Maintenance Measures for Preservation and Recovery of Permeable Pavement Surface Infiltration Rate – the Effects of Street Sweeping, Vacuum Cleaning, High Pressure Washing, and Milling

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Abstract

The surface infiltration rates (SIR) of permeable pavements decline with time as sediment and debris clog pore spaces. Effective maintenance techniques are needed to ensure the hydraulic functionality and water quality benefits of this stormwater control. Eight different small-scale and full-scale maintenance techniques aimed at recovering pavement permeability were evaluated at ten different permeable pavement sites in the USA and Sweden. Maintenance techniques included manual removal of the upper 2 cm of fill material, mechanical street sweeping, regenerative-air street sweeping, vacuum street sweeping, hand-held vacuuming, high pressure washing, and milling of porous asphalt. The removal of the upper 2 cm of clogging material did not significantly improve the SIR of concrete grid paves (CGP) and permeable interlocking concrete pavers (PICP) due to the inclusion of fines in the joint and bedding stone during construction, suggesting routine maintenance cannot overcome improper construction. For porous asphalt maintenance, industrial hand-held vacuum cleaning, pressure washing, and milling were increasingly successful at recovering the SIR. Milling to a depth of 2.5 cm nearly restored the SIR for a 21-year old porous asphalt pavement to like-new conditions. For PICP, street sweepers employing suction were shown to be preferable to mechanical sweepers; additionally, maintenance efforts may become more intensive over time to maintain a threshold SIR, as maintenance was not 100% effective at removing clogging material.

Keywords

Clogging; Low Impact Development (LID); Pervious concrete; Porous asphalt; Permeable interlocking concrete pavers (PICP); Stormwater

1 Literature Review

Less than half (46%) of the world's population resides in rural areas based on 2014 estimates; the rural to urban population shift is projected to continue and two-thirds of the world's population will reside in urban centers by 2050 (United Nations 2014). Urban development results in the introduction of impervious cover, which has been directly linked to stream health degradation (Wolman 1967; Morse et al. 2003; Schueler et al. 2009). Parking surfaces represent about 10% of the impervious surfaces in residential watersheds, and as much as 50% of imperviousness in commercial developments (Arnold and Gibbons 1996). In the United States, approximately 3500 km^2 of land is utilized for parking lots (Ben-Joseph 2012). Streets and sidewalks constitute 10-20% of commercial and residential land uses (Arnold and Gibbons 1996). Therefore, management of parking lot and roadway runoff through innovative stormwater control measures (SCMs), such as permeable pavement, is critical to watershed health and restoration of pre-development hydrology, which is the overall goal of Low Impact Development (LID; Dietz 2007; Page et al. 2015).

Permeable interlocking concrete pavers (PICP), pervious concrete, porous asphalt, and concrete grid pavers (CGP) have inherent permeability. In contrast to impermeable pavements, rainfall infiltrates and enters an underground storage reservoir. Depending on project goals and site conditions, the underground reservoir can be designed to provide extended detention, exfiltration into the underlying soil, or both (NCDENR 2012). Exfiltration systems recharge the groundwater (Brattebo and Booth 2003; Gilbert and Clausen 2006; Collins et al. 2008; Drake et al. 2014) and compared to conventional pavements, permeable pavements reduce runoff volume and peak rate while delaying peak flows (Pratt et al. 1989; Fassman and Blackbourn 2010).

Permeable pavements also provide a number of water quality benefits, including filtration and settling of sediment and sediment-bound pollutants (Roseen et al. 2012).

While many permeable pavement demonstration sites have been built and research into their water quality and hydrologic benefits completed, clogging and maintenance frequency and onerousness are commonly cited concerns with this SCM (Drake and Bradford 2013, Blecken et al. in press). Newly-installed permeable pavements provide surface infiltration rates (SIRs) well in excess of design rainfall rates, meaning they are capable of capturing and treating even infrequent return interval events (Bean et al. 2007, Al-Rubaei et al. 2013). However, build-up of sediment, organic material, and debris in the pavement and aggregate layers causes a decrease in the SIR, hampering hydraulic functionality. Factors such as particle size distribution of the runoff sediment, the pore size distribution of the void spaces, presence of trees, surrounding land use, and winter maintenance (e.g., sand application) have been suggested to influence clogging (Bean et al. 2007; Sansalone et al. 2008; Fassman and Blackbourn 2010).

Clogging can cause 100-fold or greater reductions in SIR of permeable pavements (Illgen et al. 2007). Two porous asphalt sites treating direct rainfall in northern Sweden had SIRs of 290 and 470 mm/min immediately after construction (Gyllefjord and Kangas, 1989; Bäckström and Bergström, 2000). After 2 years without maintenance, these rates had decreased to 19 and 9.5 mm/min, respectively. Without regular maintenance, pavement SIRs will continue to decrease. Seven years post-construction with no maintenance, eight PICP test sites in the Netherlands had SIRs between 3 and 37 mm/min (Boogaard et al. 2014a).

Because clogging hydraulically restricts water movement through the pavement, maintenance is needed to maintain pavement SIR. Research has, in most cases, shown clogging occurs near the pavement surface; removal of the upper 2.5 cm (Gerrits and James 2002) or 1.25-2 cm (Bean et al. 2007) of fill material resulted in significant increases in the SIR. Street sweeping is one form of recommended maintenance for permeable pavements (Baladès et al. 1995). Various types of street sweepers, including mechanical, regenerative air, and vacuum trucks, may be used to remove the clogging layer. The latter two types apply suction to the pavement, while mechanical sweepers only scarify the pavement surface. Drake and Bradford (2013) found the SIR of PICP responded more to vacuum-cleaning than did pervious concrete or porous asphalt, suggesting potentially more difficult remediation for the latter two pavement types.

Dougherty et al. (2011) studied a heavily clogged pervious concrete sidewalk, and found pressure washing (85 mm/min post-maintenance SIR) and pressure washing with power blowing (110 mm/min post-maintenance SIR) to be effective in rejuvenating pavement permeability. A porous asphalt in northern Sweden was maintained using truck-mounted vertical pressure washing and vacuum cleaning, with a subsequent increase in the mean SIR from 0.5 to 3.5 mm/min (Al-Rubaei et al. 2013). During destructive testing of PICP in Australia, Lucke (2014) showed sediment migrates to the bedding course beneath the PICP; the authors contended this is the reason efforts to return the SIR to newly-installed rates have not succeeded.

A laboratory study on clogging of pervious concrete by clay-laden runoff was conducted by Haselbach (2010). After four wet-dry cycles with clay-laden synthetic runoff, the SIR was reduced by minimum and maximum factors of 5 and 90, respectively. The SIR was substantially improved using surface sweeping and subsequent washing, albeit the SIRs never returned to their initial rates. Drake and Bradford (2013) also found various maintenance treatments (pressure washing, hand-held vacuuming, and street sweeping) for porous asphalt, pervious concrete, and

PICP only partially restored the SIR; these results suggest maintenance is not 100% effective at rejuvenating the SIR to like-new rates.

The purpose of this work was to test and compare different maintenance techniques for restoration of permeable pavement infiltration rates. While many permeable pavement applications constructed today accept run-on from impermeable pavement (as opposed to treating only direct rainfall), *none* of these have been examined for maintenance needs. All but two sites tested herein received run-on from impermeable pavement. Simulated maintenance was performed on PICPs and CGPs by removing the upper 2 cm of fill material. Full-scale maintenance was also undertaken on clogged PICPs using a mechanical street sweeper, regenerative air street sweeper, and a vacuum truck. Two clogged porous asphalt streets were maintained using pressure washing, vacuuming, and a combination of vacuum cleaning and pressure washing. Additionally, one of these streets was milled to three different depths (0.5 cm, 1.5 cm, and 2.5 cm) to test whether milling (and subsequent installation of new porous asphalt) could serve to rehabilitate porous asphalt and to determine the milling depth needed to remove the clogging layer.

2 Materials and methods

2.1 Site descriptions

To test the impact of maintenance on permeable pavement SIRs, nine permeable pavements up to 28 years old were visited during 2014 and 2015 (Table 1). The sites were located in North Carolina, USA (2); Ohio, USA (1); Växjö, southern Sweden (4); and Luleå and Haparanda, northern Sweden (2). At the Ohio site, two permeable pavement applications with different characteristics were located in the same parking lot. The sites in the United States were parking lots serving city or institutional facilities, parks, or community centers, while those in Sweden drained lightly trafficked residential or commercial streets. Sites were between 0.5 and 28 years of age at the time of maintenance and were paved with either porous asphalt, CGP, or PICP. Apart from the two porous asphalt roads in northern Sweden, all sites received run-on from impermeable asphalt. These designs are standard in North Carolina, Ohio, and Sweden where loading ratios (ratio of impermeable to permeable pavement) of 1:1, 3:1, and 5:1, respectively, are typically allowed in engineering design (ODNR 2006; NCDENR 2012). Further details on the sites in the United States, northern Sweden, and southern Sweden may be found in Winston et al. (2015), Al-Rubaei et al. (2013), and Al-Rubaei et al. (2015), respectively.

At each permeable pavement site, the SIR was monitored immediately before and after maintenance. During infiltration testing at all sites, the ambient air temperature was between 10 and 25°C. None of the sites received regularly scheduled maintenance other than occasional mechanical sweeping to remove detritus. Winter maintenance at the site in Ohio consisted of road salt application as needed and snow plowing following each winter weather event. In North Carolina, snowfall happened much more infrequently, and neither plowing nor salting was needed. In Växjö, Sweden, the PICP and CGP sites were treated with a mixture of salt and sand (0-8 mm diameter); in Haparanda, Sweden, the porous asphalt received five to 10 treatments with sand mixed with 2% salt to improve road conditions each winter, while in Luleå, fine gravel (2 – 4 mm) was applied two to four times each winter onto the street surface. At all Swedish sites, the sand or gravel was removed with a mechanical sweeper each spring after snow melt. At each site, 3-8 SIR testing locations were established for pre- and post-maintenance testing. For sites with multiple rounds of maintenance (e.g., Willoughby Hills, North Carolina Central

University [NCCU]), these initially chosen testing locations were utilized for all SIR tests. Testing locations were chosen to capture a diversity of potential clogging factors described in past research (e.g., run-on from impermeable surfaces, landscaped areas draining to permeable pavement, locations beneath trees, locations near intersections, etc.; Hunt 2011; Lucke and Beecham 2011). This included the permeable/impermeable interface (PII), or the location where run-on first enters the permeable pavement.

Table 1. Characteristics of the nine permeable pavement sites and types of maintenance performed.

Location	Pavement Type	Site Description	Year of Construction	Ratio of Impervious to Pervious Pavement Area (m^2/m^2)	Age at Time of Maintenance (Years)	Maintenance Methods	Number of SIR Testing Locations
Kockvägen, Luleå, Sweden	Porous asphalt	Residential street	1994	0	21	Vacuuming, pressure washing, milling	3
Åkergatan, Haparanda, Sweden	Porous asphalt	Residential street	1987	0	28	Vacuuming, pressure washing	3
Välluddevägen, Växjö, Sweden	PICP	Commercial street	2011	5:1	4	Manually remove upper 2 cm	3
Vaxthusgatan, Växjö, Sweden	PICP	Residential street	2006	5:1	9	Manually remove upper 2 cm	3
Kurortsvägen, Växjö, Sweden	CGP	Residential street	2005	5:1	10	Manually remove upper 2 cm	3
Schwerinvägen, Växjö, Sweden	CGP	Residential street	2004	5:1	11	Manually remove upper 2 cm	3
Willoughby Hills, OH, USA	PICP	Community center parking lot	2013	7.1:1, 2.2:1	0.75, 1.5	Vacuum truck	8
Durham, NC USA	PICP	Piney Wood Park parking lot	2014	1.8:1	0.5	Regenerative air street sweeper	6
Durham, NC USA	PICP	NCCU Law School parking lot	2013	6.5:1	1.25	Mechanical street sweeper, regenerative air street sweeper	5

2.2 Description of maintenance methods

Varying types of maintenance were performed across the nine sites. At the four Växjö, Sweden, sites, previous attempts at maintenance had included the use of a mechanical street sweeper (Bucher CityCat 5000) and a regenerative air street sweeper (Johnston Beam 800, Kelemit and Stenbeck 2012). However, the narrow width of the permeable pavement (approximately 1 meter wide) and its proximity to the curb prevented proper suction from being applied to the pavement. Since pre-maintenance testing conducted herein indicated all four sites in Växjö needed maintenance, a flat-head screwdriver was used to simulate maintenance by removing the upper 2 cm of fill material from either the PICP or the CGP (Figure 1). Bean et al. (2007) suggested this was the depth that could be removed using a street sweeper. The infiltrometer was then placed over the maintained area and post-maintenance tests were completed (Figure 1).


A B
C D
E F
G H
RS 850
Megawind
I J
K L

Figure 1. (A) Removal of the upper 2 cm of fill material from PICP and (B) installation of the infiltrometer over the maintained area. (C) Vacuuming, (D) pressure washing, (E) milling machine, and (F) milling test sections at the Luleå, Sweden, porous asphalt site. (G) Mechanical street sweeper at the NCCU site and (H) regenerative air street sweeper maintaining the Piney Wood site. (I) Elgin Megawind vacuum truck at Willoughby Hills and (J) using the vacuum hose to maintain constrained areas the truck cannot access. (K) ASTM surface infiltration rate tests on porous asphalt in Luleå, Sweden and (L) PICP in Växjö, Sweden.

At the Luleå and Haparanda porous asphalt sites in northern Sweden, three locations were established for triplicate testing of SIRs. Following SIR testing, three types of maintenance were randomly applied to each of the testing locations (Figure 1). The first was vacuum cleaning using a Dustcontrol DC 50-W industrial wet/dry vacuum. Because the sites were badly clogged and restorative maintenance was needed, the vacuuming lasted one minute. The second maintenance type was 30 seconds of high pressure washing (using a Nilfisk ALTO Poseidon 2-22 XT high pressure washer) at an approximately 30° angle to the asphalt surface. The final maintenance type was a combination of one minute of vacuuming followed by 30 seconds of pressure washing.

Milling of impermeable asphalt is a common maintenance practice aimed at improving the quality of the surface course of the pavement, extending its overall life (Frigio et al. 2014). Since past research (*inter alia* on the porous asphalt in Luleå and Haparanda) has shown most clogging material is captured near the permeable pavement surface (Lucke and Beecham 2011; Al-Rubaei et al. 2013; Yong et al. 2013), milling could potentially be used to remove the clogging layer, restoring system performance. New porous asphalt could then be overlain. To test this idea, milling of the porous asphalt at Luleå was completed at two locations and three depths: 0.5 cm, 1.5 cm, and 2.5 cm. The milled sections were cleaned with a pressure washer prior to post-maintenance SIR testing to remove fines created by the milling process (Figure 1).

At the NCCU site, the PICP was found to be heavily clogged (median SIR of 1 mm/min) during SIR testing on October 6, 2014. Two days later, an Advance RS850 mechanical street sweeper was brought to the site and made 5 passes over the entire parking lot (Figure 1). This type of street sweeper applies pressure to the surface of the pavement through rotating bristles, dislodging material accumulated in the interstitial spaces. It did not apply suction to the pavement surface. Infiltration testing was then completed and the SIRs were found to still be unsatisfactory (median SIR of 2.4 mm/min); the following day a TYMCO 600 regenerative air street sweeper performed maintenance by making 3 passes over the entire lot (Figure 1). After the first pass and at the two most heavily clogged testing locations, mechanical agitation was also applied to the interstitial spaces using a pocket knife to dislodge clogging sediment prior to street sweeping. Post-maintenance SIR testing was then completed. At Piney Wood Park, a TYMCO 600 regenerative air street sweeper made 5 passes over the permeable pavement, in some cases stopping over heavily clogged areas (Figure 1).

During the first two years following construction, the Willoughby Hills, Ohio, PICP site required maintenance on two occasions, which was performed using an Elgin Megawind vacuum truck (Figure 1). The first maintenance effort occurred approximately 10 months after construction after surface runoff was observed and consisted of 1 pass with the vacuum truck over the entire parking lot. The second maintenance effort occurred 11 months later with 3 passes over the entire lot. The operator used the 30-cm diameter vacuum hose to clean constrained areas the truck could not access as well as right-angle corners (Figure 1).

2.3 Data collection

The single ring, constant head test described in ASTM C1781 for PICP (ASTM 2013) was utilized to measure the SIR. A 30-cm diameter metal infiltrometer was sealed to the pavement surface using plumber's putty to prevent lateral leakage (Figure 1). To create an effective seal, plumber's putty was applied to both the inner and outer edges of the infiltrometer. A known volume of water was poured from a nearly-full bucket (typically about 19 liters) into the infiltrometer; water was transferred by pouring as close to the pavement surface as possible to prevent dislodging of the crusted clogging material near the pavement surface. The water level was kept at an approximately constant head of 10 to 15 mm above the pavement surface within the infiltrometer. The total time to infiltrate the known volume of water was recorded, and the SIR calculated as the quotient of the total depth of water applied within the infiltrometer to the time (e.g., mm/min). Duplicate SIR tests were carried out at each testing site both before and after maintenance.

For heavily clogged permeable pavements (<0.1 mm/min), the duration of the ASTM test exceeded 1 hour (Winston et al. submitted). To expedite testing, the ASTM methods were modified slightly: water was poured into the infiltrometer for 15 minutes using the ASTM C1781 procedure. If the entire volume in the bucket could not be infiltrated within that time, no additional water was added; the elapsed time was then recorded at the completion of the test. Then, the remaining volume of water in the bucket was recorded and subtracted from the initial volume to determine a total volume infiltrated. The SIR was then calculated as described previously. This testing method resulted in maximum test durations of approximately 1 hour.

For maintenance tests completed in Sweden (pressure washing, vacuuming, pressure washing with vacuuming, milling, and removal of the upper 2 cm of fill material), three SIR tests were completed at each monitoring location pre- and post-maintenance; two such tests were performed for street sweeping.

2.4 Data analysis

Summary statistics for pre- and post-maintenance SIR were tabulated and explored using boxplots. All data analysis was completed using R version 3.1.2 (R Core Team 2015). A criterion of 95% confidence (α=0.05) was used for this research unless otherwise stated.

Since pre- and post-maintenance infiltration testing occurred at the same locations on each permeable pavement, paired statistical tests were utilized to determine significance. Duplicate measurements at each testing location were included in the analysis. Normality was determined using quantile-quantile plots and the Shapiro-Wilk test. If data were normal or log-normal, a Student's t-test was used. Otherwise, a non-parametric test (e.g., Wilcoxon signed-rank) was employed. This procedure was utilized for all sites except Luleå and Haparanda.

Pre- and post-maintenance data sets at Luleå and Haparanda were compared using one-way analysis of variance (ANOVA) to determine if differences among maintenance treatments were significant. Treatments included pressure washing, vacuuming, and vacuuming with pressure washing: each was run in triplicate at three separate locations on each porous asphalt roadway. Additionally, ANOVA was used to test for differences in the SIR among various depths of milling (0.5 cm, 1.5 cm, and 2.5 cm) at Luleå. If the omnibus test was significant, then post-hoc pairwise comparisons were made using paired t-tests with a Bonferroni adjustment as well as Tukey's Honest Significant Difference (HSD) test.

3 Results and Discussion

3.1 Degradation of permeable pavement SIR without regular maintenance

The Haparanda and Luleå sites were constructed in 1987 and 1994, respectively. Surface infiltration testing was undertaken immediately following construction, approximately 2 years after construction [Gyllefjord and Kangas (1989) and Stenmark (1995)], and at various times in the past 20 years (data collected in Bäckström and Bergström (2000), Al-Rubaei et al. (2013), and herein). Surface infiltration rate data were regressed against age for 21 and 28 year old porous asphalt pavements in Northern Sweden (Luleå and Haparanda; Figure 2). In Haparanda, the porous asphalt had never been maintained since construction, while in Luleå, regular vacuuming of the asphalt surface was conducted during the first years of operation; however, no maintenance had been conducted for at least the past ten years. An exponential decay in SIR with time fit the data well ($R^2 = 0.89$), with infiltration rates declining to less than 0.1 mm/min. In Australia and the Netherlands, research has shown an exponential decay of SIR as a function of age of the permeable pavement, reaching 8.5-17 mm/min within 3-4 years (Boogaard et al. 2014b). Sansalone et al. (2008) also found an exponential model fit the clogging process. The results of this study confirm past research and suggest maintenance is needed to ensure long-term functionality of permeable pavements. Before widespread adoption of permeable pavements can be achieved, reliable maintenance techniques must be developed to restore pavement SIR and prevent hydraulic failure.

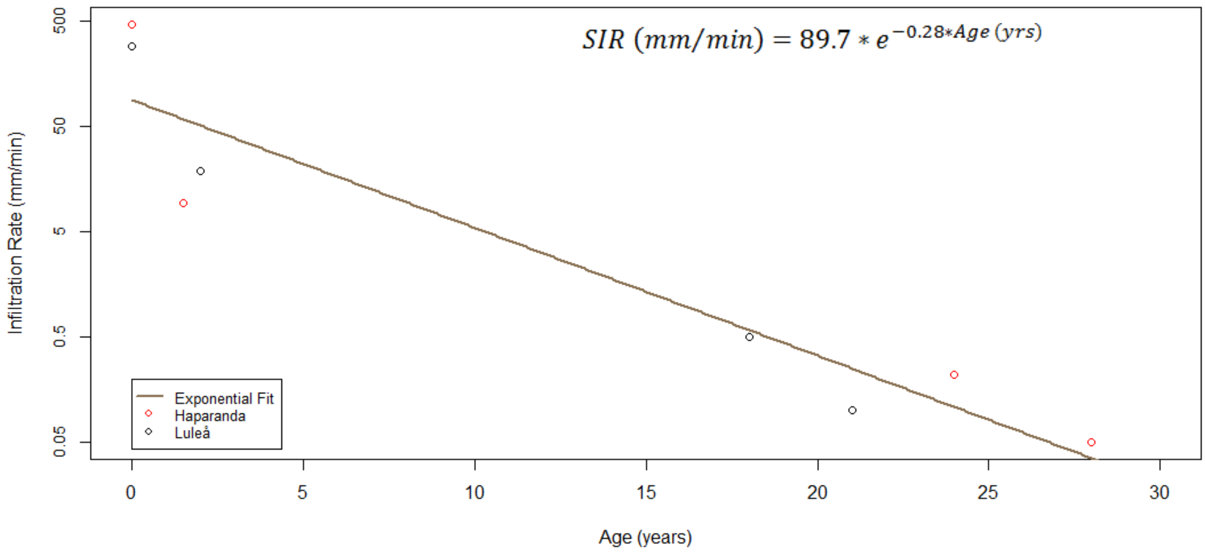

Figure 2. Infiltration rate as a function of age for two porous asphalts in northern Sweden. Data from Gyllefjord and Kangas (1989), Stenmark (1995), Bäckström and Bergström (2000), Al-Rubaei et al. (2013), and herein.

3.2 Small-scale maintenance tests on CGP and PICP

Simulated maintenance was performed at four sites in Växjö, Sweden, to see if removal of the upper 2 cm of sediment and aggregate material from the joint space of the CGP and PICP would improve the SIR (Figure 1). Prior to maintenance, the median SIRs at three of the sites in Växjö (2.6, 3.2, and 6.1 mm/min; Figure 3) were similar to those measured three years earlier by Al-Rubaei et al. (2015), suggesting maintenance at these sites was needed. At Växthusgatan, pre-maintenance infiltration rates were ten times higher than those measured three years prior by Al-Rubaei et al. (2015). In general, the variability of the SIR was attributed to improper construction which caused heterogeneity at this site. As described in Al-Rubaei et al. (2015), the PICP and CGP joints in Växjö were erroneously filled with unwashed aggregate (0-8 mm diameter) instead of the 4-8 mm aggregate typical of infiltration system design in this part of Sweden.

Student's t-tests on the paired pre- and post-maintenance data showed no significant improvement in the SIR for the PICP and CGP sites in Växjö, Sweden (all p-values>0.625; Figure 3). These results are in contrast with similar tests conducted by Bean et al. (2007) and James and Gerrits (2003), which both showed at least partial rehabilitation of permeable pavement SIR through removal of the upper 2-2.5 cm of clogging material. The purported reason for this was the incorrect aggregate material installed over the entire depth of the pavement layer (10 cm for PICP and CGP). So, the removal approximately the upper 20% of the joint material made no appreciable difference in SIR since fines were present throughout the 10-cm cross-section due to installation errors. This highlights the need for construction supervision during permeable pavement installation, as incorrect installation was not overcome with maintenance.

At Kurortsvägen, one block of CGP was removed and two additional infiltration tests were performed on the 0-8 mm bedding layer (approximately 5 cm thick underlain by a geotextile with a #57 aggregate (4.75-25 mm) base course beneath the geotextile). Mean IR for the bedding layer was 2.4 mm/min, suggesting unwashed aggregate had also been utilized for this layer. The median IR for the #57 aggregate beneath the geotextile was 1770 mm/min. To remediate the performance of this SCM, the pavers, joint stone, geotextile, and bedding course would all need to be removed. Similar IR testing was performed on the aggregate beneath the CGP at Schwerinvägen. Median IR for that aggregate was 164 mm/min, compared with the average pre-maintenance SIR of 6.1 mm/min. The Schwerinvägen results suggest restorative maintenance *could be* performed on CGP and PICP (through removal of paving and replacement of aggregate layers) until measured infiltration rates reach desired values, followed by reinstallation of aggregate and paving materials. Because an inappropriate fill aggregate was used in Växjö, no routine maintenance would have restored these CGP installations; thus, results do not imply that the maintenance method itself is inappropriate.

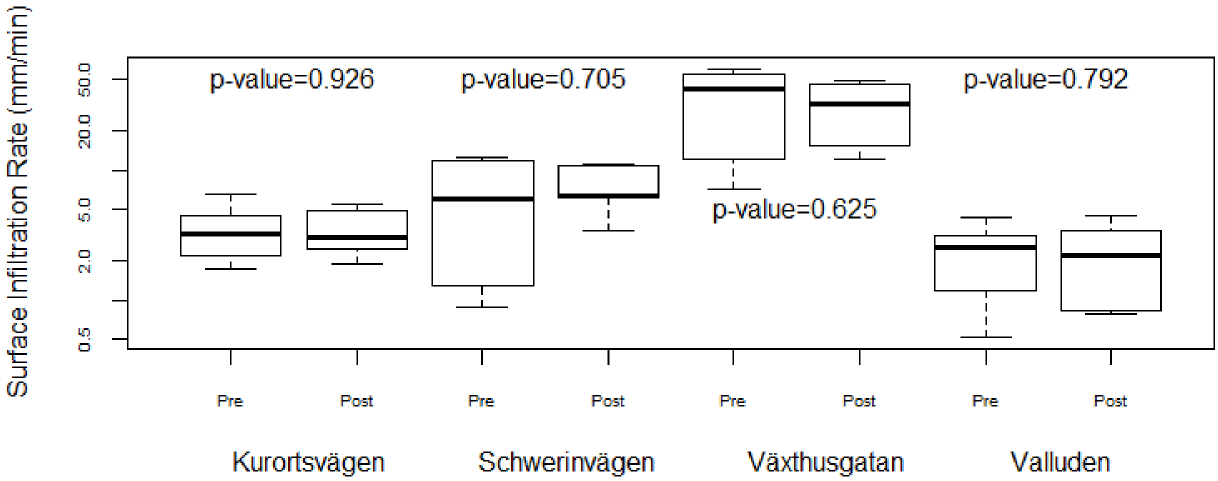

Figure 3. Surface infiltration rates (mm/min) of four permeable pavements in Växjö, Sweden pre- and post-simulated maintenance. Kurortsvägen and Schwerinvägen were paved with CGP, while Växthusgatan and Valluden utilized PICP.

3.3 Pressure washing and vacuuming of porous asphalt

Street sweepers with suction have been successfully utilized to dislodge sediment and other clogging materials from permeable pavements (Baladès et al. 1995; Al-Rubaei et al. 2013; Drake and Bradford 2013). However, two 21- and 28-year old porous asphalts in northern Sweden (Luleå and Haparanda) that had been previously maintained with a high-pressure washer/vacuum cleaner truck had post-maintenance SIRs that were either only partially restored (in Luleå) or were unaffected (in Haparanda, see Al-Rubaei et al. [2013] for details). Therefore, three other methods of maintenance were performed at these sites, including an industrial hand vacuum, pressure washing, and a combination of vacuuming followed by pressure washing (Figure 1).

Because these porous asphalts were badly clogged prior to maintenance (median SIRs <0.1 mm/min), these maintenance efforts were an attempt at restoration of system performance.

ANOVA tests for the pre-maintenance data sets at each site showed no significant differences (p-values>0.45) in SIR, suggesting existing conditions were similar where the treatments were to be applied. All maintenance treatments produced significantly greater SIRs than pre-maintenance conditions (Figure 4 and Table 2). ANOVA tests on the log-transformed post-maintenance data sets showed significant differences between the treatments at both Luleå (p-value = 0.0064) and Haparanda (p-value = 0.0067). Significant differences were observed between the pressure wash vs. vacuum treatments (p-values = 0.0087, 0.0328) and the pressure wash+vacuum vs. vacuum treatments (p-values = 0.0231, 0.0082) at both sites. No significant difference (p-values = 0.76, 1) was observed between the pressure wash vs. pressure wash+vacuum treatment at either site. While the vacuum treatments did improve the SIR substantially and significantly (3.5 and 6-fold increases in the SIR at the two sites), pressure washing as part of any treatment provided the 'lion's share' of the benefit to the porous asphalt SIR (Figure 4). Treatments involving pressure washing increased SIRs by a minimum of 8-fold and a maximum of 467-fold (bracketing the 20-fold increase observed for combined power washing and power blowing utilized in pervious concrete maintenance by Dougherty et al. [2011]). Drake and Bradford (2013) observed 1-fold to 81-fold increases in SIR through pressure washing of porous asphalt, pervious concrete, and PICP. Chopra et al. (2010) also observed substantial increases in pervious concrete SIR through pressure washing.

Following street sweeping with vacuum cleaning and pressure washing, the mean infiltration rate post-maintenance at Luleå was only 3.48 mm/min (Al-Rubaei et al. 2013). Ten-fold greater

SIRs were achieved in this study by using a hand-held pressure washer; perhaps the lower angle of water application (30° in this study vs. normal to the pavement surface with a street sweeper) more easily dislodged accumulated sediment. Luleå pavement SIRs were restored to a much greater extent than those of Haparanda. This might be due to the apparent larger pore diameter in cores obtained from the two porous asphalt pavements at Luleå (Al-Rubaei et al. 2013), allowing the water from the pressure washer to more deeply penetrate the pavement and dislodge sediment.

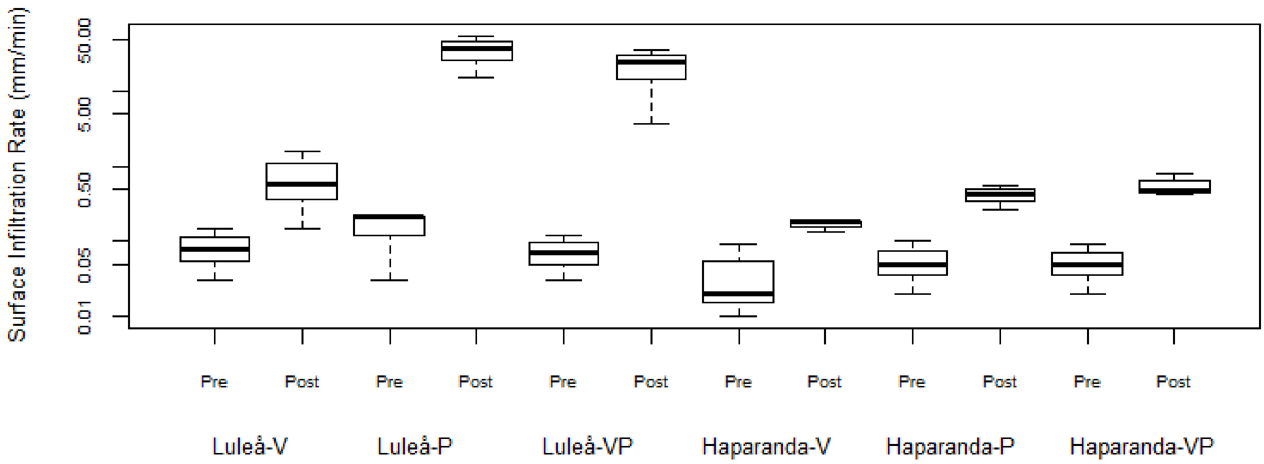

Figure 4. Effects of vacuuming (V), pressure washing (P), and vacuuming with pressure washing (VP) on porous asphalt SIR.

Table 2. Summary statistics for effects of various maintenance techniques on porous asphalt SIRs in Sweden.

Site	Maintenance Type	Number of Tests	Range (mm/min)	Median (mm/min)	Mean (mm/min)	σ (mm/min)
Kockvägen, Luleå	Pre-maintenance	9	0.03-0.22	0.08	0.10	0.07
	Vacuuming	3	0.15-1.6	0.57	0.77	0.75
	Pressure washing	3	15.7-55.0	37.4	36.0	19.7
	Vacuuming + pressure washing	3	3.71-35.0	24.8	21.2	16.0
	0.5 cm milling	6	11.0-140	71.5	73.5	67.3
	1.5 cm milling	6	17.4-153	84.1	84.5	70.6
	2.5 cm milling	6	145.5-351	243	245	104
Åkergatan, Haparanda	Pre-maintenance	9	0.01-0.1	0.05	0.05	0.03
	Vacuuming	3	0.13-0.18	0.18	0.16	0.03
	Pressure washing	3	0.27-0.56	0.43	0.42	0.14
	Vacuuming + pressure washing	3	0.43-0.8	0.48	0.57	0.20

3.4 Milling of porous asphalt

Commonly, the majority of sediment accumulates near the surface of a permeable pavement (Balades et al. 1995; Bean et al. 2007; Shirke and Shuler 2009; Al-Rubaei et al. 2013). Complete removal of the surface clogging layer might be a viable maintenance option. Standard asphalt is milled as a common maintenance practice to rejuvenate the pavement condition without needing to reconstruct the entire road cross-section (Bausano et al. 2004). Three depths of milling (0.5 cm, 1.5 cm, and 2.5 cm, Figure 1) were tested at two test sections of the Luleå porous asphalt roadway to see whether milling restored the SIR. Following milling, pressure washing removed debris created by the milling process.

The pre-milling SIR did not vary among the testing locations (ANOVA test, p-value = 0.939), and little variability existed in the pre-maintenance pavement SIR (Figure 5 and Table 2). The ANOVA p-value (0.0244) suggested statistically significant differences in SIRs existed between the different milling depths . No significant difference existed between the SIR for the 0.5 cm and 1.5 cm (p-value = 0.87) or the 1.5 cm and 2.5 cm milling treatments (p-value = 0.07). However, the 2.5 cm milling treatment produced a significantly better SIR (p-value = 0.027) than the 0.5 cm milling treatment. All post-milling SIRs were significantly better than those for pre-milling, and post-milling SIRs were at least 3 times greater than pre-milling SIRs. Post-milling SIRs also were at least twice those for pressure washing maintenance treatments at the same site.

Milling to a 2.5 cm depth appeared to be the best treatment, producing SIRs roughly three times those for the 0.5 and 1.5 cm milling depths. In fact, the median infiltration rate of 243 mm/min for the 2.5 cm milling depth was essentially the same as for that porous asphalt immediately after construction (290 mm/min, Stenmark 1995), 21 years prior to the milling. The marginal increase in the SIR from 0.5 to 1.5 cm milling depth suggested little sediment was present between 0.5-1.5 cm below the pavement surface. However, clearly additional clogging factors were eliminated when milling to a 2.5 cm depth. Three possible explanations for this exist: (1) sediment accumulated at 1.5-2.5 cm depth (not likely based on core samples presented in Al-Rubaei et al. (2013); (2) asphalt binder draindown restricted flow at 1.5-2.5 cm depth (Mansour and Putman 2013), or (3) removing 2.5 cm of asphalt allowed the pressure washer to penetrate more deeply into the bedding course, since the pre-milled pavement thickness was 4.5 cm. Considering all factors, milling (regardless of depth) appeared to be the best method tested for rejuvenation of (even completely) clogged porous asphalt SIRs.

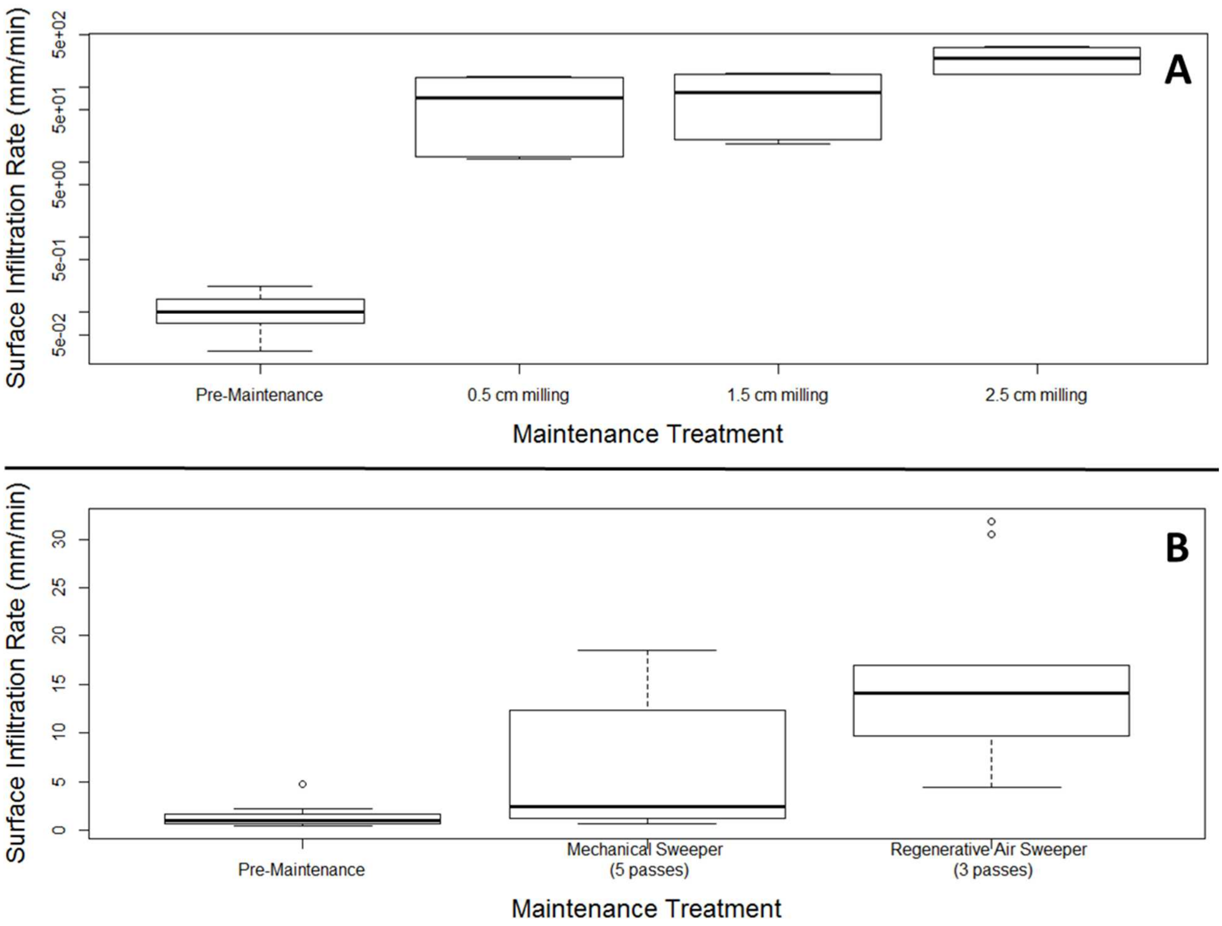

Figure 5. (A) Effects of milling on porous asphalt SIR at Luleå, and (B) effects of standard mechanical and regenerative air street sweepers on the SIR of PICP at NCCU in Durham, NC.

3.5 Street sweeping

Since street sweeping is an oft-suggested practice for maintenance of permeable pavements (Drake et al. 2013), a variety of methods of street sweeping were tested at NCCU, Piney Wood, and Willoughby Hills to determine their impact on the SIR.

Two street sweeper types were applied over a two-day period at the NCCU site: mechanical street sweeping followed by regenerative air street sweeping (Figure 1). While mechanical sweepers are not recommended for PICP maintenance due to their lack of suction, this most-prevalent type of sweeper was initially used to maintain the badly clogged site (median pre-maintenance SIR of 1.0 mm/min; Figure 5 and Table 3). Five passes were made over the entire parking lot with the mechanical sweeper, which produced a significant (350%) increase in the SIR (p-value 0.0293) to a median value of 2.40 mm/min. Observations showed mechanical sweeping dislodged only the uppermost 6-13 mm of clogging material. The SIR did not improve at the most heavily clogged measurement location. Using a hose, water was applied to the PICP surface, and surface runoff still occurred; therefore, further maintenance was scheduled the following day using a regenerative air street sweeper (Figure 1).

The regenerative air street sweeper removed, on average, the upper 5 cm of clogging material and aggregate with only 3 passes over the parking lot. However, similar to Drake and Bradford's (2013) results, removal of aggregate and sediment did not occur to a consistent depth and was highly spatially variable. SIR testing was performed immediately following this second round of maintenance, and significant improvement of the SIR was measured (p-value = 0.0035). The median SIR increased to 14.1 mm/min, a 14-fold increase over the pre-maintenance rates and a 5-fold increase over the post-mechanical street sweeper maintenance rates (Figure 5). Median SIRs pre- and post-maintenance suggested greater improvement in pavement hydraulics was provided by the regenerative air street sweeper, which was able to dislodge the clogging material at deeper depths than the mechanical street sweeper. However, the median post-maintenance SIR of 14.1 mm/min was much less than those of newly-installed PICP, which can range from 310-680 mm/min (Bean et al. 2007). None of these maintenance techniques was able to fully restore pavement hydraulics to original SIRs. Results suggest permeable pavements receiving run-on from impermeable pavements should be maintained with street sweepers providing suction, similar to the results of past studies (Baladès et al. 1995; Bean et al. 2007; Shirke and Shuler 2009).

Table 3. Summary statistics for pre- and post-maintenance SIRs using various types of street sweepers on PICP.

Site	Maintenance Type	Number of Tests	Range (mm/min)	Median (mm/min)	Mean (mm/min)	σ (mm/min)	p-value	Statistical Test
NCCU	Pre-maintenance	10	0.44-4.71	1.00	1.41	1.28	-	-
	5 passes mechanical sweeper	10	0.65-18.5	2.40	6.38	6.71	0.0293	Student's t-test
	3 passes regenerative air sweeper	10	4.45-31.9	14.1	15.7	9.07	0.0035	Student's t-test
Piney Wood	Pre-maintenance	6	1.3-10.8	1.76	3.43	3.69	-	-
	5 passes regenerative air sweeper	6	9.4-165	154	111	75.4	0.0167	Student's t-test
	Pre-maintenance	6	135-315	231	229	77.7	-	-
	1 pass regenerative air sweeper	6	103-193	143	146	36.7	0.0975	Student's t-test
Willoughby Hills	Pre-maintenance	16	1.54-361	64.4	100	108	-	-
	1 pass vacuum Truck	16	33.9-381	173	173	114	0.0148	Student's t-test
	Pre-maintenance	16	0.81-190	4.39	36.4	63.7	-	-
	3 passes vacuum truck	16	8.52-699	148	202	192	0.0020	Student's t-test

At Piney Wood, maintenance was performed using a regenerative air street sweeper (Figure 1) in the fall of 2014. The three testing locations within 2 m of the PII had pre-maintenance SIRs ranging from 1.3 to 10.8 mm/min (Figure 6 and Table 3). These three locations were swept 5 times by the street sweeper, with the sweeper moving slowly and stopping over heavily clogged areas. Personnel observed the pavement surface under the moving street sweeper to determine the depth to which the clogging material was removed. Following maintenance, the median SIR significantly increased from 1.76 to 154 mm/min, an 86-fold increase. However, this SIR is still below rates for newly installed PICP, estimated to be 310-680 mm/min (Bean et al. 2007). Additionally, one of the three locations nearest the PII had a post-maintenance SIR of 10 mm/min, which is still less than the desirable range for sites treating run-on (based on observed surface runoff from the PICP during rainfall and simulated rainfall using a garden hose for locations with SIRs less than 20 mm/min). These results reaffirmed what Drake and Bradford (2013) suggested: regenerative air street sweepers are not capable of restoring heavily clogged permeable pavements to like-new SIRs. They surmised frequent maintenance will be needed to maintain acceptable SIRs at sites receiving high particulate loading.

The other three SIR monitoring locations at Piney Wood were at least 5 m from where run-on entered the PICP and were therefore less susceptible to clogging (Brown and Borst 2013; Al-Rubaei et al. 2015). Pre-maintenance, their median SIR was 231 mm/min and by visual inspection little clogging material was present in the interstitial spaces. Due to the high SIR, only one pass was made over these locations with the regenerative air street sweeper. This pass made no significant difference in SIR; thus, the number of passes and speed at which passes are made affect maintenance success. Multiple passes over heavily clogged areas, even stopping the truck to allow the suction to have maximum effect, may be desirable as a single pass made no discernable difference in the SIR. The spatial variability in clogging at Piney Wood (mostly related to the PII) suggests simple, quick, and reliable infiltration tests are needed to determine areas of a permeable pavement lot needing maintenance (Lucke et al. 2015; Winston et al. submitted).

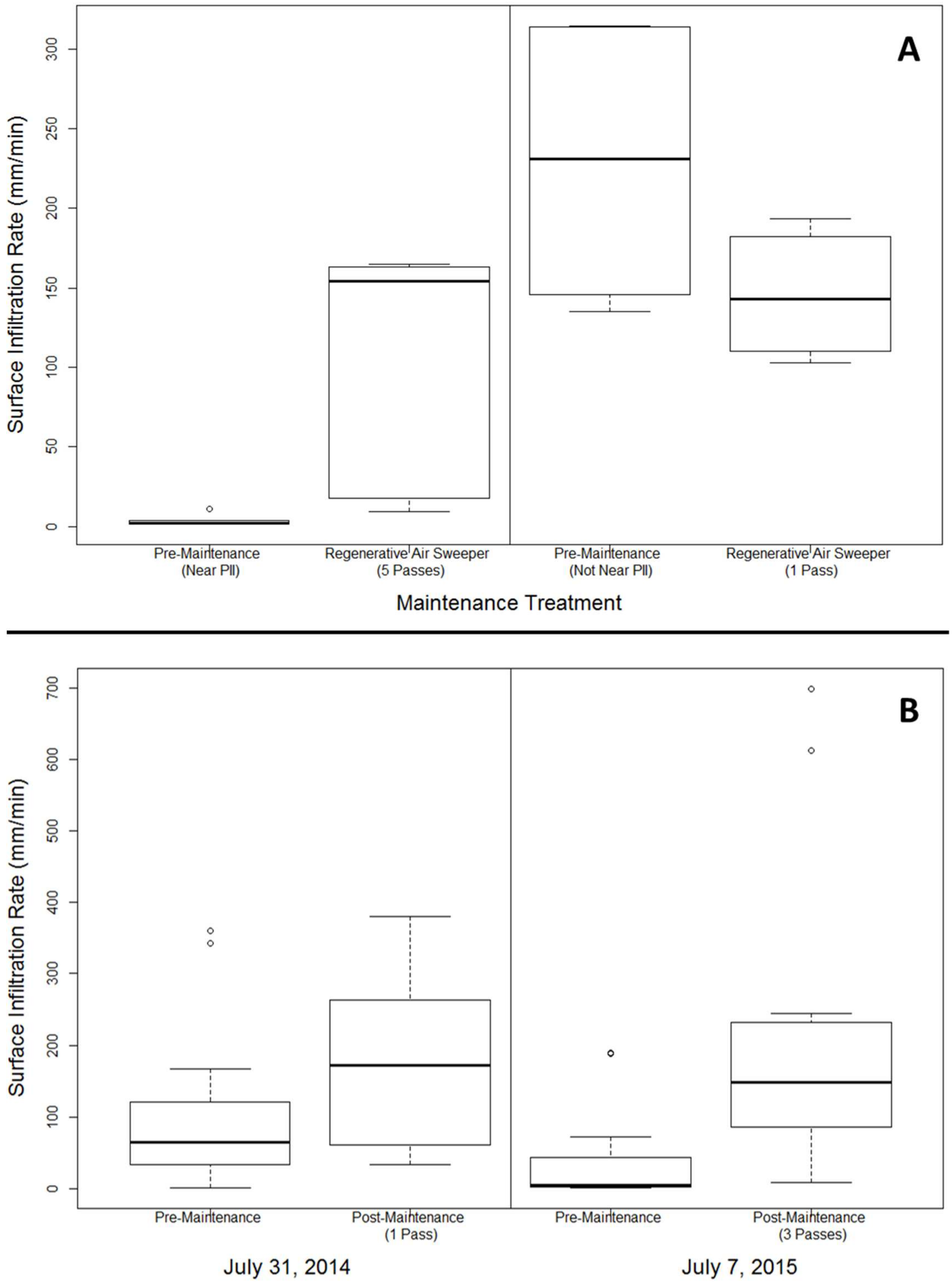

Figure 6. (A) The spatial extent of clogging at Piney Wood, Durham, NC and the effects of a regenerative air street sweeper on the SIR, and (B) improvement in the SIR through the use of a vacuum truck at Willoughby Hills, Ohio.

Similar pre- and post-maintenance infiltration testing was undertaken at Willoughby Hills using an Elgin Megawind vacuum truck (Figure 1) during July 2014 and again in July 2015 (Figure 6 and Table 3). This type of sweeper provides greater suction with dual suction hoses (86 kW provided by the engine at 2400 RPM) than the regenerative air street sweeper (one suction and one blower hose; 74 kW at 2400 RPM) used to maintain the NCCU and Piney Wood sites. Maintenance in July 2014 consisted of one pass over the entire parking lot, with replacement of stone in the interstitial spaces following maintenance. The median pre-maintenance SIR was 64.4 mm/min, but the three locations receiving run-on from impermeable asphalt (located <1 m from the PII) had SIRs <20 mm/min; surface runoff was observed during a small, minimally intense rainfall event at these locations (5 mm depth, 0.15 mm/min peak intensity). Post-maintenance, the median SIR increased significantly by 168% to 173 mm/min. While five of the eight monitoring locations had substantial increases in SIR post-maintenance (up to 8-fold), three did not. One of these sites was not clogged prior to maintenance (median SIR 352 mm/min), because it received no run-on. The other two locations were located less than 1 m from the PII, suggesting more than one pass with a vacuum truck may be needed to dislodge clogging material from heavily clogged locations. Given the large hydraulic loading to these locations (impervious flow path lengths of 21 and 42 m), frequent and intensive maintenance (perhaps the removal of the pavers and some of the bedding course, where clogging material also accumulates [Lucke and Beecham 2011]) will be needed to keep sites along the PII from failing hydraulically. This also suggests designers should be conservative when directing run-on to permeable pavement; higher run-on ratios will lead to quicker clogging and higher maintenance burden.

Following another year of rainfall, the SIRs at Willoughby Hills had degraded substantially to a median value of 4.39 mm/min; SIRs at 5 of the 8 sites were below 6 mm/min. Maintenance was completed using the same vacuum truck, but this time making 3 passes over the parking lot. In the most-clogged areas, this method was unable to uniformly remove 5 cm of clogging material; although, a sufficient number of clogged gaps were rejuvenated to allow water to pass at higher rates. Following maintenance, median SIR for the site significantly improved to 148 mm/min, a 33-fold increase. However, these rates were still significantly (at the $\alpha = 0.10$ level) below the median SIRs (173 mm/min) measured the prior year post-maintenance. In this case, more intensive maintenance produced lower infiltration rates, suggesting each maintenance effort is not 100% effective. Thus, in order to realize a similar post-maintenance SIR, maintenance intervals may become shorter as the pavement ages. At some point, major restorative maintenance, including removal of the pavers, interstitial stone, and portions of the bedding course may be needed to prevent surface runoff.

For locations most susceptible to clogging (i.e., nearest the PII), the vacuum truck and regenerative air street sweepers similarly restored SIRs. The caveat is that the vacuum truck required one or three passes to restore median SIR to 150-175 mm/min at Willoughby Hills. At Piney Wood, 5 passes with the regenerative air street sweeper were needed to achieve similar median SIR (150 mm/min). This suggests the vacuum truck was more efficient for maintenance due to its greater suction.

3.6 Effects of maintenance on retention of design rainfall intensities

One of the purported benefits of permeable pavements is the potential for peak flow mitigation during design storm events, since the aggregate reservoir can be designed to detain and slowly release stormwater through the underdrain (Drake et al. 2014; ASCE 2015). However, this benefit is lost if stormwater cannot infiltrate the pavement during extreme rainfall intensities. Design rainfall intensities were obtained for small, parking lot watersheds (i.e., time of concentration of 5 minutes) for annual recurrence intervals (ARI) between 1-year and 100-years (SWWA 2011; NOAA 2014) for all locations tested herein. These rainfall intensities were utilized to calculate the peak flow rate of runoff draining or falling onto each permeable pavement installation using the Rational Method (Kuichling 1889). The calculated peak flow rate was compared against the measured SIR at each testing location both pre- and post-maintenance. While this comparison assumed even flow distribution, in reality preferential flow onto permeable pavement occurs due to site slopes and concentration of flow along curbs and parking lot islands.

The fraction of the SIR monitoring locations able to completely infiltrate rainfall intensities with ARIs between 1-yr and 100-yr, which are typically used for flood control (Nehrke and Roesner 2004), are listed in Table 4. For each monitoring location (e.g., 12 monitoring locations at Piney Wood pre-maintenance), the percentage of the 100-yr design rainfall intensity which could be infiltrated was calculated as the quotient of the infiltration rate and the aforementioned rainfall intensity.

$$\%(100 - yr\ storm\ infiltrated) = \frac{SIR_{Meas,i}}{Q_{p,100}} \times 100 \quad (1)$$

where $SIR_{Meas,i}$ is the measured SIR at the i^{th} measurement location at a permeable pavement site and $Q_{p,100}$ is the peak flow rate from the 100-yr ARI storm event. This yielded a range of values for each site/monitoring period combination, since the pavement SIR was highly spatially variable (Table 4). While none of the monitored permeable pavements had enough void space in the aggregate to detain the 100-yr event, this method is still valuable to evaluate the predicted infiltration performance under potential engineering designs for peak flow mitigation.

At three of the four sites in Växjö, Sweden, more intense design rainfall events were able to be completely infiltrated following maintenance. However, Växthusgatan was the only site where the fraction of the 100-yr storm that could be infiltrated changed substantially, where at minimum 61% of this storm could be infiltrated post-maintenance as opposed to 36% pre-maintenance.

Results from Luleå and Haparanda showed vacuuming with a hand-held industrial vacuum had a modestly positive effect on runoff capture, but vacuuming was not as effective as high pressure washing (Table 4). While improvements in the SIR at Haparanda were significant and substantial when pressure washed, the pre-maintenance infiltration rates were so low that the site remained unable to infiltrate the 1-yr design rainfall intensity post-maintenance. Any depth of milling allowed the porous asphalt at Luleå to completely infiltrate the 100-yr design rainfall intensity.

Street sweeping increased the fraction of monitoring locations able to completely infiltrate design rainfall intensities, albeit the standard mechanical sweeper did so modestly (Table 4). The vacuum truck appeared to be able to best restore the pavement SIRs at locations with heavy clogging, such as near the PII. In general, well-maintained permeable pavements are capable of reducing the peak runoff rate through storage in the subgrade aggregate; without maintenance, clogged permeable pavement will provide little to no peak flow mitigation.

Table 4. Fraction of the SIR monitoring locations theoretically able to infiltrate design rainfall intensities and the range of the fraction of the 100-yr storm theoretically able to be infiltrated at all monitoring locations.

Site Name and Location	Monitoring Period	1-yr, 5-min	2-yr, 5-min	5-yr, 5-min	10-yr, 5-min	25-yr, 5-min	50-yr, 5-min	100-yr, 5-min	Percentage of 100-yr Storm Infiltrated
Kurortsvägen, Växjö, Sweden	Pre-maintenance	2/6	1/6	0/6	0/6	0/6	0/6	0/6	9-33%
	Post-maintenance	2/6	1/6	0/6	0/6	0/6	0/6	0/6	9-27%
Schwerinvägen, Växjö, Sweden	Pre-maintenance	3/6	3/6	2/6	2/6	2/6	0/6	0/6	4-62%
	Post-maintenance	5/6	5/6	2/6	2/6	0/6	0/6	0/6	17-55%
Växthusgatan, Växjö, Sweden	Pre-maintenance	6/6	6/6	5/6	5/6	5/6	4/6	4/6	36-100%
	Post-maintenance	6/6	6/6	6/6	6/6	6/6	4/6	4/6	61-100%
Valluden, Växjö, Sweden	Pre-maintenance	0/6	0/6	0/6	0/6	0/6	0/6	0/6	3-21%
	Post-maintenance	1/6	0/6	0/6	0/6	0/6	0/6	0/6	4-22%
Gammelstad, Luleå, Sweden	Pre-maintenance	0/9	0/9	0/9	0/9	0/9	0/9	0/9	1-5%
	Hand vacuuming	1/3	1/3	1/3	0/3	0/3	0/3	0/3	4-40%
	Pressure washing	3/3	3/3	3/3	3/3	3/3	3/3	3/3	100%
	Vacuuming + pressure washing	3/3	3/3	3/3	3/3	3/3	3/3	2/3	92-100%
	0.5 cm milling	6/6	6/6	6/6	6/6	6/6	6/6	6/6	100%
	1.5 cm milling	6/6	6/6	6/6	6/6	6/6	6/6	6/6	100%
	2.5 cm milling	6/6	6/6	6/6	6/6	6/6	6/6	6/6	100%
Åkergatan, Haparanda, Sweden	Pre-maintenance	0/9	0/9	0/9	0/9	0/9	0/9	0/9	0.3-4%
	Hand vacuuming	0/3	0/3	0/3	0/3	0/3	0/3	0/3	3-5%
	Pressure washing	0/3	0/3	0/3	0/3	0/3	0/3	0/3	7-14%
	Vacuuming + pressure washing	0/3	0/3	0/3	0/3	0/3	0/3	0/3	11-20%
Piney Wood, Durham, NC, USA	Pre-maintenance	7/12	7/12	7/12	7/12	7/12	7/12	7/12	13-100%
	Post-maintenance	12/12	12/12	12/12	12/12	12/12	11/12	11/12	91-100%
NCCU, Durham, NC, USA	Pre-maintenance	0/10	0/10	0/10	0/10	0/10	0/10	0/10	2-17%
	Post-maintenance (mechanical sweeper)	2/10	1/10	0/10	0/10	0/10	0/10	0/10	2-68%
	Post-maintenance (Regenerative Air)	4/10	2/10	2/10	2/10	2/10	2/10	2/10	16-100%
Willoughby Hills, OH, USA	Pre-maintenance	15/16	14/16	14/16	14/16	14/16	14/16	13/16	5-100%
	Post-maintenance (vacuum truck 1 pass)	16/16	16/16	16/16	16/16	16/16	16/16	16/16	100%
	Pre-maintenance	8/16	6/16	6/16	5/16	4/16	4/16	4/16	4-100%
	Post-maintenance (vacuum truck 3 passes)	16/16	16/16	16/16	16/16	15/16	15/16	15/16	76-100%

4 Summary and conclusions

Nine permeable pavement sites in four climatic regions and two countries were utilized for testing of various maintenance treatment technologies. Between 3-8 monitoring locations were established at each site for pre- and post-maintenance SIR testing to evaluate (1) locations expected to clog quickly and (2) reference locations without clogging stimuli. Maintenance treatments included manual removal of the upper 2 cm of clogging material, hand-held vacuum cleaning, pressure washing, a combination of vacuum cleaning and pressure washing, milling of porous asphalt, and three different types of street sweeping. Maintenance was performed on CGP, PICP, and porous asphalt pavements. The following conclusions are gleaned from this work:

1) Manual removal of the upper 2 cm of clogging material at the Växjö, Sweden, CGP and PICP sites did not provide significant improvement in the pavement SIR. This was due to errors in construction, where fines were present in the entirety of the joint stone and the bedding course, vastly diminishing the pavement SIRs. Routine maintenance cannot overcome poor construction practices and the lack of construction supervision.

2) Hand-held industrial vacuum cleaning, pressure washing, and a combination of vacuum cleaning and pressure washing all significantly improved the SIR of two clogged porous asphalt sites in northern Sweden. Treatments with pressure washing were significantly different from vacuuming alone. At Luleå, median post-maintenance SIRs were 0.57 mm/min for the vacuuming treatment, and 24.8-37.4 mm/min for treatments involving pressure washing. Treatments with pressure washing were able to infiltrate larger design rainfall intensities than those with vacuuming only. This suggested appropriately applied pressure washing was capable

of restoring porous asphalt permeability, especially if applied at a low angle to the pavement surface.

3) Milling of the porous asphalt at Luleå was tested to restore SIR at three different depths: 0.5 cm, 1.5 cm, and 2.5 cm. All depths of milling were successful in restoring the pavement SIR to a median rate of at least 70 mm/min. The 2.5 cm milling depth yielded a median SIR of 243 mm/min, near the 290 mm/min infiltration rate measured immediately after construction (21 years earlier). This was the only maintenance technology tested that was capable of rejuvenating the pavement SIR to nearly-newly installed rates. These results suggest milling and subsequent reinstallation of a porous asphalt is a viable option to restore porous asphalt permeability. Further, these results confirmed the clogging layer in this porous asphalt occurred within the uppermost 2.5 cm of the pavement surface.

4) Three types of street sweepers (mechanical, regenerative air, and a vacuum truck) were utilized to maintain PICP in North Carolina and Ohio, USA. All methods of maintenance produced significantly higher post-maintenance SIRs. However, maintenance of the NCCU site on successive days with a mechanical sweeper followed by a regenerative air sweeper showed that suction provided by the latter more deeply penetrates clogging layers and, therefore, the SIR benefits. For monitoring locations with high debris loading (i.e., near the PII, beneath trees, etc.), maintenance needs are more intensive than locations with few clogging stimuli. Multiple passes with a regenerative air street sweeper or vacuum truck, and even stopping over heavily clogged locations, were needed to create acceptable post-maintenance SIRs. At Willoughby Hills, maintenance regimens were performed with a vacuum truck and were separated by one year. To reach similar post-maintenance SIRs (median 150-175 mm/min), one pass with the

vacuum truck was needed during the first maintenance effort; 3 were needed one year later. To maintain a desired threshold SIR, the frequency of permeable pavement maintenance will likely increase with time.

5) To mitigate peak flows from flood-inducing events, permeable pavements must have surface infiltration rates exceeding expected peak flow rates from the catchment and have enough void space in the aggregate to detain and slowly release stormwater. In nearly every case evaluated herein, maintenance with vacuuming, pressure washing, milling, or street sweeping increased the frequency with which a permeable pavement could completely infiltrate a design rainfall intensity. Additionally, all maintenance treatments except the simulated maintenance performed in Växjö allowed a greater fraction of the 100-yr storm to infiltrate the pavement surface than during pre-maintenance conditions.

6) Since the Luleå and Haparanda sites treated only direct rainfall [while the other locations had run-on ratios ≥ 1.8:1 (ratio of impermeable:permeable pavement)], the loading of sediment onto these pavements was much less, resulting in less frequent maintenance needs. Diminishing the run-on ratio will result in a reduced maintenance burden. Concentrated flow to a permeable pavement should be avoided in engineering design because maintenance will be onerous and frequent to ensure pavement hydraulic performance.

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