PERMEABLE PAVEMENT DESIGN AND CONSTRUCTION CASE STUDIES IN NORTH AMERICA

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ABSTRACT

Permeable pavements typically consist of pervious concrete, porous asphalt, permeable interlocking concrete paving units or grid type systems over an open-graded base/subbase layer(s). Permeable pavements infiltrate stormwater, reduce peak flows, filter and clean contaminants and promote groundwater recharge. They have gained substantial popularity in North America and have become an integral part of low impact design and best management practices for stormwater management. In order to be effective, permeable pavement must be designed to provide sufficient structural capacity to accommodate the anticipated vehicle loadings, manage stormwater flowing into the surface and soil subgrade, as well water draining out of the base/subbase.

While there are many well-designed and constructed permeable pavements, they are a relatively new technology with some projects performing below design expectations. This paper describes some essential best practices for permeable pavement design and construction, and focuses on lessons learned from case studies of permeable pavement construction in North America. Included are driveways, parking areas, roadways, roadways shoulders, walkways and unusual uses of permeable pavements subjected to heavy loadings including buses and even military tanks.

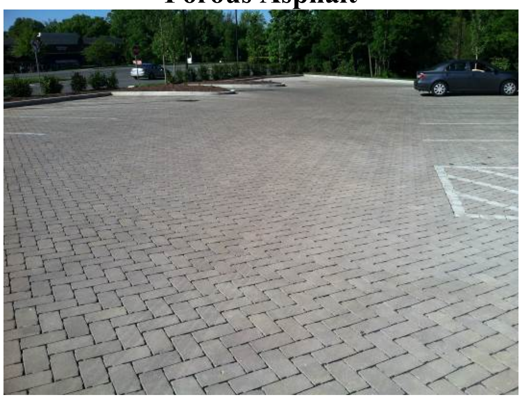
INTRODUCTION

Permeable pavements have gained very rapid use across North American in the past ten years. Examples of permeable pavement types are provided in Figure 1. For new designs and retrofit projects, permeable pavements transform conventional, non-permeable pavement into a stormwater management asset. Almost all permeable pavements use an open-graded aggregate base or subbase to store and infiltrate water into the soil subgrade. The asphalt, concrete and interlocking concrete pavement industries, as well as a number of other manufacturers of permeable surfaces, provide a variety of pavement surface options.

Regardless of the surface, permeable pavement systems include three design approaches. First, they are primarily used to promote complete or full infiltration of rainfall into the soil subgrade. Second, where soil subgrades have low infiltration rates, partial infiltration into the soil subgrade occurs and the remaining water exits via underdrains. Third, for designs that require no infiltration, permeable pavement systems are enveloped with a geomembrane that prevents detained water from entering the soil subgrade and the stored water exits via underdrains. These three design approaches are illustrated in Figure 2.

Porous Asphalt

Pervious Concrete



Permeable Interlocking Concrete Pavement

Grid Pavement

Figure 1. Examples of Permeable Pavement Types

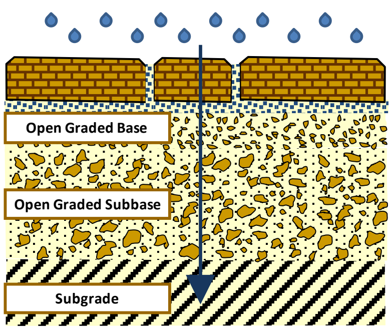


Figure 2a. Full Infiltration

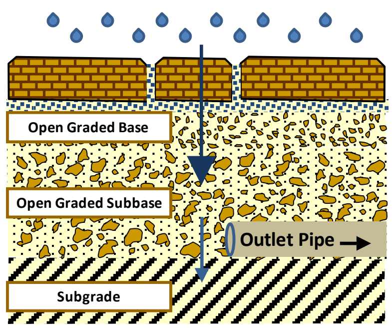


Figure 2b. Partial Infiltration

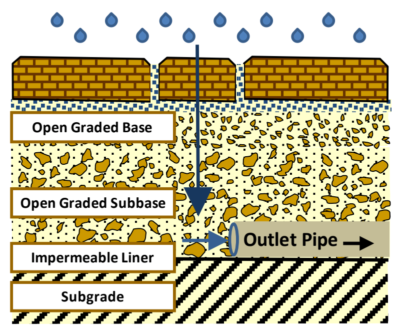


Figure 2c. No Infiltration

KEY PERMEABLE PAVEMENT DESIGN FEATURES

A successful permeable pavement considers structural and hydrologic design. Structural design considers the pavement strength required to accommodate the vehicle loadings without the pavement failing. Hydrologic design considers the capacity required to infiltrate, store and release water in a manner that contributes positively to stormwater management. Some key design, construction and maintenance considerations are as follows:

Site Drainage - Consider the overall site drainage and evaluate rainfall onto the pavement and water that may drain onto the permeable pavement from surrounding areas. This could include adjacent pavements, grassed areas, building roofs, etc.

Contaminant Loading - Consider potential contaminants such as winter sand (for traction), biomass (tree leaves and needles, grass clippings, etc.) and sediment. Contaminants may reduce the long-term permeability of the pavement system and likely require maintenance such as vacuum sweeping.

Groundwater Depth - The top of the subgrade under a permeable pavement should be no less than 0.6 m from the seasonal high groundwater level.

Subgrade Type and Strength - The type of subgrade and its compaction/consolidation govern if water can be adequately infiltrated into the ground. Permeability values in the order of 12 mm/hr permit full infiltration designs that accommodate rainstorm depths in most areas of North America. Lower permeability subgrade in high rainfall event areas may require supplemental underdrains. Permeable pavements constructed over fine-grained soils (silts and clays) generally require thicker pavements than those constructed over coarse-grained soils (sands and gravels).

Traffic Type and Composition - Avoid using permeable pavements in high, concentrated traffic areas subjected to many heavy vehicles such as trucks and buses. While permeable pavements can be designed to accommodate very heavy loads (Figure 3), a qualified pavement engineer should be consulted for these specific applications.

Figure 3. Permeable pavement to accommodate tanks

Pavement Surface - Consider the type of surface most appropriate for the traffic and infiltration capacity conditions. For example, porous asphalt or pervious concrete may be more appropriate for some slope conditions whereas permeable interlocking concrete and grid pavements may be more suitable for situations where vehicles are turning. While some projects have steeper slopes, most permeable pavements should have slopes less than 5 percent.

Aggregate Base and Subbase - Permeable pavements typically utilize open graded aggregates to provide structural and hydraulic capacity for the pavement. The aggregates should be hard, durable and have a low percentage of material passing the 75 µm sieve size. Select durable, crushed aggregate materials to maximize structural capacity and porosity for water storage. For heavier traffic conditions, a cement- or asphalt-stabilized open-graded aggregate may be more suitable. Dense-graded aggregates for road bases are generally not used because of low water storage capacity and fines that can weaken them when saturated.

To prevent migration of smaller base aggregate material into the larger subbase aggregate, aggregate gradations should satisfy the following criteria:

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

For example, the ratio of the D_{50} Subbase (subbase aggregate size at which 50 percent of the material is larger than this size and 50 percent is smaller) to D_{50} Base (base aggregate size at which 50 percent of the material is larger than this size and 50 percent is smaller) must be less than 25.

There are situations where filtering is the primary goal and not storage and infiltration. In such situations, aggregate bases with a smaller portion of aggregates are used with no greater than 2 percent passing the 75 µm sieve. Such denser-graded aggregates trade porosity for higher density and structural capacity. The hydrologic design should account for their reduced porosity and water storage capacity. Some state highway agency specifications describe such materials as drainage layers for use under conventional impervious pavements.

Subgrade Slope - Infiltration designs should minimize subgrade slope to promote water infiltration. Sites with subgrade slopes over 3 percent often require buffers, weirs, check dams, etc. to control water flow within the pavement. An example of a check dam used for a permeable alleyway project is shown in Figure 4.

Figure 4. Check dam construction for a permeable alleyway

Pavement Overflow - During high intensity/depth storm events, the pavement design should incorporate features such as curb cut outs, grading to supplementary drainage outlets such as catchbasins, stormwater ponds, etc. to prevent the pavement system from flooding.

Underdrains - For partial or no infiltration designs determine the type, location and need for underdrains. Specify outlet details and clean out provisions.

Geotextiles, Geogrids and Geomembranes - Determine the need for these geosynthetics for subgrade/ aggregate separation, filtration, containment and reinforcement.

KEY CONSTRUCTION FEATURES FOR PERMEABLE PAVEMENTS

The materials used for permeable pavements are similar to those used for conventional pavement construction. The majority of tests required to determine quality are also the same except that compliance targets, minimum and maximum values differ. Pervious concrete and porous asphalt are similar to conventional with the exception that the finer aggregate materials are removed to make the materials permeable. Permeable interlocking concrete pavers are manufactured with the same materials as traditional interlocking concrete pavers and do not require on-site curing time, nor are they subject on on-site variability in material mixes. In order to make the surface permeable, spacer bars on the pavers create widened joints when installed to permit water into them.

Some key construction features for all permeable pavements are provided below.

General Construction Site Conditions - A pre-construction site meeting is critical to the success of the permeable pavement installation. All contractors and trades must be aware of the permeable pavement and protect it from damage and contaminants during construction. An example of lack of adequate protection and an example of good protection during construction are shown in Figures 5a and 5b.

Figure 5a. Landscaping sloping to pavement and contaminating joints

Figure 5b. Pavement protected by placing landscaping materials on tarps

Subgrade Preparation - Most stormwater agency guidelines for permeable pavement construction recommend that the subgrade not be compacted in order to help promote water infiltration. While this benefits water infiltration, an uncompacted subgrade tends to consolidate when saturated under vehicular loading, causing settlement and possible rutting of the pavement surface. The design may need to balance infiltration against compaction by conducting laboratory Proctor density tests, and then compacting the in-situ subgrade in test areas followed by infiltration tests. This approach establishes a relationship between soil subgrade density and infiltration, and indirectly the strength of the soil subgrade to sustain traffic loads when saturated. In addition, subgrade preparation should be completed during dry weather conditions. Placement of the open-graded aggregate base and subbase should be completed as close in time as possible to minimize risk of sedimentation of the permeable pavement system.

Geotextiles - These materials are generally placed vertically against the walls of excavated soil for all applications to separate the permeable pavement from adjacent soils. Geotextiles are typically non-woven fabric and should be protected from contamination during installation.

Geomembranes - These are typically composed of polyvinyl chloride, ethylene propylene diene monomers or high density polyethylene. They may be used to vertically separate the open-graded base/subbase from adjacent pavements and building structures. In other cases, they may enclose the sides and bottom to create a no infiltration design for water storage and flow control. An example of placing geomembrane for a road shoulder application is shown in Figure 6.

Figure 6. Geomembrane installation

Drainage Features - Depending on the drainage design goals for the permeable pavement, perforated drainage pipes may be used to convey stormwater away from the pavement for high flow rain events. Other drainage features such as drain inlets, curb cut-outs, and additional subsurface piping may be designed to accommodate some of the surface or subsurface water flow during significant design storms.

Underdrains - These should be installed in a trench along the lowest point of the permeable pavement subgrade. The pipes are surrounded with open-graded aggregate offering protection during construction. The pipes should be perforated, polyvinyl chloride (PVC) selected according to the recommendations of the Uni-bell PVC Pipe Association. Longitudinal underdrain pipe should be underlain by at least 50 mm of clean, open graded aggregate below the pipe. Pipes should be provided with a minimum 0.5 percent slope to an outlet. The up-gradient end of underdrains in the reservoir layer should be capped. The pipe spacing and size should be selected to ensure that the pavement does not flood and become completely saturated during storm events as this can lead to instability and damage under vehicular traffic.

Supplementary Surface Drainage Features - An example of a curb cut-out is shown in Figure 7.

Figure 7. Example of a curb cut-out enabling excess runoff to drain to a bioswale for additional treatment

Outlet pipes should not be perforated. Depending on the hydraulic design goals for the particular project, the end of the outlet pipe may be upturned to promote water storage in the aggregate reservoir, increase infiltration and reduce outlet flow. Pipe outlets should be directed to outlet chambers or other protective systems to prevent soil erosion. An outlet detail is shown in Figure 8.

Figure 8. Non-perforated outlet pipe surrounded by rip-rap erosion protection

Observation Wells - These typically consist of a perforated plastic pipe placed vertically through the pavement and anchored into the subgrade. They are installed to visually observe or measure the elevation of standing water in the stone reservoir as well as drain down over time. The observation well should be fitted with a cap installed flush with the pavement surface. An observation well detail is shown in Figure 9a and installation in Figure 9b.

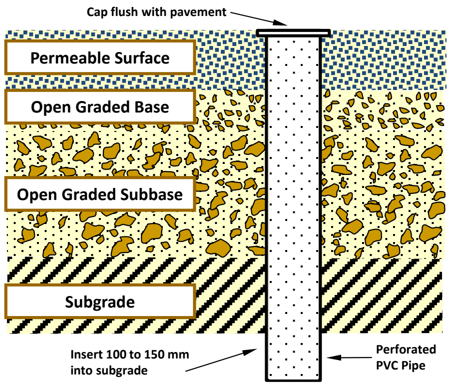


Figure 9a. Observation well detail

Figure 9b. Well cap flush with the pavement surface

Base/Subbase Aggregate Layer Compaction - Compaction of the open-graded aggregate is required for all applications. This provides a stable platform for the placement of the surface course, structural capacity for traffic support and prevention of settlement. An 8 tonne dual or single, smooth vibratory drum roller or a 60 kN reversible vibratory plate compactor with a compaction indicator are recommended.

Tests that determine the density of the stone reservoir should use the "target" density method. Field density tests should be completed using the procedures outlined in ASTM D 2922 Standard Test Methods for Density of Soil and Soil-Aggregate In-Place by Nuclear Methods (shallow Depth). Nuclear density tests cannot be done on aggregates larger than 25 mm maximum size.

After initial placement of the aggregate material, the compaction equipment should make two passes over the entire surface of a control strip using vibratory compaction. Field densities and field moisture contents, using the backscatter/indirect method, should be determined at five randomly selected locations at least 5 m apart. The dry density and moisture content should be calculated for each of these locations and the averages used as initial compaction values. The compaction equipment should then make two additional passes without vibratory compaction over the entire surface of the control strip. Three separate, random field density and moisture content determinations should be completed, using the backscatter/indirect method, and a new average dry density and moisture content should be calculated.

If the new average dry density exceeds the previous value by more than 20 kg/m^3 then two additional passes of the equipment should be out as described above. If the new average dry density does not exceed the previous value by more than 20 kg/m^3, then compaction of the control strip is considered satisfactory and complete.

Upon satisfactory completion of the control strip, seven additional field density tests should be taken at random locations. The final dry density and moisture content of the control strip is the average of these seven values plus the three most recent values obtained upon completion. Photographs of compaction equipment are shown in Figure 10.

Figure 10a. Appropriate compaction equipment for open-graded aggregate and project size

Figure 10b. Inappropriate equipment (too small for project size) for compaction of open-graded aggregate

Some key elements for the successful installation of permeable pavement surfaces include:

Edge Restraints and Interface with Non-Pervious Pavement - All permeable surfaces should have some type of edge restraint to prevent lateral movement of the surface during construction and under traffic. This could consist of concrete curbs, adjacent pavement surfaces, granular base, landscape architectural features, etc. Edge restraints are particularly important for permeable shoulder applications for vehicles traversing on the shoulder to the traveled lanes. Vehicle wheel loading near an unsupported edge may damage the permeable pavement.

Expansive Soils and Fill Conditions - Permeable pavement infiltration into expansive clay soils is not recommended. Expansion may be reduced or eliminated by removal and replacement of subgrade soil materials or stabilizing with additives such as lime or cement. Designs over expansive clay soils or other fill soils may require a geomembrane under the pavement to prevent water from leaving the pavement from areas other than the designed outlets. An example of a permeable pavement failure due to large volumes of water exiting the permeable pavement is shown in Figure 11.

Figure 11. Pavement failure due to water erosion of the base and subgrade

Contractor Certifications and Experience - The production and placement of permeable pavements generally require more attention to detail to ensure that a durable pavement is produced. In addition, contractors and trades working at or near the permeable pavement must be cognizant of the need to not contaminate and clog the pavement with particles. Avoiding this may require installation of cattle guards and/or washing stations to ensure that the construction traffic does not contaminate the pavement.

The porous asphalt industry indicates that any qualified asphalt paving contractor and produce and place porous asphalt. No specific certification is required. The concrete paving industry has a certification program for pervious concrete production and placement. Contractors installing the pervious concrete should be certified through independent organizations such as the American Concrete Institute or National Ready Mix Concrete Association. The Interlocking Concrete Pavement Institute offers a PICP specialist course and record of completion.

Figure 12a was taken immediately after the storm event and the one on the right (Figure 12b) approximately two hours after the storm. There is likely one or two conditions contributing to the surface ponding condition. First, the joints may have some sediment in them thereby slowing the surface infiltration rate. Second, the underdrain system may be working but is of insufficient capacity to accommodate full pavement structure drainage from even a modest storm event.

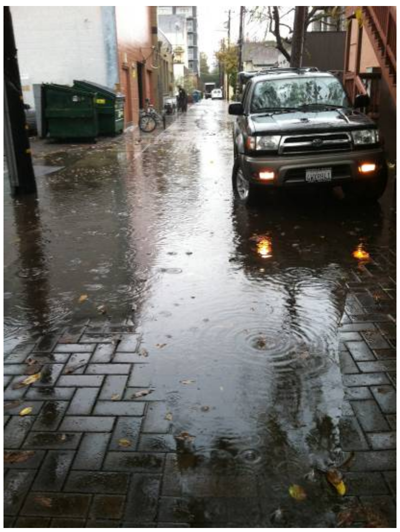


Figure 12a. A clogged surface or an undersized drain at low-point unable to accommodate rainwater

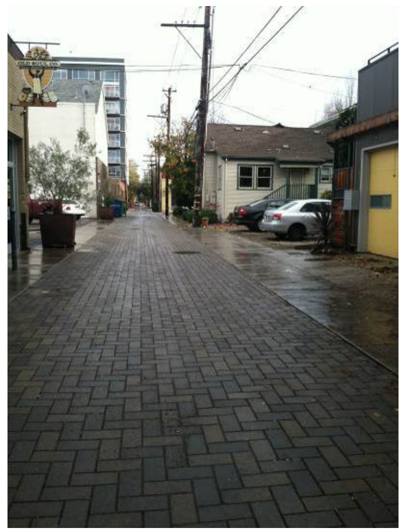


Figure 12b. The same pavement fully drained approximately 2 hours after storm event

PERMEABLE PAVEMENT MAINTENANCE

Permeable pavement systems consist of a surface with joints and/or openings that will freely allow water to infiltrate the system. The openings allow water from storm events to flow freely through the surface into a stone reservoir composed of an open-graded base/subbase where runoff is collected and stored before it leaves the pavement structure. These facilities can support vehicular traffic while minimizing stormwater runoff and recharging groundwater supplies.

Due to the open nature of the surfaces, permeable pavements will clog with sediment and debris overtime thereby decreasing its infiltration rate. The rate of decrease depends on sources of deposited sediment. Such reductions from normal use still render a surface that can infiltrate most rain events.

Gradual clogging of the surface layer can have the benefit of capturing some suspended solids that would otherwise be deposited into the subbase and/or discharge from the underdrains. With regular maintenance, the sediment that is captured near the surface can be more readily removed than sediment that accumulates in the subbase.

In order to maintain the integrity of the permeable pavement and provide the necessary support for the traffic loading, the pavement needs to be monitored for signs of distresses that could impair the structural integrity of the pavement. The following sections outline typical observed distresses that may occur for interlocking concrete block pavements. These include:

- Surface Clogging
- Depression
- Rutting
- Edge Restraint Damage
- Ravelling (Concrete and Asphalt)
- Cracking (Concrete and Asphalt)
- Excessive Joint Width (Pavers)
- Joint Filler Loss (Pavers)
- Horizontal Creep (Pavers)

Surface clogging occurs when debris and other contaminants enter the pavement and become lodged within the permeable pavement. This will reduce the permeability of the pavement and reduce the availability of the pavement to store water. It also may result in localized ponding of surface water. Pavement inspections should be completed 1 to 2 times annually (preferably after a storm event). Inspection tasks should include the following:

- Document general site features (photographs), etc.
- Note obvious sources of surface contaminants such as sediment.
- Identify any changes in adjacent land use that may impact contributing area runoff for potential sources of contaminants.
- Inspect vegetation around permeable pavement perimeter for cover and soil stability.
- Check surface for buildup of sediment. Buildup typically occurs near adjoining impervious pavements. If water ponds on the permeable pavement and remains longer than one hour after a rainstorm, then measure the permeability of the pavement surface in accordance with the procedures outlined in ASTM C1781-13 (Pavers) or ASTM C1701-09 (Concrete).

If standing water is ponding on the surface and/or infiltration rates are reduced, the pavement surface should be vacuumed swept to remove the sediment. In order to clean the pavement, sweeping alone is not recommended and vacuum sweeping equipment should be used in order to ensure the sediment is removed. When using air vacuum sweepers, adjustments must be made to the vacuum force to minimize removal of the joint filler stone from the joints.

The depth of vacuuming should be between 13-25 mm deep. For permeable paver surfaced pavements, it may be necessary to top up the joint filler. The surface should be monitored again to ensure infiltration has been improved to at least 50 percent of the design infiltration rates or a minimum of 250 mm/hr. Annual vacuum sweeping should be scheduled to take place soon after any significant biomass loading.

In order to maximize the effective life of the permeable pavement, the following activities are recommended:

- Do not use conventional oil or latex based pavement marking materials.
- Limit standing of vehicles that may leak engine oils and lubricants on the pavement.
- Limit activities which may increase the potential of pavement surface clogging.
- Limit where possible frequent heavy vehicle use of the pavement, e.g. do not increase bus traffic, do not designate as a truck route, limit the roadway use for construction detours, etc.
- Avoid the excessive use of decing chemicals and winter sand.
- Do not concentrate snow from plowing operations on the permeable pavement.
- Take caution during street cleaning where power washing equipment is used. Prevent the removal of joint filler material for permeable paver surfaced pavements.

CONCLUSIONS

Permeable pavements can be a major contributor to the effective management of stormwater. They provide the opportunity of transforming a traditional source of stormwater runoff into a best management practice for capturing, storing and infiltrating stormwater into the natural surroundings. Benefits achieved include reduced stormwater discharges as well as improvements to water quality including reduced suspended solids and reduction of chemical contaminants. While they can be an effective tool, their design and construction should carefully consider structural and hydrological concerns to ensure that they provide cost-effective solutions over their design life.