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Infiltration performance of engineered surfaces commonly used for distributed stormwater management

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Abstract

Engineered porous media are commonly used in low impact development (LID) structures to mitigate excess stormwater in urban environments. Differences in infiltrability of these LID systems arise from the wide variety of materials used to create porous surfaces and subsequent maintenance, debris loading, and physical damage. In this study, infiltration capacity of six common materials was tested by multiple replicate experiments with automated mini-disk infiltrometers. The tested materials included porous asphalt, porous concrete, porous brick pavers, flexible porous pavement, engineered soils, and native soils. Porous asphalt, large porous brick pavers, and curb cutout rain gardens showed the greatest infiltration rates. Most engineered porous pavements and soils performed better than the native silt loam soils. Infiltration performance was found to be related more to site design and environmental factors than material choice. Sediment trap zones in both pavements and engineered soil rain gardens were found to be beneficial to the whole site performance. Winter chloride application had a large negative impact on poured in place concrete, making it a poor choice for heavily salted areas.

INFILTRATION PERFORMANCE OF ENGINEERED SURFACES COMMONLY USED FOR DISTRIBUTED STORMWATER MANAGEMENT

by

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Introduction

Urban land cover is often classified as highly impervious and the negative impacts on urban hydrographs are well documented (Shuster & Rhea, 2013). Porous pavement, rain gardens, and other low-impact development (LID) strategies have become increasingly popular for reducing runoff and flashy urban hydrographs (Montalto et al., 2013; Hood et al., 2007). These LID development strategies have been particularly useful in cities where combined sewers are subject to frequent overflow events and have been used as viable alternatives to typical gray infrastructure remediation (DeSousa, Montalto, & Spatari, 2012).

Infiltration capacity is an important measure of LID performance where the design goal is to reduce runoff at impervious sources. In hardscape sites such as porous parking lots, a subsurface gravel storage bed can be developed below the pervious surface to store infiltrated precipitation. This is a common approach for sites with low permeability soils. If the surface has low intrinsic permeability or becomes clogged, it can limit stormwater capture during periods of intense precipitation or on sloping sites where concentrated flow reduces residence time. Pavement clogging can be effectively reduced by routine vacuuming and power washing to help remove sediment from winter maintenance, braking, and debris loading (Chopra, 2010).

Previous research has addressed both short term and long term hydraulic performance of porous pavements and LID projects, primarily through measurement of saturated permeability with various types of ring infiltrometers. Although ring infiltrometers are a standard method for determining hydraulic conductivity, these devices require substantial set up time, often at a fixed location within the site, which practically limits the number of experimental replicates (Chopra, 2010; Al-Rubaei, Stenglein, Viklander, & Blecken, 2013). Some novel studies have relied on embedded systems such as time domain reflectometers, but requirement that monitoring systems are installed at the time of construction limits this approach (Brown & Borst, 2013). These methodological limitations to broad replication of infiltration measurements limits the statistical power of comparative analyses across sites and does not support an understanding of spatial variability within sites. Furthermore, ring infiltrometer methods create a positive head condition above the surface which is not representative of the depth of water normally associated with sheet flow and shallow concentrated flow during a rain event. This study resolves these issues by using a survey instrument that supports measurement replication and applies a process-appropriate head at the surface boundary condition.

Automated disk infiltrometers have been widely used to characterize infiltration properties of soils and other porous media and were used in this study (Ankeny & al., 1991; Casey & Derby, 2002; Madsen & Chandler, 2007). Disk infiltrometers provide a constant positive or negative head at the surface. The cumulative infiltration record can be analyzed to determine the short term effects of sorptivity and the long term, steady state infiltration capacity at the field conditions (Wooding, 1968; Perroux & White, 1988). Unsaturated hydrophilic porous media typically exhibits early time dominance of processes contributing to sorptivity, followed by a decline in infiltration rate as the distance to the axisymmetric wetting front increases and the permeability of the field saturated media at the applied head is approached. Automated disk infiltrometers operated at a short time step provide detailed data sufficient to analyze both early time sorptivity and steady state infiltration properties, and several instruments can be operated simultaneously to leverage time in the field. One uncertainty shared by both surface mounted ring and disk infiltrometers is the time variant diameter of the wetting front in the subsurface, which is governed by capillary diffusivity in highly sorptive soils and distorted by macropores and cracks in dual permeability media at high positive heads (Haverkamp, Ross, Smettem, & Parlange, 1994).

The goal of this study is to compare the relative infiltration capacity across an array of LID projects and document any spatial variability within several types of engineered porous surfaces. The surveyed sites were mostly constructed within a three year period and provide an opportunity to compare in situ performance in a single city following typical use, seasonal weather and routine maintenance. The study will also serve as a benchmark for assessing life cycle performance. Understanding patterns in spatial variability is intended to inform site designers of areas within LID structures that are prone to degraded performance.

Sites

Syracuse, New York was the central focus of Onondaga County's Save the Rain program between 2010 and 2013 (Green Projects List, 2013), and more than 50 sites with recently installed engineered porous surfaces were available for infiltration surveys in the summer of 2013. Twelve sites were selected to represent the various porous materials, including porous asphalt, porous concrete, porous brick pavers, flexible porous pavement, engineered soils, and native soils (Table 1). Ten of these sites were a part of the Onondaga County Save the Rain program; Harrison Street Parking Lot and R2 Parking Lot are sites owned and maintained separately by Syracuse University. Infiltration surveys were made in June and July 2013, midway between biannual spring and fall maintenance routines to provide a measurement of typical performance. Additional measurements were made in July and August of 2014 to support statistical analysis and better define spatial patterns of infiltration.

Table 1: Site and material list

Site	Age	N	Surface Material(s)	Porous to runoff area ratio
City Lot #4	1 year	51	Porous Asphalt	91%
Harrison Parking Lot*	Unknown	8		0.9%
Pearl Street Parking Lot	3 years	31		65%
Skiddy Park Basketball Court	2 years	18		100%
City Lot #3	3 years	58	Porous Concrete	21%
East Genesee Street	2 years	3		16%
R2 Parking Lot*	2 years	178		100%
University Avenue	2 years	8		32%
City Lot #4 Edging	1 year	30	Precast Porous Concrete	91%
East Water Street Sidewalk	0 years	8		100%
Skiddy Park Walkway	2 years	2	Flexible Porous Pavement	100%
University Avenue	2 years	131	Porous Brick Pavers	30%
Water Street Gateway	2 years	39		30%
East Genesee Rain Garden Cutout	2 years	75	Engineered Soil	20%
Concord Place	2 years	38	Vegetated Soil (Silty loam)	100%

*Designates Syracuse University owned and maintained property

Porous asphalt is a common surface replacement for parking lots and curbside parking. Four parking lots were selected and are generally similar in construction (Table 2). None of the tested sites have a curb to limit runoff or runon, and are nearly level with the exception of Harrison Street Lot. The land cover and surface material bordering the lots varies among sites. Pearl Street Lot has heavy vegetation around the lot which may serve as a source of debris to the lot. City Lot #4 has a 45 cm porous concrete aesthetic border and bioretention gardens along two sides. Harrison Street Lot has a 1 meter strip of porous asphalt along the base of the 58 meter, 3% sloped sealed asphalt surface. These sites are represented by a total of 130 infiltration tests (Table 1).

Table 2: Typical porous asphalt bed construction depths

Depth	Material
0-1.5”	Porous asphalt surface course
1.5”-3”	Asphalt treated permeable base
3”-5”	Choker course
3”-25” min	Clean washed coarse aggregate
25”	Non-woven geotextile
>25”	Uncompacted subgrade

Porous concrete pavement was installed primarily in curbside parking zones and parking lot edges as a means to delineate parking areas from traffic lanes, with typical construction bed depths of approximately 30 inches (Table 3). Some sidewalks were also made of porous concrete. The concrete was cast in place at City Lot #3, curbside parking on East Genesee, the R2 Parking Lot, and curbside parking on University Avenue. Precast porous concrete was installed at City Lot #4 and the sidewalk at East Water Street. The R2 Parking Lot was studied extensively to identify spatial differences in infiltration among the traffic lane, parking spots, and near curb areas (Figure 1). The lot has an approximate 4% grade down to an opening for a sidewalk. A total of 178 successful tests were performed at the R2 Parking Lot. All other porous concrete surfaces were surveyed with a total of 105 successful tests.

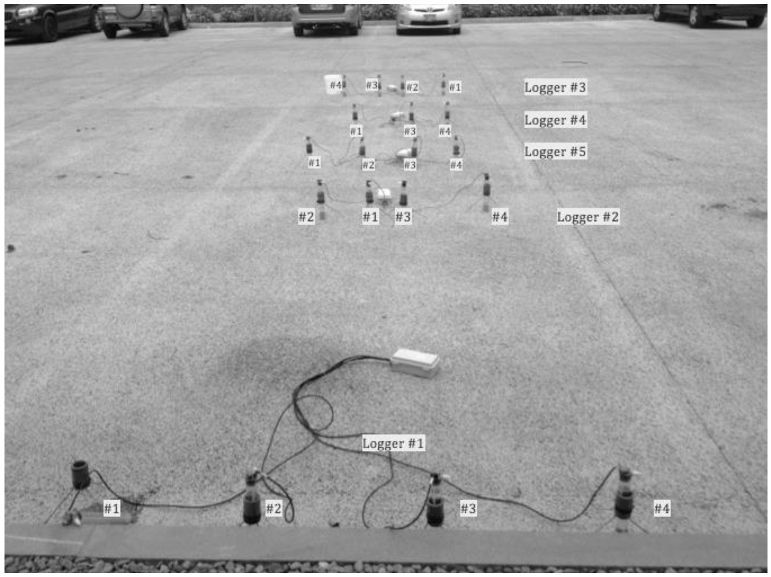

Figure 1: Infiltrometer layout for distance and edge effect testing on the Syracuse University R2 porous concrete parking lot.

Table 3: Typical porous concrete bed construction depths

Depth	Material
0-6”	Porous concrete surface coarse
6”-7”	1” Choker Course
7”-29.5” min	Clean washed, uniformly graded coarse aggregate
29.5”	Non-woven geotextile
>29.5”	Uncompacted subgrade

Flexible porous pavements were installed as walkways within Syracuse city parks. The material is a pavement composed of recycled shredded tires (Flexi-Pave, KBI Industries). The tested material at Skiddy Park was placed at a negligible grade near the entrance of the park. A total of 15 tests were performed at this site.

Several surfaces paved with a variety of permeable brick types were tested. Permeable brick pavers were used in road details and parallel parking spaces at University Avenue and the Water Street Gateway. Bricks on University Avenue were smaller (1 ¾ inch x 9 inch) with a smaller aggregate size used to fill the 1/4 inch gap between bricks. This type of brick is typically installed as road or sidewalk details (Hanover Architectural Products, Hanover, PA). Water Street Gateway bricks were a large size (4 ¼ inch x 9 inch) with larger 1/4 inch aggregate filler and installed over a larger curbside parking area following specifications in Table 4 (Pine Hall Brick Company, Winston-Salem, NC). Infiltration capacity of the brick paved surface was tested by placing the infiltrometer to span the filler material in the gap between bricks in order to test the pervious portion of the area (Figure 2). The brick face was also tested but found to be relatively impervious. A total of 131 tests were conducted on the smaller bricks at University Avenue, and 39 tests were completed on the larger bricks at Water Street.

Table 4: Typical large brick paver bed construction depths

Depth	Material
0-3”	Permeable paver, crushed open stone aggregate in gaps
3”-5”	Crushed open stone aggregate
5”-17”	Uniformly graded crushed stone blend
17”	Geotextile
17”-41” min	Structural Soil
>41”	Uncompacted subgrade

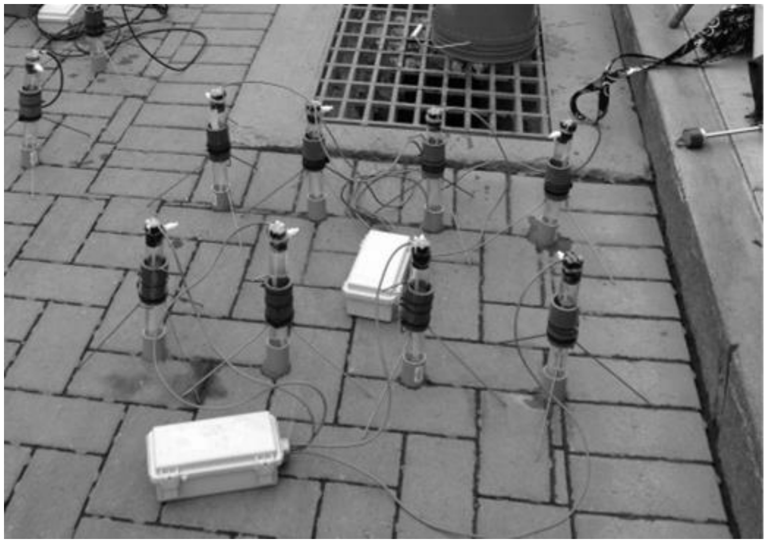

Figure 2: Infiltrometers placed on the gaps in between porous bricks at brick paver sites.

Engineered curb cutout rain gardens are a popular approach for diverting shallow channel flow, and have been installed in several locations throughout Syracuse. The studied sites were built on East Genesee Street in 2011 as triangular bioretention cells that replaced parallel parking near intersections on this sloped road. Construction depths of the various soil and drainage layers can be found in Table 5. The basins have inlets from street and sidewalk runoff and overflow through an elevated domed riser. The surface media is a New York State Department of Transportation urban planting soil (NYSDOT §613.01010011 Topsoil, Urban Planting Mix). A total of 75 tests were performed across the entire surface to identify spatial patterns in permeability arising from fluvial sorting and pollutant loading. One double ring infiltrometer test was performed to simulate a 10 cm ponded condition that is observed at the site during heavy rainfall events.

Table 5: Typical rain garden bed construction depths

Depth	Material
0-18” min	Finish grade topsoil
18”	Geotextile
18”-21”	Choker course crushed stone
>21”	Infiltration stone
>21”	Uncompacted subgrade

A broad parkway median at Concord Place was identified as a representative example of a grassed surface on native soils. It serves as a benchmark in this study to compare the relative benefit of engineered sites to traditional LID practice of grassy open space on local native soils. The site has Camillus silt loam, soil with grass and tree cover (Soil Survey of Onondaga County, New York, 1977) (Web Soil Survey). A total of 38 infiltration tests were performed survey the permeability of bare soil, dense grass cover, and tree cover and root hummocks.

Methods

Infiltration capacity was measured with automated mini disk infiltrometers (AMDI) (Madsen & Chandler, 2007). Previous laboratory tests of the infiltrometers verified a bubbling pressure of -2.0 cm (+/- 0.1 cm). For each test, the AMDI was placed on a pedestal of general purpose sand 2.2 cm in depth and 2.5 cm in diameter (11 cm^3) constrained by a PVC pipe coupling. This depth of sand was used to provide zero to 2 mm of head at the test surface. Although the sand contact layer depth is slightly greater than that recommended by Reynolds & Zebchuk (1996), this approach was convenient for simulating a boundary condition that occurs under precipitation and sheet flow without the requirement for sealing the device to the surface as with hood or ring infiltrometers (Schwaezel & Punzel, 2007). The minimum infiltration rate of the contact sand was 32 mm/min.

Data was logged by an Arduino R3 data logging shield (Adafruit Industries, New York City). The mini disk infiltrometers were automated with an analog 1 psi pressure transducer (ASCX01DN, Honeywell Sensing and Control), as in the method proposed by Madsen and Chandler (2007). Voltage was converted to total infiltration volume with the formula given by Madsen and Chandler (2007):

$$V(t) = V_T \left[\frac{v_o(t) - v_{min}}{v_{max} - v_{min}} \right]$$

where V_T is the initial volume of water in the device, v_o is the output voltage, v_{max} is the maximum voltage output at the start of the test, and v_{min} is the minimum voltage at the end of the test. The cumulative infiltration was determined by dividing *V(t)* by the contact area.

Several preliminary trials of the AMDI on porous pavements indicated that cumulative infiltration slopes were remarkably linear following the period required to wet the contact sand column. This suggests that the pavements have negligible sorptivity and that gravity flow dominates the test (Figure 3). The linearity allowed us to simplify time series analysis of K_h on hardscape surfaces to linear slope analysis. Infiltration time series of both engineered and native soils followed a more typical curve; K_h was analyzed further in the time series near steady state condition for these materials. Each K_h value was corrected for temperature by multiplying it by the dynamic viscosity correlating to the measured material temperature. In the special case of testing bricks, both the brick surface and cracks between bricks were tested. Infiltration reported from brick paver sites represent infiltration into an area of the filled crack, and is not a spatial average including the nearly impervious bricks.

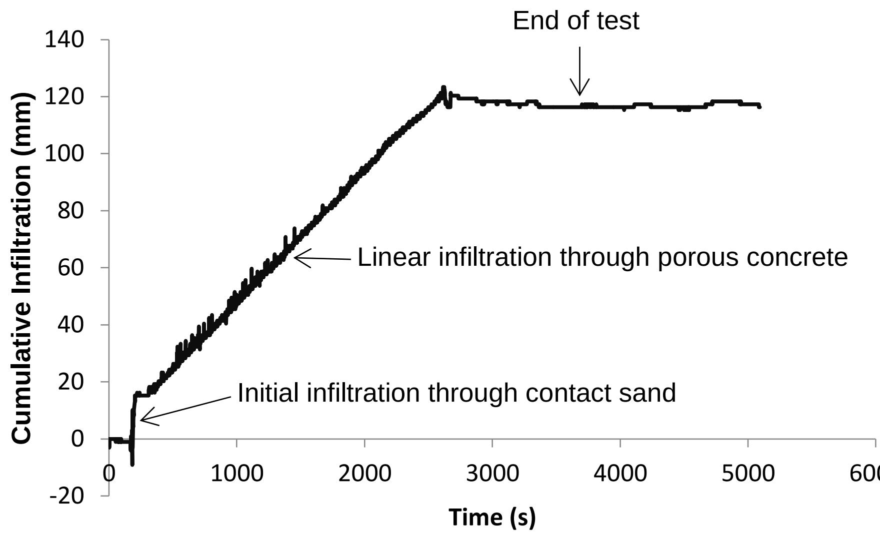

Figure 3: Example cumulative infiltration curve from the R2 Parking Lot on July 26, 2013.

The large sample size supported analysis of impact from vehicle traffic, curb effects, and areas that were neglected during maintenance or subject to abnormal environmental degradation (Figure 1). Photo documentation of each set of infiltration experiments were used to support discussion of spatial patterns within the data. Erroneous infiltration data were discarded for experimental failures such as setup error (failure to make proper contact or sand spillage), broken devices (leaking column), or electronic failure (low battery power or data logging error).

Laboratory AMDI tests of newer engineered S1 surface layer and S3 drainage layer soils were also performed to compare the performance of the NYSDOT urban planting soils on East Genesee to theoretical performance of sites installed afterwards. S1 and S3 soils were lightly packed into a 10 cm diameter PVC column and allowed to drain openly to the bottom (Figure 4). The AMDI was placed on top of the soil and refilled as needed to achieve a fully saturated state.

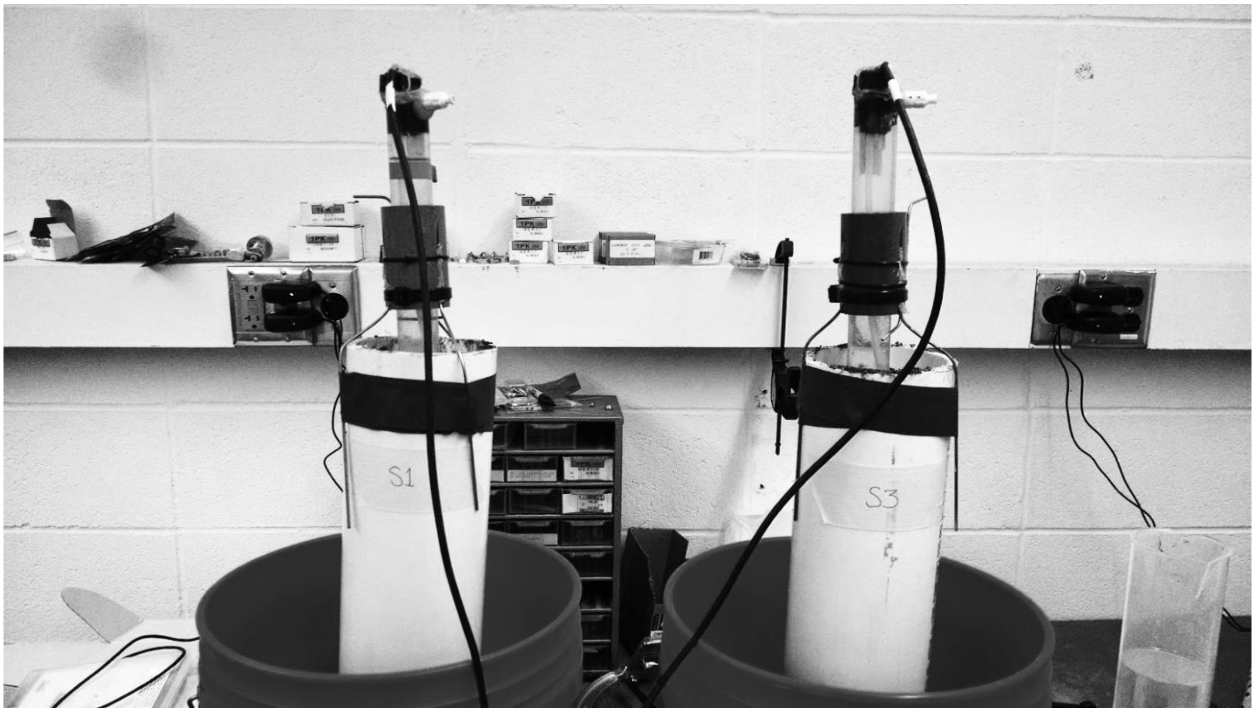

Figure 4: Lab testing of the S1 and S3 engineered soils in 4 inch PVC columns

Corrected K_h values were compared across the various sites and material types. Statistical differences between materials and sites were calculated using Minitab 17 (Minitab Incorporated, State College, PA). Data were log transformed to achieve a *p*-value of >0.05 for most normality tests. The exceptions were cases with very large sample sizes, for which plots of the log transformed data were visibly normal with the exception of a few outliers at the extreme values. Outliers were retained due to the extreme values still accurately depicting high or low infiltration of a point on a surface material. A one-way ANOVA test was used and accepted due to this visible normality. The test was performed on the log transformed data to determine statistical similarities between infiltration rates of varying classes of materials and sites.

A double ring infiltrometer test was performed on the soils at East Genesee to compare the difference between traditional testing methods and AMDIs. The outer and inner rings were 20 cm and 7.4 cm in diameter, respectively, and embedded into the surface of the soil. Marriotte bottles maintained a constant head of 10 cm in both rings for the duration of the test (Figure 5). Elapsed time was recorded for every liter (5.8 cm) of water infiltrated by the inner ring.

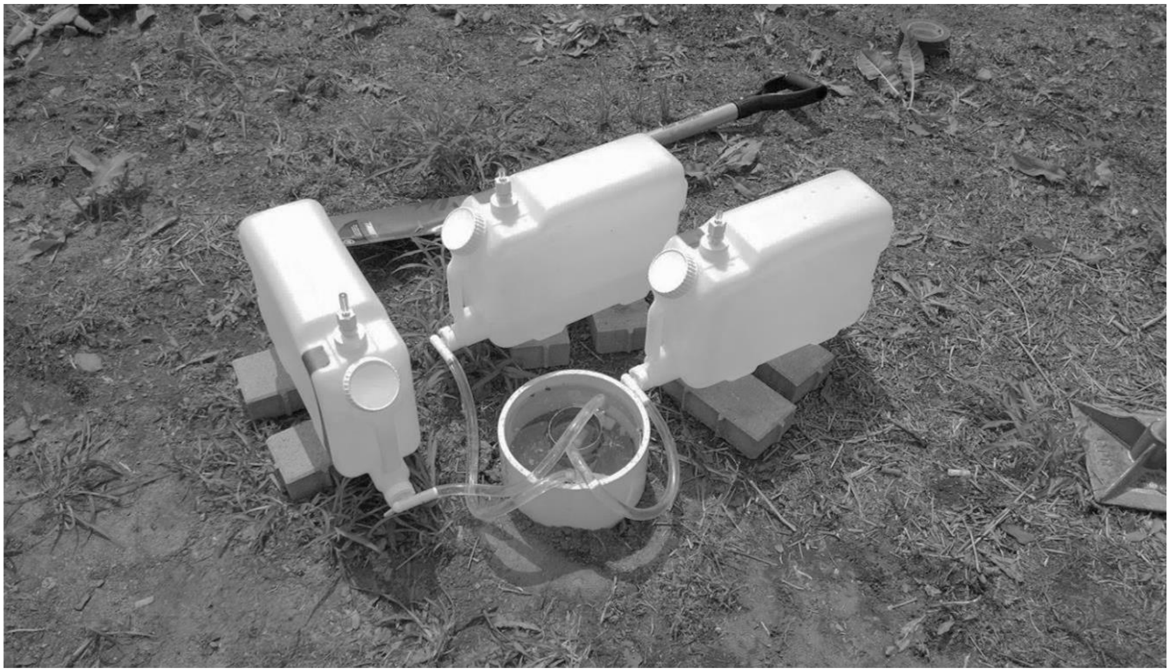

Figure 5: Double ring infiltration test at the East Genesee rain garden bumpout

Results

The results of 711 tests are reported by material type in Table 6. Data are summarized by site in Figure 6 and by material in Figure 7. The results of this study cover both the performance of individual materials used at specific sites as well as their relative spatial performance within sites.

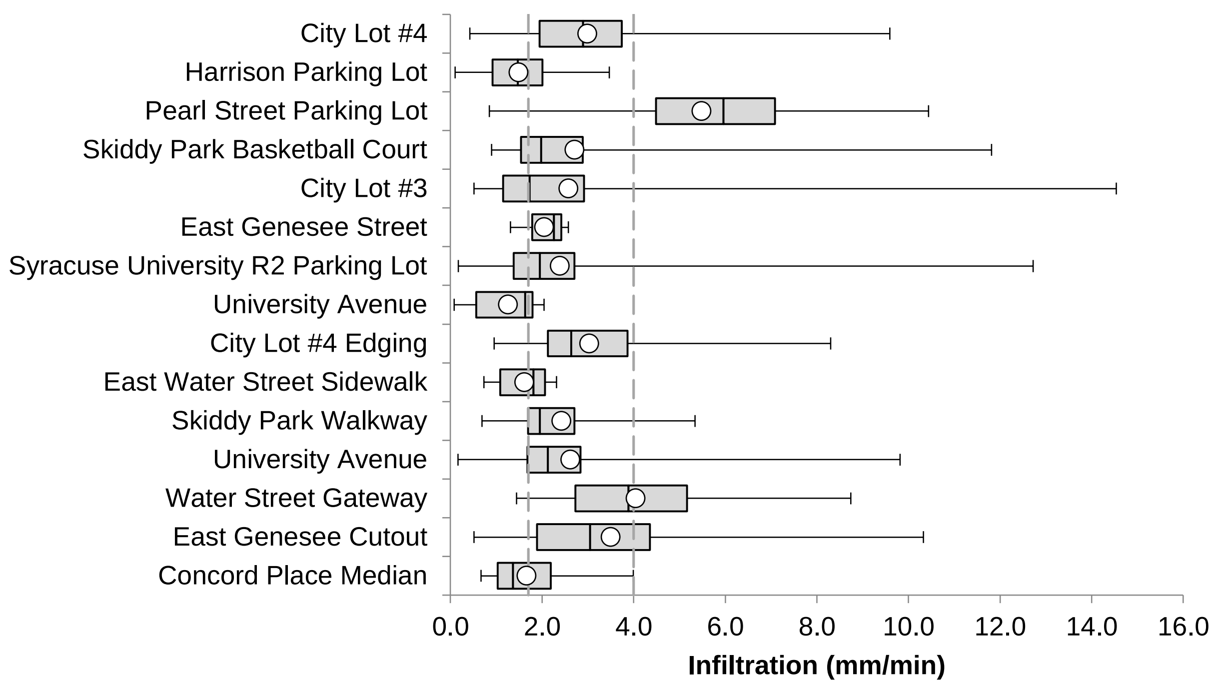

Figure 6: Infiltration capacity summary by site. Bars represent minimum and maximum infiltration values; box ends represent 25th and 75th percentiles; box band represents median values; white dot represents mean values; dashed lines represent precipitation intensity for 2 year and 100 year events.

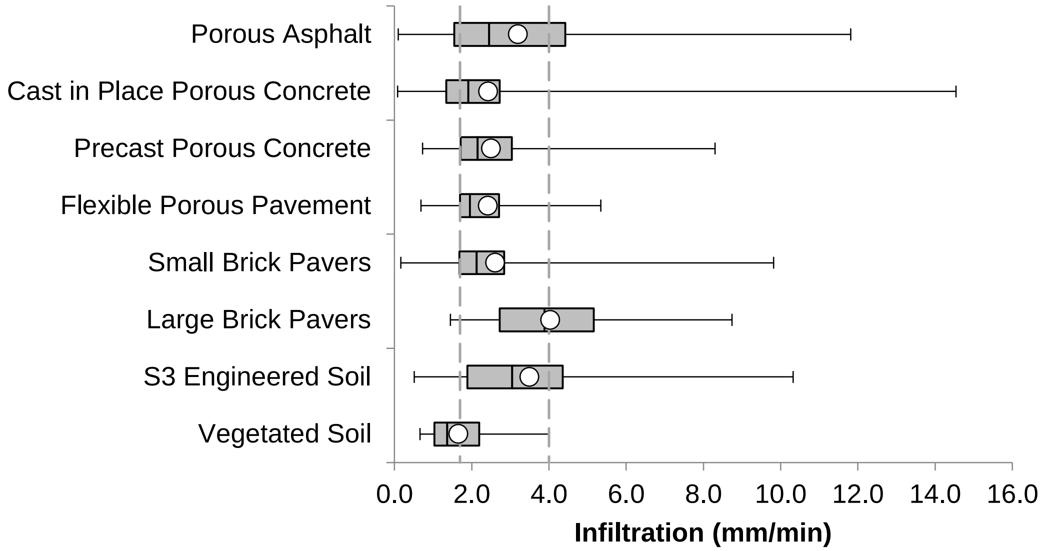

Figure 7: Infiltration capacity summary for tested materials. Bars represent minimum and maximum infiltration values; box ends represent 25th and 75th percentiles; box band represents median values; white dot represents mean values; dashed lines represent precipitation intensity for 2 year and 100 year events.

Material Performance

Porous asphalt was tested extensively (n=130) and showed some of the greatest infiltration rates in this study (3.20 ± 2.26 mm/min). Average infiltration rates of porous asphalt within sites ranged from 5.48 mm/min (± 2.17 mm/min) at the Pearl Street Parking Lot to lesser rates at City Lot #4 (2.99 ± 1.69 mm/min) and Skiddy Park Basketball Court (2.71 ± 2.41 mm/min), to markedly lower rates at Harrison Street (1.49 ± 0.82 mm/min). The surface infiltration at Pearl Street Parking Lot was the greatest observed rate among porous asphalts and all other study sites.

Porous concrete was also tested extensively (n=282) and demonstrated the second lowest average infiltration rate (2.44 ± 2.01 mm/min) of the engineered materials in this study. Average infiltration values for cast in place porous concrete were similar at City Lot #3 (2.58 ± 2.77 mm/min), Syracuse University R2 Parking Lot (2.39 ± 1.83 mm/min) and at curbside parking spaces on East Genesee Street (2.26 ± 0.54 mm/min), and lower at University Avenue (1.63 ±

0.70 mm/min). The range of performance of precast porous concrete was similar to cast in place concrete. The cast in place installed at the border of City Lot #4 had the greatest infiltration of all porous concrete materials (2.64 ± 1.55 mm/min), while precast sidewalks on East Water Street were much less permeable (1.81 ± 0.58 mm/min).

Flexible porous pavements in Skiddy Park (n=15) performed similarly to porous concrete (2.42 ± 1.20 mm/min).

Permeable bricks were tested on both the space in between bricks and the brick face, though only the permeable gap are included in later comparisons. The fill between large brick pavers at the Water Street Gateway (n=39) had infiltration rates greater than most other sites (4.04 ± 1.61 mm/min). The smaller aggregate fill between the small brick pavers on University Avenue (n=131) was much less permeable (2.62 ± 1.63 mm/min). In both cases, the brick surface was found to be relatively impervious (0.31 ± 0.54 mm/min) and make a negligible contribution to infiltration.

Engineered soils in rain gardens on East Genesee Street (n=75) had high infiltration capacity and great variability (3.50 ± 2.30 mm/min). Laboratory testing of S1 surface layer soils and S3 drainage layer soils that have since been installed in other rain gardens were found to have steady state infiltration rates of 4.75 mm/min and 10.50 mm/min, respectively (Figure 8). The steady state infiltration rate for the ponded (10 cm) in situ double ring infiltrometer test at one rain garden was 110 mm/min, approximately ten times greater than the AMDI laboratory measurements of drainage layer soils (Figure 9). Native silty loam soils had the lowest permeability of the surveyed porous materials (1.66 ± 0.88 mm/min).

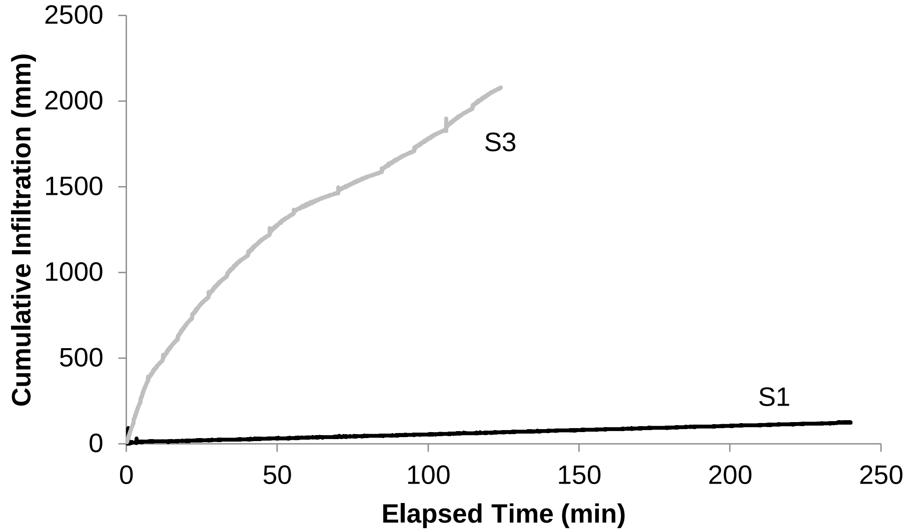

Figure 8: Cumulative infiltration curves for the lab tested S1 and S3 engineered soils

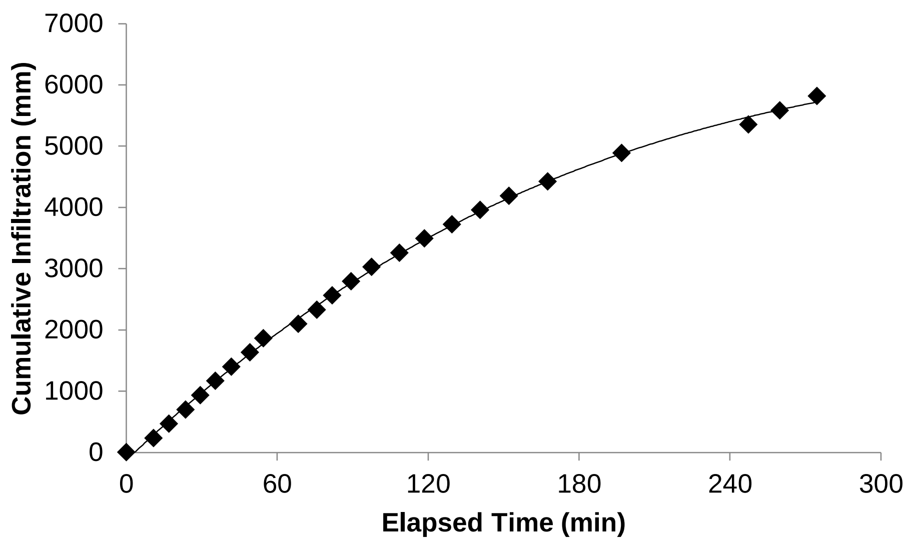

Figure 9: Double ring cumulative infiltration curve from East Genesee rain garden

Statistical comparisons across materials found groupings of material performance (Table 6). The fill for the large brick pavers was statistically the best performing material group (4.04 ±

1.61mm/min) with engineered soils being relatively close (3.50 ± 2.30 mm/min). Porous asphalt (3.20 ± 2.26 mm/min) and the fill between small brick pavers (2.62 ± 1.63 mm/min) were grouped similarly. Porous concrete (2.44 ± 2.01 mm/min) and flexible porous pavement performed similarly (2.42 ± 1.20 mm/min) but the flexible porous pavement sample size was too low for statistical comparison. All engineered porous materials were more permeable than vegetated native soils (1.66 ± 0.88 mm/min).

Table 6: Mean ± standard deviation infiltration capacity and Tukey pairwise comparison groups for tested materials.

Material	Infiltration capacity (mm/min)	N	Grouping
Porous Asphalt	3.20 ± 2.26	130	B
Cast in Place Porous Concrete	2.43 ± 2.07	246	C D
Precast Porous Concrete	2.50 ± 1.53	36	A B C
Flexible Porous Pavement	2.42 ± 1.20	15	A B C D
Small Porous Brick Pavers	2.62 ± 1.63	131	B C
Large Porous Brick Pavers	4.04 ± 1.61	39	A
Engineered Soil	3.50 ± 2.30	75	A B
Vegetated Soil	1.66 ± 0.88	38	D

Spatial Variability in Performance

Spatial variation in infiltration rate of paved surfaces was observed at multiple locations, and was associated with abrasion wear, material spalling, sedimentation, and differences and discontinuities in the surface material. Different trends in the infiltration capacity of porous concrete were observed as a function of the distance away from the curb at the R2 Parking Lot (Figure 10). Mean infiltration rate was low adjacent to the curb (1.99 mm/min), increased over the 6 meter parking zone typically occupied by a vehicle (3.11 mm/min) and declined toward the central traffic median (1.48 mm/min). The one meter porous pavement strip downslope of the impervious section of the Harrison Street parking lot (Figure 11) showed a similar pattern with the lowest mean infiltration capacity at upslope edge (0.063 mm/min), with greater mean rates in the center of the porous strip (2.12 mm/min) and declining infiltration toward the downslope seam close to the curb (1.09 mm/min). Within the strip, patterns of high and low infiltration rate corresponded to areas of concentrated runoff and accumulated sediment, respectively (Figure 12).

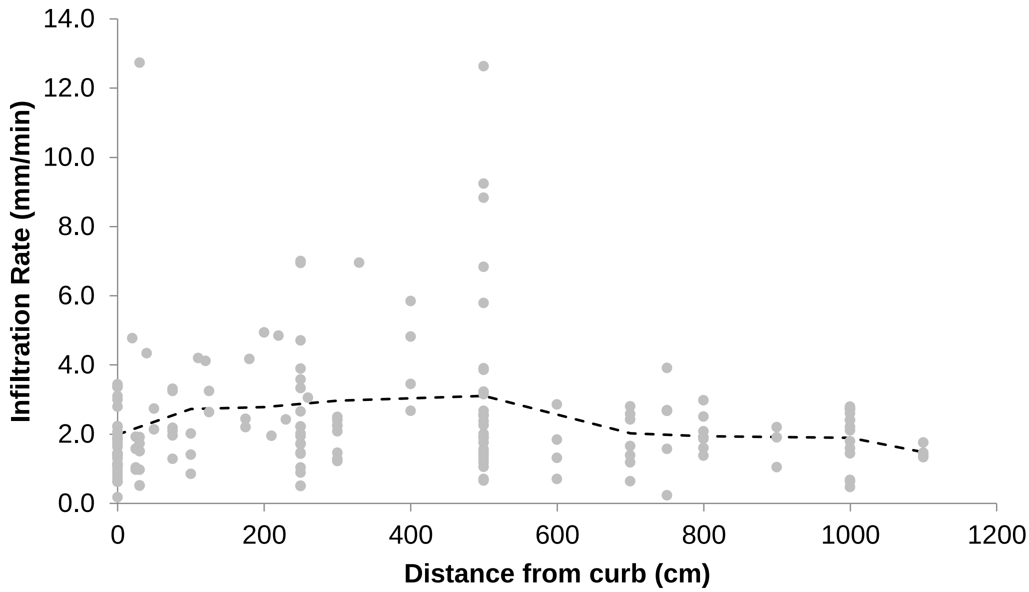

Figure 10: Moving average of infiltration capacity across a measured distance from the curb at the Syracuse University R2 Parking Lot. Distances are estimated from photographs of the initial setups.

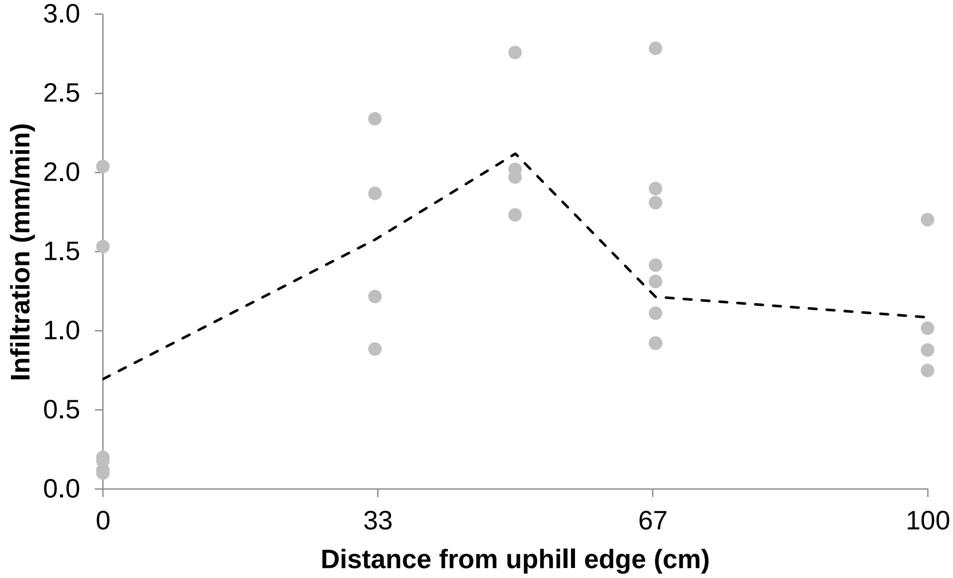

Figure 11: Moving average of infiltration capacity across a measured distance from the upgradient edge of the three foot strip of porous asphalt at Harrison Street (Figure 12). Distances are estimated from photographs of the initial setups.

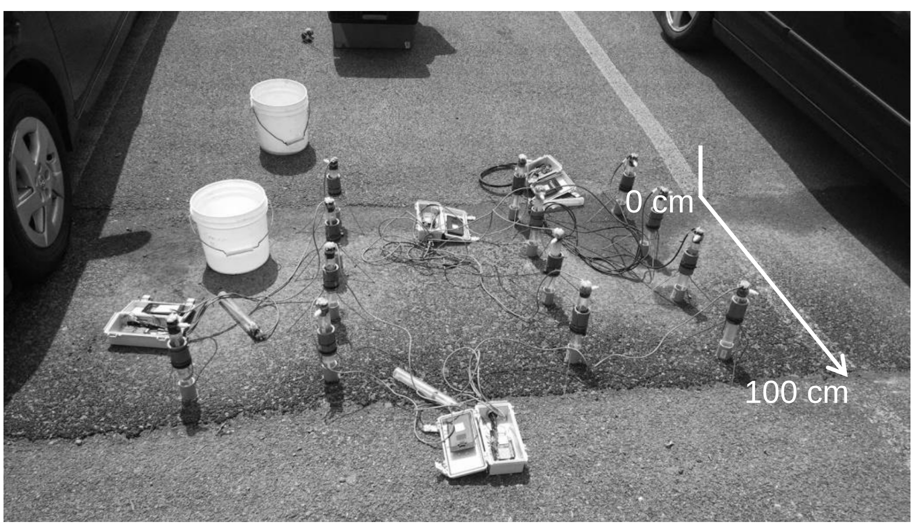

Figure 12: Distance measurement at Harrison Parking Lot. Porous asphalt is a three foot strip located down gradient from the impervious lot and approximately two feet from a curb.

Infiltration variability of engineered soils within the East Genesee rain garden was observed in seven groups of locations with different physical characteristics (Figure 13). The soils near the gravel check dam had the greatest rates of infiltration (6.32 ± 3.75 mm/min). Areas around larger plants also had high infiltration rates (4.34 ± 2.75 mm/min). Soils near the wall, both on the sides (3.35 ± 1.64 mm/min), on the outlet (3.06 ± 2.04 mm/min), and within tall grass areas (3.04 ± 1.86 mm/min) performed similarly. Infiltration rates of the inlet soils were slightly lower (2.56 ± 1.02 mm/min), with bare soils within the garden having the lowest performance (1.45 ± 0.55 mm/min).

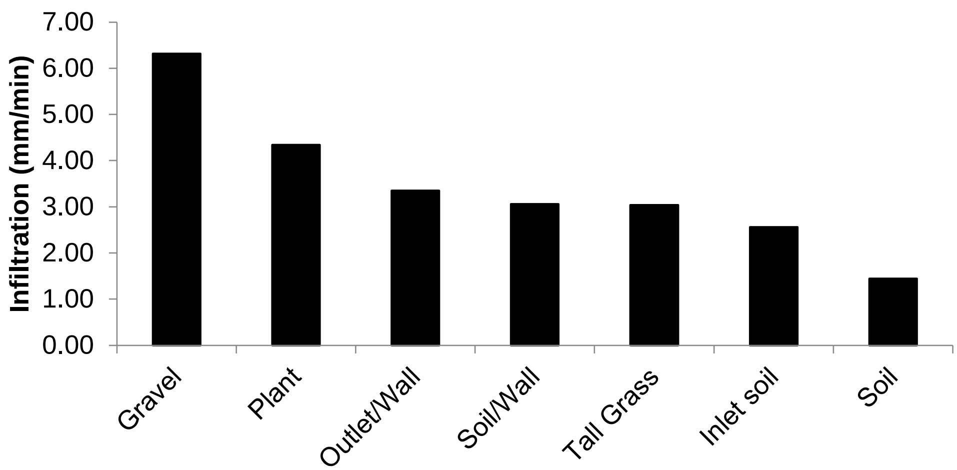

Figure 13: Infiltration rates at spatially characteristic locations within East Genesee rain garden

Spatial variability in infiltration rate was less apparent for the native soils across the Concord Place median (Figure 14). Infiltration rates were similar on soils in grassy areas (1.81 ± 0.88 mm/min) and near the tree bole (1.69 ± 1.04 mm/min). Slightly diminished infiltration capacity was observed for bare soil patches (1.51 ± 0.94 mm/min) and soils near the curb (1.27 ± 0.32 mm/min).

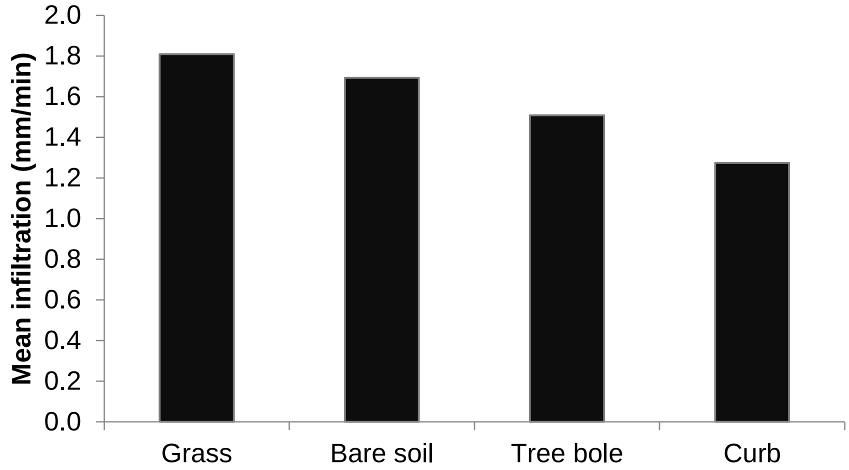

Figure 14: Infiltration rates at spatially characteristic locations within the Concord Place Green Street median

Discussion

Material Performance

The variety of materials classes and material compositions within classes tested within this study reflects the wide range of design options for LID structures. These design choices can affect infiltration performance. Site designers should be aware of tradeoffs between the goals of permeability, structural loading, ease of maintenance, and aesthetics. These tradeoffs will be considered for each material group below.

Porous asphalt installations exhibited a wide range of infiltration capacities for which the mean site value decreased by 70% over the tested sites. Differences within the material are largely attributed to the aggregate mix and binder used within each site. The construction details for Harrison Street are not available, yet the mean infiltration rate is one quarter the capacity of Pearl Street Lot. This may be more related to the small size of the porous area relative to the area contributing sediment than a result of material properties. The earliest and most permeable installation was at Pearl Street. This site was constructed of a coarse aggregate mix (approximately 80% of the material between 2.36 mm and 9.5 mm) and a PG 64-22 binding agent, typically well suited for low traffic applications. This mix resulted in high infiltration capacity across the site, but service life expectancy is a stated concern due to the susceptibility of PG 64-22 binder to structural failure. City Lot #4 is constructed of the same aggregate mix with a stronger PG 70-22 binder, similar to other newer porous asphalt installations within Syracuse. The mean infiltration capacity is 55% of that at Pearl Street, but is considered acceptable. The basketball court at Skiddy Park is constructed of smaller aggregate and PG 70-22 binder to provide a smoother playing surface so as not to impair the rebound of a basketball. The change in aggregate size reduced the infiltration capacity slightly relative to City Lot #4. The variety of asphalt mix and binder grades allow design solutions that ensure that runoff is reduced without sacrificing structural performance.

Porous concrete performance is related more strongly to environmental conditions than to installation process. Infiltration performance was expected to depend on sufficient cure time. Specifically, precast concrete ensures proper curing before installation, whereas curing conditions for cast in place installations are highly susceptible to failure due to temperatures below 40° F during curing stages (ACI Committee 306, 2010). Despite this, the mean infiltration rate of precast porous concrete surfaces was only 3% greater than the cast in place porous concrete. This general result is weighted by the poor infiltration performance of the precast sidewalk at Water Street, where maintenance was done with lower powered vacuum unit than other sites. A more direct comparison of precast porous concrete and cast in place can be made City Lot #4, where both types were maintained with a high power vacuum. The mean infiltration rate for precast was 9% greater than the cast in place installation at that site, suggesting that either precast may have an advantage when properly maintained or that porosity is better controlled in precast. At other cast in place parking lots, mean site infiltration rates were similar.

However, the mean infiltration rate for curbside parking spots on East Genesee St was one third less that the parking lots. This decreased infiltration capacity can be attributed to high sediment and salt loading, similar to the porous asphalt strip at Harrison Street Lot. Porous concrete performance was clearly more affected by sediment loading and maintenance than differences in material properties.

Flexible porous pavement appeared to suffer mostly from extreme clogging. The tested installation is within a park and maintained with a smaller, lower power vacuum, as are the porous concrete sidewalks on East Water Street. Although the mean infiltration rate of the flexible pavement is not statistically different enough from either porous concrete or porous asphalt, it is 50% greater than the native soil. Site observations of insufficient maintenance suggest flexible pavement may perform better if satisfactorily cleaned. Future studies on this material are encouraged due to test manufacturers claims variations of the material can hold up well even in trafficked parking lots (Porous Pave, 2011).

Brick paver performance appeared to be controlled by the size of the gap and spacing aggregate. The aggregate between small pavers was packed tighter and was more prone to clogging. These combined resulted in a 33% decrease in mean infiltration rate of the fill material relative to the large bricks. Increasing the brick spacing and the size of the spacing aggregate benefits the infiltration performance of the surface. The infiltration rate between brick pavers compared favorably to other material surfaces in this study, but the reported results were not corrected to account for the ratio of porous area versus the impervious brick face ratio. A conservative estimate of average areal infiltration rate can be obtained by reducing the gap material infiltration rate by a factor of 6.7 and 12.4 for the small and large bricks, respectively. It should be noted that this conservative estimate does not account for the increased head condition in the recessed gap between the larger relatively elevated bricks. The local ponding in the recesses may increase infiltration rate as a linear function of applied head. Newer installations have used even larger block systems (PaveDrain LLC, Milwaukee) that feature wider and deeper void gaps that do not require fill, and large arched voids on the underside of the block. Such large brick and even larger block systems are expected to outperform other bricks, particularly due to absence of spacer material that is subject to clogging following straining and internal sedimentation by fines.

Engineered soils have greater mean infiltration rates than most other tested porous surfaces, despite less intensive maintenance. Previous studies have found that despite sediment loading, rain gardens appear to be relatively self-maintaining even over long periods of time (Gilbert Jenkins, Wadzuk, & Welker, 2010). Rain gardens and bioretention cells also provide the opportunity for ponding, which increases the infiltration rate as a function of applied head, providing there is free drainage below the surface soil. The free drainage layer is more common in bioretention cells than rain gardens, and provides a quite different lower boundary condition for infiltration than typical native soils, where permeability decreases with depth. The combination of the freely draining lower boundary condition and greater applied head is the likely cause for the difference between double ring and surface disk infiltrometer measurements for bioretention soils in this study. Subsequent to the rain garden installations on East Genesee, specially engineered S1 surface layer and S3 drainage layer soils have been installed in rain garden and bioretention sites throughout Syracuse. Laboratory testing of the soils found a 36% greater infiltration capacity than for the surface soils and a 300% increase in the drainage soils, relative to the NYSDOT specified soils though these values are expected to vary under field conditions. High spatial variability was evident and was similar in magnitude to the variability in porous asphalt. We present spatial analyses of infiltration variability in the following sections.

Environmental Performance

The study location provided the opportunity to study infiltration into LID structures where annual temperature extremes and sediment and salt loading from winter road maintenance challenge the performance of engineered porous surfaces. Like many northern climates, Syracuse can experience below freezing temperatures for nearly half the year (Climatological Report (Annual), 2013). This results in extensive road deicing, with approximately 27 tons of salt applied per mile of road annually (Patten, 2011). Although reducing winter salt application by 64 to 77% is advised on porous pavement installations, this goal is difficult to achieve where porous materials receive runoff from large contributing areas of impervious surfaces that require deicing salts (Roseen, Ballestero, Houle, Heath, & Houle, 2014).

Winter chloride application was particularly reactive with cast in place porous concrete installations. Porous concrete surfaces that are air cured as opposed to water cured have been found to be more prone to degradation during freeze-thaw cycles, suggesting that cast in place installations are more prone to failure during freeze thaw cycles (Zhifu, 2011). Our results support this finding. We found that the poorest performing cast-in-place surfaces were installed in curbside parking spaces adjacent to traditionally sealed roads on East Genesee Street, and had an infiltration rate 12.5% lower than the rate at a similarly maintained and installed site at City Lot #3. This suggests that recommended salt reduction likely did not occur and that the surfaces were not cured in ideal water conditions as well as exposed to heavier chloride concentrations. Since this study, much of the porous concrete installed during the Save the Rain program has been replaced with either standard or porous asphalt due to poor performance and surface degradation.

Other tested materials were not affected to the same extent by winter deicing salts. Porous asphalt has traditionally not been favored in cold climate regions, previous studies based on the finding that porous asphalt retains higher concentrations of applied winter salt than porous concrete due to smaller pore size (Borst & Brown, 2014). However, porous asphalt is not chemically affected by chloride and therefore does not suffer the chloride related spalling decay of porous concrete alternatives (Wang, Nelsen, & Nixon, 2006; Flatt, 2002). This durability to chloride may explain the 13% better performance of porous asphalt than precast porous concrete at City Lot #4. Flexible porous pavements and porous pavers were most affected by the additional sediment loading, though the large gap in larger porous paver systems is easier to maintain and expected to be less likely to completely clog.

Engineered soils in rain gardens and bioswales have the advantage of being loose granular material, although capacity of these systems to maintain their infiltrability under heavy sediment loading is unclear.

Comparison of infiltration rate distributions to precipitation intensity for common and uncommon storms provides perspective on the difference among sites (Figure 6, Figure 7). Annual precipitation for Syracuse is representative of the national average (National Overview - Annual 2013, 2013). We select infiltration rates for 5-minute duration, 2 year event at (1.7 mm/min) and 5-minute duration, 100 year storm event (4.0 mm/min) (Rainfall Intensity-Duration-Frequency Curves, 1955). Mean and median infiltration values of native soils and poorly performing sites had values below the rainfall rate of a common high intensity storm. This indicates that these specific sites are not capable of completely infiltrating direct rainfall from this size storm, let alone runoff from adjacent impervious areas. Notable situations at Harrison Street and University Avenue are affected by high sediment loading due to a large impervious to porous runoff ratio (Table 1), with the material summary in Figure 7 further supporting that these low values are a matter of site design and not material performance. Other sites appear to have infiltration capacity distributions better suited to capturing rainfall from common intense storm evens, with Pearl Street evidently capable of completely infiltrating even the highest intensity storms.

Spatial Performance

Infiltration varied spatially across many of the observed sites in response to site design and environmental inputs. These spatial changes, while observed on specific materials, also show general sediment loading patterns that can be applied to other LID structures.

Porous pavement parking lots are often designed with an impervious traffic lane to resist surface wear from high traffic loading. However, Brown and Borst (2013) point out that porous media are more likely to clog as the ratio between porous surface area and total runoff area decreases (Table 1). This phenomenon was most visible in the R2 and Harrison Street parking lots (Figure 10 & Figure 11). Infiltration rates at the center of the pervious surfaces were clearly greater than at the seams between sealed and porous asphalt. Seams were prone to clogging at Harrison Street parking lot due to the high ratio of total runoff area to porous surface area and local infiltration was reduced by 67% from well washed areas. Similarly, the R2 Parking Lot exhibited a 52% reduction in infiltration capacity from the parking spaces to the central driving lane. This trend was less pronounced than at Harrison Street Parking Lot due to the greater pervious area spreading the sediment load. The greatest infiltration capacity in the R2 Parking Lot was found in parking areas where the porous surface was protected from abrasion, debris loading, snow compaction and rain impact. We expect that the sediment being more spread out is likely to cause less irreversible damage to the parking lot as a whole over time.

Porous concrete installations were likely affected by both material spalling and sediment loading. Porous concrete curbside parking spaces next to impervious roads and parking lot spaces near an impervious traffic lane had 38% lower mean infiltration capacity, than parking lots with little or no impervious surface. This result is expected to apply to materials other than porous concrete. Sediment loading is recognized to occur in an exponential fashion, with initial loading of larger particles eventually leading to increased loading of fines, until the surface is relatively impervious (Al-Rubaei, Stenglein, Viklander, & Blecken, 2013). Adjacent impervious areas increase the rate of sediment loading, which accumulates in pervious zones and can feed forward to the point where regular vacuum maintenance is not effective.

Large brick pavers appear to be an ideal solution where high sediment loading cannot be avoided. We expect that the gaps adjacent to impervious surfaces in a porous paver installation act as sediment traps that are not prone to irreversible clogging. The larger gaps in both the large bricks tested and newer PaveDrain blocks should withstand a larger sediment load and serve as a higher capacity sediment trap at the interface with impervious surfaces. The wider gap should facilitate more effective vacuum maintenance and not require higher intensity maintenance procedures such as pressure washing to reverse material clogging.

The studied rain gardens also exhibited spatial differences in infiltrability (Figure 13). Soils adjacent to gravel dams exhibited 83% higher infiltration capacity than mean site values. This may be due to sediment capture by the gravel strip. Soils in heavily vegetated areas also exhibited 26% higher infiltration rates over mean values. This effect could be attributed to structured porosity from plant roots or reduced surface compaction and sealing from raindrop impact. Similarly for the native soils, grassed areas had 15% greater infiltration rate over the mean values tested within the native soils. These results emphasize the important role vegetation plays in self-maintenance of soil based LID structures. Sediment influx can be limited by placement of a sediment trap. The structure acting as a trap at the entrance of the rain garden, infiltration rate near the entrance was 58% less than the site mean value, indicating that the structure was indeed capturing sediment that otherwise would be expected to.

In all LID structures, designers need to place special emphasis on spatial sediment loading. The ratio of impervious to pervious drainage area is a key factor in determining the likelihood that a porous media will become clogged. Sediment traps are an important element to include in areas that expect runoff from adjacent impervious areas to help decrease overall site clogging. Sediment traps should be designed to capture large volumes and be easily cleaned.

AMDI performance

The use of AMDIs on porous pavements in this study compared favorably with results from other studies using ring infiltrometers, despite being hypothesized that they would have a significantly slower rate due to the lack of a positive head condition (Huang, Valeo, He, & Chu, 2012). Individual AMDI tests had a high variation in infiltration rate due to the small footprint of the device not averaging out differences between abnormally clogged patches or preferential pathways. AMDI testing was found to be acceptable for the porous brick pavers tested in this study, but may not be a proper method to use when testing larger bricks such as the PaveDrain bricks identified previously due to the lack of a positive head condition and the contact sand likely becoming a limiting factor in infiltration rate. AMDI usage on engineered soils proved to support the original hypothesis better, most noticeably on the East Genesee rain gardens. The average infiltration rate from a double ring infiltration test was nearly four times the mean infiltration rate from AMDI testing. This was expected due to the soils having a more traditional infiltration curve found in the lab testing as opposed to the entirely sorptive linear curve obtained from the porous surfaces. The positive head condition helped drive the water through the smaller pore size of the engineered soils, which is not unrealistic for the particular site due to an overflow pipe being located approximately six inches above the soil surface.

Conclusion

The infiltration capacity of porous engineered materials commonly used in LID can vary widely between installations across a variety of LID systems. Material choice was found not to be the governing factor in infiltration performance. Rather, site design that limited debris clogging was found to have the greatest influence on performance for the tested permeable pavements and engineered soil gardens. Appropriate site design was found to effectively trap sediment in a way that facilitated maintenance of porosity at the site, whether by using porous pavements across the entirety of a parking lot, incorporating easy to clean large cracks such as with brick pavers, or by incorporating stone washout areas into a rain garden. These sediment loading zones effectively reduced clogging in the rest of the site so that the site as a whole could perform well. Poor infiltration performance in this study was largely attributed to the use of porous concrete as a material. Porous concrete was found to be severely degraded by winter chloride application which suggests that salt reductions were often not feasible and that the material is a poor choice in cold climate areas.

Infiltration values showed that porous pavements are capable of managing runoff from intense storms. With the exception of sites that suffered from high sediment loading due to a high impervious runoff ratio, all surveyed materials were found to not be the limiting factor in reducing urban runoff. This may change with long term degradation of materials.

This study has developed a baseline assessment of infiltration performance at several sites representative of many types of engineered LID surfaces. The results provide a basis to understand the long term impact on sediment trap zones to ensure that they are still functioning and not allowing sediment to escape into the rest of a site. Material degradation was observed in our study with porous concrete installations due to winter salting damage; it would be beneficial to see the long term performance of other materials in similar conditions to see if structural versus infiltration performance tradeoffs were appropriately made.

AMDIs were found to have comparable infiltration rates to ring infiltrometers in high porosity surface materials, but had lower infiltration rates in soils and materials that displayed a more traditional infiltration curve. AMDIs were suitable for performing large scale studies to achieve statistically significant results and identify spatial variability in surface properties. Further use of AMDIs and ring infiltrometers to measure infiltration capacity at site appropriate boundary conditions is recommended for future investigation of porous pavement performance.

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Vitae

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Monitored transient storage in green infrastructure designed to reduce the occurrence of combined sewer overflow events in Syracuse, NY. Developed sensors and devices for various parameters in real time.

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