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UNIVERSITY OF TORONTO

Maintenance Equipment Testing on Accelerated Clogged Permeable Interlocking Concrete Pavements

Prepared for: Interlocking Concrete Pavement Institute Foundation for Education and Research

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EXECUTIVE SUMMARY

Permeable interlocking concrete pavements (PICP) allow stormwater to infiltrate directly through aggregate-filled joints. The lack of proven cost-effective and practical approaches for permeability restoration prevents the wide-spread adoption of PICP systems in Canada (and North America). *Novel and practical* maintenance and operational methods, supported by scientifically-based proof of effectiveness, are needed. Better methods explicitly tailored for PICP is needed so that the required interval between maintenance events can be lengthened and thereby reducing overall lifecycle costs.

The University of Toronto conducted this study at a PICP test pad, constructed in 2017, located at the Toronto and Region Conservation Authority's (TRCA) Kortright Centre for Conservation in Vaughan, Ontario. The test pad included seven 3 m by 3 m (10 ft by 10 ft) PICP cells constructed with a generic grey concrete paver arranged in a herringbone pattern. A perforated pipe drained the PICP cells.

Five test cells were clogged with street sweepings graded to match clogging sediments sampled from mature PICP parking lots within the Greater Toronto Areag. The test cells we clogged over several weeks over the summer in 2017 through a controlled accelerated clogging procedure developed by UofT researchers. Surface infiltration capacity was measured following ASTM C1781 procedures, and restorative maintenance was considered required when mean surface infiltration measurements approached 250 mm/hr (10 in/hr) which is generally equivalent to a 98% overall reduction in original surface infiltration rates. Subsequently, each cell received restorative maintenance. Five different maintenance treatments were tested including a high pressurized-air and vacuum system, regenerative air street sweeping, power washing followed by vacuuming, vacuum street sweeping and waterless mechanical street sweeping.

One test cell was clogged with a mixture of street sweeping and clayey soils and maintained with the high pressurized-air and vacuum system to explore the impact that cohesive sediments have on maintenance effectiveness. Finally, one test cell was treated with early and repeated maintenance with a regenerative air street sweeper.

Study Findings

The results of this study demonstrate that all maintenance techniques significantly restore the pavement's surface infiltration capacity. Under some conditions, high pressurized-air and vacuum systems as well as vacuum street sweepers can restore surface infiltration to its original post-construction condition. Key findings of this research include the following:

Controlled Accelerated Clogging

- A new simple-to-implement and repeatable methodology to clog PICP pavement was developed for this research and was successfully used to clog several test cells to similar pre-maintenance conditions. Using this procedure, researchers and equipment manufacturers can test, evaluate and compare maintenance equipment and experimental results.

Restorative Maintenance

- Only the high pressurized-air and vacuum system fully restored the PICP to its baseline, post-construction, surface infiltration. The high pressurized-air and vacuum system produced mean surface infiltration measurements that were 2 – 6 times higher than all other tested techniques and restored PICP surface infiltration capacity to 109% of its original condition (approx.. 12,900 mm/hr or 508 in/hr). Joint aggregates were replaced following maintenance but not compacted which likely caused the higher than post-construction SI measurements.
- The vacuum street sweeper produced the second-highest amount of surface rejuvenation but also generated the most variable results. Although surface infiltration was restored to original (or higher) conditions at some locations, on average, the PICP's surface infiltration capacity was approximately 7,500 mm/hr (295 in/hr) or 70% of original SI conditions, post-maintenance. Individual surface infiltration measurements ranged from 1,280 mm/hr (50 in/hr) to 13,900 mm/hr (547 in/hr).
- The waterless mechanical street sweeper restored the PICP's surface infiltration capacity to 35% of its original condition. Post-maintenance surface infiltration capacity was approximately 3,540 mm/hr (139 in/hr). As mechanical street sweeping technologies continue to advance, its suitability as a maintenance option for PICP must continue to be re-evaluated.
- The pressure washing, followed by manual vacuuming, restored surface infiltration capacity to 25% of its original condition. This method is a manual operation and is best suited for small areas, with equipment that is readily available to owners and operators of PICP.
- The regenerative air street sweeper produced the smallest improvement in surface infiltration, restoring only 20% of the pavement's permeability. These results suggest that regenerative air street sweepers are not a preferred approach for restorative maintenance when other maintenance techniques (such as those evaluated in this study) are available.

Joint Penetration Depth

- Joint penetration depth was a strong indicator of overall maintenance effectiveness when comparing PICP clogged with similar source materials, but not when comparing pavements clogged with different source materials.
- The orientation of street sweeper vehicle and suction/collection heads greatly influenced the amount of joint materials removed by the treatment.

Cohesive Soils

- The presence of cohesive soils significantly decreased the effectiveness of restorative maintenance. The high pressurized-air and vacuum system were only able to restore the PICP's surface infiltration capacity to approximately 50% of the pavement's original surface infiltration conditions when cohesive sediments were included. In contrast, this equipment was able to fully restore a PICP's surface when only non-cohesive materials were used.

Early and Repeated Maintenance

- Not surprisingly, applied maintenance was more effective when conducted repeatedly and earlier. After two cycles of accelerated clogging (9.3 kg of applied sediment) and maintenance, the regenerative air sweeper restored the PICP to 40% of baseline surface infiltration conditions. In contrast, when used for restorative maintenance (9.3 kg of applied sediment), the regenerative air sweeper was only able to restore the surface to 20% of its baseline surface infiltration conditions.
- With each clogging cycle, the impact of maintenance declined when using a regenerative-air streetsweeper, and surface infiltration steadily decreased. Thus, more intensive restorative maintenance is eventually required.

Recommendations for further research on PICP maintenance are provided.

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1.0 BACKGROUND AND OBJECTIVES

Permeable pavements provide on-site quantity and quality control of stormwater. Quantity control is achieved through infiltration, temporary detention and some evaporation of stormwater. Quality control is achieved through several processes, including stormwater capture, filtration, sorption, and biodegradation. Researchers have evaluated long term quantity and quality performance [1]–[5], surface infiltration rates [6], permeable pavement types [7], infiltration over low permeability soils [8], clogging [9]–[11] and urban heat island effects [12], [13]. In Ontario, the benefits of permeable interlocking concrete pavements (PICP) on parking lot stormwater quality have been demonstrated at the Kortright Centre for Conservation [14]. Monitoring of this site revealed that, relative to asphalt runoff, permeable pavement effluent contains substantially reduced concentrations of many common pollutants including suspended solids, heavy metal, petroleum-based hydrocarbons, and some nutrients [14]. Despite the proven environmental benefits, PICP remains a niche product in Canada. Due to a lack of national regulations providing an incentive for PICP use, the Canadian interlocking paver industry lags dramatically behind the U.S. In the United States, 4.8% of all pavers sold are permeable pavers, whereas in Canada, on 1.8% of sold pavers are permeable [15]. Increased use of permeable pavements has been slow because consumers are concerned about winter performance and long-term operational and maintenance costs.

Permeable pavements remove stormwater pollutants through filtration and consequently, infiltration capacity declines over time with the accumulation of sediments within the permeable surface. As per the 2015 ASCE permeable pavement book [16], there are two types of permeable pavement maintenance: *routine* and *restorative*. This study addresses restorative maintenance only. Restorative maintenance is defined when a permeable pavement's surface infiltration capacity decreases below 250 mm/hr.

The lack of proven cost-effective and practical approaches for permeability restoration prevents the wide-spread adoption of PICP systems in Canada (and North America). For PICP, a pavement's infiltration capacity is a function of joint spacing and block patterns [17]. Maintenance testing to restore surface permeability of PICP has found inconclusive results. Some researchers [18] recommended washing pavement surfaces with a fire hose or power hose to rejuvenate permeable pavements while others [19], [20] have observed surface restoration from vacuum sweeping. More recent studies [21] have found surface vacuuming alone failed to improve on infiltration capacity. Pre-treatment practices, including pressure washing and power brushing, have also been tested [22]. *Novel and practical* maintenance and operational methods, supported by scientifically-based proof of effectiveness, are needed. Better methods explicitly tailored for PICP is needed so that the required interval between maintenance events can be lengthened and thereby reducing overall lifecycle costs.

The objective of this research is to test effective restorative maintenance practices for Permeable Interlocking Concrete Pavements (PICP) winter operations. This research addresses the following objectives:

1. Investigate alternative and pre-treatment practices to increase the effectiveness of maintenance for restoring surface infiltration capacity.

2. Investigate the role of sediment characteristics (cohesive vs non-cohesive) and cleaning frequency on the effectiveness of restoration practices
3. Develop best management practices for hydraulic surface restoration of PICP.

Throughout the project, the emphasis of the hydraulic surface restoration investigations changed from ‘alternative and pre-treatment practices’ to an assessment of different mechanical approaches to cleaning (e.g. high pressurized-air, suction, sweeping, pressurized washing). This change emerged at the request of the industry partners as these cleaning approaches are appropriate maintenance solutions for PICP.

2.0 STUDY SITE

A 21 m by 3 m (69 ft by 10 ft) PICP test pad with a partial infiltration system was constructed at the Toronto and Region Conservation Authority (TRCA) Living City Campus (Kortright) in Vaughan, ON, during the summer of 2017. Coloured pavers subdivided the pad into seven 3 m x 3 m cells as shown in Figure 2-1 and Figure 2-2. A cross-sectional layout is provided in Figure 2-3. The pavers were 120 mm by 240 mm by 80 mm thick (4.75 in by 9.5 in by 3 in) Enviro Midori (supplied by OAKS by Brampton Brick) marble grey with a 7.5 mm (0.3 in) spacer bar and laid in a 90° herringbone pattern with site-cast concrete for edging. A drawing of the paver is provided in Appendix A. The construction followed the Interlocking Concrete Pavement Institute (ICPI) design guidelines and those in ASCE 68-18 on PICP. This included a 50 mm (2 in) thick ASTM No. 8 bedding layer, a 100 mm (4 in) thick ASTM No. 57 base layer, a 150 mm (6 in) thick ASTM No. 2 subbase layer, geotextile and an underdrain. The joints were filled with ASTM No. 8 aggregate and, on average, had widths of 7.8 mm ± 1 mm (0.31 in ± 0.04 in). Surface openings were 10% of the total PICP surface area. All the aggregate for the construction of PICP cells were washed. A 100 mm (4 in) diameter perforated underdrain was installed in an approximately 100 mm (4 in) deep sump below the subbase and bedded within ASTM No. 57 stone. A permeable geotextile (Mirafi RS380i) with a flow rate of 3,463 l/min/mm (85 gal/min/ft^2), a permittivity of 1.2 per second and an apparent opening size of 0.30 mm was installed below the subbase and underdrain to separate the aggregates from the native soil. The PICP cells allowed for partial infiltration into the native low permeability soils, which had saturated hydraulic conductivity of approximately 2 mm/hr (0.08 in/hr). The pavement was covered and blocked from foot traffic in December of 2017 to avoid unmonitored transportation of sediment to the PICP surface.

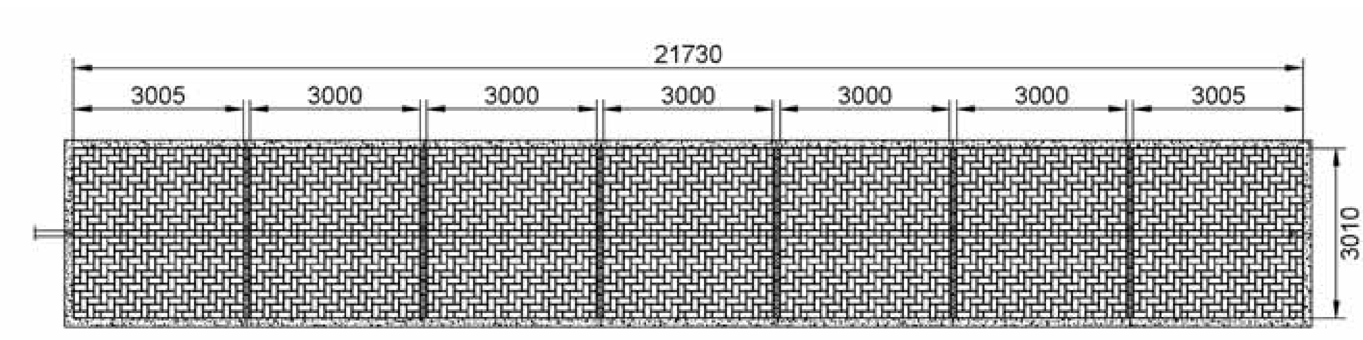

Figure 2-1: Layout of the test pad. Dimensions are shown in mm.

Figure 2-2: Test pad following construction (Aug 18th, 2017).

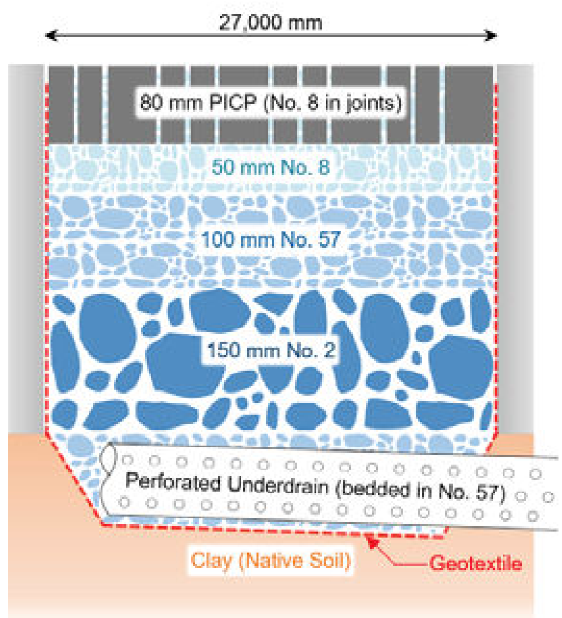

Figure 2-3: Cross-sectional layout of PICP

The joint widths, i.e., the separation space between two pavers, were measured in all cells. Ninety measurements were taken using digital callipers (0.2 mm accuracy), surrounding fifteen random pavers over the area of each PICP cell, seen in Figure 2-4. No joint width measurements were taken close to the edge of the cells because maintenance vehicles did not reach that portion. Table 2-1 below summarizes the descriptive statistics generated for the joint spacings.

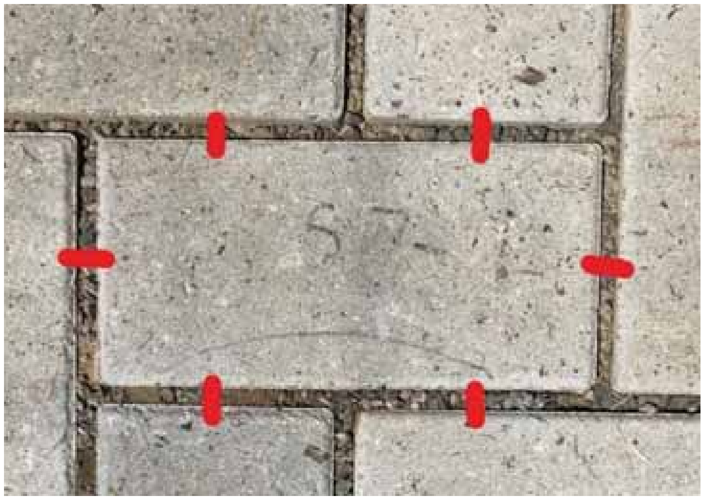

Figure 2-4: Joint width measurement locations for fifteen pavers in each cell.

Table 2-1: Descriptive statistics generated for joint spacings (mm) in all cells

Statistic	Cell 1	Cell 2	Cell 3	Cell 4	Cell 5	Cell 6	Cell 7
Mean	7.7	7.7	7.7	7.7	7.6	8.3	8.3
Median	7.6	7.6	7.6	7.7	7.5	7.9	8.1
Stand. Dev.	0.6	0.6	0.6	0.6	0.7	1.6	1.1

3.0 METHODS

3.1 Baseline Conditions

Surface infiltration rate (SIR) was measured before applying clogging materials to establish baseline conditions. ASTM C1781 procedure was used for all infiltration measurements with one minor modification, where modelling clay was used instead of plumber's putty. As per ASTM C1781 SIRs are calculated using the equation below:

$$SIR\ (mm/hr) = (K*m) / (d^{2}*t)$$

Where

- K is the conversion factor in SI unit 4,583,666,000 (mm^3•s/kg•hr),
- m is the mass of water that infiltrates inside the ring (kg),
- d is the diameter of the infiltration ring that is used for the test (mm),
- and t is the amount of time that it takes for the mass of water m to infiltrate inside the ring (s).

Three different rings, numbered 1-3, with slightly different diameters, were used in SIR testing. The ring used to conduct the first SIR test at each location was also used to carry out all subsequent SIR tests at that location. Table 3-1 summarizes the ring numbers and their diameter. The PICP was assumed to be fully clogged (i.e. SIR less than 250 mm/hr (10 in/hr)) and classified as a censored or non-detect measurement when a pre-wetting test ran longer than 30 min (i.e. SIR less than 91 mm/hr (3.6 in/hr) – 118 mm/hr (4.6 in/hr)) or when the infiltration test ran longer than 90 min (i.e. SIR less than 30 mm/hr (1.2 in/hr) – 40 mm/hr (1.6 in/hr)). Censored infiltration measurements were estimated using statistical processes with the NADA: Nondetects and Data Analysis for Environmental Data package [23] in the statistical language and environment R [24]. Detection limits calculated based on pre-wetting tests have more conservative values (i.e., higher rate set as a minimum).

Table 3-1: Diameter and the lower detection limit for every ring used in SIR testing.

Ring Number	Diameter (mm)	Detection Limit (mm/hr)	
		Cut-off at Pre-Wetting Stage (30 min)	Cut-off at Testing Stage (90 min)
1	318	91	30
2	298	103	34
3	278	118	40

On each cell, SI was measured at five locations (Locations 1 – 5, Figure 3-1) after construction in November 2017 and re-checked in July 2018 before starting the accelerated clogging.

SIR was measured at Locations 1 – 5 following each application of clogging materials. Four additional tests (locations 6 – 9, Figure 3-1) were performed on each cell to assess the overall SIR of the cells better and to evaluate if the repeated SIR tests collected during the accelerated clogging had created any localized effects on SIR measurements.

Figure 3-1: Surface infiltration test locations in each cell.

3.2 Controlled Accelerated Clogging of the PICP

This study aimed to create uniform clogged pavement conditions for restorative maintenance under an accelerated timeline using a synthetically prepared, realistic clogging material. The joints of each PICP cell received six applications of street sweepings prepared at UofT labs. Street sweeping waste material of different size ranges was separated through sieving and mixed to match the gradation of joint sediment collected from three mature PICP parking lots.

The sampling procedure followed practices described in Gerrits and James [10] and Winston et al. [21]. At each sampling location, 600 – 800 g of sediment and aggregates were manually dislodged with a screwdriver from the top 3 cm of the PICP joints and collected with a canister vacuum cleaner. A new disposable vacuum bag was used for each test. Vacuum bags were weighed and labelled in the lab before use. Vacuum bags were placed in Ziploc bags and sealed to avoid loss of any fines during transportation to the lab. All sediment samples were analyzed for gradation as per the procedure outlined in ASTM C136 [25]. Clumped materials were not broken apart with a pestle and mortar because this process would damage organic material (twigs and leaf litter) that was also collected and mixed in the PICP joints. Figure 3-2 presents the gradation of the sediment found in the joints of the sampled PICP sites (Appendix B). The gradation results confirmed Hill and Beecham's [26] observation that although particles of all class ranges are involved in the clogging of PICP, courser particles play an important role in the process. An average of the gradation of the sediment found in the PICP joints at all three PICP locations (A, B and C) was used in preparing the clogging sediment used to clog the PICP test pad synthetically.

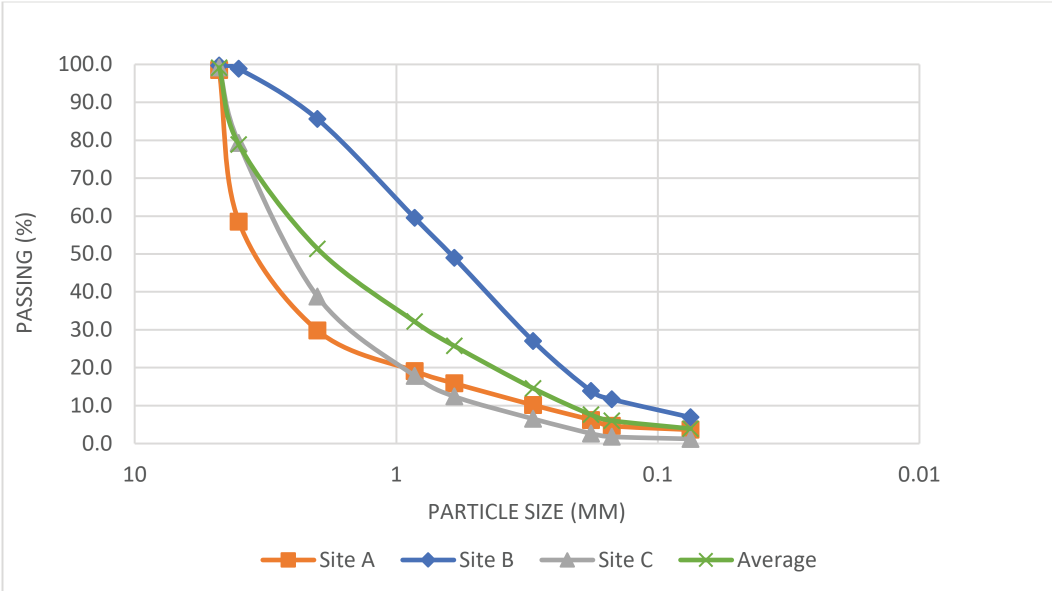

Figure 3-2: Particle size distribution of the sediment collected from within PICP joints.

Waste materials were collected from local city yards, i.e. where street sweepers dump their waste and used for the accelerated synthetic clogging of the PICP test pad. Street sweeping waste material was collected and transported in plastic buckets, dried in the oven overnight at 110° C and sieved following ASTM C136 [25]. Clogging mixes were then prepared with following the average sediment gradation found at the mature PICP parking lots. Similarly, clumped materials were not broken apart with a pestle and mortar.

Synthetic clogging of the test pad was completed between August 14, 2018, to September 24, 2018, weekly. Joint rows and columns were labelled and measured (Figure 3-3). Sediment for individual joint rows and columns was weighed, then placed in small jars at the site and applied by hand directly over the joints (Figure 3-4). After the application of sediment, water was applied gently with a watering can (enough to wet pavement and all the sediment) to prevent wind erosion of the newly applied sediment (Figure 3-4). Sediment application was always completed on dry days. Initially, each joint received 0.1 g of sediment for every 1 cm of joint, which was the slowest rate at which sediment could be consistently applied to the joints. After two applications of sediment, the application rate was increased to 0.2 g/cm to ensure that the test pad was clogged to the desired levels within the set project timeline. On average, approximately 11 kg of sediment was required to clog each of the 9 m^2 PICP cells.

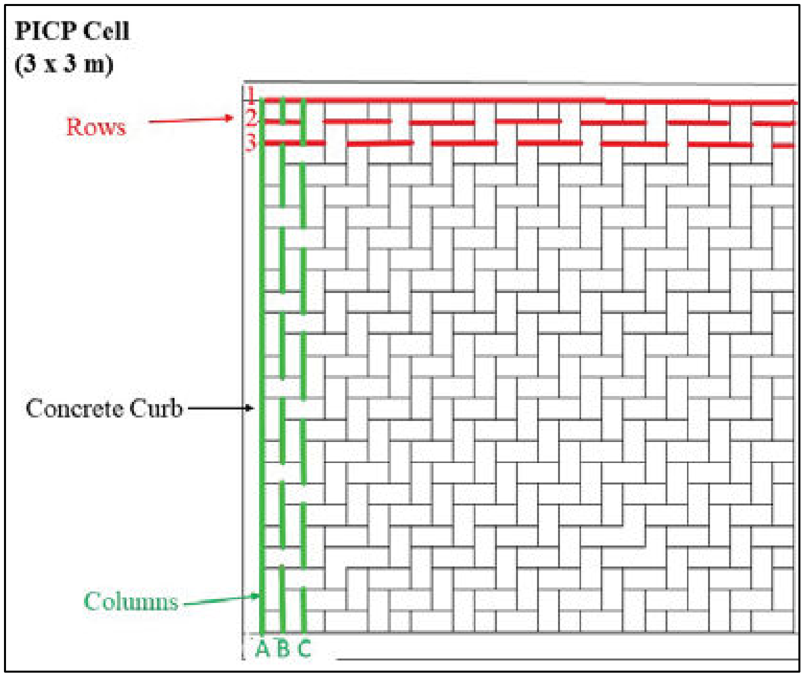

Figure 3-3: PICP joints divided into rows and columns.

Figure 3-4: Clogging procedure: A) pre-weighing sediment before application; B) pre-weighted sediment for every row and column; C) application of sediment over joints; D) application of water to move sediment into the joints.

The final target SIR for the test pad was 250 mm/hr, as this is when restorative maintenance is recommended by ICPI. SIRs were measured 24 hours following each application of sediment. Appendix C summarizes the pavement synthetic clogging schedule. After three applications of sediment, it was observed that sediment was spilling out of the joints and onto the pavers (Figure

3-5). Since the target SIR had not yet been reached, a lightweight plate compactor was applied over the pavement to consolidate the sediment further into the joints. Immediately after, water was applied to facilitate the movement of sediment further down into the joints. SIRs were measured again before the next application of sediment.

Figure 3-5: Visual inspection of the PICP joints after the third round of clogging before compaction

3.3 Restorative Maintenance Treatments (Cells 1 – 5)

Each PICP cell was treated by a different maintenance technique including three types of street sweepers: a regenerative air sweeper (Tymco DST-6®), a vacuum sweeper (Elgin WhirlWind®), a mechanical sweeper (Elgin Waterless Eagle®), pressure washing followed by manual vacuuming and specialized two-piece high pressurized-air and vacuum system (Typhoon® and Pavevac®). The Tymco DST-6® is a regenerative air street sweeper that operates by forcing pressurized-air to the pavement on one side and recycling the air through a suction head (2.2 m) on the other side. Tymco DST-6® has a 132 cm sweep path. The Elgin WhirlWind® is a vacuum street sweeper with a suction head (0.81 m) and a trailing arm broom on each side and has a sweep path of up to 366 cm. The Elgin Waterless Eagle® is a dry mechanical sweeper that includes two gutter brooms on each side and the main broom mounted at the rear of the vehicle. The sweeper has a conveyor belt as the primary collection mechanism and has a sweep path of 305 cm. The Typhoon® and Pavevac® are designed for the maintenance of PICP that consisted of a specialized blower head (0.61 m) and a vacuum head (0.71 m), that is connected to a trailered air compressor (200 psi) and a vacuum truck respectively. Figure 3-6 includes a picture of each maintenance technique, and Table 3-3 summarizes the tested maintenance techniques. During each test, adjacent cells were covered with plywood for protection. Only one pass was allowed for each technique.

Figure 3-6: Street sweepers (A, B) Tymco® DST 6 regenerative air (Tymco Inc., 2019), (C, D) Elgin® Whirlwind vacuum (Elgin Sweeper Co., 2017), (E, F) Elgin® Waterless Eagle mechanical (Elgin Sweeper Co., 2019) and (G, H) Pavetech Typhoon and PaveVac.

Table 3-2: Surface rejuvenation techniques assigned to each cell

Cell ID	Maintenance Technology	Make and model	Sweep Path	Additional components
1	High pressurized-air and vacuum system	Pave-Tech Typhoon® and Pavevac®	Typhoon: 0.61 m Pavevac: 0.71 m	Requires trailer air compressor (200 psi) and a vacuum truck
2	Regenerative air street sweeper	TYMCO DST-6®	1.32 m	
3	Pressure washing followed by manual vacuuming	3000 psi pressure washer and ShopVac	NA	
4	Vacuum street sweeper	Elgin Sweeper WhirlWind®	813 mm (Suction nozzle only)	
5	Waterless mechanical street sweeper	Elgin Sweepers Water Less Eagle®	3.05 m	

3.4 Role of Sediment Characteristic and Cleaning Frequency (Cells 6 and 7)

Two PICP pavement cells (Cells 6 and 7) were used to examine (1) the effectiveness of early and repeated maintenance on pavement longevity and (2) the impact of cohesive soils on maintenance effectiveness in July 2019.

Cell 6 was clogged half the material used on Cells 1 – 5 to represent early and repeated maintenance. No compaction was applied because sediments did not fill the joints. Sediment application cycles were shortened, and masses were adjusted to fit a compressed timeline. All other clogging procedures remained the same. Maintenance was completed with a TYMCO DST-6® regenerative air street sweeper provided by the City of Toronto. Accelerated clogging and maintenance were repeated four times.

Cell 7 was clogged with modified sediment that included 50% street sweeping materials and 50% silty clay soils collected from a construction zone near the site by weight. Following ASTM D4318 proceedures, site soils had a liquid limit of 21%, a plastic limit of 16% and a plasticity index of 5. Material preparation methods were the same as those used for clogging Cells 1 – 5 (described in Section 3.2.). Clumped materials were not broken apart with a pestle and mortar. Street sweeping and soil materials were separated by size with sieves and then combined to construct the average PICP gradation shown in Figure 3-2. Clogging material gradation data is provided in Appendix D. The same clogging procedures, described in Section 3.2, were followed at the test site. The purpose of this modification is to illustrate the impact local soils may have on clogging processes and pavement maintenance requirements. Once the surface was clogged, the high-pressurized-air and vacuum system wa used to restore surface infiltration. The equipment was limited to one pass over the pavement.

3.5 Evaluating the Impact of Maintenance Treatments

Following maintenance treatments, SIR measurements were repeated on each cell at measurement Locations 1 – 13. All infiltration measurements are provided in Appendix E and F.

Penetration depths were measured in each cell immediately after the application of maintenance and before refilling the joints with aggregate. The measurements were taken using digital callipers (0.2 mm accuracy) at the mid-point between every two adjacent pavers (Figure 3-7) along four rows, 12; 14; 16; 18 and four columns, I; K; M; P in all cells. The rows were aligned parallel to the direction of the path travelled by each maintenance technique and columns were perpendicular (Figure 3-8). Joint penetration depth measurements are provided in Appendix G.

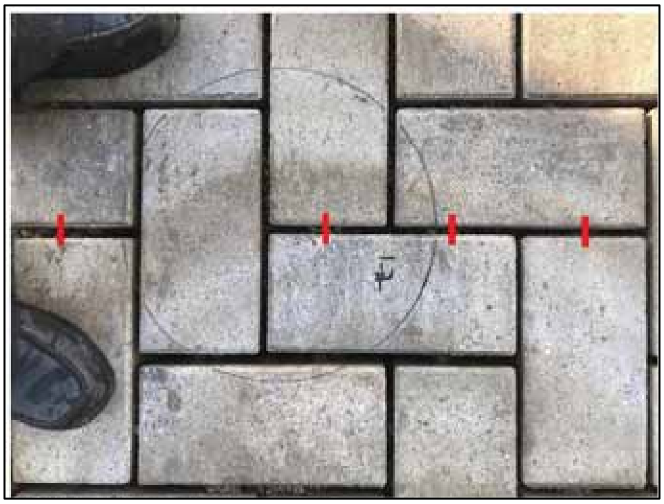

Figure 3-7: Red dashes indicate the penetration depth measurement locations at the mid-point between every two adjacent pavers.

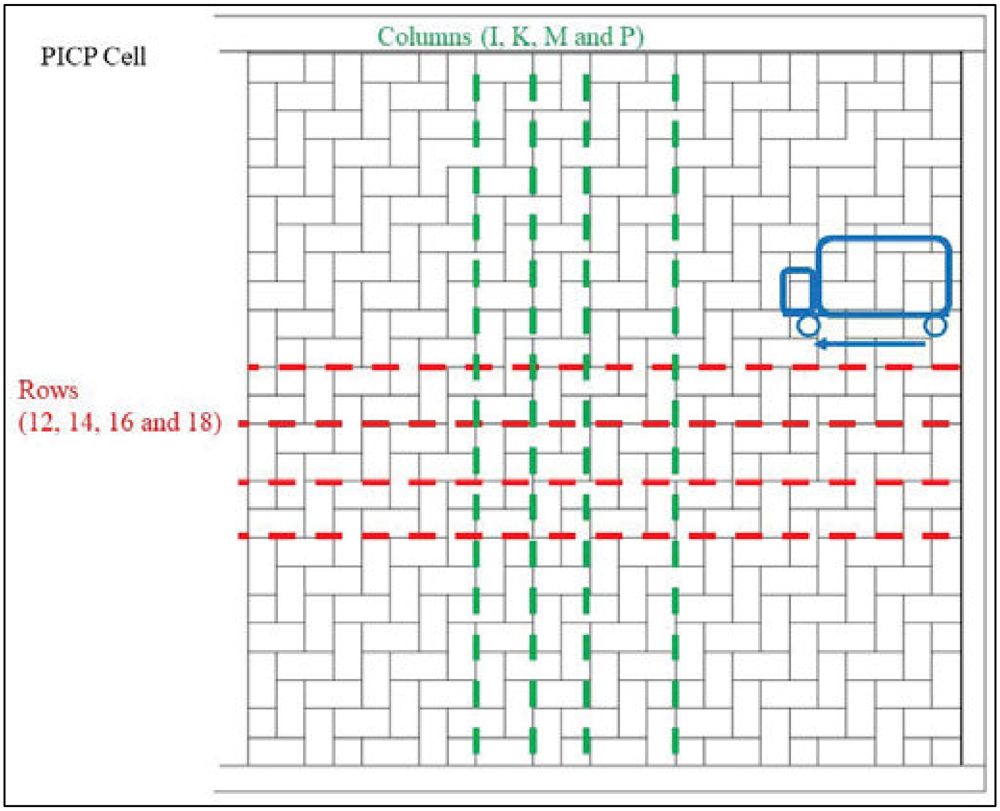

Figure 3-8: Direction of travel path for all maintenance techniques.

4.0 STUDY FINDINGS

4.1 Clogged Pavement Surface Infiltration Rates (Pre-Maintenance)

4.1.1 Restorative maintenance (Cells 1 – 5 and 7)

Surface infiltration rates were measured in November 2017 following construction and again in July 2018 and 2019 before accelerated clogging. Over the eight months, Cells 1 – 5 did not lose any surface infiltration capacity. Cell 7 which was clogged in July 2019 (a year and a half after construction), lost approximately 30% of its initial post-construction surface infiltration capacity due to natural weathering. Average SIR decreased from 12,200 mm/hr (November 2017) to 8,830 mm/hr (July 2019). Table 4-1 and Figure 4-1, present descriptive statistics and boxplots of the pavement's pre-maintenance SIR, respectively. After six applications of street sweeping, four measurement locations had SIRs below minimum detection levels; two were in Cell 2, and two were in Cell 3. Cell 7, which was clogged with the clayey soil and street sweepings, had five measurements with SIRs below minimum detection levels.

Table 4-1: Descriptive statistics of pre-maintenance surface infiltration rates.

Cell ID	**1**	**2**	**3**	**4**	**5**	**7**
Surface Infiltration Rates (9 measurements per cell) (mm/hr)						
Mean	330	300	395	525	610	255
Median	190	250	325	565	580	340
Stand. Dev	245	260	328	320	300	160
Min	120	<103	<103	65	300	<91
Max	830	735	1,040	1,060	1,260	620
Number of Censored Data	-	2	2	-	-	5

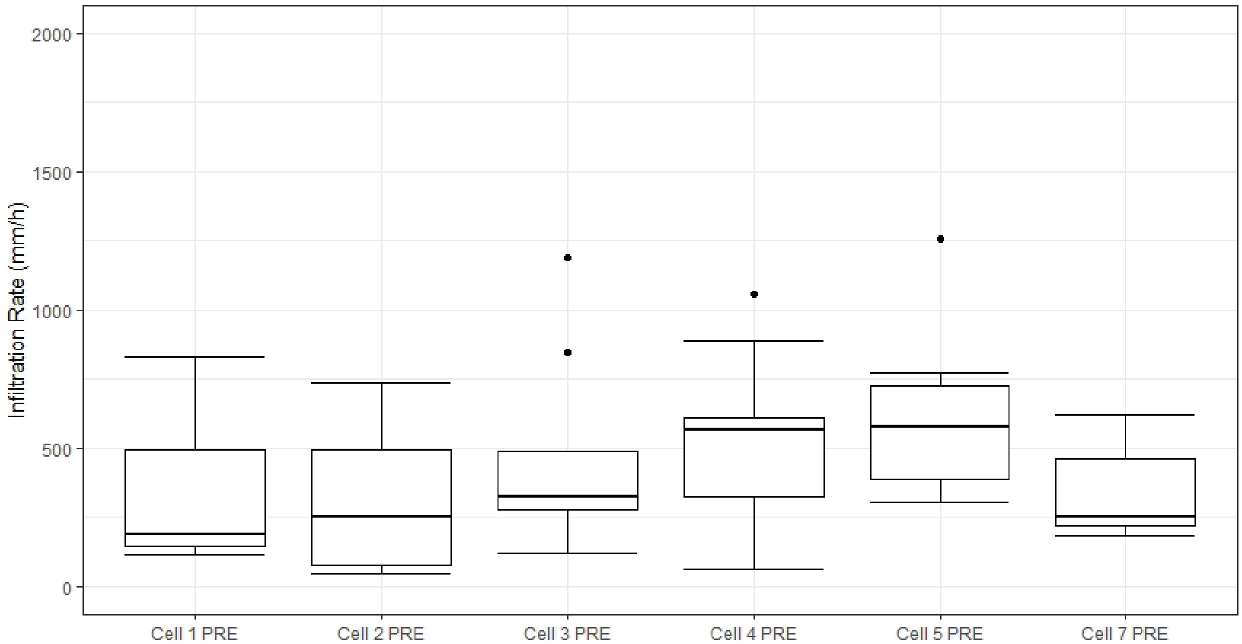

Figure 4-1: Pre-maintenance surface infiltration rates cells 1 – 5 and 7.

4.1.2 Early and repeated maintenance (Cell 6)

Table 4-2 and Figure 4-2 present descriptive statistics and boxplots of the pavement's pre-maintenance SIR, respectively. The benefits of early and repeated maintenance were evident in the test cell's pre-maintenance surface infiltration data. Cell 2, which simulated restorative maintenance, was fully-clogged (i.e. average SIR ≤ 250 mm/hr) following the application of 9.3 kg of street sweepings. **In contrast, Cell 6, which had the benefit of early and repeated maintenance, only became fully-clogged after the application of 18.5 kg of street sweepings, a doubling of the total amount of clogging materials applied to the PICP surface.**

Table 4-2: Descriptive statistics of pre-maintenance SIR Cells 2 and 6.

Statistic	Restorative (Cell 2)	Early and Repeated (Cell 6)			
		Round 1	Round 2	Round 3	Round 4
Total Applied Sediment (kg)	9.3	4.6	9.3	13.9	18.5
Mean	300	2,180	760	580	240
Median	250	2,040	320	65	115
Stand. Dev	260	1,060	760	860	270
Min	<103	870	<103	<103	<91
Max	730	3,80	2,400	2,300	810
Number of Censored Data	2	-	3	3	6

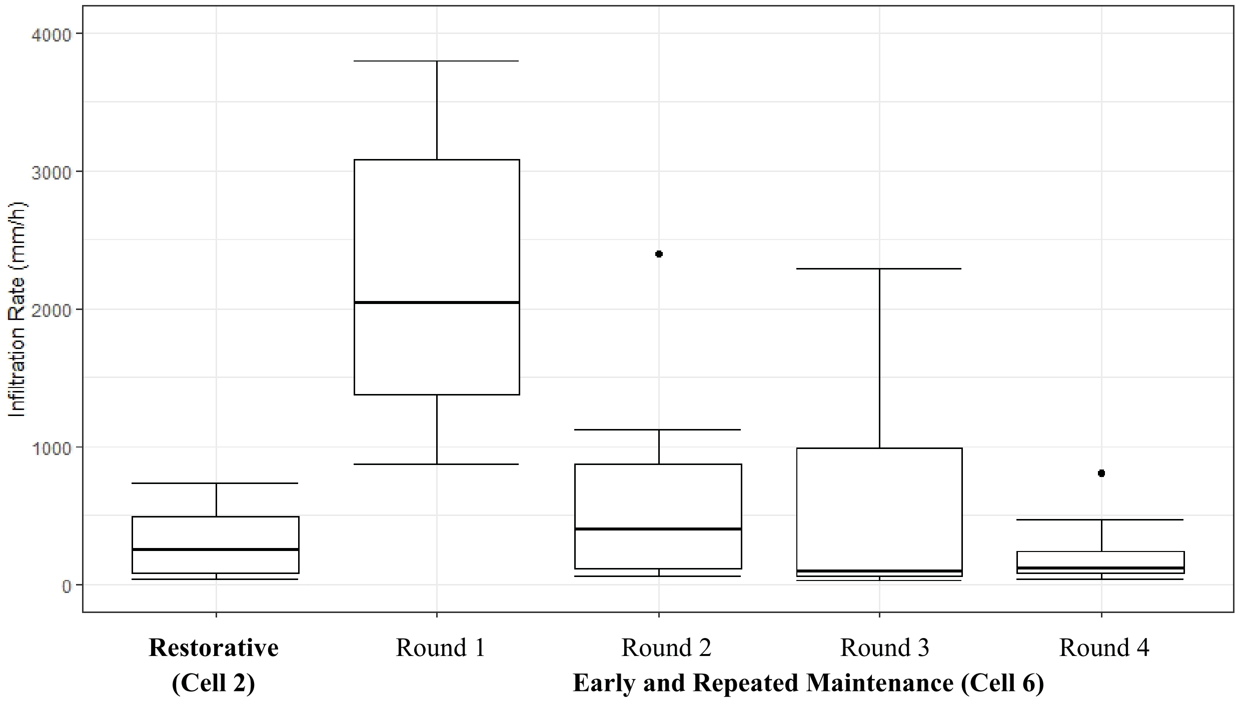

Figure 4-2: Pre-maintenance surface infiltration rates box plots of restorative (Cell 2) and early and repeated test cells (Cell 6)

4.2 Effectiveness of Tested Restorative Maintenance Treatments

4.2.1 Restoration of surface infiltration capacity

All maintenance techniques significantly restored the pavement's surface infiltration capacity even when limited to a single pass over the pavement. All post-maintenance SIR test results are provided in Appendix F. Table 4-3 and Figure 4-3 present post-maintenance descriptive statistics and boxplots, respectively. Statistical tests reported in Table 4-4 found that:

1. The high pressurized-air vacuuming provided the highest increase to PICP surface infiltration capacity than the other tested techniques;
2. Vacuum street sweeping provided a more significant increase to PICP surface infiltration capacity than the regenerative air street sweeper and the mechanical street sweeper;
3. Manual pressure washing followed by vacuuming provided similar levels of treatment as the regenerative air street sweeper and the waterless mechanical street sweeper;
4. And, the mechanical and vacuum street sweepers provided similar levels of treatment.

Table 4-3: Restoration of surface infiltration capacity

Cell ID	Maintenance Technique	Mean (mm/hr)	Median (mm/hr)	Min (mm/hr)	Max (mm/hr)	Stand Dev. (mm/hr)	Rank*	Restoration to baseline SIR levels (%)
1	High pressurized-air and vacuum	12,900	12,900	8,990	16,500	1,970	1	109
2	Regenerative air sweeping	2,030	1,550	920	4,500	1,050	5	20
3	Pressure washing and vacuuming	2,760	2,610	950	4,750	1,190	4	25
4	Vacuum sweeping	7,490	7,820	1,280	13,900	4,470	2	70
5	Waterless mechanical sweeping	3,590	3,540	1,190	5,140	1,130	3	35

*Rank is determined based on the technique which provided the most restoration of the pavement's original SIR

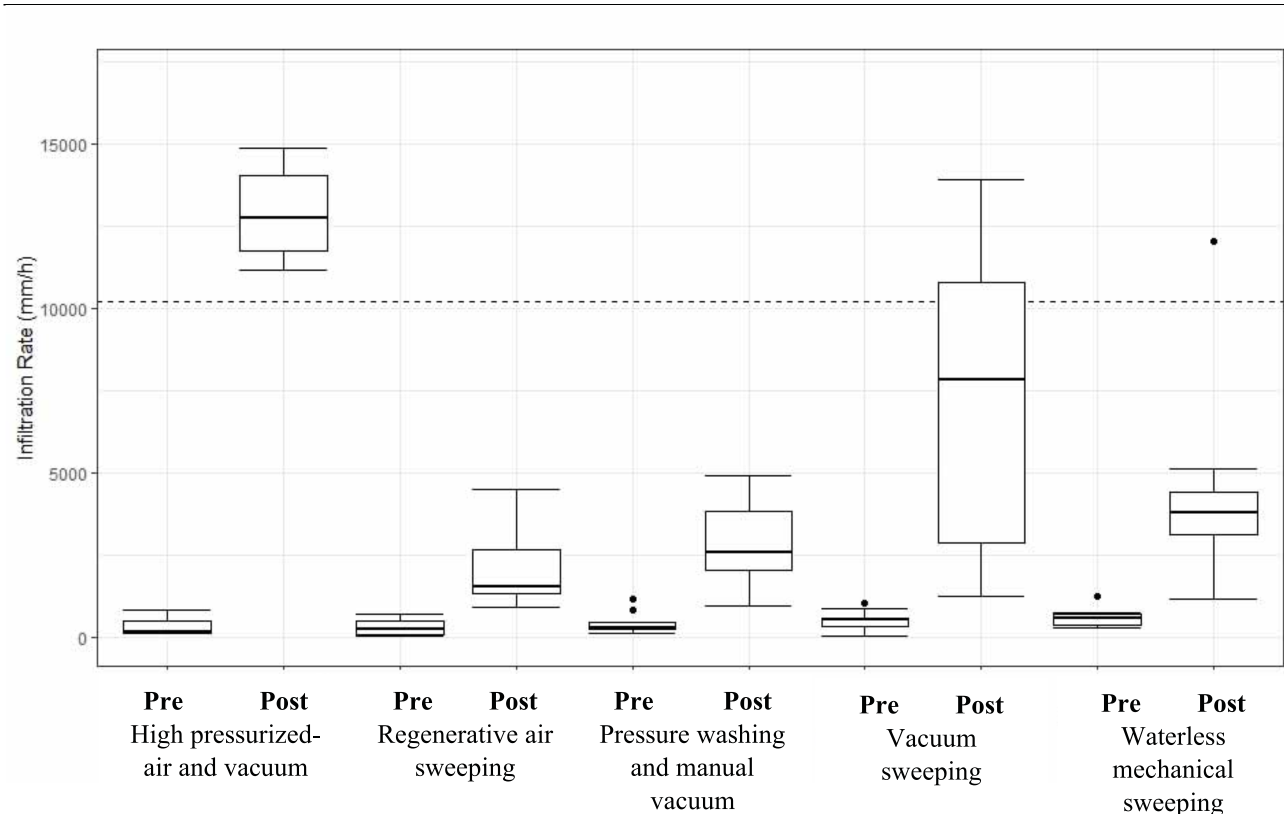

Figure 4-3: Box-plot presentation of the pre and post-maintenance surface infiltration rate for each surface treatment method.

Dashed line (---) indicated baseline conditions, average surface infiltration rate prior to clogging.

Table 4-4: p-values for two-sided Wilcoxon Signed Rank tests (bold are statistically significant) results

	Regenerative air sweeping	Pressure washing and vacuuming	Vacuum sweeping	Waterless mechanical sweeping
High pressurized-air and vacuum	**1.65E-5**	**1.65E-5**	**0.01235**	**5.09E-5**
Regenerative air sweeping	-	0.0649	**0.00103**	**0.00294**
Pressure washing and vacuuming	-	-	**0.0159**	0.0727
Vacuum sweeping	-	-	-	0.137

Although all of the surface treatments improved surface infiltration capacity, **only the high pressurized-air and vacuum system fully restored the PICP to its baseline, post-construction, condition.** The high pressurized-air and vacuum system produced mean surface infiltration measurements that were 2 – 6 times higher than all other tested techniques and restored PICP surface infiltration capacity to 109% of its original condition (approx. 12,900 mm/hr). Joint aggregates were replaced following maintenance but not compacted which likely caused the higher than post-construction SI measurements.

The vacuum street sweeper produced the second-highest amount of surface rejuvenation but also generated the most variable results. Although surface infiltration was restored to original (or higher) conditions at some locations, on average, the PICP's surface infiltration capacity was approximately 7,500 mm/hr (70% of original SIR conditions), post-maintenance. Individual SI measurements ranged from 1,280 mm/hr to 13,900 mm/hr. Despite this variability, minimum surface infiltration measurements collect on the PICP treated by the vacuum sweeper were similar or higher than measurements collected on surfaces treated by the regenerative air street sweeper, the waterless mechanical street sweeper and by power washing followed by manual vacuuming. The large variability in post-maintenance SIR was likely influenced by the truck's relatively small vacuum head (diameter ~800 mm) relative to the truck's total width (~3 m). The vacuum head should sweep the entire area to rejuvenate the entire PICP surface best. This requires repeated narrow passes with the vehicle shifting ~800 mm with each pass. Some vacuum air sweepers also have dual suction nozzle capabilities; this was not explored in this study but should be examined to optimize operational practices further.

Surprisingly, the waterless mechanical street sweeper restored the PICP's surface infiltration capacity to 35% of its original condition. Post-maintenance surface infiltration capacity was approximately 3,540 mm/hr. The street sweeper also provided a consistent level of rejuvenation, post-maintenance surface infiltration measurements range from 1,190 mm/hr to 5,140 mm/hr. Surface infiltration data had a comparable amount of variability to the other tested techniques. In the past, poor and inconsistent improvements in surface infiltration capacity have been reported with mechanical street sweepers. In 2016, Winston et al. reported positive results with maintenance using a mechanical street sweeper, but only after five passes over the pavement [21]. **As mechanical street sweeping technologies continue to advance, its suitability as a maintenance option for PICP must continue to be re-evaluated.**

The pressure washing, followed by manual vacuuming, restored SIRs to 25% of its original condition. Drake and Bradford [20] also observed positive results from maintaining a PICP area with pressure washing. Sehgal et al. [27] recommended that pressure washing was a suitable PICP surface treatment technique before the use of street sweeping equipment. **This method is a manual operation and is best suited for small areas, with equipment readily available to owners and operators of PICP.** The equipment availability combined with the outcome of the experiment suggest that pressure washing followed by manual vacuuming would be a suitable choice of maintenance for private driveways only where maintenance can be applied more frequently and in advance of the pavement reaching a clogged state (SIR $\leq$ 250 mm/hr).

The regenerative air street sweeper produced the smallest improvement in SIRs, restoring only 20% of the pavement's permeability. These results suggest that regenerative air street sweepers are not a preferred approach for restorative maintenance when other maintenance techniques (such as those evaluated in this study) are available. When regenerative air sweepers are the only available option, multiple passes over the pavement will likely be required to restore surface infiltration to initial levels. Regenerative air street sweepers are also useful for periodic routine maintenance to remove loose debris from the joints and surface.

4.2.2 Joint penetration depth of maintenance techniques

Table 4-5 summarizes the descriptive statistics generated for the joint penetration depths in each cell post-maintenance and Figure 4-4 shows the boxplots. Significant differences between the parallel and perpendicular penetration depths for all treatments except for Cell 3, which had received pressure washing and manual vacuuming. Post maintenance joint penetration depths for Cells 1 – 5 are provided in Appendix G. Pictures of the pavement surface before and after maintenance is provided in Appendix I.

Throughout the experiment, the orientation of street sweeper vehicle and suction/collection heads greatly influenced the depth of joint materials removed by the treatment. For example, the vacuum street sweeper had a rectangular vacuum nozzle aligned with the parallel joints causing higher penetration depths into them. In contrast, the round-shaped vacuum nozzle of the regenerative air street sweeper and the rounded high pressurized-air head of the Typhoon produced more uniform joint penetration depths. The waterless mechanical street sweeper, which collected material solely with brushes into a wide hopper, produced higher penetration depths in the parallel joints, which were aligned with the rotation direction of the central broom. Winston et al. [21] reported penetration depths of 6-12 mm for their mechanical street sweeper which is similar to the mechanical sweeper's penetration depth in the perpendicular direction in this experiment. For all cells, post-maintenance SIR and joint penetration depth were strongly correlated.

Variability in penetration depth was also correlated with variability in post-maintenance SI. The vacuum street sweeper had the most variable effect on surface infiltration rates and penetration depth (Stand Dev. = 4,470 mm/hr and 9.8 mm, respectively) while the regenerative air street sweeper produced the most consistent results (Stand Dev. = 1,050 mm/hr and 3.9 mm). Similar studies ([10], [20], [21], [28]) have also observed that the effectiveness of maintenance, i.e., the post-maintenance surface infiltration capacity of PICP, is dependent on how deep the maintenance technique penetrate the joints.

Both the high pressurized-air and vacuum system and vacuum street sweeper were able to restore SIR to original or close to original conditions. At locations were SIR was fully restored, the top 25-35 mm of joint materials, roughly 30-40% of the pavers' depth, were removed by the cleaning equipment.

Table 4-5: Equipment joint penetration depths in each cell post-maintenance.

Cell ID	Maintenance Technique	Joint Penetration Depth	Mean (mm)	Median (mm)	Min (mm)	Max (mm)	Stand Dev. (mm)
1	High pressurized-air and vacuum	Parallel[1]	22.9	23.1	6.7	42.9	5.3
		Perpendicular[2]	19.0	18.9	5.6	36.8	6.4
		Entire cell	20.9	21.8	5.6	42.9	6.2
2	Regenerative air sweeping	Parallel	9.6	9.0	3.8	17.3	3.0
		Perpendicular	7.6	6.6	2.1	21.8	4.6
		Entire cell	8.7	8.3	2.1	21.8	3.9
3	Pressure washing followed by manual vacuuming	Parallel	10.7	10.6	2.8	19.2	4.1
		Perpendicular	12.0	11.5	5.5	24.8	3.9
		Entire cell	11.4	11.2	2.8	24.8	4.0
4	Vacuum sweeping	Parallel	22.3	21.7	4.0	44.3	9.8
		Perpendicular	12.6	10.5	4.0	44.1	7.1
		Entire cell	17.4	15.1	4.0	44.3	9.8
5	Waterless mechanical sweeping	Parallel	24.7	24.4	6.5	50.6	6.1
		Perpendicular	9.5	7.7	2.2	28.1	5.8
		Entire cell	17.1	18.2	2.2	50.6	9.7

[1] Rows were parallel to direction of path; [2] columns were perpendicular to the direction of the path; values provided in mm

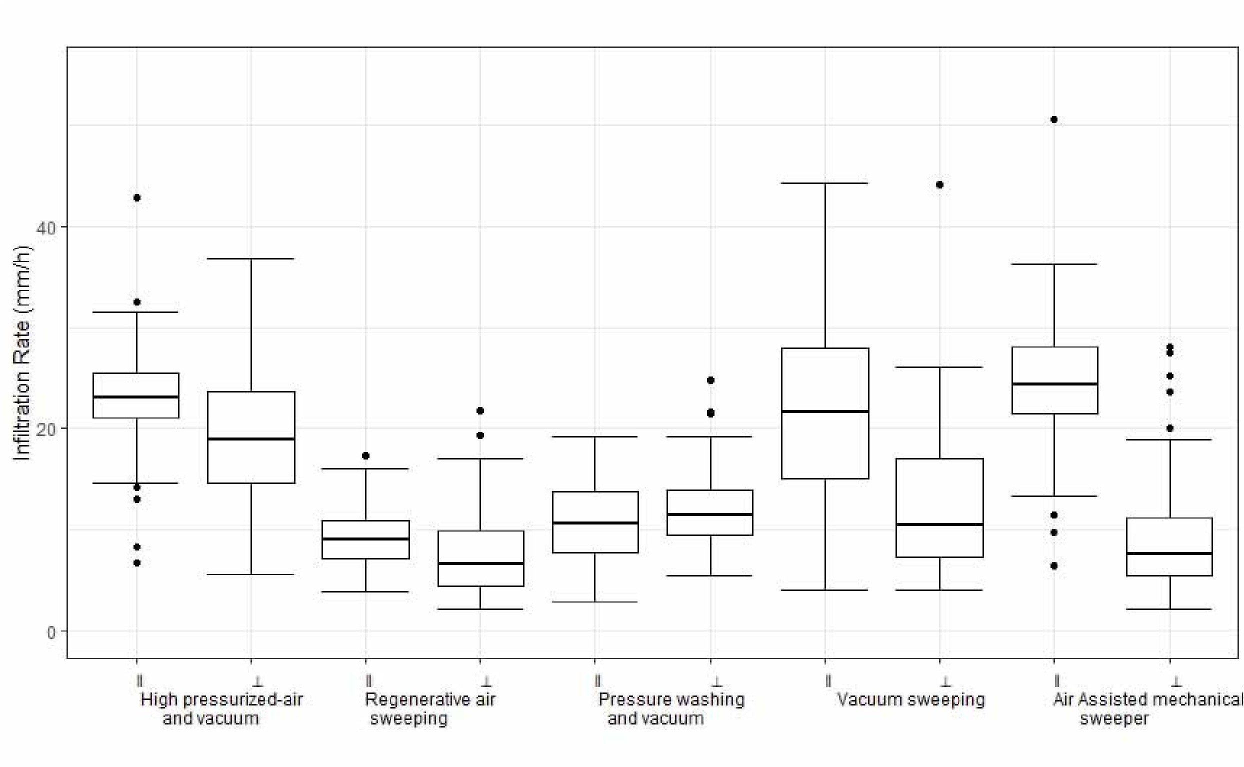

Figure 4-4: Parallel (‖) and perpendicular(⊥) joint penetration depths for each maintenance technique.

4.3 Impact of Cohesive Sediments on Restorative Maintenance

As discussed in Section 3.4, the high pressurized-air and vacuum system was re-tested on Cell 7 which was clogged with a mixture of street sweepings and clayey soils collected on site. Descriptive statistics of post-maintenance surface infiltration rates and joint penetration depths are presented in Table 4-6 and Table 4-7, respectively. Figure 4-5 presents box plots of the pre- and post-maintenance surface infiltration data. Post maintenance joint penetration depths are provided in Appendix H and pictures of the pavement surface before and after maintenance is provided in Appendix J.

The high pressurized-air and vacuum system was only able to restore the PICP's surface infiltration capacity to approximately 50% of the pavement's original conditions when cohesive sediments were added to the materials used to clog the surface.

Table 4-6: Restoration of surface infiltration capacity with and without cohesive soils in clogging materials using the high-pressurized-air and vacuum system.

Cell ID	Clogging Materials	Mean (mm/hr)	Median (mm/hr)	Min (mm/hr)	Max (mm/hr)	Stand Dev. (mm/hr)	Restoration to baseline SIR levels[1] (%)
1	Street sweepings	12,900	12,900	8,990	16,500	1,970	109
7	50% Street sweepings 50% site soils	4,380	4,630	2,300	6,680	1,550	47

[1]**Baselines surface infiltration level was calculated relative to values reported for individual cells in** Table 4-1

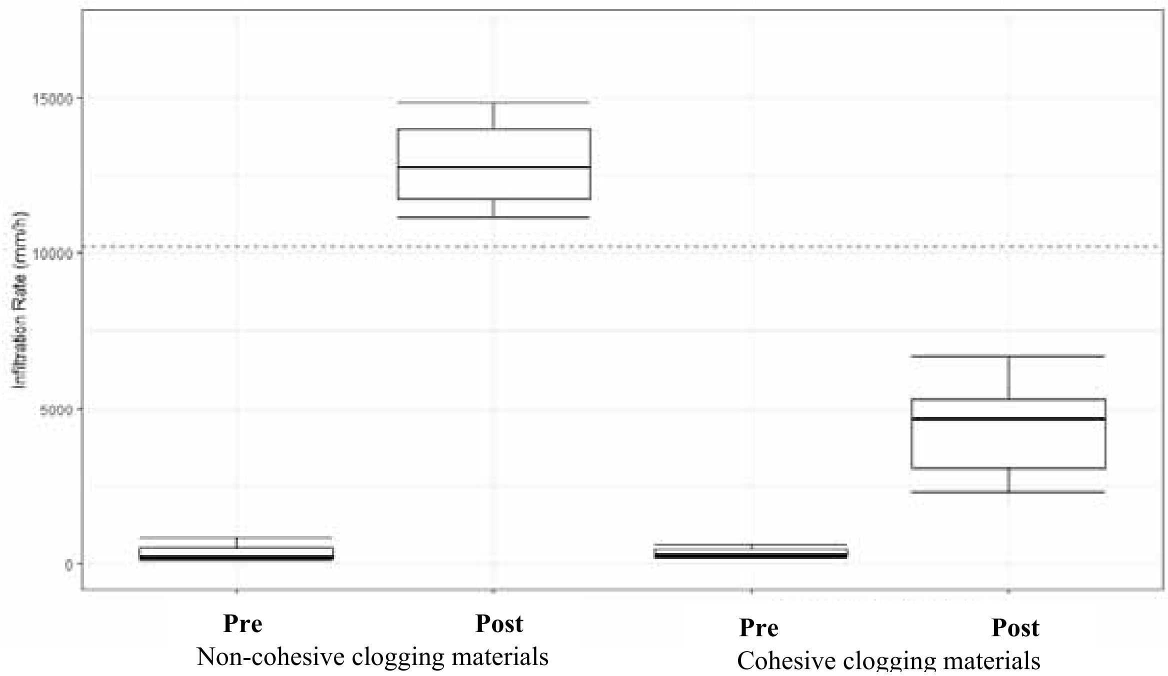

Figure 4-5: Restoration of surface infiltration capacity with and without cohesive soils in clogging materials using the high pressurized-air and vacuum system.

Joint penetration depths (Table 4-7) were statistically similar for both cells treated with the high pressurized-air and vacuum system. **Thus, joint penetration depth was not a good indicator for maintenance effectiveness when comparing pavement's clogged with different source materials.** The addition of clayey soils to the clogging mixture allowed for compacted agglomerate to form within the joints. As shown in Figure 4-6, these clumps of sediments were very tightly adhered to the pavers and sometimes formed several millimetres below the pavement surface.

Figure 4-6: Example of sub-surface clay agglomerate left following maintenance

Table 4-7: Joint penetration of the high pressurized-air and vacuum system with and without cohesive soils in clogging materials

Cell ID	Clogging Materials	Joint Penetration Depth	Mean (mm)	Median (mm)	Min (mm)	Max (mm)	STDV (mm)
1	Street sweepings	Parallel	22.9	23.1	6.7	42.9	5.3
		Perpendicular	19.0	18.9	5.6	36.8	6.4
		Entire cell	20.9	21.8	5.6	42.9	6.2
7	50% Street sweeping 50% Site soils	Parallel	27.6	25.4	5.9	51.6	10.9
		Perpendicular	22.6	22.7	5.6	41.7	8.7
		Entire cell	25.0	24.7	5.6	51.6	10.1

4.4 Early and Repeated Maintenance

As discussed in Section 3.4, the regenerative air street sweeper was used to evaluate the effectiveness of early and repeated maintenance on pavement longevity. The benefits of early and repeated maintenance were evident in the test cell's pre-maintenance surface infiltration data (discussed previously in Section 4.1.2).

Applied maintenance was more effective when conducted repeatedly and earlier. Descriptive statistics for post-maintenance infiltration capacity of Cell 1 (restorative maintenance and Cell 6 (early and repeated maintenance) are summarized in Table 4-8 and box plots are presented in Figure 4-7. Post maintenance joint penetration depths are provided in Appendix G and pictures of the pavement surface before and after maintenance is provided in Appendix K.

When implemented early, the regenerative air sweeper was more successful at restoring surface infiltration capacity. After two cycles of accelerated clogging (9.3 kg of applied sediment) and maintenance, the regenerative air sweeper restored the PICP to 40% of baseline conditions. In contrast, when used for restorative maintenance (9.3 kg of applied sediment), the regenerative air sweeper was only able to restore the surface to 20% of its baseline conditions. With each clogging cycle, the impact of the applied maintenance declined and surface infiltration capacity steadily decreased. After four cycles of clogging (18.5 kg of applied sediment) and maintenance with the regenerative air sweeper, Cell 6 had a median surface infiltration capacity of 370 mm/hr. Thus even with early and repeated maintenance, more intensive restorative maintenance is eventually required.

Table 4-8 Descriptive statistics for surface infiltration rates for restorative and early and repeated maintenance

Cell ID	Maintenance Type	Test	Total Applied Sediment (kg)	Mean (mm/hr)	Median (mm/hr)	Min (mm/hr)	Max (mm/hr)	Stand Dev. (mm/hr)	Restoration to Baseline SIR levels[1] (%)
1	Restorative		9.3	2,040	1,550	920	4,500	1,050	20
6	Early and Repeated	Round 1	4.6	5,000	6,280	2,620	7,490	1,950	60
		Round 2	9.3	3,310	1,290	90	10,170	1,930	40
		Round 3	13.9	2,150	290	<103	11,010	3,770	26
		Round 4	18.5	990	370	<103	2,770	1,060	12

[1]Restoration to baseline levels calculated using pre-maintenance surface infiltration rates of individual cells reported in Table 2-1

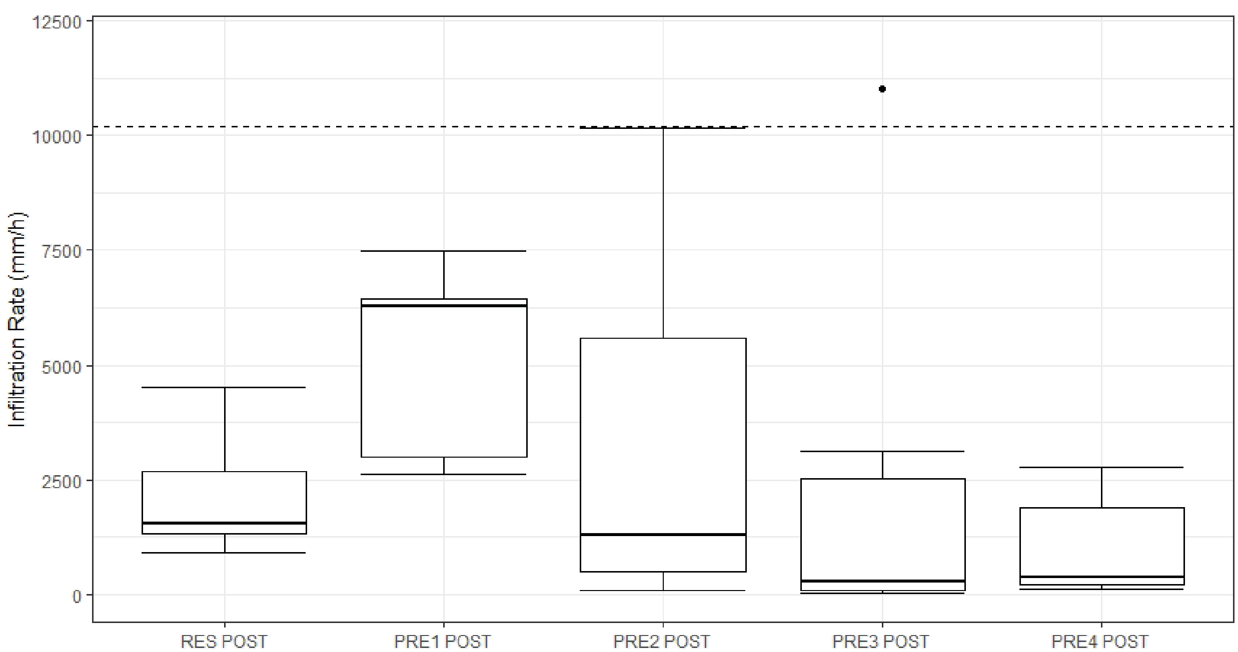

Figure 4-7: Post-maintenance surface infiltration capacity following restorative and early and repeated maintenance with a regenerative air street sweeper.

Table 4-9 summarizes descriptive statistics for joint penetration depths for restorative and early and repeated maintenance. With each clogging cycle, the penetration depth of the applied maintenance declines. After the first clogging cycle, the regenerative air sweeper penetrated on average, 9.2 mm into the joints. After the fourth cycle, when the cell is approaching fully clogged conditions, the sweeper only penetrated on average 5.8 mm into the joints. Similar to the equipment testing discussed in Section 4.2 joint penetration depth was a strong indicator of maintenance effectiveness.

Table 4-9: Joint penetration of restorative and early and repeated maintenance with a regenerative air street sweeper.

Test	Joint Penetration Depth	Mean (mm)	Median (mm)	Min (mm)	Max (mm)	Stand. Dev. (mm)
Restorative (Cell 2)						
	Parallel	9.6	9.0	3.8	17.3	3.0
	Perpendicular	7.6	6.6	2.1	21.8	4.6
	Entire cell	8.7	8.3	2.1	21.8	3.9
Early and Repeated (Cell 6)						
	Parallel	10.1	9.8	5.1	18.7	3.0
Round 1	Perpendicular	8.0	8.0	3.2	12.5	1.9
	Entire cell	9.2	8.9	3.2	18.7	2.8
Round 2	Parallel	8.5	7.9	4.7	17.1	2.2
	Perpendicular	9.2	7.8	5.4	21.9	3.8
	Entire cell	8.8	7.8	4.7	21.9	3.0
Round 3	Parallel	7.3	7.0	3.0	15.3	2.1
	Perpendicular	6.9	6.3	2.3	12.6	2.2
	Entire cell	7.1	6.8	2.3	15.3	2.2
Round 4	Parallel	6.1	5.9	0.4	9.7	1.8
	Perpendicular	5.3	4.9	1.9	10.5	2.0
	Entire cell	5.8	5.5	1.9	0.4	10.5

[1] Rows were parallel to direction of path; [2] columns were perpendicular to the direction of the path; values provided in mm

5.0 CONCLUSIONS

5.1 Study Findings

This research presents a new simple-to-implement and repeatable methodology to clog PICP pavement was developed for this research and was successfully used to clog several test cells to similar pre-maintenance conditions. Using this procedure, researchers and equipment manufacturers can test, evaluate and compare maintenance equipment and experimental results.

The results of this study found that all maintenance techniques significantly restored the PICP's surface infiltration capacity. The presence of cohesive soils within clogging materials significantly decreased the effectiveness of restorative maintenance. Applied maintenance was more effective when conducted repeatedly and earlier. Key findings of this research include the following:

Restorative Maintenance

- Only the high pressurized-air and vacuum system fully restored the PICP to its baseline, post-construction, condition. The high pressurized-air and vacuum system produced mean surface infiltration measurements that were 2 – 6 times higher than all other tested techniques and restored PICP surface infiltration capacity to 109% of its original condition (approx. 12,900 mm/hr).
- The vacuum street sweeper produced the second-highest amount of surface rejuvenation but also generated the most variable results. Although surface infiltration was restored to original (or higher) conditions at some locations, on average, the PICP's surface infiltration capacity was approximately 7,500 mm/hr (70% of original SIR conditions), post-maintenance. Individual SIR measurements ranged from 1,280 mm/hr to 13,900 mm/hr.
- The waterless mechanical street sweeper restored the PICP's surface infiltration capacity to 35% of its original condition. Post-maintenance surface infiltration capacity was approximately 3,540 mm/hr. As mechanical street sweeping technologies continue to advance, its suitability as a maintenance option for PICP must continue to be re-evaluated.
- The pressure washing, followed by manual vacuuming, restored SIRs to 25% of its original condition. This method is a manual operation and is best suited for small areas, with equipment that is readily available to owners and operators of PICP.
- The regenerative air street sweeper produced the smallest improvement in SIRs, restoring only 20% of the pavement's permeability. These results suggest that regenerative air street sweepers are not a preferred approach for restorative maintenance when other maintenance techniques (such as those evaluated in this study) are available.

Joint Penetration Depth

- Joint penetration depth was a strong indicator of overall maintenance effectiveness when comparing PICP clogged with similar source materials. Joint penetration depth is not a good indicator of maintenance effectiveness when comparing pavement's clogged with different source materials.
- The orientation of street sweeper vehicle and suction/collection heads greatly influenced the depth of joint material removed by the treatment.

Cohesive Soils

- The high pressurized-air and vacuum system were only able to restore the PICP's surface infiltration capacity to approximately 50% of the pavement's original conditions when cohesive sediments were added to the materials used to clog the surface. In contrast, this equipment was able to fully restore a PICP's surface when only non-cohesive materials were used.

Early and Repeated Maintenance

- Applied maintenance was more effective when conducted repeatedly and earlier. After two cycles of accelerated clogging (9.3 kg of applied sediment) and maintenance, the regenerative air sweeper restored the PICP to 40% of baseline conditions. In contrast, when used for restorative maintenance (9.3 kg of applied sediment), the regenerative air sweeper was only able to restore the surface to 20% of its baseline conditions.
- With each clogging cycle, the impact of maintenance declined when using a regenerative-air streetsweeper, and surface infiltration steadily decreased. Thus, more intensive restorative maintenance is eventually required.

5.2 Best Management Practices

There are two types of permeable pavement maintenance: *routine* and *restorative*. This study addresses restorative maintenance only. Restorative maintenance is defined when a permeable pavement's surface infiltration capacity decreases below 250 mm/hr. Refer to the 2015 ASCE permeable pavement book [16] for information on best management practices for routine maintenance.

Based on the experiences gained throughout this study, the following recommendations should be implemented to maximize the benefit of maintenance treatments:

- Even when limited to a single pass over the pavement, all forms of maintenance improved surface infiltration rates but had different levels of success. This gives operators flexibility and options when selecting and sourcing equipment to restore PICP.
- Vehicular speed, number of passes and vehicular direction will all affect maintenance. To maximize the impact of applied maintenance vehicles should be operated as slowly as possible. With rectangular suction heads, two passes arranged perpendicular from one another should ensure sediment is removed from all joints and maximize restoration of surface infiltration capacity.
- Equipment designed specifically for PICP maintenance outperforms generic street sweeper technologies and is the preferred approach for restoring severely clogged or neglected pavements. The specialized high pressurized-air and vacuum system was the only approach tested in this study that was shown to be capable of fully restoring PICP to its original post-construction baseline condition with minimum effort.
- Vacuum street sweeping significantly improves surface infiltration rates but is not expected to restore a severely clogged surface to baseline conditions across the entire surface if

limited to one pass in a single direction. To improve the outcomes a minimum of two passes arranged perpendicular from one another is recommended.

- Regenerative-air and some mechanical sweepers, like the waterless mechanical sweeper tested in this study, can partially restore surface infiltration rates. Regenerative-air sweepers are more effective when implemented early but are still not expected to provide full recovery of surface infiltration rates when limited to a single pass in one direction only. Early and repeated maintenance with an alternative system (waterless mechanical, vacuum, power washing) were not tested in this study.
- Power washing followed by manual vacuuming is a low-cost alternative for small PICP installations and can partially restore surface infiltration rates however, multiple passes are likely required to fully restore surface infiltration rates.
- Penetration depth is **often** a good indicator of post-maintenance surface infiltration capacity and should be used as an indicator measurement during maintenance to decide if multiple passes are required.
- Cohesive materials are more difficult to remove and thus, maintenance should be scheduled sooner. Subsurface agglomerates may remain in place following maintenance thus visual inspections of joints should be completed prior to refilling to identify areas that require additional cleaning.

5.3 Future Research

Additional research on PICP maintenance is recommended to refine further and optimize procedures. Additional questions that should be considered in future research include:

- *How well does different maintenance equipment perform when implemented early and repeatedly?* This study demonstrated that the regenerative air sweeper was more effective when implemented early and repeatedly. Similar testing is needed with other commonly available maintenance equipment.
- *Are there other equipment systems available that can be used for routine or restorative maintenance*? Some examples of equipment systems not tested in this study include small-sized street or floor sweepers and alternative systems (such as the Cyclone or the stormwater SUV).
- *What is the role of sediment characteristics (e.g. organic content, cohesive material) in the rate and progression of surface clogging? Is it a 1:1 relationship, e.g. 50% clay → 50% less effective?* This research demonstrated that the presence of cohesive soils significantly increases the rate of surface clogging in PICP and reduces the effectiveness of restorative maintenance. Joint penetration depth was also shown to be a poor indicator parameter for maintenance effectiveness when comparing pavements clogged with different source materials. The role of sediment characteristics on the rate and progression of surface clogging is poorly understood. Improved understanding of these processes will allow maintenance practices to be further improved and optimized.

- *How do paver geometry and design influence clogging progression and the effectiveness of maintenance? Can pavers be designed to be easier to clean?* In this study, a single generic paver and interlocking pattern were used. Different interlocking patterns and paver designs were not compared. It is hypothesized that these design components can increase the benefit of applied maintenance treatments.

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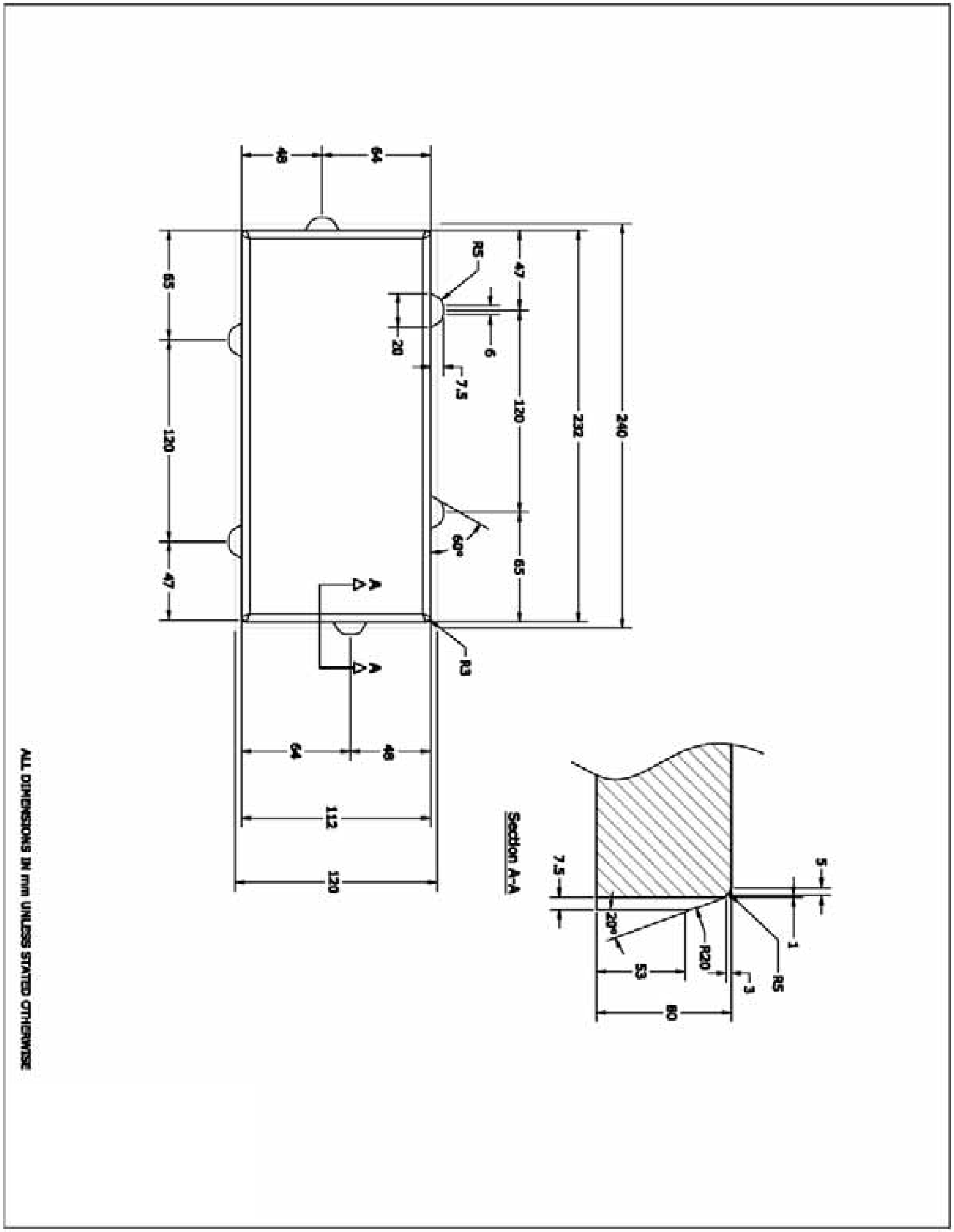
[27] W. K. Sehgal, K., Drake, J., Van Seters, T., Vander Linden, “Improving restorative maintenance practices for mature permeable interlocking concrete pavement,” *J. Environ. Manage.*

[28] B. Van Duin, C. Brown, A. Chu, J. Marsalek, and C. Valeo, “Characterization of Long-Term Solids Removal and Clogging Processes in Two Types of Permeable Pavement under Cold Climate Conditions,” in *11th International Conference on urban Drainage*, 2008.

[29] ASTM International, “D422 - 63 (Withdrawn) Standard Test Method for Particle-Size Analysis of Soils,” 2014.

APPENDICES

Appendix A: PICP Paver



Appendix B: Particle Size Distribution Analysis

Sample name: SiteB-3J11

Total weight w (g): 721.5					
ASTM No	size (mm)	Empty Sieve (g)	Sieve+sample (g)	% passing	% weight
4	4.75	776.4	780.5	99.7	0.57
5	4	532.8	536.9	99.1	0.57
10	2	647	763.6	83.0	16.16
20	0.85	427.1	613.3	57.2	25.81
30	0.6	628.2	689	48.7	8.43
50	0.3	556.1	701	28.7	20.08
80	0.18	352.3	444.2	15.9	12.74
100	0.15	313.7	335.5	12.9	3.02
200	0.075	466.6	505.7	7.5	5.42
Tray	-	335.8	389.8	7.5	7.48

Sample name: SiteB-4J11

Total weight w (g): 850					
ASTM No	size (mm)	Empty Sieve (g)	Sieve+sample (g)	% passing	% weight
4	4.75	776.4	783.5	99.3	0.84
5	4	532.9	541.1	98.4	0.96
10	2	647	829.9	76.9	21.52
20	0.85	427.2	628.2	53.2	23.65
30	0.6	628.5	707	44.0	9.24
50	0.3	556.5	719.3	24.8	19.15
80	0.18	352.5	458.4	12.4	12.46
100	0.15	313.7	327.3	10.8	1.60
200	0.075	466.8	504.6	6.3	4.45
Tray	-	335.7	389.4	6.3	6.32

Sample name SiteA-P1 PL (1)

Total weight w (g): 1175.5					
ASTM No	size (mm)	Empty Sieve (g)	Sieve+sample (g)	% passing	% weight
4	4.75	776.4	786.4	99.1	0.85
5	4	532.9	948.7	63.8	35.37
10	2	647.2	984.8	35.1	28.72
20	0.85	427.4	567.6	23.1	11.93
30	0.6	628.5	681.6	18.6	4.52
50	0.3	557	636.4	11.9	6.75
80	0.18	353.2	407.5	7.2	4.62
100	0.15	314.1	331.6	5.8	1.49
200	0.075	466.8	481.1	4.5	1.22
Tray	-	335.6	388.9	4.5	4.53

Sample name: SiteA-P1 PL (2)

Total weight w (g): 1000					
ASTM No	size (mm)	Empty Sieve (g)	Sieve+sample (g)	% passing	% weight
4	4.75	776.4	790.4	98.7	1.40
5	4	532.9	984.6	53.5	45.17
10	2	647.2	900.4	28.2	25.32
20	0.85	427.4	509.8	19.9	8.24
30	0.6	628.5	655	17.3	2.65
50	0.3	556.9	617.5	11.2	6.06
80	0.18	353.1	405.2	6.0	5.21
100	0.15	313.9	331.4	4.3	1.75
200	0.075	466.7	476.6	3.3	0.99
Tray	-	335.5	368.1		3.26

Sample name: SiteA-P1 DL (3)

Total weight w (g): 864.4					
ASTM No	size (mm)	Empty Sieve (g)	Sieve+sample (g)	% passing	% weight
4	4.75	776.4	800.5	97.3	2.79
5	4	532.8	835.7	62.2	35.04
10	2	647.2	895.5	33.5	28.73
20	0.85	427.4	539	20.6	12.91
30	0.6	628.5	659.2	17.0	3.55
50	0.3	557	607.6	11.2	5.85
80	0.18	353.2	382.6	7.8	3.40
100	0.15	314.1	334.4	5.4	2.35
200	0.075	466.8	476.1	4.4	1.08
Tray	-	335.6	373.3	4.4	4.36

Sample name: SiteA-P1 DL (4)

Total weight w (g): 898					
ASTM No	size (mm)	Empty Sieve (g)	Sieve+sample (g)	% passing	% weight
4	4.75	776.4	785.5	99.0	1.01
5	4	533	929.9	54.8	44.20
10	2	647.3	936	22.6	32.15
20	0.85	427.5	515.1	12.9	9.76
30	0.6	628.6	649.2	10.6	2.29
50	0.3	557	594.3	6.4	4.15
80	0.18	353.1	375.3	3.9	2.47
100	0.15	314	321.1	3.1	0.79
200	0.075	466.9	473.7	2.4	0.76
Tray	-	335.6	357	2.4	2.38

Sample name: SiteC-P1 DL (1)

Total weight w (g): 1137.3					
ASTM No	size (mm)	Empty Sieve (g)	Sieve+sample (g)	% passing	% weight
4	4.75	776.4	782.5	99.4	0.54
5	4	533	729.1	82.2	17.24
10	2	647.3	1116	41.0	41.21
20	0.85	427.5	686.9	18.2	22.81
30	0.6	628.5	700	11.9	6.29
50	0.3	557	629.7	5.5	6.39
80	0.18	353.2	404.5	1.0	4.51
100	0.15	314	316	0.8	0.18
200	0.075	466.8	470.2	0.5	0.30
Tray	-	335.6	341.4	0.5	0.51

Sample name: SiteC-P1 DL (2)

Total weight w (g)					
ASTM No	size (mm)	Empty Sieve (g)	Sieve+sample (g)	% passing	% weight
4	4.75	776.4	787.5	99.0	0.95
5	4	532.8	797.8	76.3	22.68
10	2	647.5	1112.8	36.5	39.83
20	0.85	427.9	650.4	17.5	19.04
30	0.6	628.8	681.7	12.9	4.53
50	0.3	557.2	620.2	7.5	5.39
80	0.18	353.2	391	4.3	3.24
100	0.15	314	332	2.8	1.54
200	0.075	466.8	476.5	1.9	0.83
Tray	-	335.5	358.2	1.9	1.94

Appendix C: Accelerated Clogging Schedules for Cells 1 – 5, 6 and 7

Table C1: Clogging schedule and sediment loading rate for Cells 1-5 in 2018

Date	Loading Factor (g/cm)	Mass of Sediment for each Cell per round (kg)			Cumulative Mass of Sediment for each Cell (kg)		
		Cell 1	Cells 2, 4 and 5	Cell 3	Cell 1	Cells 2, 4 and 5	Cell 3
14-Aug	0.1	1.12	1.17	1.17	1.12	1.17	1.17
20-Aug	0.1	1.12	1.17	1.17	2.23	2.34	2.34
28-Aug	0.2	2.23	2.34	2.34	4.46	4.68	4.67
6-Sep	Compaction	-	-	-	4.46	4.68	4.67
11-Sep	0.2	2.23	2.34	2.34	6.69	7.02	7.01
17-Sep	0.2	2.23	2.34	2.34	8.92	9.36	9.35

Table C2: Clogging schedule and sediment loading rate for Cell 6 in 2019

Date	Loading Factor (g/cm)	Mass of Sediment per round (kg)	Cumulative Mass of Sediment (kg)
		Cell 6	Cell 6
6-June	0.2	2.34	2.34
17-June	0.1	1.17	3.51
21-June	0.1	1.17	4.68
26-June	0.2	2.34	7.02
9-July	0.1	1.17	8.19
15-July	0.1	1.17	9.36
1-Aug	0.2	2.34	11.7
8-Aug	0.2	2.34	14.04
13-Aug	0.2	2.34	16.38
20-Aug	0.2	2.34	18.72

Table C3: Clogging schedule and sediment loading rate for Cell 7 in 2019

Date	Loading Factor (g/cm)	Mass of Sediment per round (kg)	Cumulative Mass of Sediment (kg)
		Cell 7	Cell 7
6-June	0.1	1.12	1.12
17-June	0.2	2.23	3.35
21-June	0.1	1.12	4.47
25-June	Compaction	-	4.47
3-July	0.1	1.12	5.59
5-July	0.2	2.23	7.82
9-July	0.1	1.12	8.94

Appendix D: Clogging Material Gradation Methods and Data

Street street sweepings and site soils were sieved and separated by size. All samples were analyzed for gradation as per the procedure outlined in ASTM C136 [25]. Clumped materials were not broken apart with a pestle and mortar because this process would damage organic material (twigs and leaf litter) that was also collected and mixed in the PICP joints. Moreover, since the pathway of clogging materials onto the pavement surface was assumed to be through pedestrian and vehicular traffic it was reasoned that clumped materials would be more representative of real-life conditions. Street sweepings and site soils were re-assembled by weight to create a gradation observed in joint material samples found in mature PICP parking lots.

Additional hydrometer analysis was completed following the field experiments following ASTM D422 – 63 (Withdrawn) [29] . The gradation of the site soils was re-analysed breaking apart clumped material with a pestle and mortar. Gradation of fines passing the No. 200 Sieve is shown in Figure D1.

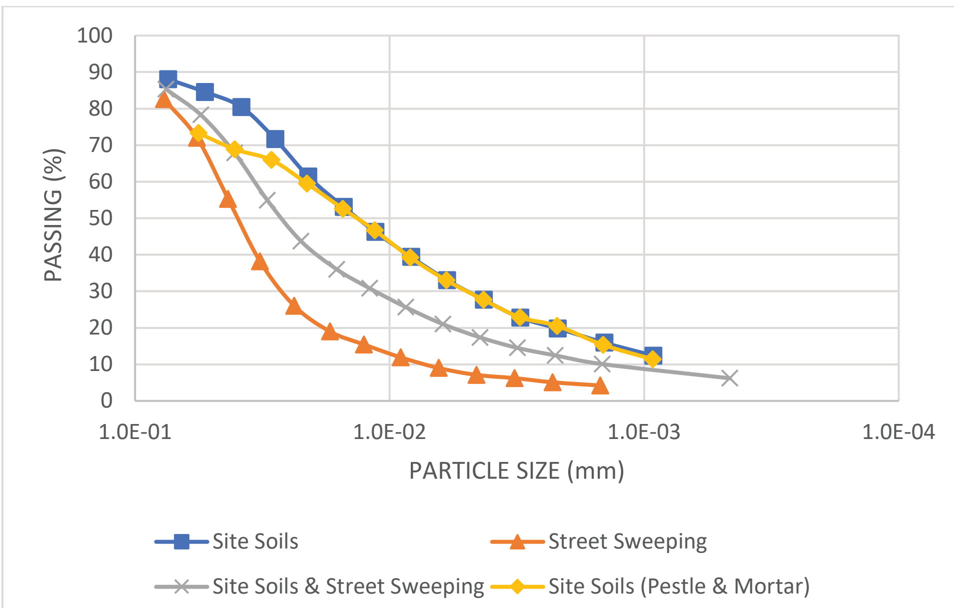


Figure D1: Gradation of fines passing No. 200 Sieve (Hydrometer data)

Table D1: Gradation Data

Variable	Street Sweeping	Site Soils (treated with a pestle & motar)
d_{60}	2.63	0.47
d_{30}	0.77	0.03
d_{10}	0.22	0.02
Coefficient of Uniformity (C_u) $C_u = \frac{d_{60}}{d_{10}}$	11.86	29.39
Coefficient of Curvature (C_c) $C_c = d_{10}^2/(d_{60}d_{10})$	1.01	0.15
Unified Soil Class for Clay	SW (Well graded sand)	SC-SM (Silty, clayey sand)

Appendix E: Surface Infiltration Rates Pre and Post Maintenance Cells 1 – 5 and 7 (mm/s)

Red- indicates that infiltration test failed

Location	Pre	Post	Location	Pre	Post	Location	Pre	Post
S1-1	0.09	3.66	**S3-10**		0.77	**S7-6**	0.15	1.02
S1-2	0.15	4.05	**S3-11**		0.57	**S7-7**	0.11	0.62
S1-3	0.05	3.89	**S3-12**		0.51	**S7-8**	0.16	0.43
S1-4	0.05	3.54	**S3-13**		0.72	**S7-9**	0.2	0.85
S1-5	0.03	3.30	**S4-1**	0.16	3.00			
S1-6	0.03	3.10	**S4-2**	0.17	0.80			
S1-7	0.14	3.17	**S4-3**	0.25	2.78			
S1-8	0.04	3.96	**S4-4**	0.11	0.35			
S1-9	0.23	3.60	**S4-5**	0.02	3.86			
S1-10		4.10	**S4-6**	0.06	2.50			
S1-11		4.60	**S4-7**	0.09	3.78			
S1-12		2.50	**S4-8**	0.29	2.17			
S1-13		3.15	**S4-9**	0.17	0.48			
S2-1	0.08	0.37	**S4-10**		0.78			
S2-2	0.07	0.35	**S4-11**		1.31			
S2-3	failed	0.72	**S4-12**		1.97			
S2-4	failed	0.38	**S4-13**		3.26			
S2-5	0.04	0.26	**S5-1**	0.22	0.87			
S2-6	0.20	0.89	**S5-2**	0.35	0.81			
S2-7	0.17	0.54	**S5-3**	0.13	0.92			
S2-8	0.02	0.38	**S5-4**	0.20	0.66			
S2-9	0.14	0.74	**S5-5**	0.16	3.34			
S2-10		1.25	**S5-6**	0.19	0.91			
S2-11		0.28	**S5-7**	0.08	1.05			
S2-12		0.43	**S5-8**	0.11	1.43			
S2-13		0.75	**S5-9**	0.09	0.33			
S3-1	0.08	0.27	**S5-10**		1.23			
S3-2	0.11	0.82	**S5-11**		1.21			
S3-3	0.09	0.52	**S5-12**		1.15			
S3-4	failed	1.19	**S5-13**		1.38			
S3-5	failed	0.45	**S7-1**	failed	0.43			
S3-6	0.29	1.19	**S7-2**	failed	0.4			
S3-7	0.20	1.07	**S7-3**	failed	0.83			
S3-8	0.12	1.32	**S7-4**	failed	0.43			
S3-9	0.07	0.57	**S7-5**	failed	0.29			

Appendix F: Pre and Post Maintenance Surface Infiltration Measurements (mm/s) – Cell 6

Location	Round 1		Round 2		Round 3		Round 4	
	Pre	Post	Pre	Post	Pre	Post	Pre	Post
S6-1	0.67	2.09	0.15	1.52	0.3	0.74	failed	0.59
S6-2	0.36	2.03	0.77	3.28	0.74	3.55	0.26	0.89
S6-3	0.97	2.03	0.25	0.59	0.02	0.15	failed	0.15
S6-4	0.28	0.96	failed	0.23	failed	failed	failed	failed
S6-5	1.13	1.08	failed	0.03	failed	failed	failed	failed
S6-6	1.2	2.37	0.36	2.56	0.36	0.99	0.15	0.64
S6-7	0.44	0.97	failed	0.05	failed	failed	failed	failed
S6-8	0.53	0.84	0.1	0.2	0.01	failed	failed	failed
S6-9	0.65	1.99	Did not take infiltration test 9 due to Typhoon					

Appendix G: Post Maintenance Joint Penetration Depths Cells 1 – 5 and 7

Cell 1 ‖	Cell 1 ⊥	Cell 2 ‖	Cell 2 ⊥	Cell 3 ‖	Cell 3 ⊥	Cell 4 ‖	Cell 4 ⊥	Cell 5 ‖	Cell 5 ⊥	Cell 7 ‖	Cell 7 ⊥
22.6	6.6	15.5	4.6	8	9.4	4	5.8	28.2	4.1	9.9	18.8
22.9	21.9	12.5	4.8	6.1	9.9	8.5	9.6	27.6	6.2	11.6	8.8
14.7	18.6	3.8	10.2	2.8	13.4	9.4	13	27	16.4	36.5	20.6
13	18.6	9.6	9.1	8.8	9.4	8	9.2	25.7	17.7	39.7	13.9
22.9	19.1	7.2	11.2	4.7	10.7	6.1	8.1	19.3	14.3	27.4	20
14.2	23.3	7	8.2	10.4	11.4	9.9	9.8	21.1	9.8	32.3	29.9
23.7	5.6	7.8	10	6.2	11.4	7.9	7.3	13.3	6.6	31.3	31.7
25.2	14.2	9.7	19.4	5.8	8.3	10.2	17.4	23.4	7.7	35.8	27.6
14.6	12.4	13.4	10.7	15.3	10.7	22.9	22.9	28.1	4.3	46	13.9
19.2	18.7	6.5	14.3	8.3	12.7	14.3	9.7	21.3	5.3	44.2	24.8
21.3	22.2	7	17	14.7	16.2	17.5	20.2	29.4	5	48.2	25.5
23.5	18.8	6.1	14	13.7	10.1	19.9	6.5	25.5	6.3	25.1	29.8
23.6	19.7	8.4	15.9	5.3	17	14.8	7.6	23.4	4.9	32.3	40.4
24.8	23.5	10.9	21.8	6.5	7.3	22.1	9	9.7	6.9	47.6	24.6
27.3	14.1	6.6	19.4	4.8	12.2	27.8	4.7	24.1	18.9	40.4	21.9
25.3	21.7	7.9	4.9	11.1	13.1	21.7	5.7	32	27.5	42.7	23.9
42.9	25.1	6.6	4.5	11.1	6.5	21.8	11.5	36.3	25.2	39.8	26.4
19.7	32	8.3	5.5	8.2	11.6	21.4	9.2	21.3	4	37.4	20.2
25.2	30.7	8.8	4.5	13.1	10	20.7	21.4	19.3	5.7	21.6	10.7
15.3	24.6	14.3	2.1	14.1	13.8	21.6	9	6.5	8.7	12.7	10.2
26.4	14.6	13.1	4.9	13.8	11.3	33.6	13	23.2	7.9	11.7	32.1
26.1	19.2	11.7	2.9	8.7	14.1	26.7	8.1	18.2	15.2	25.2	14.5
23.8	24	10.7	8	5.9	16	43.1	6.9	30.3	11	36.6	9.1
17.7	23	8.5	6.9	10.3	8.8	35.1	5.8	22.9	6.1	16.4	39.3
22.9	36.8	13.9	9.9	8.9	12	39.6	7.2	29.2	5.5	32.1	26.1
21.2	24.5	7.4	6.1	7.6	12.1	27.2	20	32.1	10.1	37.2	19.5
25.8	17.3	6.9	12.6	8.9	18.9	25.2	44.1	21.8	3.8	47	20.7
25.7	17.4	7.9	10.3	17.5	8.8	34.4	11.4	25.9	7.6	34.9	33.2
22.9	18.6	8.7	8.8	10	14.1	20.4	4	23.6	3.6	24	17.4
24	19.9	4.1	6.8	10.8	19.2	44.3	5.3	22.4	6	24.1	41.7
30.5	25	10.3	3.9	15.4	12.7	35.1	6.9	26.2	7.5	32.1	31.9
28.9	23.7	11.8	6.9	11.6	12.4	25	6.6	23.4	9.5	35.7	26.7
28.9	23.5	10.8	7	6.2	7.2	40.3	10.9	20.7	11.8	37.7	36.4
29.4	7.8	12.4	4.4	5.9	7.2	31	14	27.8	11	43.9	32.8
24.2	16.9	9	3.1	13.8	8.4	22.8	11.9	24.8	18.6	51.6	25.5
23.3	18	10.2	3.9	11.6	17.3	36.4	22.2	30.8	11	25.8	21.9
23.5	30.9	7.4	8.3	12.3	13.4	15.2	12	19.8	5.5	37.9	26.4
20.5	7.7	17.3	7.6	5.1	10.1	21.1	11.4	20.8	4.6	11.4	29.1
21.9	26.3	10.9	8.6	13.4	21.5	29.9	23.3	20.2	4.6	20.2	17.7
21.9	15.1	16	4.7	17.5	11.8	28.7	6.6	24	10.9	9.7	12.1

Cell 1 ∥	Cell 1 ⊥	Cell 2 ∥	Cell 2 ⊥	Cell 3 ∥	Cell 3 ⊥	Cell 4 ∥	Cell 4 ⊥	Cell 5 ∥	Cell 5 ⊥	Cell 7 ∥	Cell 7 ⊥
19	27.2	14.6	3.4	17.4	14.6	24.7	8.9	27.1	13	26.7	6.1
20.4	19.9	14.3	4.9	10.1	14.8	23.9	8.8	23.5	12	5.9	7.5
16.6	14.2	12.8	11.2	19.2	8.4	24.4	10.5	25.3	6.2	19.9	28
21.8	10.4	14.4	3.5	14.2	21.7	14.1	4.1	17.5	6.2	23.6	16.5
25.2	19.6	10.5	4.5	15.9	12.8	16.9	8.4	11.4	6.5	24.5	13
20.4	27.5	9.8	4.7	11.8	24.8	18.4	26.1	25.3	13.7	10.2	17.5
22.8	16.8	6.2	3.8	15.3	9.5	26.3	20.1	25.2	5.1	35.7	19
22	9.6	8.5	3.1	8.8	10.7	27.9	19.1	24.4	2.2	37.9	26.4
24.6	29.2	8.8	6.6	11.2	10.2	31.8	5.9	29.1	8.4	11.4	29.1
25.7	13.4	8.9	5.3	15.8	9.8	34.8	6.8	23.2	9.5	20.2	17.7
28.6	19	11	4.9		12.2	38.4	5	19	8.3	9.7	12.1
25.5	15.4	15.2	3.4		15.7	27.3	12.3	22.9	5.8	26.7	6.1
23	11.2	10.3	7.2		14.6	27	10.3	31.5	20.1	5.9	7.5
8.3	17.5	9.2	4		9.8	21.9	21.6	21.3	18	19.9	28
25.7	25.2	6.6	4.2		6.4	27.9	13.1	16	23.7	23.6	16.5
21.3	21.7	13.3	5		10.1	20	7.5	29.2	5.1	24.5	13
21.1	8.6	10.3	2.4		6.7	34.2	21.9	28	8.2	10.2	17.5
21.6	25.6	6.2	7.3		12.1	28.4	25.6	26.5	6	35.7	19
17.9	17.2	12.4	14.1		13.7	14.3	10.8	29.7	4.5	14.9	7
21.6	25.2	5.7			14.8	16.9	10.5	25.6	5.4	15.8	5.6
22.9	19.5	5.9			9.4	15.3	14.3	26.2	15.8	25.9	17.5
23.4	15.9	10.9			5.5	7.7	16.7	24.3	7.7	22.6	26.5
23.1	11.2	7.3			10.5	7.6	22.3	23.9	6.4	20	11.4
24.9	14.6	10.4			8.8	15.1	21.5	22.6	2.4	25.3	20.1
23.1	19.1	7.3				16.5	20.9	20.8	9.1	23.9	22.5
20.9	13.7	6.6				12.9	24	24.4	7.1	21.7	17.7
26.2	14.6	6.9				40.3	20.5	34.1	7.2	15.6	28
32.5	26.4	7.6				13.5	9.3	50.6	9	21.7	27.1
31.5	12.5	10.9				15.3	12.5	25.6	10.7	24.7	31.8
28	18.9	10.9				16.8	5	29.5	6.5	24.2	27.1
										16.4	22.9
										21.9	31.3
										21.4	15.7
											21.9
											30

Appendix H: Post Maintenance Joint Penetration Depths Cell 6

Test 1		Test 2		Test 3		Test 4	
‖	⊥	‖	⊥	‖	⊥	‖	⊥
14.7	8.7	6.4	10.7	5.8	5	6.9	5.5
10.4	10.1	9.9	9.5	7.1	7.4	7.9	7.7
10.3	8.8	5.4	9.4	3.1	7.9	3.2	5.1
15.3	5.9	5.3	8.1	3.9	11	6.4	5.1
10.5	9.3	6.4	8.2	4.5	9.1	4.4	5.2
8	6.9	7.4	7	8.5	6.6	5.1	6.9
16	6.5	7.3	7.9	5.3	7.5	5.4	4.9
6.6	9.5	7.3	6.8	3.7	5	0.4	3.9
9.4	7.4	8.2	7.6	4.9	5.7	5.5	3.7
6.7	7.5	7.5	6.4	6.5	8	7	3.4
6.7	7.6	8.6	7.4	9.8	7	6.4	3.4
6.7	9.4	8.2	7.2	7.7	6.2	6.3	5.3
14.3	9	7.9	10.7	6.4	11.7	4.8	4.1
8.4	10.6	14.4	7.2	8.4	7	7	2.9
9.7	5.8	10.6	8.3	9.7	5.9	6.5	6.7
8.8	3.2	17.1	5.7	12.4	5.9	9.6	9
9.8	5.7	12.7	5.4	10.3	4.1	9.7	6
9.9	6.6	12.8	9.4	15.3	5.4	9.1	4.2
7.5	7.2	13.9	10.2	10.1	5.3	9.4	6.6
7.7	8.6	6.5	11.8	5.4	8.8	6.3	6.6
5.8	9.2	7.5	6.4	5.2	5.6	5.5	4.1
9.7	8	8.3	8	4.9	6.8	4.1	4
11.9	7.9	8.4	6.6	5.1	5.9	4.5	3.6
18.7	7.8	6.5	7.7	4.9	6.7	4.5	2.9
10.7	6.5	9.8	7.5	6.1	6.3	2.7	4.4
7.9	9.5	9.6	6.7	8.4	3.5	5.9	3.2
5.1	8.6	5.6	8.9	6.6	5.7	4.5	3.2
7.7	9	4.7	6.5	7.1	3.2	4.7	4.9
6.3	8.4	7.4	12.9	5.1	8.1	4.2	8.9
8.3	9.7	5.3	12.8	4.6	9	5.1	10.5
6.2	7.7	8.2	5.8	6	3.4	4.9	3.7
9.8	8.4	8.2	13.6	8	12.6	8.3	6.1
7.6	6.3	8.4	12.8	8.5	8.1	7.5	5.1
6.2	8.9	7.5	10.2	7.4	5.1	6.2	4.9
6	5.3	7.7	8.7	5.3	7.5	6.8	9.1
11.3	6.3	8	7.3	7.5	6.3	7	5.1
9.6	10.8	7.9	7.3	10.5	5.1	4.5	4.8
	6	9.3	10.7	6.6	8.2	7.5	4.3
12.5	5.3	13.8	7.8	10.2	8.7	5.9	3.8
13.6	6.4	6.7	5.9	5.5	5.9	5.4	4.4

Test 1		Test 2		Test 3		Test 4	
16.7	5.2	7.3	6.7	5.6	7.5	4.9	4.6
8.8	10.7	5.9	7	6.7	6.3	5.5	6.5
9.4	9.1	8.9	13.5	6.7	10.3	4.2	9
10.7	12.5	6.4	21.9	7.6	9	5.1	8.3
10.6	5.8	7.6	21.2	5.6	9.9	5.5	5.6
8.6	12.2	7.5	5.6	5.6	3.7	5.4	1.9
8.8	4.6	7.6	8.4	6.8	11.4	5.3	2.1
9.3	7.1	7.4	11.5	6.5	8.5	6.1	4.3
13.1	6.6	9	8.3	9.6	9.1	6.3	5.6
8.3	8.3	10.1	7.4	9.9	6.3	4.9	6.2
11.1	8.5	7.4	7.7	6.7	2.3	5.2	5.7
7.7	7.2	9.6	6.2	6.8	5.2	8.3	4.8
6.8	8	7.6	6.3	8.5	4.9	7.3	4.8
12	9.7	7.4	5.9	8.4	5.2	8	3.8
9.9	6.2	10.2	7.7	8.7	5.9	9.4	8.6
8.4	9.3	7	6	8.4	4.9	9.3	10.1
10.6	10	10.6	20	10.4	10.7	4.9	
13.2	10.8	9.9	16.6	8.4	5.9	5.5	
10.6		10.1	16.3	10.1	9.2	5.7	
9.6		10.1		6		4.8	
12.8		11.8		5.7		4.4	
12.4		9.4		6.9		4.1	
15		7.8		5.8		3.4	
15.6		7.6		9.4		3.7	
6.2		7.1		7.2		6.7	
9.8		7.8		6.8		6.5	
9.8		6.8		7.3		6.1	
15		7.6		6.2		6.9	
6.9		10.1		9.1		8.4	
10.1		8.4		8.2		7	
11.7		7.5		7.4		8.1	
11.8		8.7		7		8.1	
9.8		8.9		7.7		8.4	
14.7		7.4		9		8.3	
11.4							

Appendix I: Pavement Surface Before and After Maintenance (Cells 1 – 5)

FigureI1: Pre-maintenance photos of infiltration measurement locations (1-9) on Cell 1 (Pave-Tech Typhoon® and Pavevac®).

Figure I2: Post-maintenance photos of infiltration measurement locations (1-9) following high pressurized-air system on Cell 1 (Pave-Tech Typhoon®).

Figure I3. Post-maintenance photos of infiltration measurement locations (1-9) following a vacuum system on Cell 1 (Pavevac®).

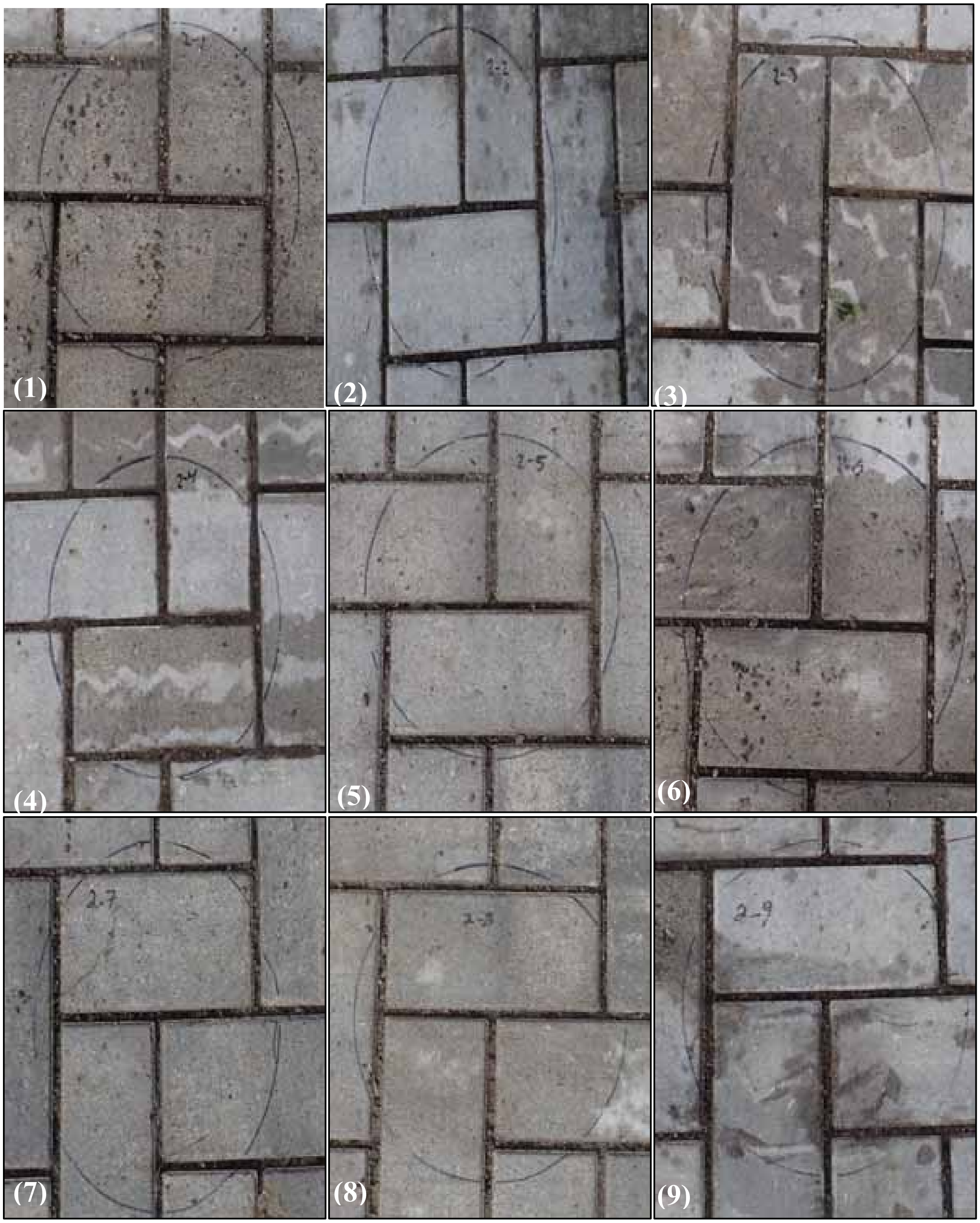


Figure I4. Post-maintenance photos of infiltration measurement locations (1-9) following a regenerative air street sweeper on Cell 2 (TYMCO DST-6®).

Figure I5. Pre- and post-maintenance following pressure washing (1,2) and vacuuming (3,4) on Cell 3.

Figure I6. Post-maintenance photos of infiltration measurement locations (1-9) following a vacuum street sweeper on Cell 4 (Elgin Whirlwind).

Figure I7. Post maintenance photos following a waterless mechanical sweeper on Cell 5 (Elgin Sweepers Water Less Eagle ®), where (1) and (2) are parallel and perpendicular to travel path respectively. (3) is an overview of the plot and (4) is a close up of parallel and perpendicular sediment removal.

Appendix J: Pavement Surface Before and After Maintenance (Cell 6)

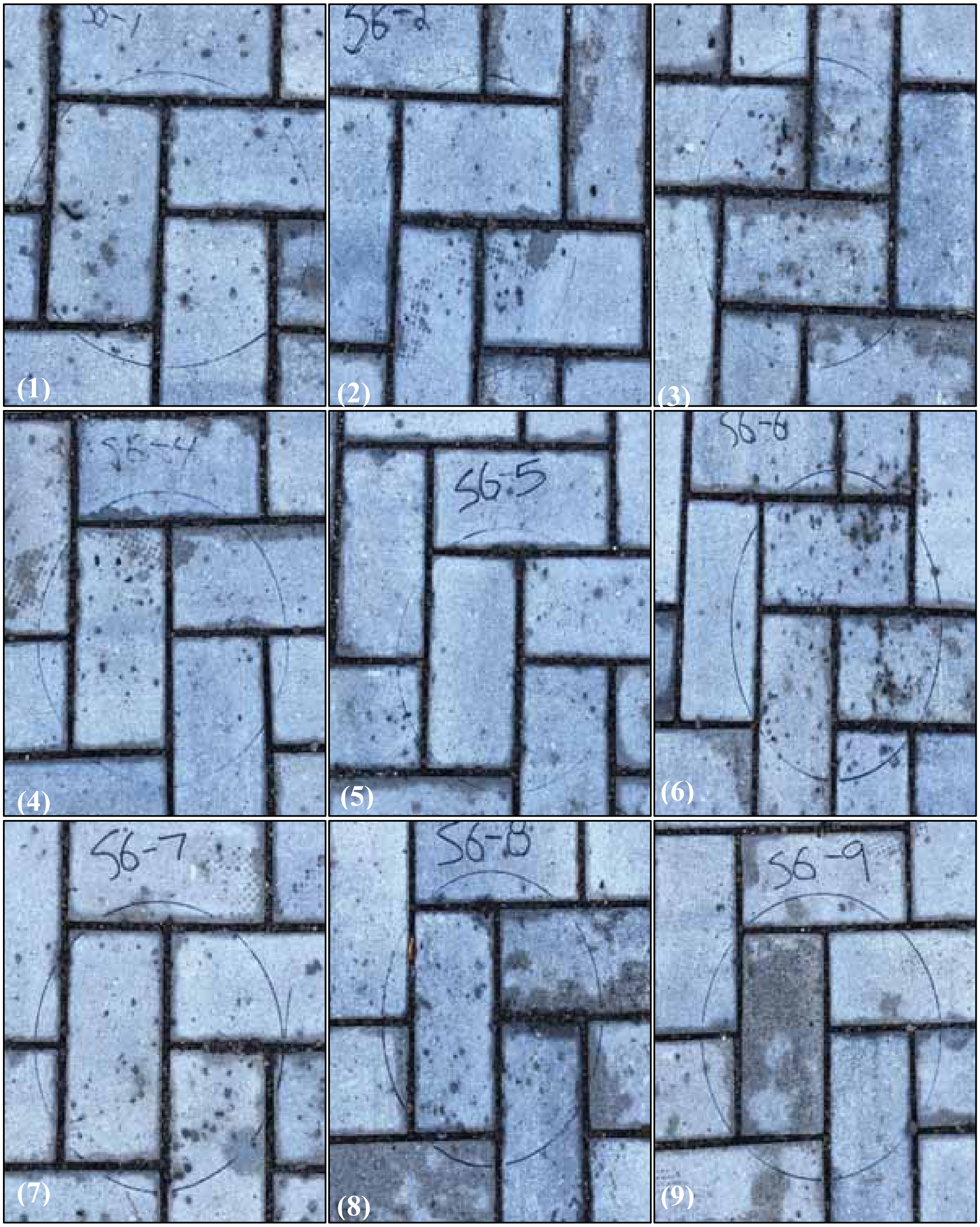


Figure J1. Pre-maintenance photos of infiltration measurement locations (1-9) on Cell 6 before maintenance (TYMCO DST-6®).

Figure J2. Post-maintenance photos of infiltration measurement locations (1-9) following a regenerative air street sweeper on Cell 6 for first early and repeated maintenance (TYMCO DST-6®).

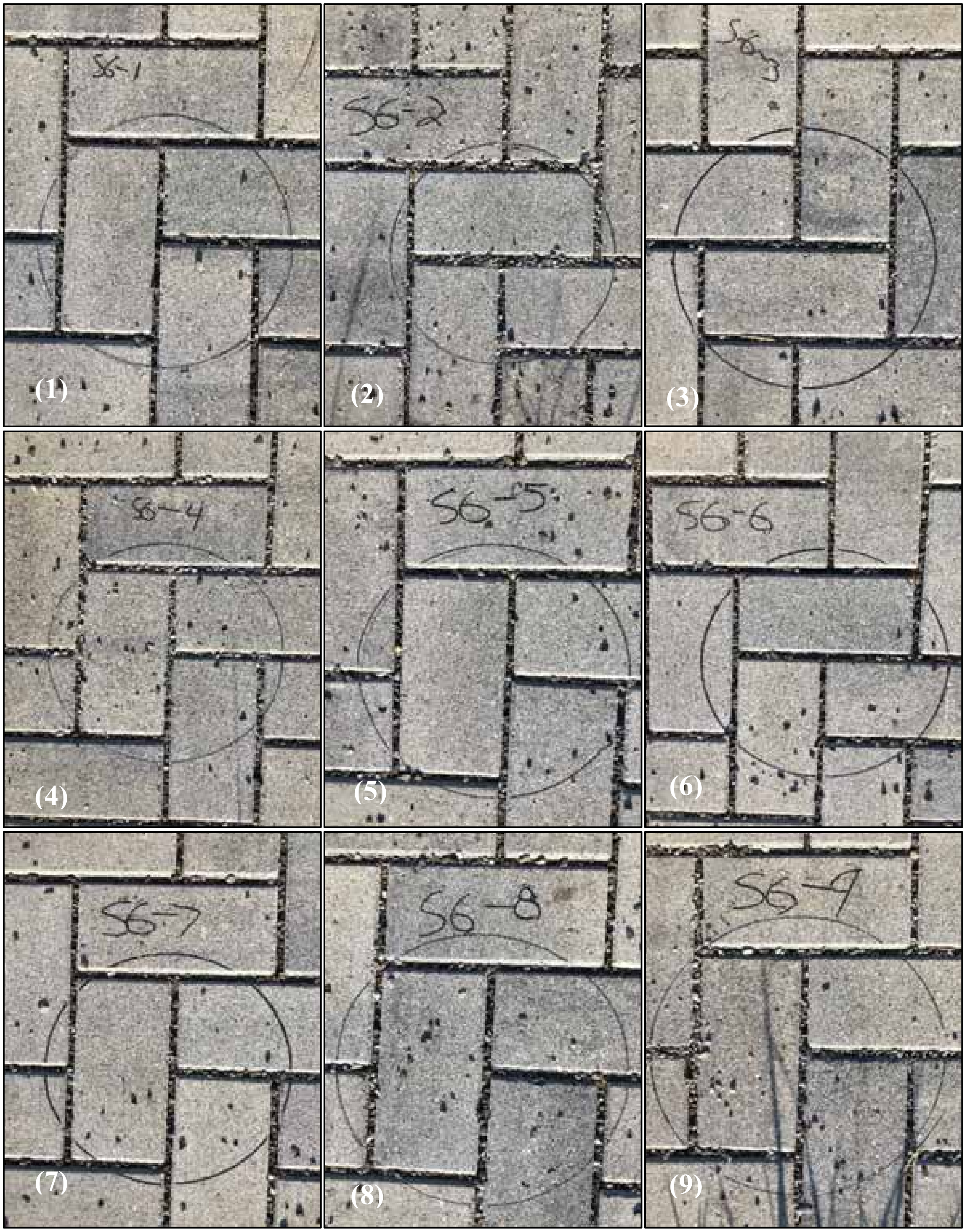


Figure J3. Pre-maintenance photos of infiltration measurement locations (1-9) on Cell 6 after first early and repeated maintenance (TYMCO DST-6®).

Figure J4. Post-maintenance photos of infiltration measurement locations (1-9) following a regenerative air street sweeper on Cell 6 for second early and repeated maintenance (TYMCO DST-6®).

Figure J5. Pre-maintenance photos of infiltration measurement locations (1-9) on Cell 6 after second early and repeated maintenance (TYMCO DST-6®).

Figure J6. Post-maintenance photos of infiltration measurement locations (1-8) following a regenerative air street sweeper on Cell 6 for third early and repeated maintenance (TYMCO DST-6®).

Figure J7. Pre-maintenance photos of infiltration measurement locations (1-8) on Cell 6 after third early and repeated maintenance (TYMCO DST-6®).

Figure J8. Post-maintenance photos of infiltration measurement locations (1-8) following a regenerative air street sweeper on Cell 6 for fourth early and repeated maintenance (TYMCO DST-6®).

Appendix K: Pavement Surface Before and After Maintenance (Cell 7)

Figure K1. Pre-maintenance photos of infiltration measurement locations (1-9) on Cell 7 (Pave-Tech Typhoon® and Pavevac®).

Figure K2. Post-maintenance photos of infiltration measurement locations (1-9) following high pressurized-air system on Cell 7 (Pave-Tech Typhoon®).

Figure K3. Post-maintenance photos of infiltration measurement locations (1-9) following a vacuum system on Cell 7 (Pavevac®).