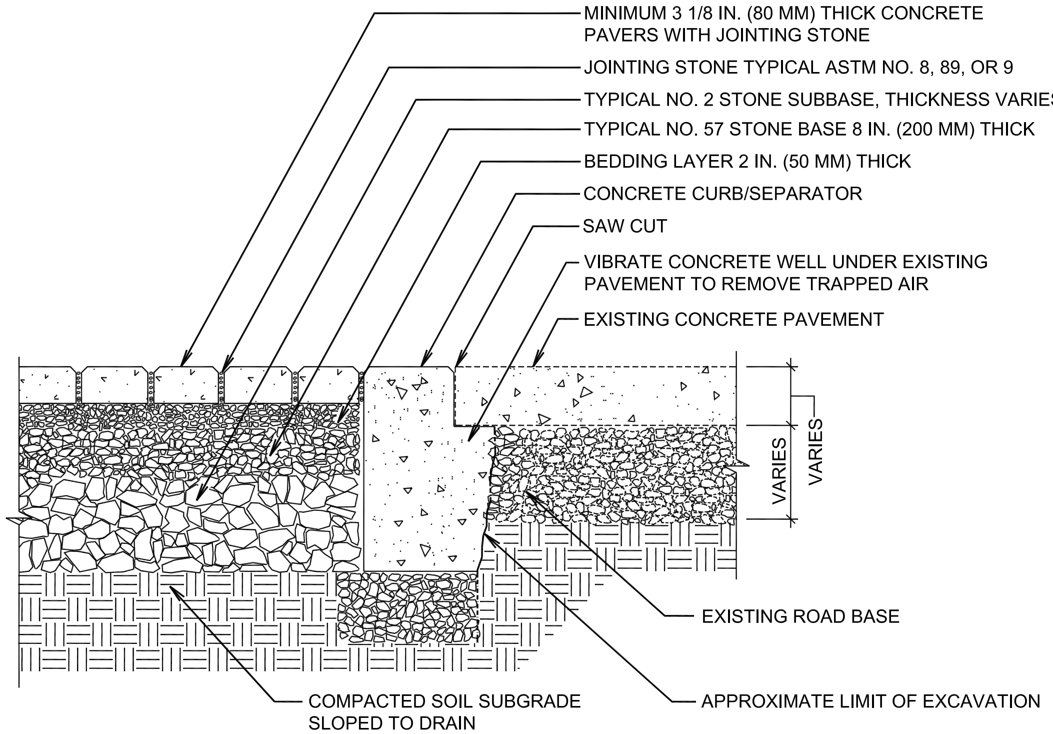
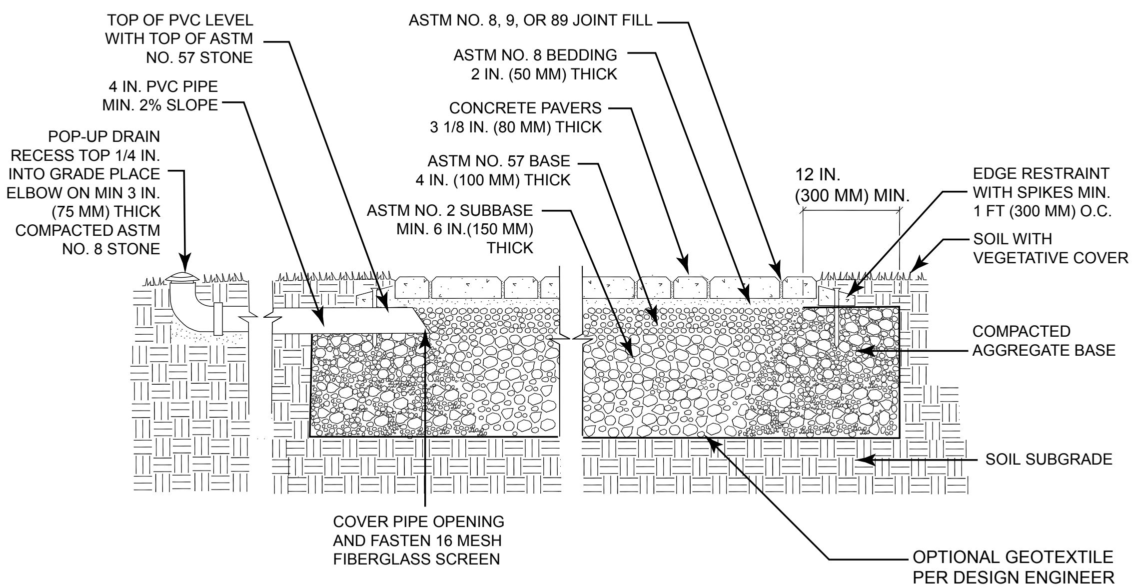


Figure 4-14. Typical cast-in-place concrete curb separates PICP from an adjacent concrete pavement.



NOTES:
1. DESIGN, MATERIAL AND CONSTRUCTION GUIDELINES TO FOLLOW ICPI GUIDE SPECIFICATIONS.
2. DAYLIGHT DRAIN PIPE TO DRAINAGE SWALE, USE POP-UP DRAIN IN YARD (AS SHOWN) OR CONNECT TO STORM SEWER.
3. APPLY WATERPROOF MEMBRANE VERTICALLY AGAINST HOUSE FOUNDATION PRIOR TO PLACING SUBBASE AND BASE.
4. ALL SOIL SUBGRADES SHALL SLOPE TOWARD STREET.
5. SUBGRADE SOIL MAXIMUM CROSS SLOPE IS 0.5%. MAXIMUM LONGITUDINAL SLOPE IS 2% TOWARD STREET.
6. USE SOIL BERMS FOR LONGITUDINAL SOIL SUBGRADE SLOPES EXCEEDING 2% TOWARD STREET.
7. 5% MAXIMUM SURFACE SLOPE.
8. THICKER SUBBASSE AND/OR ADDITIONAL DRAIN PIPES MAY BE REQUIRED IF DRIVEWAY RECEIVES RUNOFF FROM ADJACENT IMPERVIOUS SURFACES OR ROOFS.

Figure 4-15. Typical cross section detail using a dense-graded base berm as a foundation for anchoring metal or plastic edge restraints. Residential driveways may be constructed with full-depth No. 57 stone replacing the No. 2, 3 or 4 stone subbase.

Figure 4-19 illustrates a concrete toe placed against a sidewalk behind a driveway with a cast-in-place concrete edge. Concrete toes rest on the base extending at least 6 in. (150 mm) past the paver edges. The concrete should be a minimum of 4 in. (100 mm) wide by 3 in. (75 mm) deep so that it can restrain the pavers. Concrete mixed on the job site should use an approximate 5:1 aggregate-to-cement content. Once prepared in a concrete mixer, the concrete toe is typically spread with a shovel and smoothed with a trowel. Pavers are compacted once the concrete has hardened. This type of edging is not recommended in cold climate regions because of the high risk of cracking.

Other edge restraint options for pedestrian and residential driveway applications are geogrids joined to a metal or plastic edge restraint. The edging and grid typically rest on the No. 8 stone bedding layer.

Figure 4-16. Perimeter berms made with dense-graded base are in place prior to placing open-graded aggregate in the driveway.

Figure 4-17. Compacting the berms along the perimeter and the PICP base.

Figure 4-18. Plastic edge restraint is spiked into the dense-graded base berms so it can hold the pavers in place during compaction and service.

Figure 4-19. A PICP walk with a troweled concrete toe sits next to a driveway with a formed and cast-in-place concrete curb. Concrete toes should only be used for pedestrian applications.

Figure 4-20. Aluminum edge restraint for a walkway is fastened to a geogrid using a separate clamp plate.

Figure 4-21. An aluminum edge restraint with geogrid is used on this residential driveway.

Figure 4-22. Geogrid is welded to the bottom of this plastic edge restraint.

Figure 4-23. Geogrid is wrapped around this plastic edge restraint.

These edge restraints do not use metal stakes. Unlike dense-graded bases, open-graded aggregates provide little fastening capability for metal stakes. Figures 4-20 and 4-21 show applications for a residential walk and driveway. Figures 4-22 and 4-23 illustrate examples of plastic edging with geogrid fastened to and wrapped around the plastic edge restraint. As with all manufactured edge restraints, installation instructions provided by the supplier should be followed.

Place and screed the bedding layer—Metal rails are placed on the compacted ASTM No. 57 layer to guide bedding layer screeding. The surface should then be topped with a 2 in. (50 mm) thick layer of moist ASTM No. 8 crushed stone bedding layer. This layer is screeded and leveled over the ASTM No. 57 base, and not compacted. If No. 8 stone is not available, No. 89 stone can be used as a bedding course if the choke criteria are met (see page 49) with the underlying base aggregate. Various sizes of screeding equipment can be used ranging from hand tools, bucket screeds powered manually or by machine, or a modified asphalt spread that uses a laser guidance system to maintain elevations. Figures 4-24 through 4-27 illustrate examples of screeding equipment.

Figure 4-24. A hand screed is used for screeding the bedding layer in small areas.

Figure 4-25. A bucket screed powered manually is used to screed parking spaces.

Figure 4-26. For larger areas, bucket screeds can be pulled with equipment to accelerate the screeding process.

Figure 4-27. An asphalt type spreader specifically designed for spreading bedding stone uses a laser guidance system to keep elevations consistent while spreading.

The surface tolerance of the screeded ASTM No. 8 bedding material should be ±1/4 in. over 10 ft. (±6 mm over 3 m). The concrete pavers should be placed immediately after the ASTM No. 8 stone bedding is placed and screeded. Construction equipment and foot traffic should be kept off the screeded layer.

Install the pavers manually or with mechanical installation equipment—After screeding the bedding material, the pavers are placed on this layer. Paver installation can be by hand or with mechanical equipment. Prior to initial compaction, the pavers should be about 1 in. (25 mm) above adjacent curbs and protrusions in the pavement surface. Mechanized installation may be a cost-efficient means to install the units and will reduce installation time. Figure 4-28 and 4-29 shows mechanized equipment placing permeable paver layers manufactured for placement in their final laying pattern. Mechanical installation requires careful planning, including selection from available paver layer patterns from local manufactur-

Figure 4-28 and 4-29. Mechanical equipment accelerated installation of a parking lot in Illinois and a street in Oregon.

ers and well-orchestrated material flow logistics in order to gain efficiencies. For further information on mechanical installation, consult *ICPI Tech Spec 11—Mechanical Installation of Interlocking Concrete Pavement*s and *ICPI Tech Spec 15—A Guide for the Construction of Mechanically Installed Interlocking Concrete Pavements*.

Some mechanically installed paver laying patterns (e.g., herringbone) have a few pavers along the layer perimeter that are inserted or turned to create a continuous pattern. For some patterns, two adjacent half-pieces are removed and replaced with a single full-sized piece. For these patterns, the contractor must account for the extra material needed. This process of joining one layer to the next with pavers is called stitching. Stitching is not required on pedestrian or parking lot applications subject only to automobiles. The paver layers should be offset to not create continuous joint lines among the layers. Stitching is recommended for parking lots subject to trucks, as well as for alleys and streets.

Figure 4-30. Various methods of filling and sweeping PICP joints.

Figure 4-31. Prior to compaction, concrete pavers are typically as set about 1 in. (25 mm) higher than adjacent surfaces or curbs. The right-hand picture shows a pad under the plate compactor to protect the pavers' surfaces from scratches during compaction.

An important consideration with mechanical installation on projects over 50,000 sf (5,000 m^2) is monitoring paver production mold wear so that paver layers can quickly fit next to each other when installed. Among many topics, *Tech Spec 15* covers managing dimensional growth of pavers and provides means for confirming dimensions of the pavers at the factory and on the job site. Managing paver dimensions should be decided between the paver manufacturer and paver installation contractor and confirmed at the pre-construction meeting.

Border courses consisting of mostly whole (uncut) pavers are typically used against curbs at PICP edges and at transitions to other pavement surfaces. Paving units abutting border courses should be cut to fill spaces prior to compaction. Cut units should be no smaller than one-third of a whole unit if subject to tires.

Fill the paver joints and sweep the surface clean—The paver joints are filled with crushed, washed ASTM No. 8, 89 or 9 stone. The stone size used depends on the paver joint widths. The paver manufacturer can typically recommend the appropriate jointing stone size. Depending on the PICP area, spreading and sweeping can be done with shovels and brooms, or larger areas with Bobcats and swept into the paver joints with powered brooms or sweepers. Once the joints are full (within 1/4 in. or 6 mm of the paver surface), the surface must be swept clean prior to compaction, as loose stones on the surface can mar the pavers when in contact with a plate compactor. Figure 4-30 illustrates various filling and sweeping methods.

Compact the pavers—After the PICP surface is swept clean, it is compacted with a plate compactor. A minimum of two passes should be made, with the second pass in a perpendicular direction from the first pass. The path of the plate compactor should overlap several inches (cm). For paving units 3 1/8 to 4 in. (80 to 100 mm) thick, the plate compactor should exert a minimum 5,000 lbf (22 kN) at 75 to 90 Hz. Figure 4-31 shows permeable pavers being compacted for a street project using a large plate compactor.

Top up joints with joint filling stone as needed and sweep the surface clean—Compaction can cause some settlement of the stones inside the joints. If the stones are more than 1/4 in. (6 mm) from the paver surface, they should be topped up to this level, with additional stones swept into joints. All installed units should have joints filled and compacted within 6 ft (2 m) of the laying face at the end of each day. The paver surface should be swept clean prior to opening the PICP to traffic.

Aggregates in the paver joints can settle early in the life of the pavement. Some settlement can be reduced through consistent, thorough compaction of the base, pavers and bedding layers. However, it is advisable for the contractor to return to the site after six months, inspect the joints, and top them up with aggregate if they have settled to more than 1/4 in. (6 mm) below the paver surface. This service should be included in the construction specifications or provided in warranty/maintenance documents.

Construction Checklist

Planning

Pre-construction meeting

❒ Walk through site with builder/contractor/subcontractor to review erosion and sediment control plan/stormwater pollution prevention plan or "SWPPP"
❒ Determine when PICP is built in project construction sequence; before or after building construction, and measures for PICP protection and surface cleaning
❒ Aggregate material stockpile locations identified (hard surface or on geotextile)
❒ Protect finished product from contamination

Detail drawings on the plans

❒ Decide material delivery location(s) and flow
❒ Manufactured edge pavers (if applicable)
❒ String or sailor course of pavers against curbs, and concrete collars for utility structures, tree wells, and other related structures
❒ Location and size of curb cut-outs
❒ Location elevation and size of underdrains (if applicable)

Submittals

Aggregate Analysis

❒ Subbase aggregate gradation
❒ Base aggregate gradation
❒ Bedding aggregate gradation
❒ Jointing aggregate gradation
❒ Other tests results (as required by specifications) e.g. hardness
❒ All tests/reports within past 12 months

Other Materials

❒ Samples of materials with documented physical properties that meet specifications
- Edge restraint (if possible)
- Geotextiles
- Geomembranes
- Pipes

Permeable Interlocking Concrete Pavers

❒ Four paver samples
❒ Aspect ratio and thickness appropriate for application as specified by the design engineer
❒ Laboratory test results for ASTM C936 or CSA A231.2
❒ ASTM compressive strength per ASTM C140: average 8000 psi (55 MPa), min. 7200 psi (50 MPa)
❒ CSA cube/cylinder compressive strength at 7200 psi (50 MPa)
❒ Absorption per ASTM C140: average no greater than 5%, min. no greater than 7%
❒ Freeze-thaw durability per ASTM C1645 or CSA A231.2 deicing resistance test as appropriate
❒ ASTM optional abrasion durability per ASTM C418
❒ Manufacturer's product (cut) sheets for specified paver(s)
❒ Material Safety Sheet

Installer/Sub-contractor Documents

- ❒ Installer job references: minimum two references of jobs of similar size and complexity
- ❒ Current ICPI Certified Installer — PICP Specialist (full designation or at least Record of Completion): at least one person on-site with certificate (typically job foreman or crew leader)
- ❒ State/provincial, local licenses
- ❒ Contract specific insurances (liability, workers compensation, etc.), performance bonds

On Site Preparation

Mock-up

- ❒ Location, size, completion date
- ❒ Surcharge (settlement after plate compaction)
- ❒ Shows color range
- ❒ Joint widths per specs/manufacturer's literature
- ❒ Paver pattern(s) and direction per drawings (machine installation: show layer stitching per application)

Storage

- ❒ Paver bundles with steel/plastic bands or plastic wrap
- ❒ Each paver cube labeled and numbered
- ❒ Paver cubes stacked up 2 high maximum on level ground
- ❒ Pavers should be kept off any unpaved ground surface by pallets, plywood, etc.
- ❒ Stockpile aggregate on hard surfaces or geotextile to prevent contamination from site soils and sediment

Sediment Management

- ❒ Access routes for delivery and construction vehicles identified
- ❒ Vehicle tire/track washing station (if specified in Erosion & Sediment plan/SWPPP) location/ maintenance

Sediment Management Post-excavation

- ❒ Excavation hole as sediment trap: cleaned to final subgrade elevation immediately before subbase stone placement and runoff sources with sediment diverted away from the PICP

or

- ❒ All runoff diverted away from excavated area
- ❒ Temporary soil stockpiles should be protected from run-on, run-off from adjacent areas and from erosion by wind
- ❒ Ensure linear sediment barriers (if used) are properly installed, free of accumulated litter, and built up sediment less than 1/3 the height of the barrier
- ❒ No runoff enters PICP until soils stabilized in area draining to PICP

Verify Site Conditions

Foundation Walls

- ❒ PICP should be installed no closer than 10 ft (3 m) from foundation walls with no waterproofing or consideration for subsurface drainage

Proximity to Water Supply

- ❒ PICP should be installed no closer than 100 ft (30 m) from municipal water supply wells or open water

Soil Subgrade

- ❒ Rocks and roots removed, voids refilled with aggregate and compacted
- ❒ No groundwater seepage or standing water

- ❒ If no compacted subgrade, confirm no compaction from construction equipment, scarify if needed
- ❒ Soil compacted as specified, verify soil density and infiltration (saturated hydraulic conductivity)

Verify Materials Delivered to the Site

Pavers

- ❒ Source on tags match specification
- ❒ Dimensions match specification
- ❒ Colors match samples submitted and mock-up
- ❒ Delivery amounts and dates recorded

Aggregates

- ❒ Sieve analysis from quarry and general appearance of subbase, base, bedding, and jointing aggregates conforms to specifications

Additional Materials

- ❒ Edge restraints match specification
- ❒ Geotextile matches specification
- ❒ Geomembrane matches specification

Excavate and Construct Subbase & Base

Weather Conditions

- ❒ No work in heavy rain or snow; bedding is not saturated
- ❒ No aggregates and pavers placed on frozen base or subgrade
- ❒ No frozen aggregates

Excavation

- ❒ Utilities located and marked by local service
- ❒ Excavated area marked with paint and/or stakes
- ❒ Excavation size and location conforms to plan
- ❒ Soil compaction as specified: verify soil subgrade infiltration (hydraulic conductivity) with testing

Geotextile (if specified)

- ❒ Placement and down slope overlap (min. 1 ft or 0.3 m) conform to specifications and drawings
- ❒ Sides of excavation covered with geotextile prior to placing aggregate base/subbase
- ❒ No tears or holes
- ❒ No wrinkles, pulled taught and staked

Geomembranes (if specified)

- ❒ Placement (e.g., horizontally and/or vertically positioned against subgrades and foundations, covering soil walls and utility lines passing through the base/subbase, wrapping around utility lines, etc.)
- ❒ Field welding, seams, and seals at pipe penetrations done per specifications
- ❒ Top and bottom protected with non-woven geotextile (typ. 10 oz/sy)

Drain Pipes, Observations Wells and Cleanouts

- ❒ Size, perforations, locations, slope, and outfalls meet specifications and drawings
- ❒ Verify elevation of overflow pipes

Subbase, Base and Bedding Aggregates

- ❒ Spread (not dumped) with a front-end loader to avoid aggregate segregation
- ❒ Storage on hard surface or geotextile to keep sediment-free
- ❒ Thickness, placement, compaction and surface tolerances meet specifications and drawings
- ❒ Subbase and base compaction equipment meets specifications
- ❒ Subbase and base stiffness testing for consistency
- ❒ Bedding layer screeding: not compacted using various installation methods (manual & powered)

Edge Restraints
- ❒ Elevation, placement meet specifications and drawings

Install Permeable Interlocking Concrete Pavement

Paver Installation
- ❒ Elevations, slope, laying pattern, joint widths, and placement/compaction meet drawings and specifications
- ❒ No cut paver subject to tire traffic is less than 1/3 of a whole paver
- ❒ Six passes: min. 5,000 lbf (22 kN) plate compactor (or 2 passes w/ min. 10,000 lbf (44 kN) plate compactor)
- ❒ All pavers within 2 m or 6 ft of the laying face fully compacted at the completion of each day
- ❒ Surface tolerance of compacted pavers deviates no more than ±10 mm (3/8 in.) under a 3 m (10 ft) long straightedge

Jointing Aggregate
- ❒ Remove any aggregate from the pavement surface before compacting pavers and vibrating aggregate into the joints with minimum 6 passes of a plate compactor
- ❒ Broken and chipped pavers marked, removed and replaced with jointing stone
- ❒ No compaction within 6 ft (2 m) of an unrestrained edge of pavers
- ❒ All pavers compacted within 6 ft (2 m) of the laying face at the end of each day

Quality Control
- ❒ Surface elevation of pavers 1/8 to 3/8 in. (3 to 10 mm) above edge restraints, drainage inlets, concrete collars, or channels (for non-ADA accessible paths of travel); to ¼ in. or 6 mm (for ADA accessible paths of travel)
- ❒ Surface elevations conform to drawings
- ❒ Compacted pavers 1/8 to 1/4 in. (3 to 6 mm) above curbs, inlets, concrete collars and channels
- ❒ Lippage: no greater than 1/8 in. (3 mm) difference in height between adjacent pavers
- ❒ Bond (joint lines) lines: ±1/2 in. (15 mm) over 50 ft (15 m) string line
- ❒ Check filling of joints: max 1/4 in. (6 mm) below chamfer edge at completion. Fill and re-compact if necessary

Finished Project

Final inspection
- ❒ Surface swept clean
- ❒ Elevations and slope(s) conform to drawings
- ❒ Transitions to impervious paved areas separated with edge restraints
- ❒ Stabilization of soil in area draining into permeable pavement (min. 20 ft or 6 m wide vegetative strips recommended)
- ❒ Drainage swales or storm sewer inlets for emergency overflow. If storm sewer inlets are used, confirm overflow drainage to them
- ❒ Runoff from non-vegetated soil diverted from PICP surface
- ❒ Test surface for infiltration rate per specifications using ASTM C1781; minimum 100 in./hr (254 cm/hr) recommended

Maintenance Pavers
- ❒ Delivery location, date and time
- ❒ Verify amount delivered

Protection
- ❒ General contractor to protect paver area after paver installation subcontractor completes work and leaves site

PICP Specialist Course

ICPI offers a one-day PICP Specialist Course for those interested in training on PICP best construction practices. The credentials for taking this course are referenced as a requirement in an increasing number of commercial, municipal and state specifications, as well as in ICPI guide construction specifications in this section. The classroom program is for contractors who are presently doing residential and/or commercial interlocking concrete pavement installations, and who wish to move into the permeable pavement market. Participants should be experienced contractors, and it is recommended (but not required) that participants first complete the ICPI Concrete Paver Installer Course. The PICP course is approved for ICPI installer continuing education, and ICPI Certified Installers earn seven continuing education credits.

The course covers PICP systems, job planning and documentation, job layout, flow and estimating quantities, soil & site characteristics, subbase and base materials, edge restraints, bedding and jointing materials, paver selection and installation, and maintenance. Participants who take the course receive a student manual. Participants that earn a passing grade on the exam will receive a Record of Completion for the course. The Record of Completion does not expire, and does not require renewal. Installers who have earned the ICPI Certified Concrete Paver Installer designation can earn a PICP designation by submitting an application to ICPI documenting a minimum of 10 PICP projects totaling at least 50,000 sf (5,000 m^2). Most classes are sponsored by local ICPI manufacturing members. Visit **www.icpi.org/PICPS-Designation** for more information on ICPI members and designated organizations sponsoring courses, plus their dates and locations.

Guide Construction Specification

SECTION 32 14 13.19
PERMEABLE INTERLOCKING CONCRETE PAVEMENT

*Note: This guide specification for **US** applications describes construction of permeable interlocking concrete pavers with jointing, bedding, base and subbase aggregates. The joints are typically filled with ASTM No. 8, 89 or 9 aggregates and pavers rest on a bedding layer of typically ASTM No. 8 stone. (Canadian guide specifications start on page 85.) This 2 in. (50 mm) thick layer is placed over an open-graded base (typically No. 57 aggregate) no greater than 4 in. or 100 mm thick. The base typically rests on a subbase (typically No. 2 aggregate or similar sized material such as No. 3 or 4 aggregate) whose thickness depends on water storage and traffic support requirements. In low infiltration soils or installations with impermeable liners, some or all drainage is directed to an outlet via perforated drain pipes in the subbase. While this guide specification does not cover excavation, liners and drain pipes, notes are provided on these aspects.*

The text must be edited to suit specific project requirements. It should be reviewed by a qualified civil or geotechnical engineer familiar with the site conditions. Edit this specification term as necessary to identify the design professional in the General Conditions of the Contract.

PART 1 GENERAL

1.01 SUMMARY

A. Section Includes
   1. Permeable interlocking concrete pavers.
   2. Open-graded aggregate bedding material.
   3. Open-graded base aggregate.
   4. Open-graded subbase aggregate.
   5. Jointing aggregate.
   6. Edge restraints.
   7. [Geotextiles].

B. Related Sections
   1. Section [________]: Curbs.
   2. Section [________]: [Stabilized] aggregate base.
   3. Section [________]: [PVC] Drainage pipes
   4. Section [________]: Impermeable liner.
   5. Section [________]: Edge restraints.
   6. Section [________]: Drainage pipes and appurtenances.
   7. Section [________]: Earthworks/excavation/soil compaction.

1.02 REFERENCES

A. American Society of Civil Engineers (ASCE)
   1. ASCE [XX]-XX Design, Construction and Maintenance of Permeable Interlocking Concrete Pavement.

B. American Society for Testing and Materials (ASTM)
   1. C131 Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine.

2. C136 Method for Sieve Analysis for Fine and Coarse Aggregate.
3. C140 Standard Test Methods for Sampling and Testing Concrete Masonry Units and Related Units.
4. D448 Standard Classification for Sizes of Aggregate for Road and Bridge Construction.
5. C936 Standard Specification for Solid Interlocking Concrete Pavers.
6. C979 Specification for Pigments for Integrally Colored Concrete.
7. C1645 Standard Test Method for Freeze-thaw and De-icing Salt Durability of Solid Concrete Interlocking Paving Units.
8. C1781 Standard Test Method for Surface Infiltration Rate of Permeable Unit Pavement Systems.
9. D698 Test Methods for Moisture Density Relations of Soil and Soil Aggregate Mixtures Using a 5.5-lb (2.49 kg) Rammer and 12 in. (305 mm) drop.
10. D3385 Standard Test Method for Infiltration Rate of Soils in Field Using Double-Ring Infiltrometer.
11. E2835 Standard Test Method for Measuring Deflections using a Portable Impulse Plate Load Test Device.

B. Interlocking Concrete Pavement Institute (ICPI)
1. PICP Installer Course.
2. *Permeable Interlocking Concrete Pavement* manual.
3. *Permeable Design Pro* software for hydrologic and structural design

1.03 SUBMITTALS

A. In accordance with Conditions of the Contract and Division 1 Submittal Procedures Section.
B. Paver manufacturer's/installation subcontractor's drawings and details: Indicate perimeter conditions, junction with other materials, expansion and control joints, paver [layout,] [patterns,] [color arrangement,] installation [and setting] details. Indicate layout, pattern and relationship of paving joints to fixtures, and project formed details.
C. Minimum 3 lb (2 kg) samples of subbase, base and bedding aggregate materials.
D. Sieve analysis of aggregates for subbase, base and bedding materials per ASTM C136.
E. Project specific or producer/manufacturer source test results for void ratio and bulk density of the base and subbase aggregates.
F. Soils report indicating density test reports, classification, and infiltration rate measured on-site under compacted conditions, and suitability for the intended project.
G. Erosion and sediment control plan.
H. [Stormwater management [quality][quantity] calculations; structural analysis for vehicular applications] or [specify] design methods and models per ASCE [XX-XX], ICPI Permeable Interlocking Concrete Pavement Manual, or Permeable Design Pro software program.
I. Permeable concrete pavers:
1. Paver manufacturer's catalog sheets with product specifications.
2. [Four] representative full-size samples of each paver type, thickness, color, and finish. Submit samples indicating the range of color expected in the finished installation.
3. Accepted samples become the standard of acceptance for the work of this Section.
4. Laboratory test reports certifying compliance of the concrete pavers with ASTM C936.
5. Manufacturer's certification of concrete pavers by ICPI as having met applicable ASTM standards.
6. Manufacturers' material safety data sheets for the safe handling of the specified paving materials and other products specified herein.
7. Paver manufacturer's written quality control procedures including representative samples of production record keeping that ensure conformance of paving products to the product specifications.

J. Paver Installation Subcontractor:
   1. Demonstrate that job foremen on the project have a current certificate from the Interlocking Concrete Pavement Institute Concrete Paver Installer Certification program and a record of completion from the PICP Installer Course.
   2. Job references from projects of a similar size and complexity. Provide Owner/Client/General Contractor names, postal address, phone, fax, and email address.
   3. Written Method Statement and Quality Control Plan that describes material staging and flow, paving direction and installation procedures [layer stitching (as applicable)], including representative reporting forms that ensure conformance to the project specifications.

1.04 QUALITY ASSURANCE

A. Paver Installation Subcontractor Qualifications:
   1. Utilize an installer having successfully completed concrete paver installation similar in design, material and extent indicated on this project.
   2. Utilize an installer with job foremen holding a record of completion from the Interlocking Concrete Pavement Institute PICP Installer Technician Course.
B. Regulatory Requirements and Approvals: [Specify applicable licensing, bonding or other requirements of regulatory agencies.].
C. Review the manufacturers' quality control plan, paver installation subcontractor's Method Statement and Quality Control Plan with a pre-construction meeting of representatives from the manufacturer, paver installation subcontractor, general contractor, engineer and/or owner's representative.
D. Mock-Ups:
   1. Install a 10 ft x 10 ft (3 m x 3 m) paver area.

Note: Mechanized installations may require a larger mock up area. Consult with the paver installation contractor on the size of the mock up.

   2. Use this area to determine surcharge of the bedding layer, joint sizes, and lines, laying pattern, color and texture of the job.
   3. This area will be used as the standard by which the work will be judged.
   4. Subject to acceptance by owner, mock-up may be retained as part of finished work.
   5. If mock-up is not retained, remove and properly dispose of mock-up.

1.05 DELIVERY, STORAGE, AND HANDLING

A. General: Comply with Division 1 Product Requirement Section.
B. Comply with manufacturer's ordering instructions and lead-time requirements to avoid construction delays.
C. Delivery: Deliver materials in manufacturer's original, unopened, undamaged container packaging with identification tags intact on each paver bundle.
   1. Coordinate delivery and paving schedule to minimize interference with normal use of buildings adjacent to paving.
   2. Deliver concrete pavers to the site in steel banded, plastic banded, or plastic wrapped cubes capable of transfer by forklift or clamp lift.
   3. Unload pavers at job site in such a manner that no damage occurs to the product or existing construction
D Storage and Protection: Store materials in protected area such that they are kept free from mud, dirt, and other foreign materials.

1.06 ENVIRONMENTAL REQUIREMENTS

A. Do not install in heavy rain.
B. Do not install frozen aggregates.
C. Do not install aggregates on frozen soil subgrade.

1.07 MAINTENANCE

A. Extra materials: Provide [Specify area] [Specify percentage] additional material for use by owner for maintenance and repair.
B. Pavers shall be from the same production run as installed materials.

PART 2 PRODUCTS

Note: Some projects may include permeable and solid interlocking concrete pavements. Specify each product as required.

2.01 PAVING UNITS

A. Manufacturer: [Specify ICPI member manufacturer name.].
   1. Contact: [Specify ICPI member manufacturer contact information.].
B. Permeable Interlocking Concrete Paver Units:
   1. Paver Type: [Specify name of product group, family, series, etc.].
      a. Material Standard: Comply with ASTM C936. If pavers will be subject to freezing temperatures and deicers in service, conduct freeze-thaw durability testing while test specimens are immersed in a 3% saline solution per ASTM C1645.
      b. Color [and finish]: [Specify color.] [Specify finish].
      c. Color Pigment Material Standard: Comply with ASTM C979.

Note: Concrete pavers may have spacer bars on each unit. Spacer bars are recommended for mechanically installed pavers. Manually installed pavers may be installed with or without spacer bars. Verify with manufacturers that overall dimensions do not include spacer bars.

      d. Size: [Specify.] inches ([Specify.] mm) x [Specify.] inches ([Specify.] mm) x [Specify.] inches ([Specify.] mm) thick.

2.02 PRODUCT SUBSTITUTIONS

A. Substitutions: Permitted for gradations for crushed stone jointing material, base and subbase materials. Base and subbase materials shall have a minimum 0.32 porosity. All substitutions shall be approved in writing by the project engineer.

2.03 JOINTING, BEDDING, BASE AND SUBBASE AGGREGATES

A. Crushed stone with 90% fractured faces, LA Abrasion < 40 per ASTM C131.
B. Do not use rounded river gravel or recycled concrete aggregates for vehicular applications.
C. All stone materials shall be washed with less than 2% passing the No. 200 (0.075 mm) sieve.
D. Joint/opening filler, bedding, base and subbase: conforming to ASTM D448 gradation as shown in Tables 1, 2 and 3 below:

Note: No. 89 or No. 9 aggregates may be used to fill pavers with narrow joints.

Table 1. ASTM No. 8 Grading Requirements

Jointing and Bedding Aggregates	
Sieve Size	**Percent Passing**
1/2 in. (12.5 mm)	100
3/8 in. (9.5 mm)	85 to 100
No. 4 (4.75 mm	10 to 30
No. 8 (2.36 mm)	0 to 10
No. 16 (1.16 mm)	0 to 5

Table 2. ASTM No. 57 Grading Requirements

Base Aggregates	
Sieve Size	**Percent Passing**
1 1/2 in. (37.5 mm)	100
1 in. (25 mm)	95 to 100
1/2 in. (12.5 mm)	25 to 60
No. 4 (4.75 mm)	0 to 10
No. 8 (2.36 mm)	0 to 5

Note: ASTM No. 3 or No. 4 stone may be used as subbase material if ASTM No. 2 stone is unavailable.

Table 3. ASTM No. 2 Grading Requirements

Subbase Aggregate	
Sieve Size	**Percent Passing**
3 in. (75 mm)	100
2 1/2 (63 mm)	90 to 100
2 in. (50 mm)	35 to 70
1 1/2 in (37.5 mm)	0 to 15
3/4 in. (19 mm)	0 to 5

2.04 ACCESSORIES

A. Provide accessory materials as follows:

Note: Curbs will typically be cast-in-place concrete or precast set in concrete haunches. Concrete curbs may be specified in another Section. Do not use plastic edging with steel spikes to restrain the paving units for vehicular applications.

1. Edge Restraints
    a. Manufacturer: [Specify manufacturer.].
    b. Material: [Pre-cast concrete] [Cut stone] [Concrete].

b. Material Standard: [Specify material standard.].

Note: See ICPI publication, Permeable Interlocking Concrete Pavements for guidance on geotextile selection. Geotextile use is a designer option.

2. Geotextile:
   a. Material Type and Description: [Specify material type and description.].
   b. Material Standard: [Specify material standard.].
   c. Manufacturer: [Acceptable to interlocking concrete paver manufacturer]]

PART 3 EXECUTION

3.01 ACCEPTABLE INSTALLERS

A. [Specify acceptable paver installation subcontractors.].

3.02 EXAMINATION

Note: The elevations and surface tolerance of the soil subgrade determine the final surface elevations of concrete pavers. The paver installation contractor cannot correct deficiencies excavation and grading of the soil subgrade with additional bedding materials. Therefore, the surface elevations of the soil subgrade should be checked and accepted by the General Contractor or designated party, with written certification presented to the paver installation subcontractor prior to starting work.

A. Acceptance of Site Verification of Conditions:
   1. General Contractor shall inspect, accept and certify in writing to the paver installation subcontractor that site conditions meet specifications for the following items prior to installation of interlocking concrete pavers.

Note: Compaction of the soil subgrade is optional and should be determined by the project engineer. If the soil subgrade requires compaction, compact to a minimum of 95% standard Proctor density per ASTM D698. Compacted soil density and moisture should be checked in the field with a nuclear density gauge or other test methods for compliance to specifications. Stabilization of the soil and/or base material may be necessary with weak or continually saturated soils, or when subject to high wheel loads. Compaction will reduce the permeability of soils. If soil compaction is necessary, estimate the infiltration rate per ASTM D3385 for hydrologic design after compacting the test area(s) and measuring density. Reduced infiltration may require drain pipes within the open-graded subbase to conform to local storm drainage requirements.

      a. Verify that subgrade preparation, compacted density and elevations conform to specified requirements.
      b. Provide written density test results for soil subgrade to the Owner, General Contractor and paver installation subcontractor.
      c. Verify location, type, and elevations of edge restraints, [concrete collars around] utility structures, and drainage pipes and inlets.
   2. Do not proceed with installation of bedding and interlocking concrete pavers until subgrade soil conditions are corrected by the General Contractor or designated subcontractor.

3.03 PREPARATION

A. Verify that the soil subgrade is free from standing water.
B. Stockpile joint/opening filler, base and subbase materials such that they are free from standing water, uniformly graded, free of any organic material or sediment, debris, and ready for placement.
C. Edge Restraint Preparation:
   1. Install edge restraints per the drawings [at the indicated elevations].

3.04 INSTALLATION

Note: The minimum slope of the soil subgrade is typically 0.5%. Actual slope of soil subgrade will depend on the drainage design and exfiltration type. All drain pipes, observation wells, overflow pipes, and (if applicable) geotextiles, berms, baffles and impermeable liners should be in place per the drawings prior to or during placement of the subbase and base, depending on their location. Care must be taken not to damage drainpipes during compaction and paving. Base/subbase thicknesses and drainage should be determined using ICPI's Permeable Interlocking Concrete Pavements manual and Permeable Design Pro software.

A. General
   1. Any excess thickness of soil applied over the excavated soil subgrade to trap sediment from adjacent construction activities shall be removed before application of the [geotextile] and subbase materials.
   2. Keep area where pavement is to be constructed free from sediment during entire job. [Geotextiles] Base and bedding materials contaminated with sediment shall be removed and replaced with clean materials.
   3. Do not damage drainpipes, overflow pipes, observation wells, or any inlets and other drainage appurtenances during installation. Report any damage immediately to the project engineer.
B. Geotextiles
   1. Place on [bottom and] sides of soil subgrade. Secure in place to prevent wrinkling from vehicle tires and tracks.
   2. Overlap a minimum of [12 in. (0.3 m)] [24 in. (0.6 m)] in the direction of drainage.
C. Open-graded subbase and base

Note: Compaction of areas or sites that cannot accommodate a roller vibratory compactor may use a minimum 13,500 lbf (60 kN) vibratory plate compactor with a compaction indicator. At least two passes should be made over each lift of the subbase and base aggregates.

   1. Moisten, spread and compact the No. 2 subbase in maximum 8 in. (200 mm) thick lifts [without wrinkling or folding the geotextile. Place subbase to protect geotextile from wrinkling under equipment tires and tracks.]
   2. For each lift, make at least two passes in the vibratory mode then at least two in the static mode with a minimum 10 t (8 T) vibratory roller until there is no visible movement of the No. 2 stone. Do not crush aggregate with the roller
   3. Use a minimum 13,500 lbf (60 kN) plate compactor with a compaction indicator to compact areas that cannot be reached by the vibratory roller. Do not crush the aggregate with the plate compactor.
   4. The surface tolerance of the compacted No. 2 subbase shall be ± 2 in. (± 50 mm) over a 10 ft (3 m) straightedge.

5. Moisten, spread and compact the No. 57 base layer in one 4 in. (100 mm) thick lift. On this layer, make at least two passes in the vibratory mode then at least two in the static mode with a minimum 10 t (8 T) vibratory roller until there is no visible movement of the No. 57 stone. Do not crush aggregate with the roller.
6. The surface tolerance the compacted No. 57 base should not deviate more than ± 1/2 in. (13 mm) over a 10 ft (3 m) straightedge.

Note: At the option of the designer, this supplemental test method bracketed in item C6 describing the use of a lightweight deflectometer (LWD) can be used for in-situ deflection testing of the compacted open-graded compacted aggregate subbase layer (typically ASTM No. 2, 3 or 4 stone) and the compacted base layer (typically ASTM No. 57 stone). This test method can assist contractors in reaching adequate job site compaction and offer an additional level of confidence for the project owner and designer. This test method is appropriate for pavements subject to consistent vehicular traffic such as parking lots, alleys and roads. The LWD test method should comply with ASTM E2835. This test protocol is not needed for pedestrian areas and residential driveways.

[7. Light Weight Deflectometer (LWD) for Compacted Subbase and Base Aggregate Deflection Testing
   a. Test a minimum of every [500 sf (50 m^2)] of compacted subbase and base area. In addition, test areas next to other pavements, curbs, buildings, and protrusions.
   b. Do not test aggregate over saturated soil subgrades.
   c. The maximum average of three deflections deemed acceptable shall be 0.5 mm.
8. Report
   a. The report shall include the following:
      1) Project description.
      2) Aggregate type and layer thicknesses.
      3) Aggregate characteristic properties: gradation, porosity, bulk density.
      4) Compaction equipment type and weight.
      5) Static and/or vibratory compaction.
      6) Number of passes of the compaction equipment.
      7) Sketch of test area and numbered LWD test locations on the compacted subbase and base.
      8) Average of three LWD deflections for each location in millimeters.]

Note: If No. 8 stone is not available, No. 89 stone can be used as a bedding course if the choke criteria are met (see page 49) with underlying base aggregate.

D. Bedding layer
   1. Moisten, spread and screed the No. 8 stone bedding material.
   2. Fill voids left by removed screed rails with No. 8 stone and smooth to conform to adjacent screeded bedding material.
   3. The surface tolerance of the screeded No. 8 bedding layer shall be ±3/8 in. (10 mm) over a 10 ft (3 m) straightedge.
   4. Do not subject screeded bedding material to any pedestrian or vehicular traffic before paving unit installation begins.
E. Permeable interlocking concrete pavers and jointing aggregates
   1. Lay the paving units in the pattern(s) and joint widths shown on the drawings. Maintain straight pattern lines.
   2. Fill gaps at the edges of the paved area with cut units. Cut pavers subject to tire traffic shall be no smaller than 1/3 of a whole unit. Cut pavers placed in other areas shall no less than 2 in. (50 mm) long.

3. Cut pavers with a masonry saw and place them at the edges.

Note: Some paver joint widths may be narrow and not accept most of the No. 8 stone. Use joint material that will fill joints such as washed ASTM No. 89 or No. 9 stone.

4. Apply jointing stone to the paver surface, sweeping it across and filling the paver joints.
5. Remove excess aggregate on the surface by sweeping the pavers clean.
6. Compact and seat the pavers into the bedding material using a low-amplitude, 75-90 Hz plate compactor capable of at least 22 kN (5,000 lbf). Make at least two passes in perpendicular directions with the plate compactor.
7. Apply additional aggregate to the openings and joints if needed, filling them completely.
8. Remove excess aggregate by sweeping.
9. All pavers within 6 ft (2 m) of the laying face must be left fully compacted at the completion of each day.
11. The final surface tolerance of compacted pavers shall not deviate more than ±3/8 in. (10 mm) under a 10 ft (3 m) long straightedge.
12. The surface elevation of pavers shall be 1/8 to 1/4 in. (3 to 6 mm) above adjacent drainage inlets, concrete collars or channels.

3.05 FIELD QUALITY CONTROL

A. After sweeping the surface clean, check final elevations for conformance to the drawings.
B. Lippage: No greater than 1/8 in. (3 mm) difference in height between adjacent pavers.

Note: The surface of the pavers may be 1/8 to 1/4 in. (3 to 6 mm) above the final elevations after compaction. This helps compensate for possible minor settling normal to pavements.

C. The surface elevation of pavers shall be 1/8 to 1/4 in. (3 to 6 mm) above adjacent drainage inlets, concrete collars or channels.
D. Bond lines for paver courses: ±½ in. (±15 mm) over a 50 ft (15 m) taut string line.
E. Verify the surface infiltration at a minimum of 100 in./hr (250 cm/hr) using test method C1781.

3.06 PROTECTION

A. After work in this section is complete, the General Contractor shall be responsible for protecting work from sediment deposition and damage due to subsequent construction activity on the site.
B. PICP installation contractor shall return to site after 6 months from the completion of the work and provide the following as required: fill paver joints with specified crushed, washed aggregate, typically ASTM No. 8, 89 or 9 stone, replace broken or cracked pavers, and re-level settled pavers to initial elevations. Any additional work shall be considered part of original bid price and with no additional compensation.

END OF SECTION

SECTION 32 14 13.19
PERMEABLE INTERLOCKING CONCRETE PAVEMENT

*Note: This guide specification for **Canadian** applications describes construction of permeable interlocking concrete pavers with jointing, bedding, base and subbase aggregates. The joints between the pavers are typically filled with CSA A23.1 Group II, 5-2.5 mm nominal size aggregate (or similar) and placed on a permeable, open-graded crushed stone bedding layer (typically CSA A23.1 Group II, 10-5 mm nominal size aggregate). This 50 mm thick bedding layer is placed over an open-graded base (typically CSA A23.1 Group II, 28-14 mm nominal size aggregate) that is 100 mm thick. This base rests on a subbase (typically CSA A23.1 Group II, 80-40 mm nominal size aggregate) whose thickness depends on water storage and traffic support requirements. In low infiltration soils or installations with impermeable liners, some or all drainage is directed to an outlet via perforated drain pipes in the subbase. While this guide specification does not cover excavation, liners and drain pipes, notes are provided on these aspects.*

The text must be edited to suit specific project requirements. It should be reviewed by a qualified civil or geotechnical engineer familiar with the site conditions. Edit terms in this specification as necessary to identify the design professional in the General Conditions of the Contract.

PART 1 GENERAL

1.01 SUMMARY

A. Section Includes
   1. Permeable interlocking concrete pavers.
   2. Coarse aggregate bedding material.
   3. Coarse aggregate base aggregate.
   4. Open-graded subbase aggregate.
   5. Jointing aggregate.
   6. Edge restraints.
   7. [Geotextiles].

B. Related Sections

1. Section [________]: Curbs.
2. Section [________]: [Stabilized] aggregate base.
3. Section [________]: [PVC] Drainage pipes
4. Section [________]: Impermeable liner.
5. Section [________]: Edge restraints.
6. Section [________]: Drainage pipes and appurtenances.
7. Section [________]: Earthworks/excavation/soil compaction.

1.02 REFERENCES

A. American Society of Civil Engineers (ASCE)
   1. ASCE [XX]-XX Design, Construction and Maintenance of Permeable Interlocking Concrete Pavement.

B. American Society for Testing and Materials (ASTM)
   1. C131 Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine.
   2. C1781 Standard Test Method for Surface Infiltration Rate of Permeable Unit Pavement Systems.

3. D698 Test Methods for Moisture Density Relations of Soil and Soil Aggregate Mixtures Using a 5.5-lb (2.49 kg) Rammer and 12 in. (305 mm) drop.
4. D3385 Standard Test Method for Infiltration Rate of Soils in Field Using Double-Ring Infiltrometer.
5. E2835 Standard Test Method for Measuring Deflections using a Portable Impulse Plate Load.

C. Canadian Standards Association (CSA)
1. A23.1/A23.2 Methods of Test for Concrete Materials and Methods of Concrete Construction/Methods of Test for Concrete.
2. A23.2A Sieve Analysis of Fine and Coarse Aggregates.
3. A23.2-10A Density of Aggregate.
4. A23.2-16A Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine (for aggregate ≤ 40 mm).
5. A23.2-17A Resistance to Degradation of Large-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine (for aggregate > 40 mm).
6. A231.2 Precast Concrete Pavers.

D. Interlocking Concrete Pavement Institute (ICPI)
1. PICP Installer Course.
2. Permeable Interlocking Concrete Pavement manual.
3. Permeable Design Pro software for hydrologic and structural design

1.03 SUBMITTALS

A. In accordance with Conditions of the Contract and Division 1 Submittal Procedures Section.
B. Paver manufacturer's/installation subcontractor's drawings and details: Indicate perimeter conditions, junction with other materials, expansion and control joints, paver [layout,] [patterns,] [colour arrangement,] installation [and setting] details. Indicate layout, pattern and relationship of paving joints to fixtures, and project formed details.
C. Minimum 2 kg samples of subbase, base and bedding aggregate materials.
D. Sieve analysis of aggregates for subbase, base, bedding and jointing materials per CSA A23.2A.
E. Project specific or producer/manufacturer source test results for porosity and bulk density of the base and subbase aggregates per CSA A23.2-10A.
F. Soils report indicating density test reports, classification, and infiltration rate measured on-site under compacted conditions, and suitability for the intended project.
G. Erosion and sediment control plan.
H. [Stormwater management [quality][quantity] calculations; structural analysis for vehicular applications] or [specify] design methods and models per ASCE [XX-XX], ICPI Permeable Interlocking Concrete Pavement Manual, or Permeable Design Pro software program.
I. Permeable concrete pavers:
1. Paver manufacturer's catalog sheets with product specifications.
2. [Four] representative full-size samples of each paver type, thickness, colour, and finish. Submit samples indicating the range of colour expected in the finished installation.
3. Accepted samples become the standard of acceptance for the work of this Section.
4. Laboratory test reports certifying compliance of the concrete pavers with CSA A231.2.
5. Manufacturer's certification of concrete pavers by ICPI as having met applicable ASTM standards.
6. Manufacturers' material safety data sheets for the safe handling of the specified paving materials and other products specified herein.
7. Paver manufacturer's written quality control procedures including representative samples of production record keeping that ensure conformance of paving products to the product specifications.

J. Paver Installation Subcontractor:
   1. Demonstrate that job foremen on the project have a current certificate from the Interlocking Concrete Pavement Institute Concrete Paver Installer Certification program and a record of completion from the PICP Installer Course.
   2. Job references from projects of a similar size and complexity. Provide Owner/Client/General Contractor names, postal address, phone, fax, and email address.
   3. Written Method Statement and Quality Control Plan that describes material staging and flow, paving direction and installation procedures [layer stitching (as applicable)], including representative reporting forms that ensure conformance to the project specifications.

1.04 QUALITY ASSURANCE

A. Paver Installation Subcontractor Qualifications:
   1. Utilize an installer having successfully completed concrete paver installation similar in design, material and extent indicated on this project.
   2. Utilize an installer with job foremen holding a record of completion from the Interlocking Concrete Pavement Institute PICP Installer Technician Course.
B. Regulatory Requirements and Approvals: [Specify applicable licensing, bonding or other requirements of regulatory agencies.].
C. Review the manufacturers' quality control plan, paver installation subcontractor's Method Statement and Quality Control Plan with a pre-construction meeting of representatives from the manufacturer, paver installation subcontractor, general contractor, engineer and/or owner's representative.
D. Mock-Ups:
   1. Install a 3 m x 3 m paver area.

Note: Mechanized installations may require a larger mock up area. Consult with the paver installation contractor on the size of the mock up.

   2. Use this area to determine surcharge of the bedding layer, joint sizes, and lines, laying pattern, colour and texture of the job.
   3. This area will be used as the standard by which the work will be judged.
   4. Subject to acceptance by owner, mock-up may be retained as part of finished work.
   5. If mock-up is not retained, remove and properly dispose of mock-up.

1.05 DELIVERY, STORAGE, AND HANDLING

A. General: Comply with Division 1 Product Requirement Section.
B. Comply with manufacturer's ordering instructions and lead-time requirements to avoid construction delays.
C. Delivery: Deliver materials in manufacturer's original, unopened, undamaged container packaging with identification tags intact on each paver bundle.
   1. Coordinate delivery and paving schedule to minimize interference with normal use of buildings adjacent to paving.
   2. Deliver concrete pavers to the site in steel banded, plastic banded, or plastic wrapped cubes capable of transfer by forklift or clamp lift.
   3. Unload pavers at job site in such a manner that no damage occurs to the product or existing construction
D. Storage and Protection: Store materials in protected area such that they are kept free from mud, dirt, and other foreign materials.

1.06 ENVIRONMENTAL REQUIREMENTS

A. Do not install in heavy rain.
B. Do not install frozen aggregates.
C. Do not install aggregates on frozen soil subgrade.

1.07 MAINTENANCE

A. Extra materials: Provide [Specify area] [Specify percentage] additional material for use by owner for maintenance and repair.
B. Pavers shall be from the same production run as installed materials.

PART 2 PRODUCTS

Note: Some projects may include permeable and solid interlocking concrete pavements. Specify each product as required.

2.01 PAVING UNITS

A. Manufacturer: [Specify ICPI member manufacturer name.].
    1. Contact: [Specify ICPI member manufacturer contact information.].
B. Permeable Interlocking Concrete Paver Units:
    1. Paver Type: [Specify name of product group, family, series, etc.].
        a. Material Standard: Comply with CSA A231.2 compressive strength and deicer durability requirements. Colour [and finish]: [Specify colour.] [Specify finish].

Note: Concrete pavers may have spacer bars on each unit. Spacer bars are recommended for mechanically installed pavers. Manually installed pavers may be installed with or without spacer bars. Verify with manufacturers that overall dimensions do not include spacer bars.

        b. Size: [Specify] mm long x [Specify] mm wide x [Specify] mm] thick.

2.02 PRODUCT SUBSTITUTIONS

A. Substitutions: Permitted for gradations for crushed stone jointing material, base and subbase materials. Base and subbase materials shall have a minimum 0.32 porosity. All substitutions shall be approved in writing by the project engineer.

2.03 CRUSHED STONE FILLER, BEDDING, BASE AND SUBBASE

A. Crushed stone with 90% fractured faces, LA Abrasion < 40 per CSA A23.2-16A or A23.2-17A as applicable to the largest aggregate size of each material gradation.
B. Do not use rounded river gravel or recycled concrete aggregates for vehicular applications.
C. All stone materials shall be washed with less than 2% passing the 0.075 mm sieve.
D. Joint/opening filler, bedding, base and subbase: conforming to CSA A23.1 Group II, Grading Requirements for Coarse Aggregates in Tables 1, 2 and 3 below:

Note: Group II 5-2.5 mm aggregate may be used to fill paver joints. Confirm recommended gradations from the concrete paver supplier.

Table 1. 10-5 mm Aggregate Grading Requirements for the Bedding Layer

Sieve Size	Percent Passing
14 mm	100
10 mm	85 to 100
5 mm	0-20
2.5 mm	0 to 5

Table 2. 28-14 mm Aggregate Grading Requirements for the Base

Sieve Size	Percent Passing
40 5m	100
28 mm	90 to 100
20 mm	30 to 65
14 mm	0 to 15
5 mm	0 to 5

Note: 56-28 mm size aggregate may be used as subbase material.

Table 3. 80-40 mm Aggregate Grading Requirements for the Subbase

Sieve Size	Percent Passing
112 mm	100
80 mm	90 to 100
56 mm	25 to 60
40 mm	0 to 15
20 mm	0 to 5

2.04 ACCESSORIES

A. Provide accessory materials as follows:

Note: Curbs will typically be cast-in-place concrete or precast set in concrete haunches. Concrete curbs may be specified in another Section. Do not use plastic edging with steel spikes to restrain the paving units for vehicular applications.

1. Edge Restraints
   a. Manufacturer: [Specify manufacturer.].
   b. Material: [Pre-cast concrete] [Cut stone] [Concrete].
   b. Material Standard: [Specify material standard.].

Note: See ICPI publication, Permeable Interlocking Concrete Pavements for guidance on geotextile selection. Geotextile use is a designer option.

2. Geotextile:
   a. Material Type and Description: [Specify material type and description.].
   b. Material Standard: [Specify material standard.].
   c. Manufacturer: [Acceptable to interlocking concrete paver manufacturer]]

PART 3 EXECUTION

3.01 ACCEPTABLE INSTALLERS

A. [Specify acceptable paver installation subcontractors.].

3.02 EXAMINATION

Note: The elevations and surface tolerance of the soil subgrade determine the final surface elevations of concrete pavers. The paver installation contractor cannot correct deficiencies excavation and grading of the soil subgrade with additional bedding materials. Therefore, the surface elevations of the soil subgrade should be checked and accepted by the General Contractor or designated party, with written certification presented to the paver installation subcontractor prior to starting work.

A. Acceptance of Site Verification of Conditions:
   1. General Contractor shall inspect, accept and certify in writing to the paver installation subcontractor that site conditions meet specifications for the following items prior to installation of interlocking concrete pavers.

Note: Compaction of the soil subgrade is optional and should be determined by the project engineer. If the soil subgrade requires compaction, compact to a minimum of 95% standard Proctor density per ASTM D698. Compacted soil density and moisture should be checked in the field with a nuclear density gauge or other test methods for compliance to specifications. Stabilization of the soil and/or base material may be necessary with weak or continually saturated soils, or when subject to high wheel loads. Compaction will reduce the permeability of soils. If soil compaction is necessary, estimate the infiltration rate per ASTM D3385 for hydrologic design after compacting the test area(s) and measuring density. Reduced infiltration may require drain pipes within the open-graded subbase to conform to local storm drainage requirements.

      a. Verify that subgrade preparation, compacted density and elevations conform to specified requirements.
      b. Provide written density test results for soil subgrade to the Owner, General Contractor and paver installation subcontractor.
      c. Verify location, type, and elevations of edge restraints, [concrete collars around] utility structures, and drainage pipes and inlets.
   2. Do not proceed with installation of bedding and interlocking concrete pavers until subgrade soil conditions are corrected by the General Contractor or designated subcontractor.

3.03 PREPARATION

A. Verify that the soil subgrade is free from standing water.
B. Stockpile joint/opening filler, base and subbase materials such that they are free from standing water, uniformly graded, free of any organic material or sediment, debris, and ready for placement.
C. Edge Restraint Preparation:
   1. Install edge restraints per the drawings [at the indicated elevations].

3.04 INSTALLATION

Note: The minimum slope of the soil subgrade is typically 0.5%. Actual slope of soil subgrade will depend on the drainage design and exfiltration type. All drain pipes, observation wells, overflow pipes, and (if applicable) geotextiles, berms, baffles and impermeable liners should be in place per the drawings prior to or during placement of the subbase and base, depending on their location. Care must be taken not to damage drainpipes during compaction and paving.

A. General
   1. Any excess thickness of soil applied over the excavated soil subgrade to trap sediment from adjacent construction activities shall be removed before application of the [geotextile] and subbase materials.
   2. Keep area where pavement is to be constructed free from sediment during entire job. [Geotextiles] Base and bedding materials contaminated with sediment shall be removed and replaced with clean materials.
   3. Do not damage drainpipes, overflow pipes, observation wells, or any inlets and other drainage appurtenances during installation. Report any damage immediately to the project engineer.

B. Geotextiles
   1. Place on [bottom and] sides of soil subgrade. Secure in place to prevent wrinkling from vehicle tires and tracks.
   2. Overlap a minimum of [0.3 m] in the direction of drainage.

C. Open-graded subbase and base

Note: Compaction of areas or sites that cannot accommodate a roller vibratory compactor may use a minimum 60 kN vibratory plate compactor with a compaction indicator. At least two passes should be made over each lift of the subbase and base aggregates.

   1. Moisten, spread and compact the 80-40 mm subbase aggregate in maximum 200 mm thick lifts [without wrinkling or folding the geotextile. Place subbase to protect geotextile from wrinkling under equipment tires and tracks.]
   2. For each lift, make at least two passes in the vibratory mode then at least two in the static mode with a minimum 8 T vibratory roller until there is no visible movement of the 80-40 mm aggregate. Do not crush aggregate with the roller
   3. Use a minimum 60 kN plate compactor with a compaction indicator to compact areas that cannot be reached by the vibratory roller. Do not crush the aggregate with the plate compactor.
   4. The surface tolerance of the compacted 80-40 mm aggregate shall be ±70 mm over a 3 m straightedge.
   5. Moisten, spread and compact the 28-14 mm aggregate base layer in one 100 mm thick lift. On this layer, make at least two passes in the vibratory mode then at least two in the static mode with a minimum 8 T vibratory roller until there is no visible movement of the aggregate. Do not crush aggregate with the roller.
   6. The surface tolerance the compacted 28-14 mm aggregate base shall be ±15 mm over a 3 m straightedge.

Note: At the option of the designer, this supplemental test method bracketed in item C6 describing the use of a lightweight deflectometer (LWD) can be used for in-situ deflection testing of the compacted open-graded compacted aggregate subbase layer and the compacted base layer. This test method can assist contractors in reaching adequate job site compaction and offer an additional level of confidence for the project owner and designer. This test method is appropriate for pavements subject to consistent vehicular traffic such as parking lots, alleys and roads and can be used on pedestrian and residential driveway projects to help minimize settlement. The LWD test method should comply with ASTM E2835.

[7. Light Weight Deflectometer (LWD) for Compacted Subbase and Base Aggregate Deflection Testing
   a. Test a minimum of every [50 m^2] of compacted subbase and base area. In addition, test areas next to other pavements, curbs, buildings, and protrusions.
   b. Do not test aggregates on saturated soil subgrades.
   c. After three seating blows, the maximum average of three deflections deemed acceptable shall be 0.5 mm.
8. Report
   a. The report shall include the following:
      1) Project description.
      2) Aggregate type and layer thicknesses.
      3) Aggregate characteristic properties: gradation, porosity, bulk density.
      4) Compaction equipment type and weight.
      5) Static and/or vibratory compaction.
      6) Number of passes of the compaction equipment.
      7) Sketch of test area and numbered LWD test locations on the compacted subbase and base.
      8) Average of three LWD deflections for each location in millimeters.]

Note: If 10-5 mm aggregate is not available, a finer gradation can be used as a bedding course if the choke criteria are met (see page 49) with underlying base aggregate.

D. Bedding layer
   1. Moisten, spread and screed the 10-5 mm aggregate.
   2. Fill voids left by removed screed rails with 10-5 mm aggregate and smooth to conform to adjacent screeded bedding material.
   3. The surface tolerance of the screeded 10-5 mm aggregate bedding layer shall be ±10 mm over a 3 m straightedge.
   4. Do not subject screeded bedding material to any pedestrian or vehicular traffic before paving unit installation begins.
E. Permeable interlocking concrete pavers and permeable joint/opening fill material
   1. Lay the paving units in the pattern(s) and joint widths shown on the drawings. Maintain straight pattern lines.
   2. Fill gaps at the edges of the paved area with cut units. Cut pavers subject to tire traffic shall be no smaller than 1/3 of a whole unit. Cut pavers placed in other areas shall no less than 50 mm long.
   3. Cut pavers with a masonry saw and place them at the edges.
   4. Apply [10-5 mm aggregate][ASTM][No. 8][No. 89][No. 9] joint/opening fill material to the paver surface, sweeping it across and filling the paver joints.
   5. Remove excess aggregate on the surface by sweeping the pavers clean.

6. Compact and seat the pavers into the bedding material using a low-amplitude, 75-90 Hz plate compactor capable of at least 22 kN. Make at least two passes in perpendicular directions with the plate compactor.
7. Apply additional aggregate to the openings and joints if needed, filling them completely.
8. Remove excess aggregate by sweeping.
9. All pavers within 2 m of the laying face must be left fully compacted at the completion of each day.
10. The final surface tolerance of compacted pavers shall not deviate more than ±10 mm under a 3 m long straightedge.
11. The surface elevation of pavers shall be 3 to 6 mm above adjacent drainage inlets, concrete collars or channels.

3.05 FIELD QUALITY CONTROL

A. After sweeping the surface clean, check final elevations for conformance to the drawings.
B. Lippage: No greater than 3 mm difference in height between adjacent pavers.

Note: The surface of the pavers may be 3 to 6 mm above the final elevations after compaction. This helps compensate for possible minor settling normal to pavements.

C. The surface elevation of pavers shall be 3 to 6 mm above adjacent drainage inlets, concrete collars or channels.
D. Bond lines for paver courses: ±15 mm over a 15 m taut string line.
E. Verify the surface infiltration at a minimum of 250 cm/hr using test method ASTM C1781.

3.06 PROTECTION

A. After work in this section is complete, the General Contractor shall be responsible for protecting work from sediment deposition and damage due to subsequent construction activity on the site.
B. PICP installation contractor shall return to site after 6 months from the completion of the work and provide the following as required: fill paver joints with specified crushed, washed aggregate, typically ASTM No. 8, 89 or 9 stone, replace broken or cracked pavers, and re-level settled pavers to initial elevations. Any additional work shall be considered part of original bid price and with no additional compensation.

END OF SECTION

Section 5. Maintenance

This section provides maintenance guidelines plus an in-service inspection checklist for municipalities and project owners. Also included is a model maintenance agreement between a project owner who has installed PICP and the local municipality to help ensure maintenance. As an additional resource, a model zoning ordinance is provided as a template or starting point for a city enabling PICP use by property owners. Besides zoning ordinances, a growing number of municipalities provide financial incentives to homeowners and commercial developers for using permeable pavements. The cost to the municipality can be less than upsizing storm sewer systems operating at their capacity.

Like all permeable pavements, PICP surfaces can become clogged with sediment over time, thereby slowing their infiltration rate. The rate of sedimentation mostly depends on deposition from contributing drainage areas into the joints, base and soil. Other sources can be eroding soil, leaves, mulch, grass clippings and sediment deposited from vehicles. In northern climates sediment sources also come from winter traction control/de-icing materials spread on the PICP area. These sources on PICP streets and parking lots can be removed with municipal street cleaning equipment.

Traffic and sediment sources vary with every PICP project. Regular surface cleaning will help maintain a high surface infiltration rate and keep out vegetation. ICPI recommends inspection and cleaning once or twice in the first year of service and adjusting cleaning intervals higher or lower as needed. The higher the contributing drainage area and the smaller the paver joint width, the more frequently vacuum cleaning will be required. Cleaning can be done with vacuum sweeping equipment such as regenerative air vacuum sweepers. Adjustments to the vacuum force likely will be required to minimize removal of stones from the openings. Jointing stones will need to be replenished if they are more than 1/2 in. (13 mm) below the top of pavers. Sweeping alone generally is not as effective compared to vacuuming, which removes much of the sediment. The following provides guidelines on managing surface infiltration based on research and experience.

Practices Supporting Surface Infiltration

PICP doesn't use sand. Unlike interlocking concrete pavements, sand jointing or bedding materials to support paving units (and dense-graded aggregate bases) are not used in PICP. Sand joints and bedding allow some water to initially infiltrate, and often eventually clog from traffic-borne detritus and sediment. Research has demonstrated that initial infiltration rates of sand joints in interlocking concrete pavements are quite low, typically a few inches (cm) per hour. Clogging of the sand joints over time renders very low or no surface infiltration rates, thereby making interlocking concrete pavement surfaces almost impermeable (Hade 1988) (Madrid 2003). Not surprisingly, jointing sand stablizers and liquid sealer applied to interlocking concrete pavement joints also decrease permeabilty.

Figure 5-1. Sand-filled joints and bedding common to interlocking concrete pavement ***are not used*** *in PICP.*

Construction E & S control is essential. Erosion and sediment control during construction is customized to each project via the Stormwater Pollution Prevention Plan or SWPPP. An inspection checklist is provided at the end of this Section that includes sediment control. If the PICP is built first and construction traffic must use it, then it will very likely require vacuum cleaning upon construction completion. The ideal situation is PICP constructed late in the project such that it will not receive much construction traffic and sediment. This may require using temporary construction roads.

Figure 5-2. Whether eroded onto or dumped on PICP, erosion and sediment control are essential during construction.

If PICP receives run-on from upslope pervious or impervious areas, inspect these areas for erosion and sediment, yard waste, materials storage, etc. Sweep, vacuum or blow the contributing drainage area clean and free of any dirt, leaves and mulch, as they are a major source of PICP clogging. Lawn and planting beds should be sloped away from PICP areas.

Maintain filled joints with stones. Settlement of jointing stones in the first few months is normal to PICP, as open-graded aggregates for jointing and bedding choke into the larger base aggregates beneath and stabilize. This settlement can require refilling the joints with aggregates three to six months after their initial installation. If possible, this service should be included in the initial construction contract specifications.

Keeping the joints filled during the PICP service life is essential to trapping sediment and facilitating removal at the surface. Permeable segmental paving systems with no jointing aggregates may incur higher maintenance time and costs to extract accumulated sediment from deep within the joints and bedding, or eventually move through the base/subbase aggregates onto the subgrade and reduce infiltration.

Filled paver joints means filled to the bottom of the paver chamfers with jointing stone. If the pavers have very small or no chamfers, then they should be filled within ¼ in. (6 mm) of the paver surface. Should the top of jointing stone settle below ¼ in. (6 mm), regenerative air vacuum equipment can be less effective in removing sediment and cleaning becomes potentially more expensive. See Figure 5-3.

Manage mulch, topsoil and winter sand. Stockpiling mulch or topsoil on tarps or on other surfaces during site maintenance activities rather than directly on the PICP surface helps maintain infiltration. Figure 5-4 illustrates an example of correct management of landscaping material on PICP, as well as the need to stabilize exposed soil on slopes.

Figure 5-3. Keeping PICP joints filled with permeable aggregate facilitates removal of accumulated sediment.

Sand for traction on snow and ice can be used, but it must be removed with vacuuming in the spring to prevent a substantial decrease in surface infiltration. Clogging will increase rapidly, especially if traffic consolidates sand into the joints. Figure 5-5 illustrates the consequence to PICP joints when subjected to winter sanding for traction. Using jointing aggregate for winter traction may be a better alternative than using sand because the former has a coarser gradation and can refill available joints while providing traction.

Figure 5-4. Mulch placed on tarps prevents more expensive cleaning of PICP.

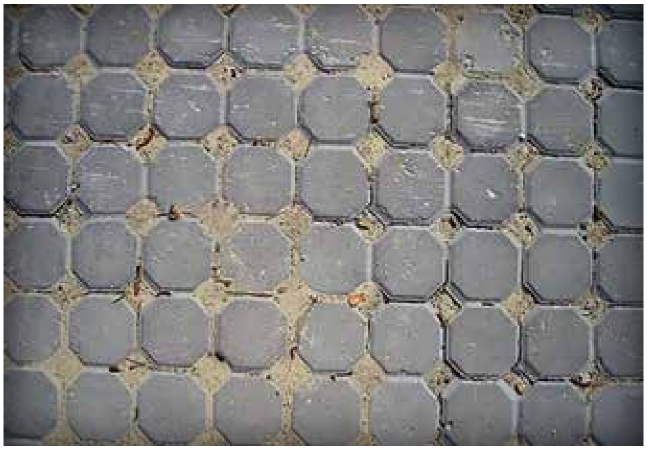


Figure 5-5. Sand from winter maintenance must be removed the following spring.

Surface Infiltration Inspection & Testing

Visual Inspection—Effective ways to assess PICP surface infiltration is by conducting visual inspections or tests on the surface before, during and immediately after rainfall.

Inspect Before a Rainfall—Sediment crusted in the joints when dry is the most opportune time to remove it. During dry periods, the sediment layer in each joint can sometimes dry out and curl upward. This layer can be easily loosened by vacuum equipment.

Additionally, deciduous leaves and pine needles eventually get crushed by tires, decompose, and work their way into the joints, thereby reducing infiltration. See Figures 5-6 and 5-7. These materials should be removed as soon as possible by sweeping or vacuuming. In addition, the site should be inspected for sediments from adjacent eroding areas and those areas stabilized immediately.

Figures 5-6 and 5-7. Pine needles and leaves eventually will degrade and get compacted into the joints from traffic. They should be removed by sweeping or vacuuming before that happens.

Figure 5-8. Weeds indicate sediment accumulation and lack of surface cleaning to remove it.

Weeds growing from within joints indicate accumulated sediment in the joints and neglected maintenance. See Figure 5-8. Weeds should be removed by hand. Herbicide may be used to kill weeds, but dead vegetation and roots will remain. They typically reduce infiltration and should eventually be removed.

Inspect During and Just After a Rainstorm— The extent of puddles and bird baths observed during and especially after a rainstorm can indicate a need for surface cleaning. A minor amount of ponding is likely to occur particularly at transitions from impervious pavement surfaces to PICP. This often occurs first as sediment is transported by runoff and vehicles. See Figures 5-9 and 5-10. Should ponding areas occupy more than 20% of the entire PICP surface, then surface cleaning should be conducted. While a rainstorm's exact conclusion is difficult to predict, standing water on PICP for more than 15 minutes during or after a rainstorm likely indicates a location approaching a near-completely clogged condition.

Test Surface Infiltration—A quick, subjective test used to assess surface infiltration is pouring water on PICP. If the water spreads rather than infiltrates, the extent of spreading suggests an area that may be clogging. Pay particular attention to transitions from impervious pavements to PICP. These areas are often the first to experience clogging due to sediment run-on from the impervious area, or being tracked on by vehicles. Should more than approximately 20% of the surface area see ponding during or immediately after a rainstorm, a more objective measure of surface infiltration of these areas can be accomplished using ASTM C1781 *Standard Test Method for Surface Infiltration Rate of Permeable Unit Pavement Systems.* Figure 5-11 illustrates the test set up using a 12 in. (300 mm) diameter ring set on plumber's putty. (The ring can be metal or plastic.) Figure 5-12 illustrates the test apparatus in place with water being poured into it. YouTube videos can be accessed that demonstrate the following test procedure.

ASTM C1781 test method begins with "pre-wetting" an area inside the ring to ensure the surface and materials beneath are wet. This is done by slowly pouring 8 lbs (3.6 kg) of water into the ring while maintaining a head between 0.4 and 0.6 in. (10 and 15 mm) depth. If the time to infiltrate 8 lbs of water is less than 30 seconds (using a stopwatch typically on a cell phone), the subsequent test is done using 40 lbs (18 kg) of water. If more than 30 seconds, then 8 lbs of water is used in the subsequent tests. Again, a 3/8 in. (10 mm)

Figure 5-9. Erosion of adjacent asphalt and sediment deposition on PICP.

Figure 5-10. Ponding on PICP typically first occurs at the junction with impermeable pavement.

Figure 5-11. Steps in setting up test equipment for measuring surface infiltration using ASTM C1781. Left to right: Marking the location for the plumber's putty; placing the putty on the mark; seating the ring onto the putty; and pressing the putty against the outside and inside of the ring to help create a waterproof seal.

head is maintained during the pour while being timed with a stopwatch. The surface infiltration rate is calculated using formulas in the test method.

If infiltration measurements on ponded areas consistently result in rates below 10 in./hour (254 mm/hr), they require immediate surface cleaning. An infiltration rate of 20 in./hr equates to 30 minutes' infiltration time and 40 in./hr results in 15 minutes. Table 5-1 further illustrates the relationship between time for 40 lbs (18 kg) of water to infiltrate and the calculated infiltration rate. ICPI offers a downloadable calculator for converting time of infiltration to infiltration rates when using C1781. See **www.icpi.org/resource-library/software-programs**.

Table 5-1. ASTM C1781 test results: relationship among time required to infiltrate, calculated surface infiltration rate, and recommended surface cleaning.

Seconds to Infilrate 40 lbs (18 g) Water	Minutes to Drain	Approximate Surface Infiltration Rate in./hr (mm/hr)	
30	0.5	1000 (25,400)	
60	1	600 (15.240)	Okay
100	1.7	360 (9,144)	
200	3.3	180 (4,572)	
360	6	100 (2,540)	Clean before it clogs
450	7.5	80 (2,032)	
900	15	40 (1,016)	
1800	30	20 (508)	Clean NOW
3600	60	10 (254)	

Note:

$I = (K \cdot M)/(D^2 \cdot t)$, where

I = Surface infiltration rate, in./hr (mm/hr)

K = 126,870 for lbs (4,583,666,000 for kgs)

M = water mass, lbs (kg)

D = ring diameter (12 in. or 300 mm)

t = time for water to infiltrate in seconds

Figure 5-12. ASTM C1781: pouring the water into a 12 in. (300 mm) inside diameter ring set on plumber's putty. A maximum 0.6 in. or 15 mm deep head of water is maintained on the paver surface while pouring. Depth marks written on the inside of the ring can help establish consistency for pouring to this depth.

Surface Infiltration Maintenance Types

Preventive and Restorative Maintenance—There are two approaches or service types for maintaining PICP surface infiltration: preventive and restorative. Preventive maintenance is done regularly to maintain infiltration. It removes most loose sediment and debris from the surface before being trapped in the jointing aggregates thereby causing clogging. Preventive maintenance may require reinstating jointing material in any areas where it's not near the surface of the pavers.

Preventive Maintenance Equipment: Options for Maintaining Various Sized PICP Applications

Cleaning Small Pedestrian Areas and Driveways

These areas are typically under 2,000 sf or 200 m^2 and include patios, plazas, sidewalks, and driveways. Equipment options follow:

Hand-held Bristle Broom—Sweep as needed to clear the surface of loose debris. Approximate cost: $15 (Figure 5-13).

Leaf Blower (electric or gas powered)—A minimum air speed of 120 mph (190 kph) is recommended. Jointing aggregates remain in place while removing loose debris such as leaves from the surface. Approximate cost: $50 to $300 (Figure 5-14).

Figure 5-13. Bristle broom for removing loose debris.

Figure 5-14. Blowing debris to curbs or gutters for removal and disposal.

Figure 5-15. Rotary brushes increase cleaning efficiencies.

Rotary Brush with Plastic Bristles—These are often used to spread jointing stone during construction. The same equipment can be used to clean the top of the joints. Bristles can flip debris out of joints (depends on bristle reach into the joints). A small amount of aggregate may need to be replaced in the joints after using. Approximate cost: varies depending on operating vehicle. (Figure 5-15).

Wet/Dry Shop Vacuum or Walk-behind Vacuum—Use equipment with a minimum 4 (peak) HP motor with minimum 130 cubic feet (3.7 m^3) per minute suction. These machines can remove some jointing aggregates so they may require replenishment. Approximate cost: \$100 to \$1,700 (Figures 5-16 and 5-17).

Cleaning Large PICP Areas

These are typically over 2,000 sf or 200 m^2 such as large plazas, long sidewalks and driveways, parking lots, alleys and streets. Equipment options are as follows:

Street Sweepers—These typically have rotating plastic bristle brushes positioned near the curb side and center pickup into a hopper at the rear. Do not use water, as it slows removal of loose dirt into the machine. This machine applies no vacuum force, only mechanical sweeping, so it is least effective

Figure 5-16. Wet/dry shop vacuum cleans loose sediment from a PICP residential driveway

Figure 5-17. Walk-behind vacuum cleans a small parking area. Use a screen over the intake to prevent jointing stone ingestion.

Figure 5-18. Power washing isn't recommended, as it displaces jointing stone and sediment rather than removing it.

among large machines for removing loose sediment in the joints. Approximate cost: $100 to $120 per hour from a service company and used by many municipalities (see Figure 5-19).

Regenerative Air Sweepers—Includes a box positioned under the truck and on the pavement through which air is blown and recirculated (hence the term regenerative air). The pavement must have no crown in order to create an adequate seal to maintain suction inside the box. Air pressure flowing through it picks up loose debris and sediment. Rotating brushes can be used to direct dirt and debris toward the box. The effective depth for sediment removal is typically 1/2 in. (13 mm). Approximate cost: $100 to $120 per hour from a service company. Used by some municipalities. See Figure 5-20.

Figure 5-19. Mechanical sweepers use no vacuum, making them the least effective of large cleaning machines.

Restorative Infiltration Maintenance for Large Clogged Surfaces

Restorative maintenance is conducted when sediment has lodged in the jointing stones deposited from tires and weather. The condition indicates that the PICP surfaces have not been regularly cleaned. Restorative maintenance requires some or complete removal of the jointing aggregates to increase infiltration. The depth of jointing stone needing removal depends on the penetration depth of the sediment into the joints. This can be determined on a sample of a few clogged joints (typically where ponding occurred) by prying out jointing aggregates and sediment with a flat head screwdriver until little or no accumulated sediment appears.

True Vacuum Sweepers—These can withdraw jointing material and even the concrete pavers. Therefore, the vacuum engine revolutions must be adjusted by the machine operator during a few test runs to find the setting that withdraws the needed depth of sediment and jointing aggregate. After withdrawal, jointing aggregates will require replenishment. The suction orifice is typically about a yard (meter) wide and positioned on the curb side (or both sides)of the truck. Extremely clogged surfaces will require two or more passes. Approximate cost including aggregate replenishment: $0.20 per sf ($2.14/m^2). Figure 5-21 shows this machine. It is often used by municipalities to clean out catch basins and may require a separate vacuum attachment to clean pavements.

Figure 5-20. A regenerative air machine cleaning a PICP parking lot.

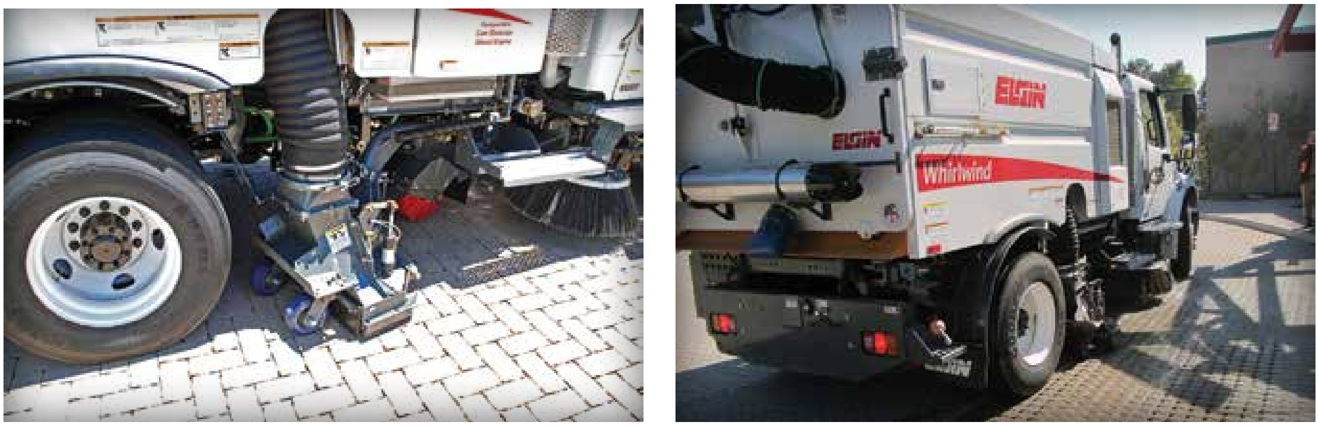


Figure 5-21. A true vacuum machine cleaning neglected PICP.

Combined Power Washing and Vacuum Equipment—This machine includes power washing between 1,200 psi (8 MPa) at 4,300 psi (30 MPa) with turbine blades to create a vacuum. Most of the water is recovered and recirculated. Jointing stones are dispersed on the surface and can be reinstated. Some joints will require replenishment. Extremely clogged surfaces will require two or more passes. Productivity is approximately 10,000 sf/hour (1,000 m^2/hour) assuming two passes with the equipment illustrated in Figure 5-21 This type of equipment is also designed into a truck for large (street) areas and walk-behind devices for small areas, as well as spaces with tight turning radii for trucks.

Inspection Intervals and Procedures for Maintaining Surface Infiltration

Preventive maintenance provides the best infiltration performance by implementing the following procedures:

1. **Weekly—**Prevent contamination from routine landscape maintenance such as grass clippings from mowing, hedge trimming, mulching plant beds, etc.,
    - Broom sweep debris from the paver surface, or;
    - Blow debris from the paver surface with a powered leaf blower onto other surfaces that will not re-transmit it to the PICP surface.
    - Mechanically sweep paver surface.
    - Remove loose debris, leaves, needles, sediment, topsoil, mulch, etc., after severe rain storms using the above procedures.
    - Collect and dispose of debris.

Figure 5-22. Equipment that provides combined power washing and vacuum.

2. **Semi-annually—**Remove loose surface debris from the pavers and jointing aggregate (1) when trees have defoliated in the fall and (2) at the end of winter snowfall.
    - Use a wet/dry vacuum for small areas and a regenerative air machine for larger areas.
    - Replenish jointing aggregate as needed to the bottom of the paver chamfers.
    - Check any observation wells and outlet pipes from underdrains to confirm drain down and water outflows.

Winter Maintenance

Snow Removal—Unlike other permeable pavement surfaces, PICP demonstrates durability in the winter. PICP can be plowed with steel or hard rubber blades. Steel blades typically scratch all pavement surfaces. If scratching is unacceptable, then ask commercial snow removal companies to confirm in writing that they provide protective edges on the snowplow equipment to avoid scratching the surface. Most pavers have chamfers on their surface edges which can help protect the edges from chipping by snow plows. For smaller areas, use a plastic snow shovel and fit snow blowers with plastic on the scoops and gliders. When possible, deposit plowed snow onto grassy areas and not on the PICP when the plowed snow is dirty. Such dirt will remain and likely clog the PICP surface after the snow melts. See Figure 5-23.

Figure 5-23. This is an example of snow that should have been deposited on a grassy area. If such areas are not available, then vacuum clean the PICP in the early spring.

Deicers—When used sparingly, deicers should not damage PICP surfaces, as the brine typically forms on the surface to lower the freezing temperature of water and eventually moves into the joints with melting ice or snow. Sealers applied to the pavers may help reduce the risk of deicer damage.

Deicer types acceptable for use on PICP surfaces include sodium chloride and calcium chloride. Do not use magnesium chloride, as it will eventually destroy all concrete materials. Anti-icing agents that contain ammonium nitrate and ammonium sulfate should not be used since they can also erode concrete. Always read and follow the manufacturer's recommendations for use, and heed all warnings and cautions.

Remedial Maintenance for Other Distresses

Over time and traffic, PICP can exhibit other distresses besides surface ponding from clogged joints. These are outlined in Table 5-2 and remedies are provided.

Table 5-2. Maintenance guidelines for all PICP surface distresses

Distress	Activity	Inspection Frequency
Clogging	Vacuum sweep surface to remove sediment.	1 to 2 times annually; adjust frequency based on sediment loading and ponding
Clogged/Damaged Secondary Features	Clean out or repair secondary drainage features.	Annually, after major rain event
Depressions	Repair paver surface depressions exceeding 1/2 in. (13 mm).	Annually, repair as needed
Rutting	Repair paver surface rutting exceeding 0.5 in. (13 mm).	Annually, repair as needed
Faulting	Repair paver surface faulting exceeding 1/4 in. (6 mm).	Annually, repair as needed
Damage Paver Units	Replace medium to high severity cracked, spalled or chipped paver units.	Annually, repair as needed
Edge Restraint Damage	Repair pavers offset by more than 1/4 in. (6 mm) from adjacent units or curbs, inlets, etc.	Annually, repair as needed
Excessive Joint Width	Repair pavers exhibiting joint widths exceeding 1/2 in. (13 mm).	Annually, repair as needed
Joint Filler Loss	Replenish aggregate in joints.	As needed
Horizontal Creep	Repair areas exhibiting horizontal creep exceeding 0.4 in. (10 mm).	Annually, repair as needed
Additional Distresses	Replace missing pavers. A geotechnical investigation is recommended for (rare) pavement heaves.	Annually, repair as needed

Utility Restoration Guidelines

1. Remove and store pavers for reuse. Secure undisturbed pavers in opening perimeter with a wood or metal frame.
2. Remove and dispose of all jointing and bedding aggregate, as they typically cannot be re-used.
3. Remove the aggregate base and subbase material. Incidental mixing of base and subbase aggregates is acceptable, but make every effort to separate them. Store on impermeable pavement or on geotextile to prevent contamination. Do not reuse contaminated aggregate.

4. Re-compact subgrade material as required for stability during utility repairs.
5. Repair or install utility as required.
6. If below the bottom of the subbase, place and compact dense-graded road base in lifts not exceeding 6 in. (150 mm), and compact to 100 percent of standard Proctor maximum dry density. The top of the dense-graded aggregate should meet elevation at the bottom of the open-graded subbase aggregate.
7. Reinstate and compact the subbase aggregate in minimum 6 in. (150 mm) lifts. Use a minimum 13,500 (60 kN) plate compactor with a compaction indicator. Add new subbase aggregate if needed.
8. Reinstate and compact the base aggregate as one 4 in. (100 mm) lift. Use a minimum 13,500 lbf (60 kN) plate compactor with a compaction indicator. A lightweight deflectomer (LWD) can be used to ensure that deflections of the compacted base aggregate are below an average of 0.5 mm (assuming a minimum 10 in. (250 mm) compacted aggregate subbase). An LWD should be used according to ASTM E2835.
9. Place and screed new bedding aggregate in a consistent thickness layer between 1.5 and 2 in. (38 and 50 mm).

Figure 5-24. Reinstatement of concrete pavers in a PICP street.

10. Reinstate pavers with their surface at least 1 in. (25 mm) higher than the final elevation. Compact the pavers in two perpendicular directions with a minimum 5,000 lbf (22 kN) plate compactor. Fill joints with aggregate, sweep away excess, and compact the pavers in two perpendicular directions again. Compact pavers level with surrounding pavers.
11. Sweep surface clean and remove any excess aggregate and debris.

Figure 5-24 illustrates the final steps in reinstating the concrete pavers. Unlike monolithic surfaces, utility cuts and reinstatement of the pavers do not waste pavement materials or damage and decrease pavement life. Minor surface settlements (generally up to 3/4 in. or 15 mm) can be raised with additional bedding aggregate under pavers.

Other recommendations include keeping all removed materials held for later reinstatement clean and free of sediment and debris. Minimize excess debris from construction activities and equipment entering the permeable surface. Store all materials away from the permeable surface, or store on geotextile placed over the permeable surface. Pavement cuts located parallel and close to the wheel path should be extended to include the wheel path. Cuts located within 3 ft (1 m) of a curb or construction joint should include the removal of the adjacent base and subbase to the edge of the curb or construction joint.

Long-Term Performance and Maintenance Agreements

When carefully constructed and regularly maintained, PICP can provide at least 40 years of service. Their structural service life is primarily measured by the extent of rutting in the base/subbase or soil subgrade. Their hydrologic service life is measured by the extent to which they continue storing and infiltrating runoff.

At some point later in the life of the pavement, PICP may no longer store the required amount of water to control runoff. In such cases, the pavers will need to be removed, the base materials and geotextile removed and replaced. Clogged or broken drain pipes will require replacement. Once new materials are in place, the same pavers can be reinstated. Removal and replacement of the base and pavers is an expensive operation. Other lower-cost alternatives may be possible, such as designing underdrains with cleanouts and cleaning them, replacing selected clogged pipes (rather than the entire base and pipe system) or diverting drainage to another BMP. Regular maintenance and inspection are important to tracking drainage performance, sources of problems, and deciding on possible solutions.

The PICP owner plays a key role in maintenance and successful long-term performance of permeable interlocking concrete pavements. The owner should have oversight of the property and be aware of maintenance requirements. A growing trend to help ensure oversight is a maintenance agreement. It is typically between the property owner and the local city or county, and the agreement is recorded and attached to the deed for the property.

The model agreement presented below is applicable to many BMPs. It can be edited to suit local situations and customized for PICP maintenance. A list of maintenance items should be an attachment to this agreement, as well as an inspection schedule. This list of items to be inspected can be developed from the in-service inspection checklist in this section as well as from requirements established by the local government. A growing number of local governments are creating databases (i.e., asset management systems) in which to place inspection data per NPDES permit requirements. This provides continual documentation of care and performance.

An alternative to municipal-landowner maintenance agreements is the use of performance bonds. The owner typically posts a bond or promise, often as a bank letter of credit, that the municipality can draw money from if written maintenance criteria are not met. Other municipalities may have the right to enter private property, conduct maintenance on BMPs, and invoice the land owner or attach a tax lien on the property.

Model Maintenance Agreement

This Maintenance Agreement made this _____ day of _________, [year], by and between [property owner/s], hereinafter referred to as "Grantor," and the [city/county of state/province] hereinafter referred to as the "[city/county]."

WITNESSETH

WHEREAS, the [city/county] is authorized and required to regulate and control disposition of storm and surface waters within the [city/county/watershed] as set forth by [city/county] [state/provincial] ordinances; and

WHEREAS, the Grantor is the owner of a certain tract or parcel of land more particularly described as [legal description].

ALL THOSE certain lots, pieces or parcels of land, together with buildings and improvements thereon, and the appurtenances thereunto belonging, lying, situated and being in the [city/county] of [state/province] as shown on [tax maps/subdivisions plats numbers and names], duly recorded in the Clerk's Office of the [court] of [city/county] in Deed Book or Plat Book [number] at page [number] reference to which the plat is hereby made for a more particular description thereof.

It being the said property conveyed unto the Grantor herein by deed dated _________ from _________ and recorded in the Clerk's office aforesaid in Deed Book_____________ at Page _________ such property being hereinafter referred to as "the property."

WHEREAS, the Grantor desires to construct certain improvements on the property which will alter existing storm and surface water conditions on the property and adjacent lands; and

WHEREAS, in order to accommodate and regulate these anticipated changes in existing storm and surface water flow conditions, the Grantor, its heirs and assigns, desire to build and maintain at their expense a storm and surface water management facility and system [more particularly described as a permeable interlocking concrete pavement]. This is shown on plat titled ________________ and dated ___________________; and

WHEREAS, the [city/county] has reviewed and approved these plans subject to the execution of this agreement;

NOW THEREFORE, in consideration of the benefit received by the Grantor, its heirs and assigns, and as a result of the [city/county] approval of its plans, the Grantor, its heirs and assigns, with full authority to execute deeds, deeds of trust, other covenants and all rights, title and interest in the property described above hereby covenant with the [city/county] as follows:

1. Grantor, its heirs and assigns shall construct and perpetually maintain, at its sole expense, the above referenced permeable interlocking concrete pavement [storm and surface management facility and system] in strict accordance with the plan approval granted by the [city/county].
2. Grantor, its heirs and assigns shall, at its sole expense, make such changes or modifications to the permeable interlocking concrete pavement [storm drainage facility and system]. Changes or modifications may, in the [city's/county's] discretion, be determined necessary to ensure that the facility and system are properly maintained and continues to operate as designed and approved.
3. The [city/county], its agents, employees and contractors shall have the perpetual right of ingress and egress over the property of the Grantor, its heirs assigns, and the right to inspect [at reasonable times and in a reasonable manner,] the permeable interlocking concrete pavement [storm drainage facility and system]. Inspection is in order to ensure that the system is being properly maintained and is continuing to perform in an adequate manner. [Attachment A to this agreement provides a list of items to be inspected by the [city/county]].

4. The Grantor, its heirs and assigns agree that should it fail to correct any defects in the above described facility and system within [ten (10)] days from issuance of written notice, or shall fail to maintain the facility in accordance with the approved design standards and in accordance with the law and applicable regulations, or in the event of an emergency as determined by the [city/county] in its sole discretion, the [city/county] is authorized to enter the property to make all repairs, and to perform all maintenance, construction and reconstruction the [city/county] deems necessary. The [city/county] shall assess the Grantor, its heirs or assigns for the cost of the work, both direct and indirect, and applicable penalties. Said assessment shall be a lien against all properties described within this Maintenance Agreement and may be placed on the property tax bills of said properties and collected as ordinary taxes by the [city/county].
5. Grantor, its heirs and assigns shall indemnify, hold harmless and defend the [city/county] from and against any and all claims, demands, suit liabilities, losses, damages and payments, including attorney fees claimed or made against the [city/county] that are alleged or proven to result or arise from the Grantor, its heirs and covenant.
6. The Covenants contained herein shall run with the land and the Grantor, its heirs assigns further agree whenever the property shall be held, sold and conveyed, it shall be subject to the covenants stipulations, agreements and provisions of this Agreement, which shall apply to, bind all present and subsequent owners of the property described herein.
7. Grantor agrees to not transfer or assign responsibility.
8. The provisions of this Maintenance Agreement shall be severable and if any phase, clause, sentence or provision is declared unconstitutional, or the applicability of the Grantor, its heirs and assigns is held invalid, the remainder of this Covenant shall not be affected thereby.
9. The Maintenance Agreement shall be recorded at the Clerk's Office of the [court] of [city/county], [state/province] at the Grantor's, its heirs and assign's expense.
10. In the event that the [city/county] shall determine in its sole discretion at any future time that the facility is no longer required, then the [city/county] shall at the request of the Grantor, its heirs and assigns execute a release of this Maintenance Agreement, which the Grantor, its heirs and assigns shall record, in the Clerk's Office at its expense.

IN WITNESS THEREOF, the Grantor has executed this Maintenance Agreement

On the ______ day of ______, [year].

By Officer/Authorized Agency

[State/Province] of:

[City/County] of :

To wit: The foregoing instrument was acknowledged before me this______day of______________, [year], by ____________________________

PICP Maintenance Checklist

This can be included in the above agreement or used separately to manage in-service PICP.

PICP In-service Inspection Checklist

❒ 2 times annually (typically spring/fall): vacuum surface, adjust vacuuming schedule per sediment loading and/or any sand deposits from winter

❒ Winter: Remove snow with standard plow/snow blowing equipment; apply deicers as needed to reduce surface ice. Note: deicer use may decrease compared to impervious pavements.

❒ As needed, indicated by at least 20% area of water ponding on the surface immediately after a storm (paver joints or openings severely loaded with sediment): test surface infiltration rate using ASTM C1781. Vacuum to remove surface sediment and soiled aggregate (typically 1/2 to 1 in. or 13-25 mm deep), refill joints with clean aggregate, sweep surface clean and test infiltration rate again per C1781 to minimum 50% increase or minimum 20 in./hr (508 mm/hr).

Annual Inspection

❒ Replenish aggregate in joints if more than 1/2 in. (13 mm) from chamfer bottoms on paver surfaces
❒ Inspect vegetation around PICP perimeter for cover & soil stability, repair/replant as needed
❒ Inspect and repair all paver surface deformations exceeding 1/2 in. (13 mm)
❒ Repair pavers offset by more than 1/4 in. (6 mm) above/below adjacent units or curbs, inlets, etc.
❒ Replace cracked paver units impairing surface structural integrity
❒ Check drain outfalls for free flow of water and outflow from observation well after a major storm

Model Stormwater Ordinance

The following model stormwater ordinance gives local governments a start in developing a stormwater ordinance that includes PICP. The ordinance should be adjusted to accommodate local conditions.

Stormwater Management Using PICP (Community) Ordinance No. __________

(a) Purpose. The purpose of this Ordinance is to promote health, safety, and welfare within (community) and its watershed by minimizing the harms and maximizing the benefits, through provisions designed for allowance of permeable interlocking concrete pavement (PICP) as part of a stormwater management planning and implementation of stormwater goals for (Community). (Community) recognizes that stormwater runoff has been traditionally treated as a by-product of development and mainly from impervious surfaces (roofs and paving) to be disposed of quickly and efficiently. The result is typically increased flooding, degradation of surface and subsurface water quality, soil erosion and sedimentation, reduced groundwater resources, as well as reduced recreational and economic opportunities. These conditions engender the need to implement site-specific technologies and practices to filter and infiltrate stormwater and thereby reduce impacts from development.

This Ordinance encourages the use of technologies called Best Management Practices (BMPs) which are structural, vegetative, or managerial practices designed to treat, prevent, or reduce degradation of water quality due to stormwater runoff. All development projects subject to review under the requirements of this Ordinance shall be designed, constructed, and maintained using BMPs to prevent flooding, protect water quality, reduce soil erosion, maintain and contribute to the aesthetic values of the project. (Community) recognizes that PICP is one of several BMPs for achieving stormwater goals.

(b) General Requirements for PICP

(1) The surfacing materials for pedestrian and vehicular uses shall consist of concrete paving units that conform to ASTM C936 including an average 8,000 psi compressive strength.

(2) Whenever possible, PICP shall be used to reduce post-development peak flows and total water volumes to pre-development conditions. Pre-development is defined as the conditions on the existing site prior to the proposed development project.
(3) Development plans shall be provided that include post-construction BMPs. PICP shall be designed to manage stormwater to help reduce local minor flooding, degradation of water quality related to stormwater runoff, and increase groundwater recharge and opportunities for water harvesting for irrigation where possible.
(4) PICP shall be designed by a registered professional engineer or landscape architect and installed by a contractor who has successfully completed the requirements of the Interlocking Concrete Pavement Institute (ICPI) PICP Installer Technician Certificate course;
(5) PICP shall include maintenance instructions to the property owner including a maintenance inspection schedule;
(6) At a minimum, PICP surface, base/subbase shall be designed to adequately accommodate the rainfall depth of [insert local storm event requirements]. The base/subbase layers shall be designed to have sufficient detention capacity that stormwater will infiltrate into the soil below and can accommodate a second [insert local storm event requirements] depth within 5 days of the previous storm;
(7) PICP shall be designed in accordance with guidelines in the ICPI manual, *Permeable Interlocking Concrete Pavements*, guide specifications on **www.icpi.org**, and ASCE standard entitled *Design, Construction and Maintenance of Permeable Interlocking Concrete Pavement*.
(8) PICP shall be installed by a person holding an ICPI PICP Certificate of Completion who shall be onsite to oversee each installation crew during all PICP construction.

(c) Development of New Properties
(1) Property is considered new property if the property proposed for development has no existing construction.
(2) Impervious cover (total roof area, pedestrian and vehicular paving) shall not exceed a maximum of ___% of the total property according to the specific land use and zoning designation. See (reference section/pages) for specific land uses and maximum allowable impervious cover for each land use.
(3) One-hundred (100) percent of the total area covered by PICP shall be considered a pervious or permeable surface.

(d) Re-development of Existing Properties
(1) Property is considered existing property if the property proposed for re-development has existing construction.
(2) Existing properties that do not exceed the maximum allowed impervious surface for new properties shall meet the requirements under (c) Development of New Properties.
(3) Existing properties that exceed the maximum allowed impervious surface as stated in (c) Development of New Properties may construct new impervious surfaces if the proposed new impervious surface meets all setback and other regulations of this ordinance and if the following conditions are met:
i. The applicant removes existing impervious surfaces exceeding the maximum allowed impervious surface under (c) Development of New Properties and restores those areas to a PICP surface at a 1 to 1 ratio.
ii. Applicant shall submit a comprehensive stormwater management plan that emphasizes infiltration and onsite retention of stormwater for at the [insert design storm event(s)]. This shall be achieved through a combination of structural BMPs such as PICP and buffer strips, swales, rainwater gardens, bioswales, and other low impact development methods. The stormwater management plan must be designed by a registered professional engineer or landscape architect and installed as designed by a qualified contractor.

(4) One-hundred (100) percent of the total area covered by PICP designed to allow for infiltration of water into the soil subgrade may be considered pervious;
(5) A survey shall be submitted showing calculations of the exact dimensions of all existing impervious surfaces and of the lot before and after completion of the project;
(6) In replacing existing impervious surfaces with surfaces designed to be PICP, the applicant must give priority to replacing those surfaces closest to natural bodies of water (lakes, ponds, rivers, streams or ocean) or those surfaces where the replacement is most likely to improve stormwater management;

(e) Streets and Access
(1) PICP shall be considered a viable option for paving residential streets.
(2) Street right-of-way widths shall be designed to reflect the minimum PICP required to accommodate the travel-way, parking lanes, sidewalks, and vegetated open channels.
(3) PICP shall be considered a viable option for parking lanes on collector and thoroughfares.

(f) Parking Lots
(1) Parking requirements shall be based on requirements described in (reference parking lot ordinance).
(2) Parking lot designs shall reduce the overall impervious area by providing compact car spaces, minimizing stall dimensions, incorporating efficient parking lanes, and using PICP.

(g) Site Design
(1) Direct rooftop runoff to PICP, open channels, or vegetated areas and avoid routing rooftop runoff to the roadway and to the stormwater conveyance system.
(2) Create a variable width, naturally vegetated or permeable buffer system along all drainage ways that also encompasses critical environmental features such as the 100-year floodplain, steep slopes, and wetlands.
(3) Minimize clearing and grading of woodlands and native vegetation to the minimum amount needed to build lots, allow access, and provide fire protection.
(4) Conserve trees and other vegetation at each site by planting additional vegetation, clustering tree areas, and promoting the use of native plants.
(5) Use PICP for paved areas and schedule installation to protect PICP from construction borne sediment.
(6) Newly constructed stormwater outfalls to public waters must provide for filtering or settling of suspended solids and skimming of surface debris before discharge. PICP may be used as one method to achieve this requirement.

(h) Inspection and Maintenance Reporting
(1) (Community) shall ensure that preventive maintenance is performed by inspecting PICP and all stormwater management systems draining into and from it.

(2) Applicant shall provide an inspection plan and maintenance plan for PICP and other BMPs on the project site. Inspection reports shall be maintained by (community) for all stormwater management systems. Section(s) (___) provides inspection plans and maintenance requirements for other BMPs.

(3) PICP inspection and maintenance shall include the items and intervals listed in the table below:

PICP Inspection and Maintenance Checklist	
Activity	**Inspection Frequency**
Vacuum/sweep surface	Annually, based on sediment loading. Power washing is not recommended.
Replenish aggregate in joints	As needed
Inspect vegetation and/or filter media around PICP perimeter for cover & soil stability	Annually, repair/replant as needed
Repair all surface deformations exceeding 1/2 in. (13 mm)	Annually, repair as needed
Repair pavers offset by more than 1/4 in. (6 mm) above/below adjacent units	Annually, repair as needed
Replace broken units impairing surface structural integrity	Annually, repair as needed
Check drainage inlets and outfalls for free flow of water & outflow from an observation well	Annually, after a major storm

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Appendix—Glossary of Terms

AASHTO—American Association of State Highway and Transportation Officials

Aquifer—A porous water bearing geologic formation that yields water for consumption.

ASTM—American Society for Testing and Materials

Best Management Practice (BMP)—A structural or non-structural device designed to infiltrate, temporarily store, or treat stormwater runoff in order to reduce pollution and flooding.

Bioretention—A stormwater management practice that uses soils and vegetation to treat pollutants in urban runoff and to encourage infiltration of stormwater into the ground.

Bioretention basins—Landscaped depressions or shallow basins used to slow and treat on-site stormwater runoff. Stormwater is directed to the basin where it is treated by physical, chemical and biological processes. The slowed, cleaned water infiltrates native soils or is directed to nearby stormwater drains or receiving waters. PICP overflow can drain into such basins.

California Bearing Ratio or CBR—A test that renders an approximation (expressed as a percent) of the bearing strength of soil compared to that of a high quality, compacted aggregate base.

Cation—A positively charged atom or group of atoms in soil particles that, through exchange with ions of metals in stormwater runoff, enable those metals to attach themselves to soil particles.

Choke course—A layer of aggregate placed or compacted into the surface of another layer to provide stability and a smoother surface. The particle sizes of the choke course are generally smaller than those of the surface into which it is being pressed.

Clay soils—1. (Agronomy) Soils with particles less than 0.002 mm in size. 2. A soil textural class. 3. (Engineering) A fine-grained soil with more than 50% passing the No. 200 sieve with a high plasticity index in relation to its liquid limit, according to the Unified Soil Classification System.

Combined sewer system or CSO—Conveyance of storm and sanitary sewage in the same pipes. CSOs are generally found in older urban areas. CSOs do significant damage to water quality, resulting in diminished economic and recreational activities.

Crushed stone—Mechanically crushed rock that produces angular particles.

CSA—Canadian Standards Association

Curve Number (CN)—A numerical representation of a given area's hydrological soil group, plant cover, impervious cover, interception and surface storage. The US Soil Conservation Service (SCS), now the Natural Resources Conservation Service, originally developed the concept. A curve number is used to convert rainfall depth into runoff volume.

Dense-graded base—Generally a crushed aggregate base with fines that, when compacted, creates a foundation for pavements and does not allow significant amounts of water into it. Particle sizes can range from 1.5 in. (40 mm) to smaller than the No. 200 (0.075 mm) sieve.

Detention pond or structure—The temporary storage of stormwater runoff in an area with the objective of decreasing peak discharge rates and providing a settling basin for pollutants.

Equivalent Single Axle Loads or ESALs—Characterization of all axle loads that render damage to pavements and used as a means to define pavement life; one ESAL is 18,000 lbs or 80 kN.

Erosion—The process of wearing away of soil by water, wind, ice, and gravity. 2. Detachment and movement of soil particles by same.

Evapotranspiration—The return of moisture to the atmosphere from the evaporation of water from soil and transpiration from vegetation.

Exfiltration—The downward movement of water through an open-graded, crushed stone base into the soil beneath.

Fines—Silt and clay particles in a soil, generally those smaller than the No. 200 or 0.075 mm sieve.

First flush—The initial portion of a rainstorm that flushes high concentrations of accumulated pollutants into the storm drainage system. High concentrations are usually due to antecedent dry weather conditions that create an accumulation of pollutants on pavements washed away by the rainstorm.

Grade—1. (Noun) The slope or finished surface of an excavated area, base, or pavement, usually expressed in percent. 2. (Verb) To finish the surface of same by hand or with mechanized equipment.

Gravel—1. Aggregate ranging in size from 1/4 in. (6 mm) to 3 in. (75 mm) which naturally occurs in streambeds or riverbanks that has been smoothed by the action of water. 2. A type of soil as defined by the Unified Soil Classification System having particle sizes ranging from the No. 4 sieve (4.75 mm) and larger.

Hotspot—A land use that generates highly contaminated runoff with concentrations higher than those typical to stormwater.

Hydrological Soil Group—The soils classification system developed by the U.S. Soil Conservation Service (now the Natural Resource Conservation Service) that categorizes soils into four groups, A through D, based on runoff potential. A soils have high permeability and low runoff, whereas D soils have low permeability and high runoff.

Impervious cover—Any surface in the built environment that prohibits percolation and infiltration of rainwater into the ground; a term for pavements and roofs.

Infiltration rate—The rate at which stormwater moves through soil measured in inches per hour or meters per second.

Interlocking concrete pavement—A system of paving consisting of discrete, hand-sized paving units with either rectangular or dentated shapes manufactured from concrete. Either type of shape is placed in an interlocking pattern, compacted into coarse bedding sand, the joints filled with sand and compacted again to start interlock. The paving units and bedding sand are placed over an unbound or bound aggregate layer. Also called concrete block pavement.

Karst geology—Regions of the earth underlain by carbonate rock typically with sinkholes and/or limestone caverns.

MS4s—Municipal Separate Storm Sewer System: A conveyance or system of conveyances that is:

- Owned by a state, city, town, village, or other public entity that discharges to waters of the US;
- Designed or used to collect or convey stormwater (including storm drains, pipes, ditches, etc.);
- Not a combined sewer; and
- Not part of a Publicly Owned Treatment Works (sewage treatment plant)

Observation well—A perforated pipe inserted vertically into an open-graded base used to monitor its infiltration rate.

One year storm—A rainfall event that has a 100% chance of occurring in a given year.

One hundred year storm—A very unusual rainfall event that has a 1% chance of occurring in a given year.

Open-graded base—Generally a crushed stone aggregate material used as a pavement base that has no fine particles in it. The void spaces between aggregate can store water and allow it to freely drain from the base.

Outlet—The point at which water is discharged from an open-graded base through pipes into a stream, lake, river, or storm sewer.

Peak discharge rate—The maximum instantaneous flow from a detention or retention pond, open-graded base, pavement surface, storm sewer, stream or river, usually related to a specific storm event.

Permeability—The rate of water movement through a soil column under saturated conditions, usually expressed as k in calculations per specific ASTM or AASHTO tests, and typically expressed in inches per hour or meters per second.

Permeable interlocking concrete pavement—Concrete pavers with wide joints (5 mm to 10 mm) or a pattern that creates openings in which rainfall and runoff can infiltrate. The joints/openings are filled with permeable aggregate. The pavers and a permeable aggregate bedding layer are typically placed on an open-graded aggregate base/subbase which filters, stores, infiltrates, and/or drains runoff. Sand is not used within the pavement structure.

Permeable pavement —A surface with penetrations capable of passing and spreading water capable of supporting pedestrians and vehicles, e.g., permeable interlocking concrete pavement.

Pervious or permeable surfaces/cover— Surfaces that allow the infiltration of rainfall, such as vegetated areas.

Porosity—Volume of voids in a base divided by the total volume of a base.

Porous pavement—A surface full of pores capable of supporting pedestrians and vehicles, e.g., porous asphalt, porous concrete (cast-in-place or precast units).

Pretreatment—BMPs that provide storage and filtering pollutants before they enter another BMP for additional filtering, settling, and/or processing of stormwater pollutants.

Rain gardens—Gardens containing flowers and grasses (preferably native species of both) that can survive in soil soaked with water from rain storms. Rain gardens do not have standing water. Rain gardens collect and slow stormwater run off and increase infiltration into the soil.

Retention pond—A body of water that collects runoff and stays full permanently. Runoff flowing into the pond that exceeds its capacity is released into a storm sewer, stream, lake, or river.

Runoff coefficient—Ratio of surface runoff to rainfall expressed as a number from 0 to 1.

Sand—1. (Agronomy) A soil particle between 0.05 and 2.0 mm in size. 2. A soil textural class. 3. (Engineering) A soil larger than the No. 200 (0.075 mm) sieve and passing the No.4 (4.75 mm) sieve, according to the Unified Soil Classification System (USCS).

Sediment—Soils transported and deposited by water, wind, ice, or gravity.

Sheet flow—The laminar movement of runoff across the surface of the landscape.

Silt—1. (Agronomy) A soil consisting of particle sizes between 0.05 and 0.002 mm. 2. A soil textural class. 3. (Engineering) A soil with no more than 50% passing the No. 200 (0.075 sieve) that has a low plasticity index in relation to the liquid limit, according to the Unified Soil Classification System.

Structural Number (SN)—A calculation used by AASHTO to assesses the structural capacity of a pavement to handle loads based on ESALs and soil subgrade strength.

Swale—A small linear topographic depression that conveys runoff

Time of concentration—The time runoff takes to flow to a drainage area's most distant point to the point of drainage, such as a storm sewer inlet.

TMDL—Total Maximum Daily Load - A term in the U.S. Clean Water Act describing the maximum amount of a pollutant a body of water can receive without significantly impairing the water quality or health of the existing aquatic ecosystem.

Void Ratio—Volume of voids around the aggregate divided by the volume of solids.

About the Author

David R. Smith is the Technical Director for the Interlocking Concrete Pavement Institute or ICPI (www.icpi.org). Key players in the US, Canadian, and overseas industry started the ICPI in 1993 with 66 charter members. At this writing, the association has more than 1000 members representing producers, contractors and suppliers.

His first encounter with interlocking concrete pavements was building an entry walkway in 1977. He has been hooked ever since. While a student, his first encounter with permeable pavements was investigating the runoff and pollutant reduction of concrete grid pavements from 1977 through 1980 at Virginia Tech.

His exposure to sustainable neighborhood design began in the early 1980s. Mr. Smith studied European approaches to urban climatology, green infrastructure, neighborhood design and traffic calming. He served on a UNESCO Man and Biosphere committee that studied urban climatology, the urban heat island and the benefits of urban forestry and green infrastructure for reducing runoff, air pollution, and summer electrical consumption in U.S. cities. He has contributed to national and international conferences on urban forestry and green infrastructure management. In 1987, he consulted with the City of Valencia, Spain, on the urban climate benefits of that city's master plans to plant street trees, revitalize parks, and expand green space.

Mr. Smith's exposure to the concrete paver industry began in 1984 when he presented a paper on concrete grid pavement research at the Second International Conference on Concrete Block Paving in The Netherlands. This led to facilitating design and construction of the first mechanically installed, municipal concrete paver street in the U.S. (Dayton, Ohio) in 1985. He began supporting the concrete paver industry directly in 1987. Since then, he has worked with architects, engineers, landscape architects and contractors on design and construction of every kind of concrete paver project from patios to streets, to ports and airports.

He has written dozens of articles, peer-reviewed technical papers, guide specifications and ICPI Tech Spec technical bulletins on interlocking concrete, permeable, slab, and grid pavements. Many of the subjects in these publications have been presented at national and international conferences. Mr. Smith has contributed to three ICPI student and instructor manuals for contractors, and taught many classes. Also, he authored three design idea books for residential, commercial and municipal applications. Additionally, he contributed to ICPI engineering design manuals for port and airport pavements constructed with interlocking concrete pavements. Since 1994, he has been editor of the quarterly *Interlock Design* magazine (circ. 25,000), which features stories on interlocking and permeable interlocking concrete pavement.

As a leading authority in North America on concrete segmental paving and permeable paving, Mr. Smith has been active in ASTM since 1988, having written or updated several product standards and test methods in support of the industry. He is a past chair of CSA A231 on precast concrete paving products. He is a vice-chairman of the ASCE Permeable Pavements Technical Committee and is co-editor of the ASCE EWRI book, *Permeable Pavements*. He is also a member of Transportation Research Board AFD30 Committee on General and Emerging Pavement Design.

Continued next page

His background in stormwater management comes from research while at Virginia Tech, as well as teaching and modeling storm drainage design with sustainable, site-scale stormwater management approaches and stream restoration. He has written or contributed to many state and municipal guidelines for PICP and other permeable pavements. Mr. Smith was editor of and contributor to the 2006 *Proceedings* of the 8th International Conference on Concrete Block Paving held in San Francisco, California, which was hosted by the ICPI Foundation for Education and Research. Mr. Smith is Chairman of the Small Element Pavement Technologists (www.sept.org), segmental paving experts from around the world whose mission is to perpetuate the triennial international conferences on concrete block paving. The group also maintains a publicly accessible database of technical papers from the international conferences from their start in 1980. His education includes a Bachelor of Architecture and Masters of Urban and Regional Planning with a concentration in environmental planning from Virginia Tech.

Interlocking Concrete Pavement Institute®

Interlocking Concrete Pavement Institute
14801 Murdock Street, Suite 230
Chantilly, VA 20151

Tel: 703.657.6900
Fax: 703.657.6901
E-mail: ICPI@icpi.org
www.icpi.org

Canada Office:
P.O. Box 1150
Uxbridge, ON L9P 1N4
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