URBAN Waterways

Permeable Pavement: Research Update and Design Implications

As the use of permeable pavement increases in North Carolina, practitioners can look to research findings for design guidance.

In 2006 and 2007, the Division of Water Quality, North Carolina Department of Environment and Natural Resources (NCDENR), implemented design guidance and a design requirement that will dramatically increase the use of permeable pavement. In July 2006, NCDENR began to credit permeable pavement with runoff reduction. It did this by allowing certain designs of permeable pavement to be treated as if they were 60 percent permeable, such as an urban lawn in a sandy-loam soil. In 2007, the N.C. Legislature enacted a law (Bill H1473) that required 20 percent of a parking lot to be made of permeable pavement or a suitable, environmentally-friendly, alternative stormwater management practice.

Much research has been conducted across North Carolina, the United States, and in other countries on permeable pavement. It has generally focused on four areas: permeable pavement runoff reduction, clogging, long-term hydrology, and water quality. In this update for practitioners, we provide a brief overview of permeable pavements, highlight research findings, provide direct links to the research, and discuss its design implications. This update serves as a companion to an earlier Urban Waterways publication: *Low Impact Development Technologies: Permeable Pavements, Green Roofs, and Water Harvesting* (AG-588-6).

IS IT PERMEABLE, PERVIOUS, OR POROUS PAVEMENT?

All three of these terms are used interchangeably to describe pavement that allows water to flow through it rather than shedding water. Only two of these words, however, are synonymous: *permeable* and *pervious*. Both mean that water can flow through the material via a series of connected holes or pores.

The term *porous* simply means that there are holes in the substance, but does not necessarily mean that these holes are connected. For example, pumice is a porous rock, yet it is not permeable because many of its holes do not connect.

The more technically specific terms are, therefore, *permeable* and *pervious*. However, much of the pavement and design industry uses *porous* instead. According to NCDENR, *permeable* is the preferred term.

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OVERVIEW OF PERMEABLE PAVEMENT

Typical Cross-section

Nearly all permeable pavement types have the same general structure (see Figure 1).

Surface Layer (Cover). This is the top layer that drivers and users see. It is identified by the type of pavement used, such as permeable concrete, permeable interlocking concrete pavers filled with gravel, or segmental plastic pavers to be filled with grass. More on pavement type follows in this section.

Gravel Base. Most pavement types, with the notable exception of permeable concrete, need a gravel (or aggregate) support layer to bear vehicles. The base is immediately below the surface layer (cover). It also stores water during and immediately after a storm event. Despite the fact that permeable concrete does not need an aggregate base layer for structural support, such a layer is often included in permeable concrete designs so that additional water can be stored.

Sub-base. This is the layer of soil immediately below the base layer. The sub-base is necessarily compacted during construction of the permeable lot. It is also referred to as *in situ soil* or *underlying soil*.

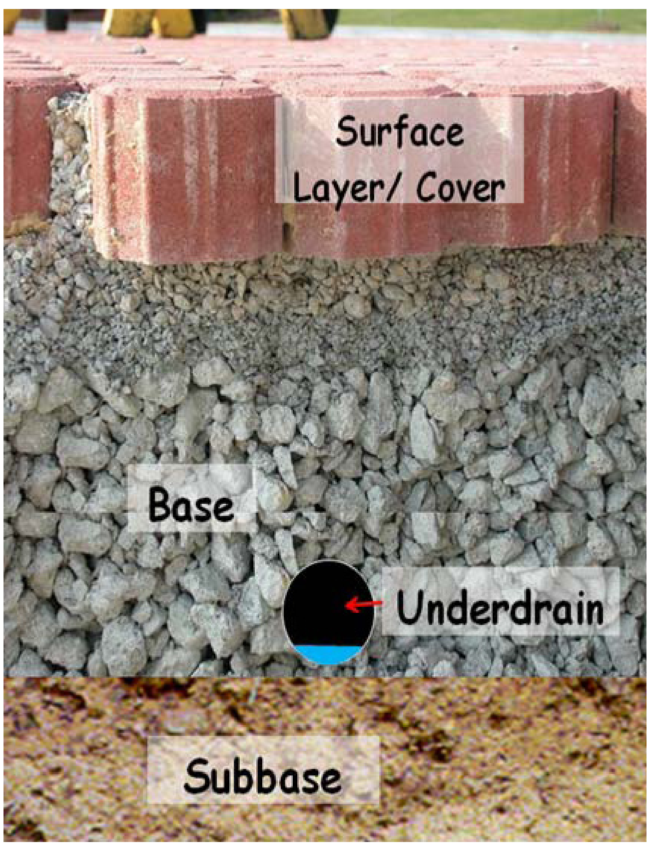

Figure 1. Cross-section of permeable pavement, including the surface layer (cover), a gravel base, the soil sub-base, and the underdrain.

Underdrains. These drains are typically small plastic pipes, 4 to 8 inches in diameter. These drainage lines are located at or near the bottom of the sub-base to collect water and convey it to the storm sewer network. Underdrains are most often used when permeable pavements are located in soils that contain clay.

Types of Permeable Pavements

There are five types of permeable pavements: permeable asphalt (PA), permeable concrete (PC), permeable interlocking concrete pavers (PICP), concrete grid pavers (CGP), and plastic grid pavers (PG). The pictures in Figure 2 (page 3) illustrate the five types and a variation of fill for plastic grid pavers. General structural design considerations are discussed for each of the pavements below. For further information about pavement design, see the references to research provided throughout this update.

(PC) Permeable concrete is a mixture of Portland cement, fly ash, washed gravel, and water. The water to cementitious material ratio is typically 0.35 – 0.45 to 1 (**NRMCA, 2004**). Unlike traditional installations of concrete, permeable concrete usually contains a void content of 15 to 25 percent, which allows water to infiltrate directly through the pavement surface to the subsurface. A fine, washed gravel, less than 13 mm in size (No. 8 or 89 stone), is added to the concrete mixture to increase the void space (**GCPA, 2006**). An admixture improves the bonding and strength of the pavements. These pavements are typically laid with a 10 to 20 cm (4 – 8 in) thickness and may contain a gravel base course for additional storage or infiltration. Compressive strength can range from 2.8 to 28 MPa (400 to 4,000 psi) **(NRMCA, 2004)**.

(PA) Permeable asphalt consists of fine and course aggregate stone bound by a bituminous-based binder. The amount of fine aggregate is reduced to allow for a larger void space of typically 15 to 20 percent. Thickness of the asphalt depends on the traffic load, but usually ranges from 7.5 to 18 cm (3 – 7 in). A required underlying base course increases storage and adds strength (**Ferguson, 2005**). Minimal amounts of permeable asphalt have been used in North Carolina.

(PICP) Permeable interlocking concrete pavements are available in many different shapes and sizes. When lain, the blocks form patterns that create openings through which rainfall can infiltrate. These openings, generally 8 to 20 percent of the surface area, are typically filled with pea gravel aggregate, but can also contain top soil and grass. **ASTM C936** specifications (**200 1b**) state that the

Figure 2. Types of permeable pavement

pavers be at least 60 mm (2.36 in) thick with a compressive strength of 55 MPa (8,000 psi) or greater. Typical installations consist of the pavers and gravel fill, a 38 to 76 mm (1.5 – 3.0 in) fine gravel bedding layer, and a gravel base-course storage layer (**ICPI, 2004**).

(CGP) Concrete pavers conform to ASTM C 1319, *Standard Specification for Concrete Grid Paving Units* (2001a), which describes paver properties and specifications. CGP are typically 90 mm (3.5 in) thick with a maximum 60 × 60 cm (24 × 24 in) dimension. The percentage of open area ranges from 20 to 50 percent and can contain topsoil and grass, sand, or aggregate in the void space. The minimum average compressive strength of CGP can be no less than 35 MPa (5,000 psi). A typical installation consists of grid pavers with fill media, 25 to 38 mm (1 – 1.5 in) of bedding sand, gravel base course, and a compacted soil subgrade (**ICPI, 2004**).

(PG) Plastic reinforcement grid pavers, also called geocells, consist of flexible plastic interlocking units that allow for infiltration through large gaps filled with gravel or topsoil planted with turfgrass. A sand bedding layer and gravel base-course are often added to increase infiltration and storage. The empty grids are typically 90 to 98 percent open space, so void space depends on the fill media (**Ferguson, 2005**). To date, no uniform standards exist; however, one product specification defines the typical load-bearing capacity of empty grids at approximately 13.8 MPa (2,000 psi). This value increases up to 38 MPa (5,500 psi) when filled with various materials (**Invisible Structures, 2001**).

Designing Permeable Pavement in Sandy Versus Clayey Sub-bases

There are a few more factors to consider when designing and installing permeable pavement in clayey soils than when placing them in sandy soils. (Further details are provided in the "Review of Permeable Pavement Research" section of this update.)

Clay soils do not provide as much structural support as sandy soils, on average. This means the gravel layer underlying nearly all pavement types will need to be deeper in clay soils than in sandy soils to provide additional strength to the pavement system. The lone exception is permeable concrete, which does not need a gravel layer for structural strength.

Clay soils will not provide as much infiltration as sandy soils, on average. As is discussed in the following sections, necessary compaction can severely limit infiltration to the sub-base. This will probably lead to underdrains being used to slowly drain the base layer of the permeable pavement. Sometimes an impermeable liner will be needed to separate the base from the sub-base, if the underlying clay has a high shrink-swell potential.

Other differences in design are discussed in the "Review of Permeable Pavement Research" section. North Carolina stormwater regulations make it substantially easier to have

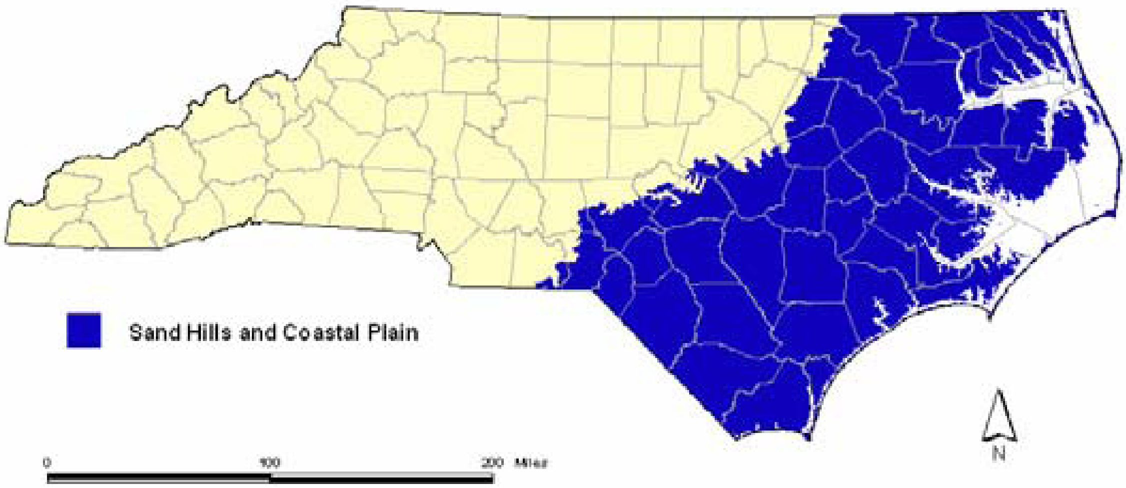

Figure 3. Sandier soil regions of North Carolina, where permeable pavement use is more easily permitted by NCDENR. *(Image courtesy of NCDENR – Division of Water Quality)*

a permeable pavement application approved in sandier soils than clayey soil regions of the state. See Figure 3 for state-delineated sandier soil regions.

Hydrologic Terminology

Terminology for pavement hydrologic terms is presented below. Please refer to Figure 4.

Runoff. Amount of water leaving (or shedding) the surface of the pavement. This water enters the storm sewer network.

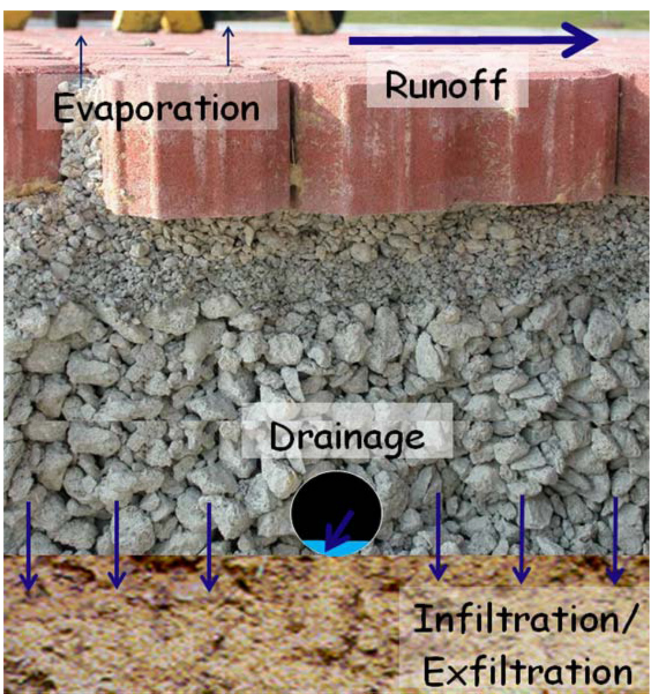

Figure 4. Common hydrologic pathways for permeable pavement include runoff, drainage, infiltration, and evaporation. Note that runoff + drainage = outflow.

Drainage. Water that has passed through the surface of the permeable pavement may still be recollected in underdrain pipes. This water is also discharged to the storm sewer network.

Outflow. The total water leaving a pavement application and entering the storm sewer network. With permeable pavement, outflow is the sum of runoff and drainage. An impermeable pavement's outflow is simply equal to runoff.

Exfiltration/Infiltration. Water that leaves the bottom or sides of the permeable pavement and enters the soil. Water *exfiltrates from* the pavement base layer. It *infiltrates* the surrounding soil.

Evaporation/Evapotranspiration. Water stored in puddles on an impermeable surface or temporarily trapped near the surface of permeable pavement will eventually evaporate to the atmosphere. If plants aid in the release of water to the atmosphere, as some permeable pavements are designed to be vegetated, this process is termed *evapotranspiration*.

REVIEW OF PERMEABLE PAVEMENT RESEARCH

The remaining portions of this update summarize research findings that apply to permeable pavement runoff reduction, clogging, long-term hydrology and water quality, and their implications for permeable pavement design. Major findings are numbered. Citations of work that support these findings are also given, and a complete reference list is provided at the end of this update.

Runoff Reduction

1. Do permeable pavements have a positive hydrologic impact? Yes. Permeable pavements have been regarded as an effective tool in reducing stormwater runoff. Because of their high surface infiltration rates, permeable pavements can reduce runoff quantity and peak runoff rates, and delay peak flows (**Pratt et al., 1989; Hunt et al., 2002; Brattebo & Booth, 2003; Bean et al., 2007b, Kwiatkowski et al., 2007; Collins et al., 2008a**). This finding has been verified worldwide.

2. Can permeable pavements reduce runoff volumes? If so, by how much? Yes. Permeable pavements substantially reduce surface runoff quantities (**Day et al., 1981; Hunt et al., 2002; Brattebo & Booth, 2003; James & Shahin, 1998**). The most commonly used measure of runoff quantity is the Natural Resources Conservation Service's (NRCS) curve number. The curve number indicates how much runoff will occur from a given land use for a given storm event. The higher the curve number, the more runoff will be generated by a storm event. Studies in North Carolina have shown the average curve number of permeable pavements to range from a low of 45 to a high of 89 (**Bean et al., 2007b**). The curve number for standard impermeable pavement is 98. The variation in the North Carolina study was due to two factors: base (or storage) depth and underlying soil composition. The less the water storage and the more clayey the underlying soil, the higher the curve number.

3. What causes runoff? Does the permeable system fill with water, or does it rain too intensely for water to infiltrate the pavement surface? The amount of surface runoff generated from permeable surfaces is more dependent on rainfall intensity than rainfall depth (**Day et al., 1981; Hunt et al., 2002; Valavala et al., 2006; Collins et al., 2008a**). Therefore, storms of low intensity that have a long duration (and therefore produce a lot of rainfall), are much less likely to produce runoff than very intense, quick duration storms that might have a lower rainfall total. This means that the vast majority of storms do not "fill up" permeable pavements and that when runoff was observed, it was most often due to the rainfall intensity overwhelming the surface infiltration ability of the pavement. The majority of surface infiltration rates examined in one study (**Bean et al., 2007a**) exceeded 2 in/hr. This means that a rainfall event would need to have an intensity of greater than 2 in/hr to produce any runoff.

4. Do different types of permeable pavement types reduce runoff better than others? Not really. In a North Carolina comparison study of PC, two types of PICP, and CGP (**Collins et al., 2008a**), no substantial difference was detected in the amount of runoff from each type (See Table 1). The one pavement type studied that produced *slightly* more runoff was CGP filled with sand. A study in Washington state (**Brattebo and Booth, 2003**) examined PICP, CGP, and two types of PG, found very similar results: only subtle differences in runoff reduction could be detected among the permeable pavement types. *The important implication of these two studies is that different types of permeable pavement systems should probably be treated the same when assigning runoff reduction credit.*

5. Is there a difference between outflow and runoff? If so, do permeable pavements exhibit outflow? Yes, there is a difference (refer to the "Hydrologic Terminology" section). Runoff is part of total outflow (Runoff + Drainage = Outflow). Drained permeable pavement systems do have more outflow. Moreover, the outflow rates and volumes can be dramatically higher than permeable pavement runoff rates and volumes (Collins et al., 2008a). (See Figure 5.)

Table 1. Percent Reduction of Runoff Volume Relative to Rainfall Volumes in Kinston, N.C. Number of storms exceeds 40 in all cases. Data collected in 2006 and 2007.

Pavement Type	Mean (%)	Medium (%)	Minimum (%)
Standard Asphalt	34.6	29.4	0
Pervious Concrete	99.9	99.9	99.0
PICP – Type 1	99.3	99.4	97.8
PICP – Type 2	99.5	99.7	96.9
Concrete Grid Pavement (Sand)	98.2	98.7	91.1

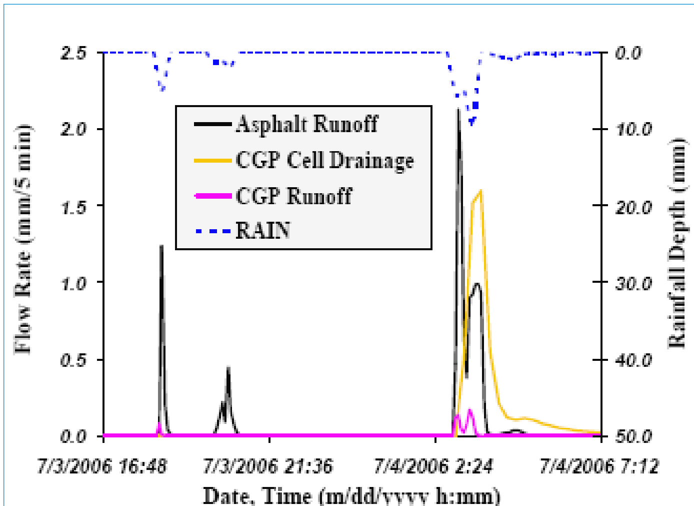

Figure 5. Substantially more water drains from a permeable pavement cell than runs off as is shown for a 1.25-in event that fell on CGP filled with sand.

This study showed that in some cases, drainage + runoff volumes from permeable pavements were essentially equal to the runoff volume associated with an adjoining standard asphalt lot. The study site had underdrains, in part, because the underlying soil (sub-base) was clayey.

6. Can anything be done to reduce outflow from drained permeable pavements? Yes. Research indicates (**Collins et al., 2008a**) that an upturned underdrain—one that creates a storage zone in the bottom of the pavement base layer—can reduce outflow volumes. See Figure 6. A specific study, however, has yet to be conducted on this design feature. Water that initially pools internally in the pavement (1) does not drain and (2) can slowly infiltrate the sub-base, increasing times to peak, reducing runoff volumes, and lowering peak outflow rates. This is not an option when permeable pavement is located in highly plastic soils. Another option with the underdrains is to size them so that they have limited outflow rates. That is, use underdrains with a small diameter. Another option is to cap the underdrains with a restrictive orifice or hole. While this might not substantially reduce outflow volumes, it would dramatically reduce peak flows and increase times to peak for a given storm event. Doing this is akin to using a small orifice to dewater a pond or wetland over a two- to three-day period.

Clogging

Clogging is a very important concern when considering the long-term function of permeable pavements.

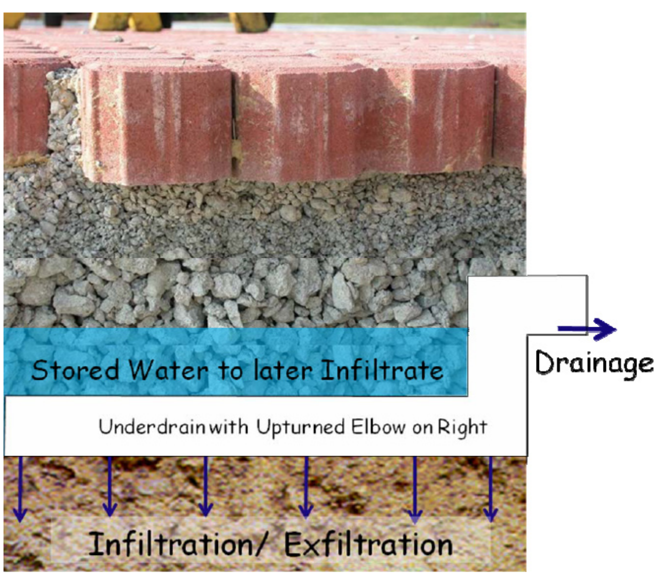

Figure 6. An upturned underdrain elbow creates an internal storage zone for water. This adds to the pavement's ability to infiltrate.

Figure 7. Permeable pavement with gaps clogged with silty-clay soil.

1. Do permeable pavements clog? Yes, but clogging does not always mean sealing. Fine particles will be deposited on the surfaces of permeable pavements. This is typically a result of passing cars, wear of the pavement surface, or transport via wind and runoff from nearby disturbed soils (**Balades et al., 1995**; **Bean et al., 2007a**). See Figure 7.

2. Have factors been found to "predict" the amount of clogging that may have occurred? Yes, there are several. As pavements age and with increasing traffic usage, clogging of pavement increases (**Kresin et al., 1996**; **James & Gerrits, 2003**). Close proximity to sediment can also accelerate clogging (**Bean et al., 2007a)**.

3. To what extent will pavements clog? It is important to note that clogging of pavements does not necessarily mean the "sealing" of permeable pavements. While very few permeable applications will display their initial, and often extremely high, infiltration rates (sometimes exceeding 1,000 in/hr) a few years after installation, this does not mean that these pavements' infiltration rates clog to the point of impermeability (0 in/hr). A study of surface infiltration rates conducted in North Carolina, Virginia, Maryland, and Delaware (**Bean et al., 2007a**) found that the surface infiltration rate of pavements that had clogged was usually higher than 1 in/hr.

4. What makes the extent of clogging better or worse? There are a couple of factors: the frequency of maintenance (discussed in the next section) and surrounding soil type. **Bean et al.** (**2007a**) observed that the surface infiltration rate of the permeable pavement (or the extent of clogging) mirrored that of the surrounding soil's permeability. In other words, if the pavement was located in a sandy part of the state and it was clogged by sand particles, the permeable pavement's surface infiltration rate was similar to that of sand (3 to 4 in/hr), even 20 years after installation.

Figure 8. Brushes from a standard street sweeper can rip apart the clogged portions at the top of CGP filled with sand.

Conversely, the lowest infiltration rate was observed at a lot that had clogged in Cary, N.C., which was located in the piedmont and more clayey soils (less than 0.4 in/hr). *Mainly because of this research finding, N.C. stormwater regulations limit widespread use of permeable pavement in tighter (or more clayey) soil regions of the state*. (See Figure 3, page 4.)

5. Can't clogging be prevented? Clogging is an ongoing process, but it can be restricted by regularly maintaining permeable pavement and, of course, locating permeable pavements away from areas with soil disturbance. Several researchers (**Balades et al. 1995; Hunt et al. 2002; Bean et al., 2007a**) recommend using a street sweeper or a special vacuum street sweeper to maintain lots. The most proven maintenance technique is for CGP and PG filled with sand. These sand-filled pavements tend to have clogging near the surface (top 1 in) of the sand (**James & Gerrits, 2002**), so that a standard street sweeper can scarify the surface of the pavement and break apart the top clogged layer (Figure 8). By simply doing this, permeable pavement surface infiltration rates were shown to improve by 66 percent (**Bean et al., 2007a**). For all other forms of maintenance, only anecdotal (and in some cases minimal) evidence of their effectiveness is available.

Long-Term Hydrology

Studies also indicate some potential water cycle benefits associated with permeable pavement. This is an important part of Low Impact Development (LID), which is predicated on taking what was once runoff and "converting" a portion of it to either evapotranspiration (ET) or infiltration.

1. Does permeable pavement allow for infiltration? Yes. The base layer of permeable pavements retains a portion of the infiltrated rainfall. Some percentage of this stored water will infiltrate (**Brattebo & Booth, 2003**). One study in eastern North Carolina had 100 percent infiltration over the course of the 10-month monitoring period (**Bean et al. 2007b**).

2. Does permeable pavement allow for evaporation and evapotranspiration? A few types of permeable pavement may have surprisingly high infiltration rates. Others probably do not. A system that captures and stores water near the surface of the pavement, such as CGP and PG filled with sand, have been estimated to temporarily store at least 6 mm of most storms and presumably "release" this water to the atmosphere by evaporation or evapotranspiration (**Collins et al. 2008a**). On an annual basis, up to 33 percent of all precipitation events would be "captured" in this way by these pavements. A similar effect was not found for PC or PICP filled with gravel.

3. What are the important properties of permeable pavement that will enhance water retention? The retention properties, along with the permeability, evaporation rate, and drainage rate of concrete block permeable pavements largely depend on the surface void size and the particle size distribution of the bedding material (**Pratt et al. (1989)**; **Andersen et al., 1999; James & Shahin, 1998; Collins et al., 2008a**). Materials with greater surface area (e.g., sand or loamy sand) can retain more water. Incorporating a storage zone (shown in Figure 6) will increase infiltration.

Water Quality

Permeable pavements often improve stormwater runoff quality, but not always. Many states, including North Carolina, do not assign pollutant removal credit to these systems. Research has investigated how well permeable pavements remove metals, sediment, motor oil and nutrients and their impact on pH and temperature.

1. In general, have permeable pavements been shown to remove pollutant concentrations? Yes. As compared to asphalt runoff, permeable pavement drainage has been shown to have decreased concentrations of several stormwater pollutants, including heavy metals, motor oil, sediment, and some nutrients **(Pratt et al., 1989; Pratt et al., 1995; James & Shahin, 1998; Brattebo & Booth, 2003; Bean et al., 2007b).** All but nutrient removal has been repeatedly shown in many research locations. Nutrients are specifically discussed later in this section.

2. How are pollutant loads impacted by permeable pavement? Because most permeable pavements substantially reduce the volume of runoff and outflow, it stands to reason that they will also reduce pollutant loads. Several studies confirm that permeable pavements demonstrate lower total pollution loadings than standard pavements. **(Day et al., 1981; Rushton, 2001; Bean et al., 2007b)**.

> **CONCENTRATIONS VERSUS LOADS**
> Pollutant removal is often presented as a reduction in either concentrations or loads. They are not the same thing, but they are related. A *load* is a mass of pollutant determined by multiplying *concentration* by volume of runoff. In stormwater, *concentration units* are nearly always shown as mg/L*; measures of load* are g, Kg, and lb. North Carolina's nutrient removal requirements for nitrogen and phosphorus are established for loads.

3. How about thermal pollution (temperature)? Permeable pavements can cause a reduction of thermal pollution **(Karasawa et al., 2006**) compared to conventional asphalt. The decrease in the cited research was between 10 to 25°F. This is in great part due to the pavement's color. Only results for PICP have been published in a peer-reviewed format, so it is possible that not all permeable pavement types, such as PA, will have such an impact.

4. Do permeable pavements buffer pH? Permeable pavements can buffer acidic rainfall pH **(Pratt et al., 1995; James & Shahin, 1998; Dierkes et al.,2002; Collins et al., 2008b)** likely due to the presence of calcium carbonate and magnesium carbonate in the pavement and aggregate materials. They provide a greater buffering capacity than asphalt due to the greater surface area provided by contours in the pavement geometry and the additional coarse aggregate layer through which water migrates. Of all pavement types, PC provided the most buffering capacity, because PC provided influent water the greatest contact time with cementitious materials (**Collins et al., 2008b)**. See Figure 9.

5. North Carolina's stormwater rules target nutrients. How well do permeable pavements remove nutrients? The nutrient removal capabilities of permeable pavements are less understood. Some permeable pavement studies have shown removal of total phosphorus (TP) (**Day et al., 1981, Bean et al., 2007b, Gilbert and Clausen, 2006)**, often attributed to adsorption to the sand and gravel sub-base materials. Similar studies have observed little change in TP concentrations of permeable pavement drainage **(James & Shahin, 1998; Bean, 2005; Collins et al., 2008b)**. A few studies have shown a decrease in concentrations of all measured nitrogen species (NH4-N, TKN, and NO3N) **(Pagotto et al., 2000; Gilbert & Clausen, 2006),** but several studies have also shown certain forms of nitrogen concentrations to increase or be unchanged **(Day et al., 1981, Bean et al., 2005, Collins et al., 2008b).** *In general, as of June 2008, the state of North Carolina does not offer blanket nutrient removal credit to all types of permeable pavement. However, some pavement types may be able to receive "special" consideration*. This is discussed next.

6. What features can be included to improve nutrient removal? Several studies have suggested that aerobic conditions, which result as permeable pavement drains, can result in nitrification of ammonia-nitrogen (NH_4-N) to nitrate-nitrogen (NO_3-N). Compared to asphalt, substantially lower NH_4-N and total Kjeldhal nitrogen (TKN) concentrations, and higher NO_3-N concentrations in permeable pavement drainage have been measured in multiple experiments **(James & Shahin, 1998; Bean et al., 2007b, Collins et al., 2008b).** It also appears that CGP and PG filled with sand are more able to reduce total nitrogen

Figure 9. All permeable pavements were able to buffer acidic rainfall. PC provided the most buffering.

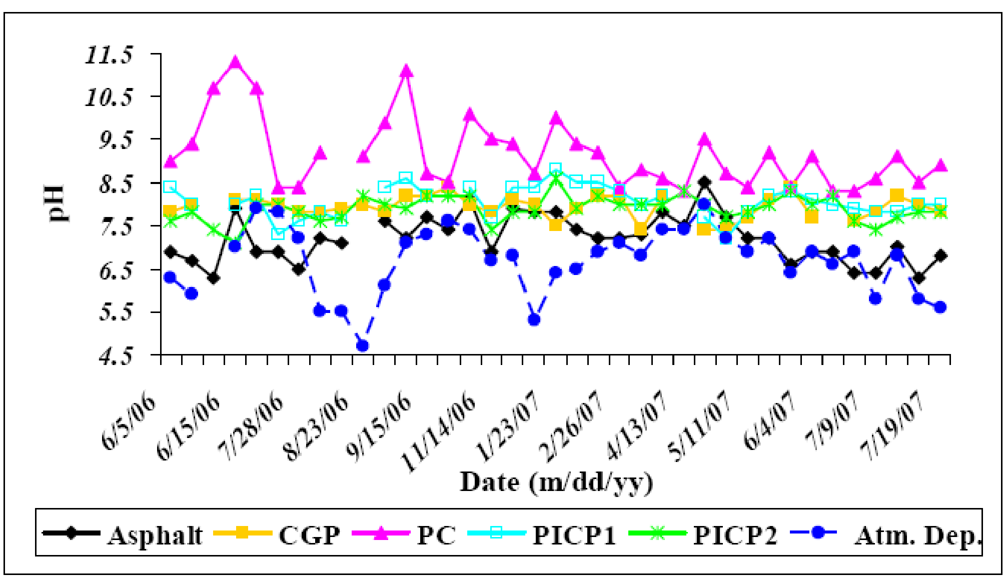

Figure 10. Concrete grid pavers filled with sand (left) employ many of the same removal properties of standard sand filters (right).

(TN). This occurs, because CGP filled with sand very much resembles a low-head, limited-media, depth sand filter (**Collins et al., 2008b**). See Figure 10. Sand filters have repeatedly been shown to improve TN concentrations (**Barrett, 2003**). *This is an important finding, as it means that one type of pavement type (CGP with sand) appears to be "preferable" to other pavement types with respect to nitrogen removal*. Another possibility is to include a sand layer at the bottom of any permeable pavement type. However, this option has not been well tested. More research probably needs to be conducted to verify this finding. If the efficiency of a sand layer is verified, perhaps this type of permeable pavement could receive TN removal allowances.

7. Besides sand, what other factors seem to impact pollutant removal rate? Pollutant removal rates depend upon the material used for the pavers and sub-base material, as well as the surface void space **(Fach and Geiger, 2005; Pratt et al., 1989)**. Fach and Geiger (**2005**) found that installing permeable pavement over a crushed brick base increased the level of metals removal.

8. Where are metals captured in permeable pavements? Most heavy metals are captured in the top layers (1 to 2 in) of material in permeable pavement void space (**Colandini et al., 1995; Dierkes et al., 2002).** For PICP, CGP, and PG that are filled with sand, this implies that *standard street sweeping will probably remove the majority of heavy metals* collected in the pavement fill material. Exact recommendations for disposal have yet to be made.

9. If we are concentrating "all this pollution" in a permeable pavement cell, won't these pollutants impact groundwater? This is possibly the greatest concern regarding long-term pollutant control. Long-term studies and simulations of permeable pavement pollutant distributions have revealed low risks of subsoil pollutant accumulation and groundwater contamination **(Legret et al. 1999; Legret & Colandini, 1999; Dierkes et al., 2002; Kwiatkowski et al., 2007)**. It is important, however, that seasonally high water tables (SHWT) do not encroach the interface of the base and the sub-base, as a high water table would saturate soil that would collect pollutants and eventually leach them into the groundwater. SHWT should be at least 1 foot, and preferably 2 feet from the bottom of the pavement base.

SUMMARY

Permeable pavement use is expected to continue to grow due to recent NCDENR and N.C. Legislative action. As summarized in Table 2 (page 10), several design recommendations can be inferred from research conducted on permeable pavements in North Carolina and elsewhere.

Table 2. Summary of Permeable Pavement Design Guidance		
Design Parameter	**Guidance**	**Rationale**
Optimal pavement types for runoff reduction	All are excellent. PC, PICP, and CGP filled with gravel are best.	Research shows that all types of pavement types reduce runoff substantially. CGP and PG filled with sand have slightly higher runoff rates.
Design surface infiltration rate	1 to 3 in/hr	Studies show that 90% of all study sites had at least 1 in/hr surface infiltration rates, with 2 to 3 in/hr being a median range for partially clogged permeable pavement.
Design base exfiltration rate	0.01 to 1 in/hr. 0.10 in/hr is default for loamy sand.	Even in somewhat sandy soils, exfiltration rates from the base were affected by compaction that occurred during construction.
Curve number	45 to mid 80s, depending upon site. 75 to 80 is recommended.	If the site is free from clogging, extremely low CNs are possible. With moderate clogging, CNs tend to be in the mid-70s. If the pavement is clogged with clay, the CN may exceed 90.
Underdrain flow rate	Release water so that a 2-year event is emptied in 2 – 4 days.	Allows a mimicking of pre-development hydrology stream recharge post event. Mitigates peak flow.
Increasing infiltration to sub-base	Create a sump in base of pavement.	A sump allows water to pool and slowly infiltrate the sub-base. Even at low infiltration rates of 1-2 in/day, many storms are fully captured in the sump. Not recommended in highly plastic sub-base soils.
Optimal pavement types for metal removal	All are excellent. CGP and PG filled with sand are easiest to maintain.	It is easier for street sweepers to remove the *smützdecke* (or clogged layer) from the top of the sand column associated with CGP and PG.
Optimal pavement types for nutrient removal	CGP and PG filled with sand.	These pavements act as if they are low-head, shallow-depth sand filters. More research is needed to confirm this interim finding.
Seasonally high water table (SHWT)	1 foot, preferably 2 feet, from the bottom of the pavement base	SHWT closer to the base will (1) impede exfiltration from the pavement, and (2) lead to pollutant leaching from the pavement.

REFERENCES

Most of these references were published in major peer-reviewed journals and are available to anyone with access to a university library's collection. Nearly all of these articles are available on-line. References for research conducted in North Carolina are in **bold**.

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Related Web Sites

N.C. State University—BAE Permeable Pavement Research Web site: http://www.bae.ncsu.edu/topic/permeable-pavement

N.C. State University—Stormwater Engineering Group Web site: http://www.bae.ncsu.edu/stormwater

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