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Sustainability Benefits of Pervious Concrete Pavement

Norbert Delatte[1], P.E., Ph.D., F.ACI, and Stuart S. Schwartz[2] Ph.D.

[1]*Professor, Civil & Environmental Engineering Department, Stilwell Hall Room SH 121, Euclid Avenue at East 24th Street, Cleveland State University, Cleveland, Ohio 44115, Email: <n.delatte@csuohio.edu>*
[2]*Senior Research Scientist, Center for Urban Environmental Research and Education (CUERE), University of Maryland Baltimore County (UMBC), 1000 Hilltop Circle TRC102, Baltimore, MD 21250, Email: <stu_schwartz@umbc.edu>*

ABSTRACT

Portland Cement Pervious Concrete (PCPC) is a material of increasing interest for parking lots and other applications because of its important sustainability benefits. PCPC pavements greatly reduce the quantity of runoff and “first flush” pollution from parking areas, and can enhance groundwater recharge. Light colored paving materials such as PCPC can help mitigate urban heat island effects. In urban landscapes, PCPC provides durable cost-effective pavements that restore hydrologic function and generate environmental services as integral elements of sustainable design. PCPC pavements are an important tool for stormwater management, and offer considerable environmental benefits. However, building high quality, durable PCPC pavements is still not an easy task. A proper PCPC mixture must be developed, and it must be placed, compacted and cured correctly. When properly specified, designed, installed and maintained, PCPC pavements provide a valuable portfolio of environmental services by integrating green infrastructure systems in the design of sustainable landscapes.

INTRODUCTION

Portland Cement Pervious Concrete (PCPC) is a material of increasing interest for parking lots and other applications. Similar materials are used for cement-stabilized drainage layers in highway and airport pavements. PCPC pavements greatly reduce the quantity of runoff and “first flush” pollution from parking areas, and can enhance groundwater recharge. Light colored paving materials such as PCPC can help mitigate urban heat island effects. In urban landscapes, PCPC provides durable cost-effective pavements that restore hydrologic function and generate environmental services as integral elements of sustainable design.

PERVIOUS CONCRETE PAVEMENTS

PCPC typically consists of coarse aggregates, portland cement, water, and various admixtures [Delatte et al., 2007, 2009]. Exclusion of fine aggregates and uniform size of coarse aggregates leaves open voids that give the material its porosity and permeability [ACI 522R-06, 2006]. Details of typical mixtures may be found in the literature [Tennis et al. 2004].

Unlike conventional concrete, the material properties of PCPC are highly dependent on both concrete materials and placement techniques [Delatte et al., 2007, 2009]. If the mixture is too dry or is under-compacted, then the PCPC will be weak, non-durable, and subject to surface raveling. If, instead, the mixture is too wet or over-compacted, then it will not be pervious and will defeat the purpose of using PCPC. PCPC requires interconnected voids to maintain high hydraulic conductivity and allow water to pass through rapidly. Using pervious concrete for stormwater management therefore entails the design of a pervious concrete *system* consisting of a hydrologic design for stormwater requirements and a structural design for pavement load carrying requirements.

Hydrologic design

Since the primary purpose of a PCPC pavement is to provide surface drainage, it is necessary to design the pavement system to handle the projected runoff. The system consists of the PCPC surface, a base drainage layer, and in some cases pipes to carry off water within the base. Leming et al [2007] provide a spreadsheet-based design tool to size simple pervious concrete systems without drains. Schwartz [2009] developed hydrologic design criteria to size subgrade storage and drains (as necessary) based on consistent risk-based criteria for freeze thaw performance and reliable subbase drainage.

The load-bearing pervious concrete pavement is best viewed as the *inlet* to a stormwater management practice. Stormwater infiltrates through the pervious concrete pavement and percolates through the subbase to the underlying subgrade soils. The design of a pervious concrete system is primarily constrained by site-specific infiltration properties of subgrade soils. Inflow in excess of the underlying soil infiltration rate is temporarily stored in the subbase voids before draining to the subgrade soils (referred to as exfiltration) or discharging back to surface runoff through subbase drains.

If the system does not have sufficient water retention capacity, the capacity may be increased by increasing the thickness of the permeable subgrade or increasing drain sizes or numbers. The thickness of the PCPC itself, however, would not be changed.

Structural design

PCPC is usually somewhat weaker than conventional concrete, and so the pavement must be thicker. As a rule of thumb, 150 mm of PCPC can carry the same light traffic that would normally be carried by 100 mm of conventional concrete. The vast majority of light duty PCPC pavements have been 150 mm thick.

Traditional concrete pavement design is carried out on the basis of fatigue. The pavement thickness is increased until the flexural stresses are low enough that the pavement will not fail in fatigue during its projected life. However, to date fatigue testing has not been carried out on PCPC. Delatte [2007] published some design tables, but because of the lack of knowledge about fatigue behavior these should be used with caution.

In many cases, parking lots or streets may use two paving materials. The more heavily trafficked sections, such as the driving portions of parking lots or through lanes of streets, can be made of conventional concrete or asphalt pavement, which drains onto pervious concrete in the parking spaces or lanes. In this case, the pervious concrete system must be designed hydraulically to accommodate the runoff from the adjacent impervious pavement as well as the rain falling onto the pervious concrete itself. This approach also increases the risk of clogging the pervious pavement due to fine material washing off of the impervious pavement.

PCPC CONTRIBUTIONS TO SUSTAINABILITY

PCPC has an important place in the green building and sustainability toolbox.

Hydrologic Benefits

Profound hydrologic changes accompany urban land transformations, motivating the continuing development of environmentally sensitive approaches for onsite stormwater management. Pervious concrete systems can restore the hydrologic services of the urban landscape, reducing runoff volumes and restoring infiltration and groundwater recharge. By eliminating surface runoff, pervious concrete designed as drainage conveyance eliminates sheet flow runoff that flushes trash and gross solids into storm sewers and surface receiving waters. By controlling rather than generating stormwater runoff, PCPC systems decrease the hydraulic loads to combined sewer systems, and moderate erosive velocities and peak discharges that degrade urban stream systems.

Environmental Benefits

The National Research Council (NRC) Committee on Urban Stormwater Management in the United States [NRC 2008] described contaminants in stormwater runoff as a principal contribution to water quality impairment of the nation's waters, and one of the greatest challenges in water pollution control. Most of the problems associated with land transformation and stormwater runoff were fundamentally attributed to lost water retention and evapotranspiration services of developed landscapes. The NRC found roads and parking lots can be the most significant type of land cover with respect to stormwater, and described stormwater control measures that harvest, infiltrate, and evapotranspire stormwater as "critical for reducing the volume and pollutant loading of small storms."

As integrated landscape elements for the control of urban stormwater, PCPC systems directly reduce the delivery of urban non-point pollutants to surface waters. Particle bound contaminants are largely retained in the surface and subbase of pervious concrete systems. Elevated concentrations of urban contaminants have been consistently observed in the subgrade soils underlying PCPC systems, indicating the potential for adsorption and retention of aqueous phase contaminants [Clark and Pitt 2007]. Though widely observed in stormwater infiltration practices, the long term fate and transport of the full suite of urban contaminants remains an area of active research, and many state and municipal jurisdictions restrict infiltration in active groundwater management areas.

The effective use of pervious concrete presents an especially rich opportunity to incorporate onsite stormwater infiltration within traditional development forms. The value of pervious pavements in sustainable landscape designs may be greatest in urban and suburban environments where the availability of land for conventional stormwater best management practices (BMPs) is a limiting constraint [Bean et al. 2007a; Booth and Leavitt 1999; Kwiatowski et al. 2007]. A variety of approaches have been used to quantify the hydrologic services provided by PCPC systems using standard curve number hydrology [Bean et al. 2007a; Leming et al. 2007; Schwartz 2009].

Although the production of conventional Portland cement is a significant source of CO_2 emissions, the potential for CO_2 sequestration through the carbonation reaction that naturally occurs in installed concrete is an intriguing focus of emerging strategies to offset greenhouse gas emissions. Factors influencing the diffusion-limited concrete carbonation reaction include pH, moisture, and the exposed area of finished concrete surfaces. The frequent wetting cycles and high surface area within a typical pervious concrete pavement profile create an ideal environment for enhanced carbonation. The potential for enhanced CO_2 sequestration within PCPC pavements is a particularly timely area of active sustainability research [Haselbach and Ma 2008].

Urban Heat Island Effect

Like conventional concrete, the higher albedo of pervious concrete reflects more incoming shortwave radiation than asphalt pavements, lowering ambient surface temperatures in the built environment. The lower thermal mass of the pervious concrete matrix retains less heat than solid pavements, lowering night-time temperatures (by reducing re-radiation of stored heat). The lower thermal conductivity of unsaturated pervious concrete can also insulate underlying soils and subgrades, reducing the variation and extremes of observed temperatures throughout the year [Schaefer et al. 2006]. Infiltrated stormwater that is available for evapotranspiration shifts the surface heat balance from sensible to latent heat, further reducing ground level temperatures. Water retentive pervious concrete systems have been tested in Tokyo and Osaka, Japan, as part of landscape-based strategies to reduce urban heat islands [EPA 2005]. Pervious concrete can generate multiple benefits thatt mitigate urban heat islands. Scaling these benefits from material properties and parcel-scale footprints to aggregate impacts on metropolitan and regional scales, remains an area of active research in the design of sustainable landscapes [Stone and Norman 2006].

PCPC PAVEMENT PERFORMANCE

PCPC pavements have generally performed well, but some distresses have been observed.

Raveling

Raveling of aggregate occurs when the aggregate to paste bond is broken, and the aggregate is dislodged from the pervious matrix. This can occur if surface aggregates are not adequately compacted, or if the mixture is too dry, or if it is not properly cured. The pavement may also be raveled by aggressive power washing. Although most new PCPC pavements have a small amount of surface raveling, it generally stops fairly quickly. Extensive surface raveling of PCPC pavements is often a sign of substandard materials, construction, or curing practices.

Cracking and disintegration

PCPC pavements may crack if the pavement is overloaded by heavy vehicles. Severe raveling may also progress until the pavement disintegrates. In some cases, PCPC parking lots have used signs intended to forbid heavy vehicles. It is probably better to anticipate those areas that heavy vehicles are likely to drive onto, and provide a heavy duty pavement for those areas.

Clogging

Site design to minimize clogging and routine maintenance to inspect and mitigate clogging are essential for the reliable performance of pervious concrete systems. As with all infiltration practices, good site design minimizes surface clogging by locating pervious concrete away from direct sources of particulate loading, and protecting the pavement by pre-treating run-on (e.g. with a vegetative filter strip or gravel filter buffer), as feasible.

Like every stormwater management practice, reliable performance of pervious concrete systems depends on proper care in site preparation, construction, reliable inspection, and maintenance. Conventional excavation and grading practices can result in significant reductions in subgrade infiltration due to inadvertent compaction and surface sealing [Gregory et al. 2006, Pitt et al. 2008, Pitt et al. 1999, Tyner et al. 2009]. For this reason, standard construction requirements for infiltration practices (with or without pervious concrete) routinely call for restricting or excluding heavy earthmoving equipment from the subgrade excavation [VADCR 2009], and scarifying the final subgrade surface, to minimize compaction during site preparation. This needs to be a particular point of emphasis during construction, because it is the opposite of the practice for conventional pavements which generally requires that the subgrade be compacted as densely as possible.

Surface clogging is effectively managed through routine maintenance, but fine grained particles can penetrate the full pavement and subbase and accumulate at the subgrade surface [Joung and Grasley 2008; Mata 2008; Siriwardene et al. 2007]. The use of non-woven geotextile between the subbase and the subgrade can exacerbate the development of a fine particulate layer that may significantly reduce exfiltration and lead to premature clogging failure. The risk of clogging at the subbase-subgrade interface may be reduced by incorporating a filter layer of quartz sand between the undisturbed soil and the stone subbase. Alternate designs [ACI 2006] include a filter layer between the subbase and the soil, with a geotextile between the subgrade soils and the filter layer.

The high infiltration rate of the pervious concrete pavement (commonly exceeding 1,000 cm/hr [Bean et al. 2007b; Houle 2006]) rarely limits the performance of pervious concrete stormwater systems. Although some surface clogging can be tolerated without a significant loss of stormwater services, clogged pavements can increase the risk of freeze thaw damage, and chronic sources of clogging demand prompt mitigation. Good practice requires routine inspection of the pavement surface for evidence of clogging, and maintenance, as needed, to restore surface infiltration capacity. The quick drain test used by Delatte et al [2007] offers a rapid assessment of the magnitude and extent of surface clogging, and provides a simple consistent criterion to initiate pavement maintenance. Dry vacuum sweeping and pressure washing have been shown to restore up to 90% of the infiltration capacity of pervious concrete pavements [Wanielista et al. 2007].

DEMONSTRATION SITES AND FIELD PERFORMANCE

Hundreds of PCPC pavements have been built across the US and Canada, but few have been carefully monitored for performance. There have been a few that have been built on university property to make performance monitoring easier.

RMC Research & Education Foundation Study [Delatte et al. 2007, 2009, Miller 2007, Mrkajic 2007]

There have been concerns about performance and sustainability benefits of PCPC pavements in freeze-thaw regions such as the northern US and Canada. Twenty-four in-service PCPC pavements were inspected in the field, and cores were removed in order to investigate properties in the laboratory. Field evaluation methods included visual inspection, two surface drainage measurements, and indirect transmission ultrasonic pulse velocity (UPV).

Laboratory testing methods included void ratio, unit weight, compressive strength, splitting tensile strength, hydraulic conductivity, and direct transmission UPV. Because it is compacted on the surface with screeds or rollers, PCPC generally has higher strength, lower void ratio, and lower permeability at the surface than at the bottom. Therefore, the properties of the tops and bottoms of core samples were compared.

None of the sites investigated showed any sign of freeze-thaw damage. The damage observed was either due to early age raveling or to structural overload. This was probably because the sites were adequately drained, and therefore the pervious concrete was not saturated when the temperature was below freezing.

In conventional concrete, however, freeze-thaw damage may take many years to become apparent. It eventually results in disintegration. Therefore, in pervious concrete, freeze-thaw damage would be expected to take the form of widespread raveling progressing through the thickness of the pavement. This was not observed at any of the sites visited.

Generally, the PCPC installations evaluated under this research project have performed well in freeze-thaw environments with little maintenance required. No visual indicators of freeze-thaw damage were observed. With the exception of some installations where the pore structure was sealed during construction with wet mixtures or over-compaction, nearly all sites showed fair to good infiltration capability based on drain time measurements. Most of the sites visited do not yet require maintenance.

Because use of PCPC in this region began fairly recently, the sites visited were less than four years old. Although they are performing well as of 2007, it would be useful to revisit them periodically in the future. If future visits are made, the results reported in the earlier research will provide a useful baseline for comparing performance [Delatte et al. 2007, 2009, Miller 2007, Mrkajic 2007].

Cleveland State University Demonstration Sites

Two pervious concrete parking lot demonstration sites were built on the campus of Cleveland State University in 2005 and 2007. The first site was included in the RMC Research & Education Foundation study. Both sites performed well, although there was some clogging from fine material flowing onto the sites. Unfortunately, both sites were removed during campus construction in late summer 2009. At the time of removal, there was no observed cracking, extensive raveling, or other observed distress on either site. Both had been in nearly constant use for parking by light vehicles.

University of Maryland Baltimore County Demonstration Sites

Two pervious concrete demonstration sites were built on the campus of the University of Maryland Baltimore County in August 2008. Extensive contributing drainage area from a deteriorating asphalt parking lot maintained a relatively high particulate load, resulting in heavy clogging over portions of the pavement. Pressure washing proved extremely effective at quickly restoring surface infiltration, even for the most heavily clogged areas of the pavement that had become effectively sealed by the accumulation of fine-grained particulates.

ENSURING QUALITY AND DURABILITY

Ensuring quality and durability in PCPC pavements requires that care be taken with respect to materials and mixtures, compaction, and curing. The American Concrete Institute Committee 522 on Pervious Concrete has published a Specification for quality construction of PCPC pavements [ACI 2008].

Materials and mixtures

Generally PCPC is made from a single size, relatively small coarse aggregate (around 10 mm) with no fine aggregate. Water cement ratios are relatively low, as low as 0.25, so admixtures such as superplasticizers or viscosity modifiers are often necessary. Extensive information on PCPC mixtures is provided by Schaefer et al. [2006].

Compaction

Proper compaction is important. If the PCPC is over-compacted it will not allow water to drain through. Generally, at least 15 % voids are necessary for drainage [Delatte et al. 2009]. On the other hand, PCPC pavements that are not properly compacted may have low strength and may be prone to surface raveling. Compaction is discussed extensively in ACI 522R-06 [ACI 2006].

Curing

Because PCPC has very little water, a low water to cementitious materials ratio, and an open structure, it is highly susceptible to drying out. It must be kept securely covered by plastic sheeting for a minimum of seven days. If the plastic is damaged or removed, the PCPC will dry out and the hydration of the paste will stop, and the pavement will be weak.

SUMMARY AND CONCLUSIONS

PCPC pavements offer important sustainability benefits. They are an important tool for stormwater management, and offer considerable environmental benefits. In warmer climates, PCPC pavements can help mitigate heat island effects.

However, building high quality, durable PCPC pavements is still not an easy task. The PCPC pavements must be designed with care, considering all hydrologic and structural requirements. A proper PCPC mixture must be developed, and it must be placed, compacted and cured correctly.

When properly specified, designed, installed and maintained, PCPC pavements provide a valuable portfolio of environmental services by integrating green infrastructure systems in the design of sustainable landscapes.

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