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Permeable Interlocking Concrete Pavement

Contents

This TechBrief presents an overview of permeable interlocking concrete pavement (PICP) and its use. General information is provided on PICP composition with a summary of benefits, limitations, and characteristics. Important considerations such as hydrological design, structural design, construction, and maintenance are also provided.

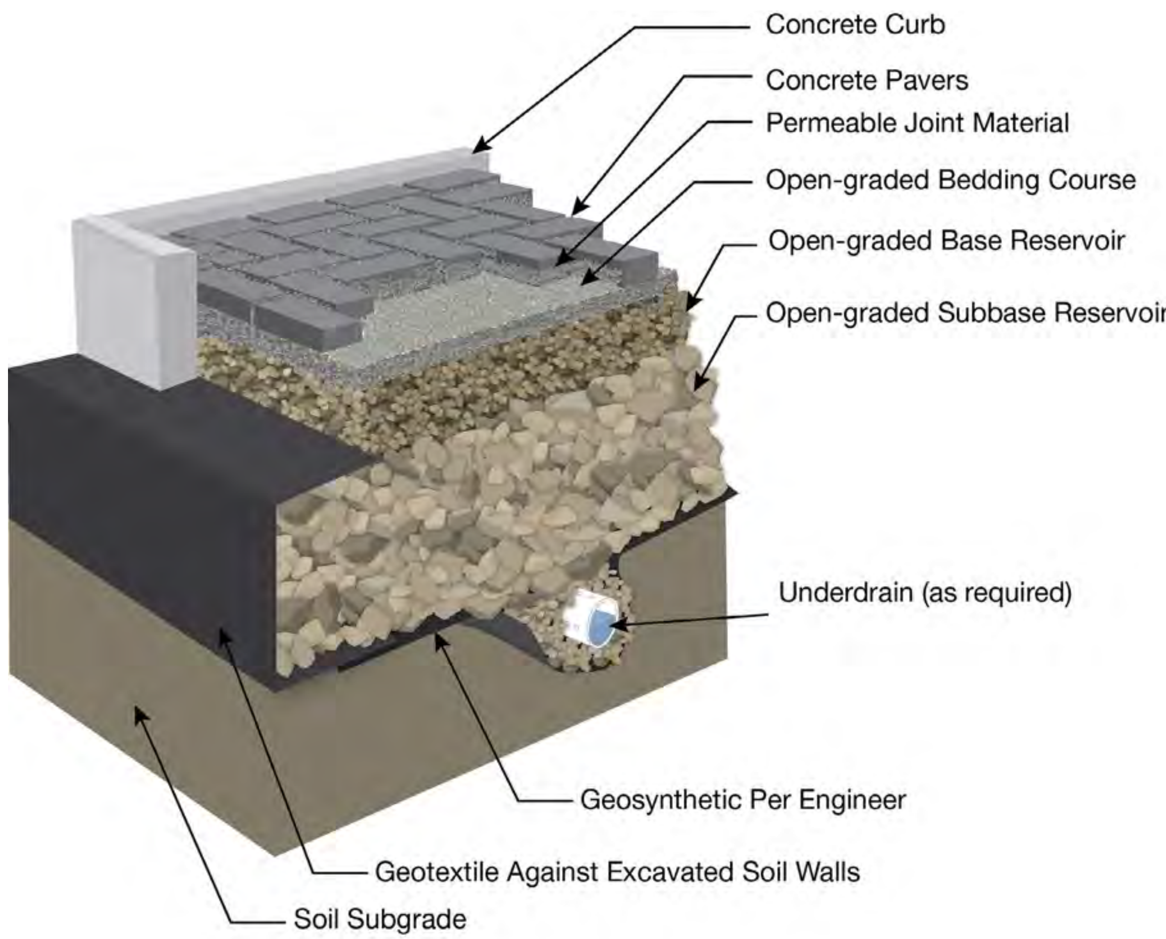
U.S. Department of Transportation
Federal Highway Administration

Introduction

Permeable interlocking concrete pavement, also referred to as PICP, consists solid concrete paving units with joints that create openings in the pavement surface when assembled into a pattern. (The USEPA has a fact sheet on PICP.) The joints are filled with permeable aggregates that allow water to freely enter the surface. The permeable surface allows flow rates as high as 1,000 in./hr (2,540 cm/hr) (Borst 2010). The paving units are placed on a bedding layer of permeable aggregates which rests over a base and subbase of open-graded aggregates. The concrete pavers, bedding and base layers are typically restrained by a concrete curb in vehicular applications. The base and subbase store water and allow it to infiltrate into the soil subgrade. Perforated underdrains in the base or subbase are used to remove water that does not infiltrate within a given design period, typically 48 to 72 hours. Geosynthetics such as geotextiles, geogrids or geomembranes are applied to the subgrade depending on structural and hydrologic design objectives. Separation geotextiles are used on the sides of the base/subbase to prevent entrance of fines from adjacent soils.

Figure 1. Typical permeable interlocking concrete pavement cross section.

Figure 1 illustrates PICP components. The figure shows a partial infiltration design with drainage to accommodate some water that does on enter low infiltration soils. PICP over high infiltration subgrade soils may not require an underdrain(s) and these are called are called full infiltration designs. Other designs over expansive or fill soils or close to buildings may enclose the pavement structure with geomembrane (impermeable liner). An outlet pipe provides temporary storage and outflow control. This design approach also can be used for water harvesting or for horizontal ground source heat pumps. The use of a geomembrane to restrict infiltration into the soil subgrade is often called a no infiltration design.



Benefits

PICP may help achieve compliance with many national, provincial, state and local regulations as well as transportation agency design requirements for stormwater runoff control. These requirements may include the following:

- National Pollutant Discharge Elimination System (NPDES) permit compliance
- Runoff volume and pollutant control for new development and redevelopment
- Limits on impervious cover (i.e., roofs and pavements) and resulting runoff
- Runoff volume storage and/or infiltration to reduce overflows, especially combined sewer overflows.
- Meeting total maximum daily load (TMDL) requirements for receiving waters.
- Managing water quality volume capture and or quantity storm events, typically expressed as a percentile; e.g. 85th percentile storm depth, or the 95th percentile storm depth as required for U.S. federal government facilities in Section 438 of the Energy Independence and Security Act.

- Building code requirements. Examples include CALGreen in California, the International Green Construction Code, ASHRAE Standard 189.1, or other codes that require compliance to Leadership in Energy and Environmental Design (LEED®) or similar sustainable design and construction rating systems.

There are non-regulatory drivers that influence PICP use. These include; economics that often make PICP a lower-cost alternative to conventional drainage system designs, gaining stormwater utility fee credits, and project owner preference for conformance to sustainable rating systems for roads/transportation infrastructure. Examples of rating systems include the Institute for Sustainable Infrastructure's Envision™ evaluation system, Greenroads, GreenPave or the Federal Highway Administration INVEST or Infrastructure Voluntary Evaluation Sustainability Tool.

PICP benefits are listed below (Smith 2011).

Construction

- Paving materials require no time-sensitive site forming
- Immediately ready for traffic upon completion, no time needed for curing
- Can be installed in freezing temperatures if subgrade and aggregates remain unfrozen
- Capable of wet weather (light rain) installation

Reduced Runoff & Improved Water Quality

- 100% surface runoff reduction
- 100% infiltration depending on the design, inflows, and soil subgrade infiltration rate
- Capable of installation over or next to plastic underground storage vaults or crates
- Can be designed with water harvesting systems for site irrigation and gray water uses
- Reduces nutrients, metals and oils (Collins 2008) (TRCA 2007) (TRCA 2012) (Fassman 2010) (Brattebo 2003) (Clausen 2007).
- Does not raise runoff temperature which can damage aquatic life (Wardynski 2013)

Site Utilization

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

Figure 2. Parking lot in Elmhurst, IL.

Figure 3. Green alley in Richmond, VA.

Drainage System

- Reduced downstream flows and stream bank erosion due to decreased peak flows and volumes
- Increased groundwater recharge
- Decreases risk of salt water incursion and drinking water well pollution in coastal areas
- Reduced peak discharges and stress on storm drainage pipes
- 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 (COE 2009)
- Capable of integration with horizontal ground source heat pumps to reduce building heating and cooling energy costs (Coupe 2009)
- Enables landowner credits for stormwater utility fees

Paver Surface/Units

- Produced in a factory and testing to ASTM standards prior to placement
- 50-year concrete material life based on field performance
- ADA compliant
- Colored units can mark parking stalls and driving lanes
- Eliminates puddles on parking lots, walkways, entrances, etc.
- Capable of plowing with municipal snow removal equipment
- Concrete units resist freeze-thaw and degradation from deicing materials
- Reduces ice and deicing material use/costs and related liability due to faster ice melt and surface infiltration
- Provides traffic calming
- Paver surface can be coated with photocatalytic materials to reduce air pollution
- High solar reflectance index (SRI) surface helps reduce micro-climatic temperatures and contributes to urban heat island reduction

Ease of Maintenance & Repairs

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

Applications and Limitations

PICP is used for walkways, driveways, parking lots, alleys, low-speed roads and road shoulders. Figures 2, 3 and 4 below illustrate vehicular applications. PICP is intended for areas with posted vehicle speeds no greater than 35 mph (50 kph). PICP is generally used in areas exposed to less than 1 million 80 kN lifetime equivalent single axle loads (ESALs) (or Caltrans Traffic Index < 9). These applications use unstabilized open-graded aggregates. Open-graded bases stabilized with cement or asphalt, or the use of pervious concrete or porous asphalt bases can provide higher lifetime ESALs and accommodate heavier load applications. PICP has seen limited use in heavy load applications with permeable asphalt stabilized bases (Knapton 2003, Sieglen 2004). Design guidance for heavy loads can be found in overseas sources Knapton 2007 and Knapton 2012. Research is being conducted on the structural behavior of PICP at the University of California (Davis) Pavement Research Center and specifically that of the open-graded aggregate base materials. In addition, the American Society of Civil Engineers is preparing a national standard with guidance on design, construction and maintenance for release in 2015.

PICP should not be used in areas subject to loading/unloading or storage of hazardous materials. It is generally not placed in areas with high depth to seasonal water tables (i.e. less than 2 ft or 0.6 m) although it has been used in coastal areas with sandy soil subgrades in Maryland, Virginia, South Carolina and Georgia. Like all permeable pavements, PICP should not be used on extremely dirty sites where there is uncon-trolled water borne sediment or wind borne dust that can rapidly clog the surface.

Typical Properties and Characteristics

Concrete paving units and jointing materials – Concrete pavers conform to ASTM C936 Standard Specification for Solid Interlocking Concrete Paving Units. Minimum 3 1/8 in. (80 mm) thick units are used in vehicular areas and pedestrian areas may use 2 3/8 in. (60 mm) thick units. Depending on joint widths, they are filled with permeable, small-sized aggregates such as ASTM No. 8, 89 or 9 stone per ASTM D448 Standard Classification for Sizes of Aggregate for Road and Bridge Construction or AASHTO M-43 Sizes of Aggregate for Road and Bridge Construction.

Open-graded Bedding Course

This permeable layer is typically 2 in. (50 mm) thick and provides a level bed for the pavers. It consists of small-sized, open-graded aggregate, typically ASTM No. 8 stone or similar sized material.

Figure 4. Main Street, Warrenville, IL.

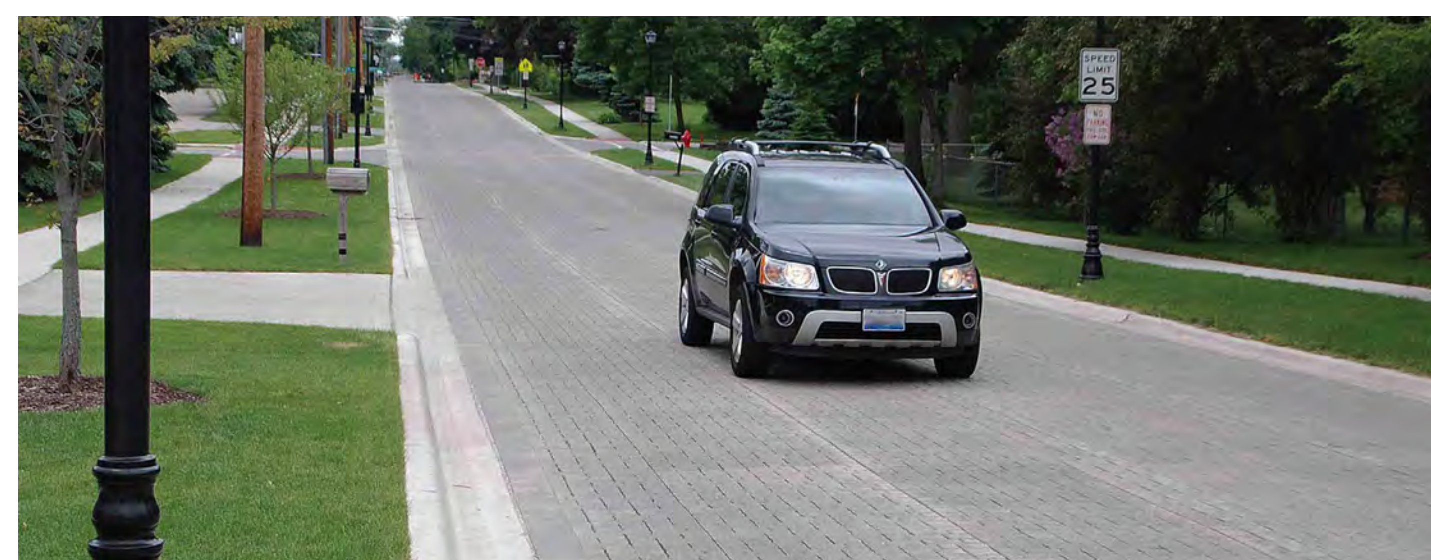


Table 1. Site characteristics, hydrologic and structural design considerations.

Site Characteristics

Drainage Path	Assess drainage patterns in the surrounding area to determine possible impact on PICP.
Traffic Type and Patterns	Assess traffic type and composition. Avoid using PICP in high traffic areas subjected to traffic such as high bus or heavy truck repetitions. Avoid use where traffic will contaminate the pavement surface with dirt, oils and grease.
Winter Maintenance	Avoid winter sand which may clog the pavement and if used, remove in the following spring. Limit use of deicing chemicals.
Groundwater Depth	PICP is generally not used in areas where the groundwater is within 2 ft (0.6 m) of the bottom of the pavement.
Subsurface Conditions	Underground utilities, presence of bedrock etc. may require special considerations. Utility lines in the base or subbase may require encasement.
Surrounding Land Use	Avoid use of high sediment and/or contaminant generating activities.
Rainwater Capture and Re-Use	Limit use of deicing chemicals or other contaminants for systems where stormwater is captured for re-use.

Structural Design

PICP structural design adopts the AASHTO 1993 design procedure for flexible pavements. The AASHTO 1993 Guide is applied because the load distribution and failure modes of PICP are similar to those for other flexible pavement systems (i.e., the main failure mode is increasing roughness due to repetitive shear deformations) (Hein 2011) (Smith 2011). The AASHTO procedure is used for non-permeable interlocking concrete pavement as well (ASCE 2010). The PICP design process includes an analysis of the expected axle loads, followed by characterization of subgrade strength and evaluation of the surface and subbase thickness to support the design traffic for the life of the PICP.

Feature	Description
Traffic	Consider current and future expected traffic types and frequency and convert to ESALs.
Subgrade Characteristics	Carefully evaluate subgrade structural capacity and assume values in "soaked" condition which can characterize a saturated, worst case condition. Determine infiltration capacity with field testing. Assess need for compaction to uniform density and assess infiltration in compacted state if required for structural support.
Surface	PICP pavers with the bedding layer use an AASHTO layer coefficient of 0.3. Carefully assess impact of construction conditions and equipment on the stability of the surface.
Base/Subbase	Determine layer coefficients and structural capacity which may be less than that of conventional, dense-graded base materials. Select durable, crushed materials (LA Abrasion < 40) to maximize structural capacity and porosity for water storage. Select clean materials with < 2% passing the No. 200 (0.075 mm) sieve.
Reliability	Assess design reliability and select appropriate value for intended traffic and maintenance activities. 80% is typically used.

Hydrologic Design

Feature	Description
Design Storm	Determine expected storm duration, frequency and intensity and depth.
Surface	Determine initial surface infiltration and long-term if subject to sediment loads.
Surface Slope	Typically < 5 percent although higher slopes have been successfully used.
Subgrade Slope	Maintain < 1% for full or partial infiltration designs. Consider berms or other intermittent structures for subgrades exceeding 3% slope.
Contributing Area Runoff	Determine runoff volume, velocity, etc. from contributing areas. Consider potential sediment loads and design to capture before reaching the PICP surface.
Supplemental Surface Drainage	Design supplemental surface drainage (overflow) for high intensity storms. The PICP surface should not be designed as a detention area as this can mobilize sediment and other pollutants captured in the surface.
Subgrade Infiltration	Determine potential for infiltration based on soil type, and density. Subgrade compaction is desirable to support vehicular traffic but lower compaction is desired to provide maximum infiltration capability. Designer must balance these to achieve design objectives.
Underdrains	For partial or no infiltration designs, determine the type, location and need for underdrains. Specify outlet details and cleanout(s).
Outflow Details	Design outflow from underdrains to meet detention goals. Ensure detailing of outflow elements meets stormwater capture and release goals.
Observation well	Place capped, vertical perforated pipe near lowest elevation to monitor drain down time.
Geosynthetics (geotextile, geogrid, geomembrane)	Assess the need and/or benefit for geosynthetics for separation, filtration, containment, reinforcement, etc.

Open-graded Base Reservoir

This is an aggregate layer 4 in. (100 mm) thick and made of crushed stone primarily 1 in. down to 1/2 in. (25 mm down to 13 mm). Besides storing water, this highly permeable layer provides a structural transition between the bedding and subbase aggregate layers. The stone size for the base is typically ASTM No. 57 or similar sized material.

Open-graded Subbase Reservoir

The stone sizes are larger than those in 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 is stored in the spaces among the stones. The subbase layer thickness depends on water storage requirements and traffic loads. A subbase layer may not be required in pedestrian or residential driveway applications. In such instances, the base layer thickness is increased to provide water storage and support.

Geosynthetics

These consist of geotextiles, geogrids or geomembranes. Geotextiles can separate the subbase from the subgrade and help prevent migration of soil into the aggregate subbase or base. When applied horizontally, they should be designed for subsurface drainage applications be carefully selected and evaluated for clogging potential. Separation geotextiles should be applied vertically to the sides of the base/subbase in designs that do not use full depth curbs or are against other structures. Geotextiles should conform to AASHTO M-288 Geotextile Applications for Highway Applications, subsurface drainage. Geogrids or geocells can be used to support the subbase in very low strength soils, i.e. CBR < 2%. Geomembrane material encases the pavement structure and is used for no infiltration designs. Geosynthetic manufactures should be consulted for recommended material selections and thicknesses.

Figure 5. Mechanical installation of concrete paving units for PICP.

Design

As with all permeable pavements, site characteristics are initially reviewed, then consideration is given to hydrologic design for stormwater management and to structural design to support anticipated vehicle axle loads and repetitions. The thicker of the two bases from structural and hydrologic designs is selected. These design considerations are briefly described in Table 1 on the next page.

Construction Considerations

The following provides a construction checklist for project use. The Engineer should edit according to specific project requirements. In recognition of the special construction requirements of PICP, the Interlocking Concrete Pavement Institute developed a program designed to educate, train, and recognize individual contractors in PICP construction. This is called the PICP Specialist Course. Project specifications should state that the project foreman holds a record of completion in this course. (See www.icpi.org/installercourses for more information).

Most PICP projects are machine installed to accelerate construction time over manual installation. Figure 5 illustrates a machine that lifts and places about a square yard (m^2) of concrete pavers in their final laying pattern. The units are placed on the screeded bedding layer of aggregate, the joints filled with aggregate, and the paver surface swept clean and compacted.

Construction Checklist

Pre-construction meeting

- Walk through the site with builder/contractor/subcontractor to review erosion and sediment control plan/stormwater pollution prevention plan (SWPPP)
- Determine when PICP is built in project construction sequence and confirm specified measures for PICP protection and surface cleaning

- Aggregate material storage locations identified (hard surface or on geotextile)
- Sediment management
- Access routes for delivery and construction vehicles identified
- Vehicle tire/track washing station (if specified in Erosion & Sediment plan/SWPPP) location/maintenance

Excavation

- Utilities located and marked by local service
- Excavated area marked with paint and/or stakes
- Excavation size and location conforms to plan
- Excavation hole used as sediment trap: cleaned immediately before subbase stone placement and runoff sources with sediment diverted away from the PICP, or all runoff diverted away from excavated area
- Protect temporary soil stockpiles from erosion from water and wind
- Ensure linear sediment barriers (if used) are properly installed, free of accumulated litter, and built up sediment against them
- No runoff enters PICP until soils stabilized in area draining to PICP

Foundation Walls

- At least 10 ft (3 m) from foundations with no waterproofing or drainage

Water Supply

- At least 100 ft (30 m) from municipal water supply wells

Soil Subgrade

Rocks and roots removed, voids refilled with open-graded aggregate

- Soil compacted to specifications (as required) and field tested with density measurements per specifications
- No groundwater seepage or standing water

Geosynthetics

- Meet specifications for materials, placement and down slope overlap
- Sides of excavation covered with separation geotextiles prior to placing aggregate base/subbase
- No tears or holes
- No wrinkles, pulled taught and secured during construction
- Geomembrane placement, field welding, and seals at pipe penetrations meet specifications
- Drain pipes/observation wells
- Size, perforations, locations, slope, and outfalls meet specifications and drawings
- Verify elevation of overflow pipes

Subbase, base, bedding & jointing aggregates

- Sieve analysis from quarry conforms to specifications
- 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
- Testing and written field verification of subbase/base compaction prior to placement of bedding layer

Edge Restraints

- Elevation, placement, and materials meet specifications and drawings

Permeable Interlocking Concrete Pavers

- Meet ASTM C936
- 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
- All pavers within 6 ft (2 m) of the laying face fully compacted at the completion of each day
- Surface tolerance of compacted pavers deviate no more than ±3/8 in. (10 mm) under a 10 ft (3 m) long straightedge

Final Inspection

- Surface swept clean
- Elevations and slope(s) conform to drawings
- Transitions to impervious paved areas separated with edge restraints
- Surface elevation of pavers no greater than ¼ in. (6 mm) above adjacent drainage inlets, concrete collars or channels
- Lippage: no greater than 1/8 in. (3 mm) difference in height between adjacent pavers
- Bond lines for paver courses: ½ in. (±15 mm) over a 50 ft (15 m) string line
- Stabilization of soil in area draining into PICP
- 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 Standard Test Method for Surface Infiltration Rate of Permeable Unit Pavement Systems. This minimum acceptable rate should be 2,500 mm/hr (100 in./hr).
- Contractor to revisit site 6 months from date of substantial completion to re-inspect joint fill material and refill as required; replace any paver areas not conforming to specifications.

Maintenance

PICP inspections should be completed 1 to 2 times annually (preferably after a storm event). Inspection tasks should include the following:
- Review maintenance and operations records and incidences to determine indictors of maintenance
- Document general site features, take pavement photographs, etc.
- Note obvious sources of surface contaminants such as sediment
- Identify the extent and severity of any damage or deficiencies (settlement, ponding, cracked pavers, etc.) Structural related condition can be documented and a pavement condition index created using ASTM E2840 Standard Practice for Pavement Condition Index Surveys for Interlocking Concrete Roads and Parking Lots.
- Identify any changes in adjacent land use that may impact contributing area runoff for potential sources of contaminants that may reduce system permeability
- Inspect vegetation around PICP perimeter for cover and soil stability
- Inspect edge restraints to ensure continued functioning
- Check observation well(s) and outlet drain(s) to ensure continued water drainage from the pavement structure
- Check surface for buildup of sediment in joints. Buildup typically occurs near adjoining impervious pavements. If water ponds on the PICP and remains longer than one hour after a rainstorm, then conduct ASTM C1781to determine surface infiltration rate.

The results of the inspection should be documented and used to assist in updating the maintenance plan for the PICP system. The information should be used to assist in predicting future maintenance needs and be part of an overall management system for the pavement. Based on the results of the inspection, it may be appropriate to conduct remedial maintenance particularly if the surface has not been vacuumed regularly.

Routine Maintenance

The following provides a checklist for PICP routine maintenance:

- Inspect, and if necessary, clean the surface using regenerative air equipment to remove debris and sediment in the spring and late fall.
- Repair/replant vegetative cover for areas up slope from the PICP
- Replenish aggregate in joints if more than ½ in. (13 mm) from paver chamfer bottoms
- Repair all paver surface deformations exceeding ½ in. (13 mm)
- Repair pavers offset by more than ¼ in. (6 mm) above/below adjacent units or curbs, inlets etc.
- Replace cracked paver units impairing surface structural integrity
- Clean and flush underdrain system if slow draining
- Clean drainage outfall features to ensure free flow of water and outflow

Remedial Maintenance

- If ASTM C1781 test results are below 10 in./hr, vacuum surface to remove sediment jammed into joints and soiled aggregate (typically ½ to 1 in. or 13 to 25 mm deep) using a full or true vacuum machine (not regen-erative air) (Chopra 2010). Refill joints with clean aggregate, sweep surface clean and test infiltration rate again per ASTM C1781 to minimum 50% increase or minimum 10 in. /hr (250 mm/hr).
- Repair and/or reinstatement of damaged edge restraints and resulting movement in the pavers; this may require removal and reinstatement of adjacent paving units
- Repair localized settlement greater than ½ in. (13 mm) and rutted pavement areas
- Repair outflow features, piping, energy dissipaters, erosion protection systems, etc. as required

Winter Maintenance

Avoid the use of winter sand for traction; if used, remove with regenerative air cleaning equipment in the spring (regenerative equipment does not evacuate jointing materials)
- Remove snow with standard plow/snow blowing equipment
- Stockpile plowed snow onto turf or other vegetated areas and not on the PICP.
- Monitor temperatures and apply anti-icing/deicing materials such as sodium chloride, calcium chloride or magnesium calcium acetate.

Performance

Properly designed, constructed and maintained PICP will provide decades of service in reducing stormwater runoff and pollutants while supporting pedestrian and vehicular traffic. Pavement stability and winter durability has been documented with PICP use in a Chicago in a parking lot (Attarian 2010) as well as in Toronto (TRCA 2008) (TRCA 2012) and Durham, New Hampshire (UNHSC 2013). Additional experience has been gained with PICP in 'green' alley projects in Los Angeles and Sacramento, CA, Richmond, VA, Longmont, CO, St. Louis, MO, Lancaster, PA, and Dubuque, IA. In addition PICP streets in Warrenville, IL, Moline, IL and Charles City, IA have solved stormwater problems in a cost-effective manner.

Summary and Future Needs

PICP use has seen increased use since its introduction from Germany to the US in the mid-1990s. The water volume and pollution reduction capabilities are well-established from research. Winter durability and maintenance procedures have been established through research and experience. Additional research and full-scale load testing will better define structural behavior for applications that receive more ve-hicular traffic than residential collector streets.

Research

This TechBrief was developed by David R. Smith as part of FHWA's ACPT product implementation activity. The TechBrief is based on research cited within the document. All figures are provided by the Interlocking Concrete Pavement Institute.

Distribution

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Availability

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Key Words

Permeable pavement, permeable interlocking concrete pavement, permeable pavement design, construction, maintenance, LEED® credit, maintenance, pavement design, pavement construction, permeability, pervious concrete, porous concrete, stormwater, sustainability.

Notice

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The Advanced Concrete Pavement Technology (ACPT) Products Program is an integrated, national effort to improve the long-term performance and cost-effectiveness of the Nation's concrete highways. Managed by the Federal Highway Administration through partnerships with State highway agencies, industry, and academia, the goals of the ACPT Products Program are to reduce congestion, improve safety, lower costs, improve performance, and foster innovation.

The ACPT Products Program identifies, refines, and delivers for implementation available technologies from all sources that can enhance the design, construction, repair, and rehabilitation of concrete highway pavements. The ACPT Marketing Plan enables technology transfer, deployment, and delivery activities to ensure that agencies, academia, and industry partners can derive maximum benefit from promising ACPT products in the quest for long-lasting concrete pavements that provide a safe, smooth, and quiet ride.

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For More Information

U.S. Department of Transportation

Federal Highway Administration

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