The Engineer's View

David R. Smith—ICPI Technical Director and Rob Burak, P. Eng.—ICPI Director of Engineering

Construction of Permeable Interlocking Concrete Pavements

Permeable interlocking concrete pavements provide attractive solutions to stormwater runoff while creating places for cars and people.

As urbanization increases, so does the concentration of pavements, buildings, and other impervious surfaces. These surfaces generate additional runoff and pollutants during rainstorms causing stream-bank erosion, as well as degenerating lakes and polluting sources of drinking water. Increased runoff also deprives groundwater from being recharged, decreasing the amount of available drinking water in many communities.

With a North American population that lives in close proximity to water resources, there is growing concern regarding the management of stormwater runoff and pollutants. In the United States, federal law mandates that states control water pollution in runoff through the National Pollutant Discharge Elimination System (NPDES). Among other things, the law requires that states and localities implement best management practices, or BMP's, to control non-point source pollution from new development.

BMP's can include storage, filtration, and infiltration land development practices. Infiltration practices capture runoff to various degrees and rely on filtration through soils, vegetation, or aggregates for the reduction of pollutants. Detention ponds are a common example of a BMP used to hold, infiltrate, and release stormwater. Infiltration trenches are another type used for decades to reduce stormwater runoff and pollution, and to recharge groundwater.

In terms drainage design, permeable interlocking concrete pavements (PICPs) are no different than infiltration trenches. Like infiltration trenches, PICPs filter water and provide a driving surface. Since PICPs take in rainfall, the U.S. Environmental Protection Agency and several state agencies consider PICPs an infiltration BMP. This enables them to be part of runoff regulations, guidelines, and design manuals on stormwater control published by states, counties, and cities. With proper design, material selection and proper construction, PICPs are another sustainable,

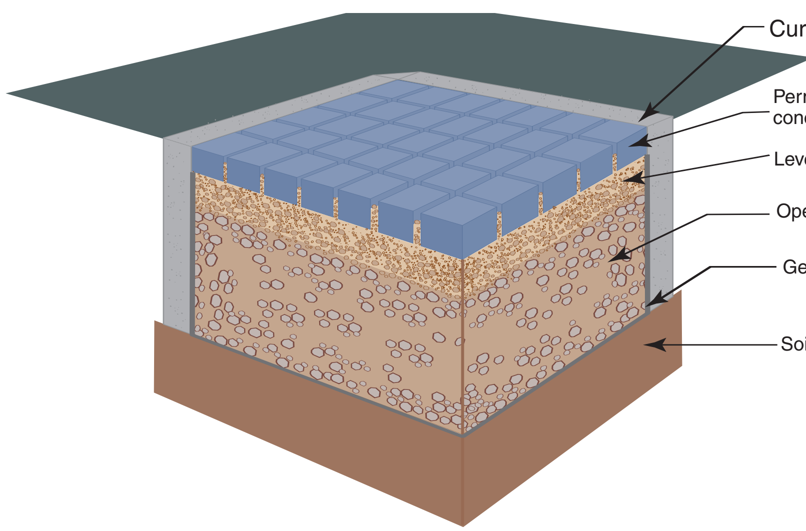

Figure 1. Typical components of a permeable interlocking concrete pavement: the base thickness will vary depending on the runoff storage requirements for a particular site.

Figure 2. A storm sewer inlet receives overflow from the surface at this residential development near Seattle, Washington.

Figure 3. Curb cuts at this hotel parking lot in southern California allow overflow water to drain from the parking lot during flood conditions.

Figure 4. A grass swale receives overflow from this museum parking lot in Portland, Oregon.

low-impact tool in the kit of BMPs for landscape architects, architects, engineers, developers, as well as for those who regulate runoff. This article provides some guidelines for construction. The photos are from various PICP projects across the U.S.

Drainage Options

Permeable interlocking concrete pavements (PICPs) consist of an open-graded, crushed stone base paved with units that allow runoff to enter it. Figure 1 shows a cut-away drawing of a typical PICP. Like infiltration trenches, the open-graded base helps improve water quality, decrease water quantity, and preserve the hydrologic cycle through infiltration.

PICPs provide these benefits via three base drainage options; full, partial and no exfiltration. (Exfiltration means the outflow of water from the base.) All three base exfiltration options require drainage away from the top of the base should the base completely fill with water from heavy, flood-prone storms or experience reduced capacity later in its life. Ways of handling overflows are storm sewer inlets in the pavement or directing overflowing water to a side of the site and draining it through grass swales. Examples are shown in Figures 2, 3 and 4.

Figure 5 illustrates a full infiltration typically built over sandy soils. The drawing includes an overflow standpipe right in the base to handle excess water. This another means to handle excess water that fills the base in continually wet weather and heavy rains.

Partial exfiltration (see Figure 6) has the characteristics of a full exfiltration design. However, partial exfiltration design is used when some of the water can't infiltrate into the soil within 24 hours. Twenty-four hours is the target design time for water to drain from base and into the soil. Longer drainage times can weaken most soils.

Excess water not infiltrated by the soil within a 24-hour time frame drains from the bottom of the base through perforated pipes. This design is used with slow-draining silt and clay soils typically with infiltration rates less than 0.27 in./hr or 2 x 10-6 m/sec). Partial exfiltration designs act like an underground detention pond by storing water in the base and then slowly releasing it through pipes.

Designs for no exfiltration of water from the base will be on sites with low strength, almost impervious soils, or high depth to bedrock. In such cases, the open-graded base detains and filters the stormwater before it drains (see Figure 7). An impermeable liner under the base is typically used, especially if the depth to bedrock or water table is less than 2 ft (0.8 m) from the bottom of the base. The liner creates an enclosed pond or "tanked" system.

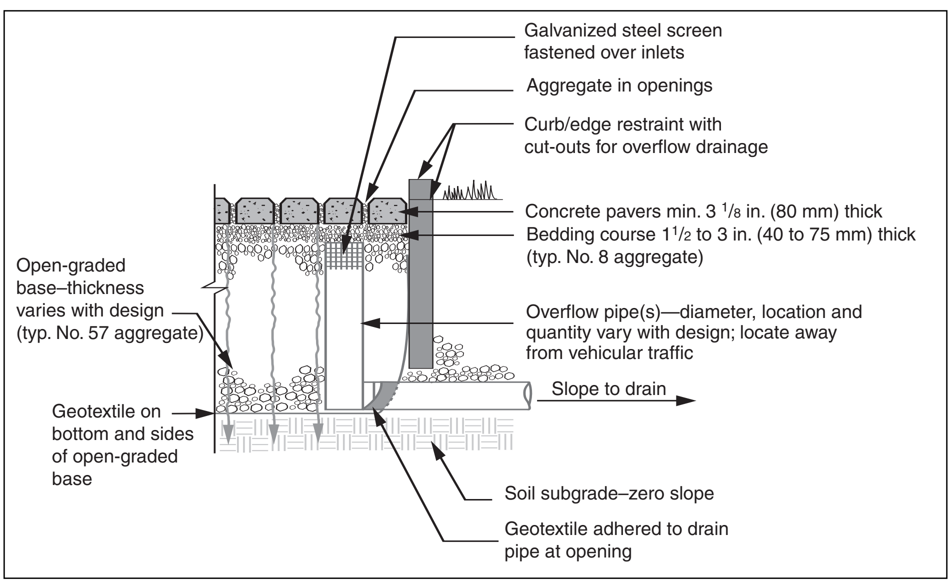

Figure 5. A typical design for full exfiltration: the system infiltrates most of the water into the soil.

Keep Sediment Out During Construction

The highest priority during construction of PICPs is preventing sediment from entering the base materials. Any contaminated aggregates must be removed and replaced as sediment on them will clog the system and render the system less effective in storing and filtering runoff. Means to preventing or diverting sediment include staged excavation to minimize drainage of sediment from disturbed soil, keeping muddy construction equipment off the base, installing silt fences and temporary drainage swales to direct sediment away from the base. Figures 8 and 9 show some good housekeeping practices. Figure 10 shows dense-graded base placed over an open-graded aggregate base to create a

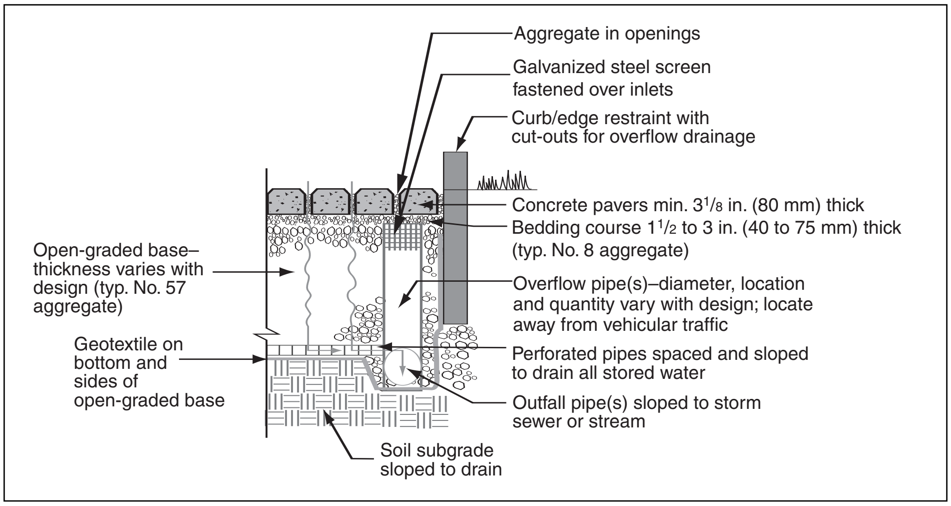

Figure 6. Partial exfiltration of the base means that some of water goes into the soil and some is drained out through perforated pipes located at the bottom of the base. The system detains some and infiltrates some water.

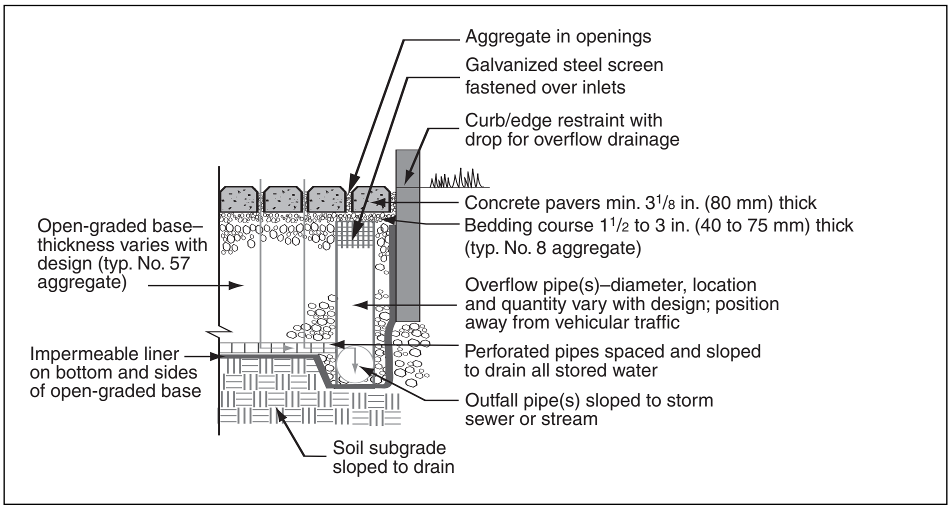

Figure 7. No exfiltration of water from the base means that the water is completely detained within an impermeable liner and released slowly to storm sewer or stream.

Figure 8. Dumping aggregate on geotextile rather than directly on bare soil helps keep the aggregate from becoming contaminated with sediment.

small ramp for trucks to supply a job site with aggregate. This area should have geotextile directly under the temporary dense-graded base.

Subgrade Preparation

In some cases, particularly in clay soils, the soil subgrade is compacted prior to placing the geotextile and base. Compaction of soil will reduce its permeability; therefore analysis of the relationship between density and infiltration may be needed. Prior to design and construction, the standard laboratory Proctor density should be determined from soil samples taken from the site per ASTM D 698. Proctor density of soil on the site using increasing levels compaction can be measured with a nuclear density gauge. At various levels of tested density, infiltration tests can be conducted using ASTM D 3385 or D 5093. A geotechnical engineer can determine the right combination of density (from compaction) and infiltration for use in base and drainage design. The designer should use a lower (conservative) infiltration rate than what was actually measured from the compacted soil at a given percentage of laboratory Proctor density. This allows for some clogging and reduction of infiltration of the soil over time.

Geotextile is recommended for permeable pavement applications. It should line the bottom and sides of the opening. It separates and contains the base from the soil subgrade. This reduces potential contamination of the base materials by soil particles from the bottom and sides of the excavation. The fabric should overlap down slope (like roof shingles) a minimum of 24 inches (0.6 m). Figure 11 shows installation of geotextile.

Storing Excess Water

Partial or no exfiltration designs should have a network of perforated pipes placed at the bottom of the base (over the geotextile) to handle storage and outflow. A civil engineer experienced with hydraulic design should determine the size and spacing of these pipes. Care should be taken to ensure that pipes subjected to traffic withstand repeated vehicular loads. Perforations in the pipes should be 3/8 inch (10 mm) in diameter and terminate within 1 foot (0.3 m) of the edge of the base to prevent possible clogging by surrounding soil. See Figure 12.

A network of perforated drain pipes will collect at least one (non-perforated) outlet pipe and it will penetrate the geotextile. The fabric should be glued to the pipe to prevent ingress of soil. Additional layers of fab-

Figure 9. Routine practices such as sweeping away dirt from the pavement while it's under construction will maintain storage capacity in the open-graded aggregate base.

Figure 10. The geotextile on the sidewalk didn't quite make it under the small ramp area made with dense-graded base that rests on installed open-graded base. If it were under the dense-graded material it would help keep some of the fines from contaminating the base. Two or three layers of geotextile would provide a substantial filter of fines.

ric wrapped on the pipe and cut fabric at the penetrations may be needed for reinforcement.

In all designs, a 6 inch (150 mm) diameter vertical perforated pipe placed in the down slope position of the pavement (1 m from the outside edge of the base) acts as an observation well. The pipe is fastened to a plastic or metal base and placed on the geotextile. The stand pipe is capped at the top. See Figure 13. The lid should be hidden under the pavers to avoid vandalism. The purpose of the pipe is to monitor the rate of drainage.

Installing the Open-Graded Aggregate Base

All aggregates in PICPs should be washed. Use of rounded gravel (such as river gravel) is not recommended PICPs. Open-graded, crushed stone base typically consists of particles ranging in approximate size from $1^{1}/_{4}$ inches to $^{1}/_{8}$ inch (37 to 3 mm). Figure 14 shows a range of stone sizes. The gradation in ASTM No. 57 crushed stone has been used successfully in some applications. Local open-graded, clean crushed stone used for drainage applications may differ somewhat from No. 57 in gradation. The key is to find crushed stone with a gradation that offers stability under loads while having a void ratio of 30% to 40%.

The ICPI Construction Committee has assigned a task group to review current ICPI specifications for permeable pavement aggregate bases. A task group was appointed at the February 2004 ICPI Annual Meeting in Atlanta and is primarily focusing on the current specifications in terms of constructability. The task group has not finalized their recommendations, but a summary of their discussion follows:

The task group is investigating the effectiveness of utilizing a larger size (maximum 3 inch or 75 mm size aggregate) layer as a subbase material under a smaller size (maximum $^{3}/_{4}$ inch or 20 mm) layer for the base material in PICP applications. Three inch size aggregate subbase is being successfully utilized in Europe. This differs from current industry specifications which use a full depth base of ASTM No. 57 aggregate (maximum 1 or 25 mm size aggregate).

The task group reports favorable contractor experience using larger size (3 inch or 75 mm) aggregate subbase layer, at a minimum thickness of 6 inches (150 mm) to assist during the construction phase of PICP's by providing excellent support for trucks and loaders. The $^{3}/_{4}$ inch aggregate base at a 4 inch (100 mm) thickness over this subbase is reported to offer the best "choking" of the No. 8 bedding layer.

The task group is also investigating the effectiveness of alternative geotextiles (woven versus non-woven) between the base and the subgrade as well as the current European practice which uses no fabric to separate the base and subgrade. In addition, the task group is investigating other alternatives for edge restraints that may be effective for some PICP installations.

Base materials are spread in 4 to 6 inch (100 to 150) mm lifts (Figure 12) and compacted with a 10 ton (9 T) steel drum roller. The initial passes can be made with vibration on and the final passes should be made with no vibration. There should be no visible movement of the crushed stone during the final passes of the static roller. Take caution to not over-compact the stone. If it begins to crush it will decrease storage capacity through an increase in smaller particles.

A frequently asked question is can density of the compacted base be measured? If so, how? Proctor density (per ASTM D 698 or D1557) does not apply to measuring density of open-graded materials. Instead, a density range for open-graded aggregate can be established with laboratory tests and they are compared to field measurements taken with a nuclear density gauge. Specifically, the minimum and maximum index density of the base material is established in the lab per ASTM D4254 and ASTM D4253. The wet density is measured with a nuclear density gauge in the field using backscatter with no probe extension (rather than direct transmission with the probe extended in the base). Compacted base lifts should not exceed 4 inches (100 mm) when taking backscatter density measurements with a nuclear density gauge.

Since testing aggregates and measuring density of open-graded aggregate is quite involved, ICPI guide specifications provide a simpler approach. They spell out a compaction procedure using a roller. Acceptance of the work is based on no visible movement of the aggregate under the roller during a static roll.

Figure 11. Geotextile is placed over the soil subgrade and lines the bottom and sides of the base.

Figure 12. Perforated pipes will be used at the bottom of the base for projects over slower draining silt and clay soils.

Figure 13. An perforated access pipe at the low side of the pavement allows monitoring of drainage rates.

Figure 14. Stone sizes are shown here for a base in a parking lot application in North Carolina. They are compacted and an elevation string line is set for the bedding course and paver installation.

Installing the Bedding Layer

The bedding layer should never be concrete sand typically recommended for interlocking concrete pavements. Instead, ICPI recommends installing 2 to 3 inch (50 to 75 mm) of ASTM No. 8 stone (size range $^1/_2$ to $^1/_{16}$ inch or 13 to 2 mm) or similar sized material that chokes into the base course surface with the same roller. This will typically result in a 1 to 2 inch (25 to 50 mm) layer stone as the bedding layer for the pavers. In addition, the stone should be moist to help move it into the spaces between the larger stones in the surface of the base course. Figure 15 shows powered screeding which is necessary on large projects. The screed rails are set on the compacted base and levelled. With the help of the Bobcat, the screed pulls the bedding material across the base.

Bedding material such as No. 8 stone provides for ample infiltration of stormwater into the open-graded base. The top of bedding should be checked for a surface tolerance that is $\pm^3/_8$ inch over a 10 ft ($\pm$10 mm over a 3 m) straight edge.

Another frequently asked question: should a layer of geotextile be placed between the bedding and base layers? The answer depends on the sources and sizes of aggregates. No fabric should be needed if the stone for the bedding and base layers meet the following criteria:

$$D_{15\ \text{open-graded base}}/D_{50\ \text{bedding layer}} < 5 \text{ and } D_{50\ \text{open-graded base}}/D_{50\ \text{bedding layer}} > 2$$

Dx is the particle size at which x percent of the particles are finer. For example, D15 is the particle size for which 15% of the particles are smaller and 85% are larger.

There are hundreds of PICP projects that do not use geotextile between the bedding and base layers thanks to locally available crushed stone with the right gradations. However, optimum gradations that allow the bedding to lock or choke into the base from compaction cannot always be found locally. In addition, some quarries may supply stones that are somewhat rounded. While rounded materials are discouraged from use in PICPs, they may be the only material available. In such situations it may be necessary to use a geotextile for additional stability. The geotextile adds some filtering and may be removed and replaced at some point in the life of the pavement. That point will depend on how much sediment is deposited on the pavement.

Recommended edge restraints for PICPs

Figure 15. Powered screeding of the bedding layer saves much time compared to hand screeding.

Figure 16. A large plate compactor seats the pavers in the bedding material.

on open-graded bases are cast-in-place and precast concrete curbs. They should be at least 6 in. wide and extend at least to the bottom of the aggregate base. This helps direct water to the outlets and contains the base materials during compaction. They should be installed prior to placing the geotextile and base. A stable footing of base under curbs may be required.

Selecting the Paver Surface

Pavers used as PICPs should be at least 3 1/8 inch (80 mm) thick for pedestrian and vehicular applications. With interlocking concrete pavements, normally 2 3/8 in. (60 mm) thick pavers are recommended. Since joints can be fairly wide and they are filled with small stones, 3 1/8 in. (80 mm) thick pavers will contribute additional stability in pedestrian applications.

Pavers for PICPs are laid similarly to a standard interlocking pavement and can be laid either by hand or mechanically. The paver manufacturer can provide guidance on joint spacing. Care should be exercised in using PICPs in disabled-accessible areas. Generally, the disabled-accessible areas should be paved with solid units and permeable ones left for remaining areas.

Once the bedding material is compacted it may require some touch-up of re-screeding in certain areas to maintain a smooth surface for receiving the pavers. The pavers are compacted into the bedding layer (see Figure 16), the openings filled with the same stone as was used for the bedding (Figure 17). For pavers that are 3 1/8 inch (80mm) to 4 in. (100 mm) thick, the plate compactor should exert at least 4,000 lbf (18 kN) at 75 to 90 Hz. For units thicker than 4 inches, the compactor should exert at least 6,800 lbf or 30 kN.

Like any paving project, the work is divided into job functions for recording productivity on time sheets during the project. The job functions fall along the similar lines as constructing ordinary interlocking concrete pavement. These include excavation and grading the subgrade; geotextile, base and compaction; bedding layer placement and compaction; cutting pavers; placing, compacting, filling with bedding material and compacting the pavers, plus clean up. Job functions are recorded per the units of consumption (lineal feet, tons, square foot, etc.) per person per hour.

Keep in mind that some shapes will be more efficient to install—whether by hand or mechanically—than others. Tracking job costs including labor hours by job function will provide information on this aspect as well as many others such as the job size, application, and site access. Collecting this information is vital for accurate bidding of future jobs. Accurate grading of the soil subgrade for drainage, installation of the drainage system using perforated pipe, and taking special efforts to store and move aggregates so they do not get contaminated with sediment are among some items that will incur additional costs.

Conclusion

When carefully constructed and regularly maintained, permeable interlocking concrete pavements should provide at least 20 years of service. Their service life is measured by the extent to which they continue to store runoff while supporting traffic without excessive rutting. Periodic maintenance and inspection are required to monitor drainage and pavement distresses, to decide on remedies. The cooperation of the owner of a permeable interlocking concrete pavement plays a key role in maintenance which results in successful, long-term performance of PICPs.

The ICPI has several resources available to assist with design and construction. The 50-page manual, *Permeable Interlocking Concrete Pavements*, provides a comprehensive treatment of selection, design, construction and maintenance. It should be read by design professionals and contractors who design and build these pavements. In addition, there are two PowerPoint presentations. One is aimed at contractors and is entitled *Construction of Permeable Pavements*. It is eligible for continuing education credits for maintaining ICPI installer certification. Taking the program earns two credits. The other presentation is called *Permeable Interlocking Concrete Pavements* and is intended for presentation to design professionals and to those who regulate stormwater runoff. In addition, ICPI *Tech Spec 9, Concrete Grid Pavements*, covers design and installation of this low-traffic permeable pavement related to PICPs. To order these publications, contact ICPI at 202-712-9036 or visit www.icpi.org.

Figure 17. The material used for bedding is also used to fill the openings in the pavers. Powered sweepers are used to distributed stone for large projects. All excess stones are removed from the surface and the pavers are compacted.