Long-Term Field Monitoring and Evaluation of Maintenance Practices of Pervious Concrete Pavements in Vermont

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Words: 5,245
Tables: 0 x 250 = 0
Figures: 9 x 250 = 2,250
Total Words: 7,495

ABSTRACT

Pervious concrete pavement (PCP) is used due to its unique properties allowing water to infiltrate into the surface. The objectives of this study were to observe the performance of PCP in the field; determine the effectiveness of cleaning methods to restore infiltration rates; and compare field observations to available laboratory results when possible. Two PCP sites in Vermont were monitored over a year long period by measuring infiltration rates at several locations. Facility-wide cleaning operations such as street sweeping and vacuum truck cleaning were tested for their ability to restore infiltration rates along with spot cleaning methods including hand vacuuming, pressure washing and a combined method. Infiltration rates decreased gradually during the monitoring period with average reductions of 59% at the first facility and 26% at the second facility. Street sweeping and vacuum truck cleaning were found to restore infiltration rates by 21% and 30% respectively, but were not able to restore severely clogged areas. Spot cleaning methods increased infiltration rates by 85% after pressure washing, 10% after vacuuming and 100% after pressure washing followed by vacuuming. Vacuum truck cleaning is recommended; however, either method should be used for maintenance operations starting after construction. Spot cleaning methods with the exception of vacuuming were found to restore infiltration rates of severely clogged areas and are recommended for localized cleaning. Results of long-term monitoring compared reasonably well with previous studies; whereas the results associated with cleaning were substantially lower compared to results found in the literature.

Key Words: Pervious concrete, Infiltration Rate, Maintenance, Cleaning, Pressure Washing, Vacuuming, Clogging.

INTRODUCTION

Research Motivation

Pervious concrete pavements (PCP) have been identified by federal and state agencies as a management practice for the treatment of stormwater by reducing the volume of runoff from impervious surfaces (*1*). PCP incorporates an open pore structure allowing water to travel from the surface into a gravel subbase and subsequently into the native soil. PCP has additional benefits including, reducing noise from vehicles, improving skid resistance and reducing heat island effects (*2*, *3*, and *4*). Due to the open pore structure, PCP is generally limited to areas where lower strength is acceptable such as parking lots, low volume roads, driveways and sidewalks.

Ensuring the long-term performance of PCP is a major concern to designers and maintenance personnel. PCP can be compromised in two ways; clogging of the pores reducing infiltration capacity or damage to the structure of the PCP leading to failure of the pavement. The open pore structure of PCP gradually accumulates inorganic and organic materials leading to reduced infiltration rates. This reduction could lead to the PCP becoming an impervious surface unless periodic facility-wide maintenance such as street sweeping or vacuum truck cleaning is performed or hand-held spot cleaning methods such as hand vacuuming or pressure washing are performed (*1*). Several researchers have attempted to model the effects of clogging and cleaning on PCP in the laboratory; however, there are only a few field studies available to compare with laboratory results.

In order to ensure the long-term performance of PCP, their maintenance practices must be understood. The purpose of this study is to evaluate the effects of typical maintenance practices used on PCP by conducting field investigations and comparing the results to laboratory studies. The specific objectives of this study are to (i) monitor infiltration rate of two PCP facilities in Vermont; (ii) determine the effectiveness of various methods to restore infiltration rate in the field; and (iii) compare field observations to previous laboratory studies.

BACKGROUND

This section presents a literature review related to the effects of maintenance activities on PCP. Studies related to clogging and cleaning of PCP in the field and in the laboratory are also presented.

Field Infiltration Measurements and Restoration

The field infiltration rate of various pervious pavement surfaces including PCP have been investigated using single and double ring infiltrometers modified from soils testing (5). Results from various PCP facilities showed infiltration rates ranging from 5 to 2,750 in/hr (0.003 to 1.91 cm/sec). The authors noted that areas with visible signs of clogging had much lower infiltration rates when compared to areas that showed no signs of clogging. Based on these results the authors recommended that regular cleaning be performed to prevent clogging.

Henderson et al. (*6*) measured infiltration rates using a Gibson asphalt permeameter at sixteen locations at each of the three PCP study sites in Canada during summer 2007, winter 2008 and summer 2008. Sites were classified into areas receiving sand as a winter maintenance practice and areas not receiving sand. The infiltration rate decreased over time at two of the tested locations. Based on the results it was determined that sanding did not increase the clogging of PCP compared to areas not sanded. Sites were cleaned with a 6-hp wet-dry vacuum to restore infiltration rate at one facility. Prevacuuming infiltration rates ranged from 4.2 to 150 in/hr (0.003 to 0.106 cm/sec) while postvacuuming rates ranged from 190 to 5,200 in/hr (0.139 to 3.72 cm/sec) increasing infiltration rates by a factor of 1.3 to 287. Based on these results the researchers recommended vacuuming as a rehabilitation method.

Chopra et al. (*7*) conducted field and laboratory investigations into various methods to restore infiltration rates of PCP. Eight facilities were selected in southeastern United States with infiltration rates measured in the field using a modified single ring infiltrometer. This infiltrometer penetrated both the PCP and the subsoil, reducing lateral flow during testing. The infiltration rates of the PCP and subsoil were measured; the PCP section was then removed and measured for hydraulic conductivity in the laboratory. Based on the results of the field and laboratory testing the authors were able to determine if the PCP or subsoil was the limiting factor for infiltration. The results showed several PCP cores were limiting sections. These cores were cleaned using vacuuming, pressure washing or a combination of both methods, and tested for hydraulic conductivity before and after cleaning to determine treatment efficiencies. Results indicated that hydraulic conductivity values could be increased by a factor of 10 by vacuuming, 56 by pressure washing and 66 by combining the two methods. The authors concluded that these rejuvenation methods should be useful in the field.

Laboratory Studies

Haselbach et al. (*8*) covered PCP specimens with fine sand of known permeability and simulated various rain events and slopes in a flume. Infiltration rates decreased significantly during testing, with pre-clogging values ranging from 280 to 1,400 in/hr (0.2 to 1.0 cm/sec) and post-clogging values ranging from 3 to 7 in/hr (0.002 to 0.005 cm/sec). The researchers concluded that the observed infiltration rates were sufficient to handle the expected 100-year storm event.

Joung and Grasley (*9*) investigated the hydraulic conductivity of clean and clogged PCP samples with a falling head permeameter. Clogging was accomplished by passing a mixture of sand and water through the sample multiple times. After water had drained from the sample, hydraulic conductivity tests were performed a second time to measure the reductions. The results showed the sand did not clog PCP samples with a void ratio of 33% or greater. Samples with a lower void ratio were affected, with the hydraulic conductivity reduced by approximately 40%.

Deo et al. (*10*) investigated the clogging of PCP for varying aggregate size by measuring hydraulic conductivity using a falling head permeameter. Clogging was accomplished by adding 25g of sand to the top of the sample and performing additional permeability testing that allowed water to transport sand into the PCP sample. This process was repeated until additional sand application did not result in further reductions in infiltration rate. They observed 30% reductions in hydraulic conductivity after clogging.

RESEARCH METHODS

Field Investigations

Field investigations were conducted to determine the following; (i) how infiltration rate of PCP changes over time, (ii) how facility-wide cleaning operations such as street sweeping and vacuum truck cleaning restore infiltration rates, and (iii) how spot cleaning methods such as hand vacuuming and pressure washing restore infiltration rate of PCP in severely clogged locations.

Surface Infiltration Capacity

A falling head infiltrometer was designed and built at the University of Vermont to monitor the long-term infiltration rate of two PCP facilities. A sheet of PVC measuring 2' x 2' x ¾ in (60.9 cm x 60.9 cm x 1.90 cm) with a circular opening for a standpipe was used as a base. The standpipe was made with PVC pipe 0.25 in (0.63 cm) thick and with an internal diameter of 4 in (10.1 cm). Milled viewports on the standpipe allowed for monitoring of water levels during testing. A foam rubber ring was attached to the underside of the device around the standpipe to create a seal between the infiltrometer and the PCP surface. Weights (about 120 lbs [55 kg]) were placed onto the device to compress the foam during testing as seen in Figure 1.

The infiltration rate was determined by filling the standpipe and measuring the time for the water level to drop from 15 in (38.1 cm) to 3 in (7.6 cm) above the PCP. Previous research on PCP indicated laminar conditions would exist for the head values used during testing (*8*). Measurements were taken three times at each location to ensure consistent results. Infiltration rate was determined using Eq. 1 below. This falling head infiltrometer method has been found to correlate well with the ASTM standard (single ring) for infiltration measurements of PCP and to saturated hydraulic conductivity measurements with a relation of 1 : 1.8 : 9 (hydraulic conductivity : ASTM standard : falling head infiltrometer) (*11*)

$$I = \frac{c(h_1 - h_2)}{t} \qquad (1)$$

where,

I	=	Infiltration rate, (in/hr),
t	=	Recorded time, (s),
h_1	=	Initial water level, (in),
h_2	=	Finial water level, (in), and
c	=	Conversion factor = 3,600 s/hr.

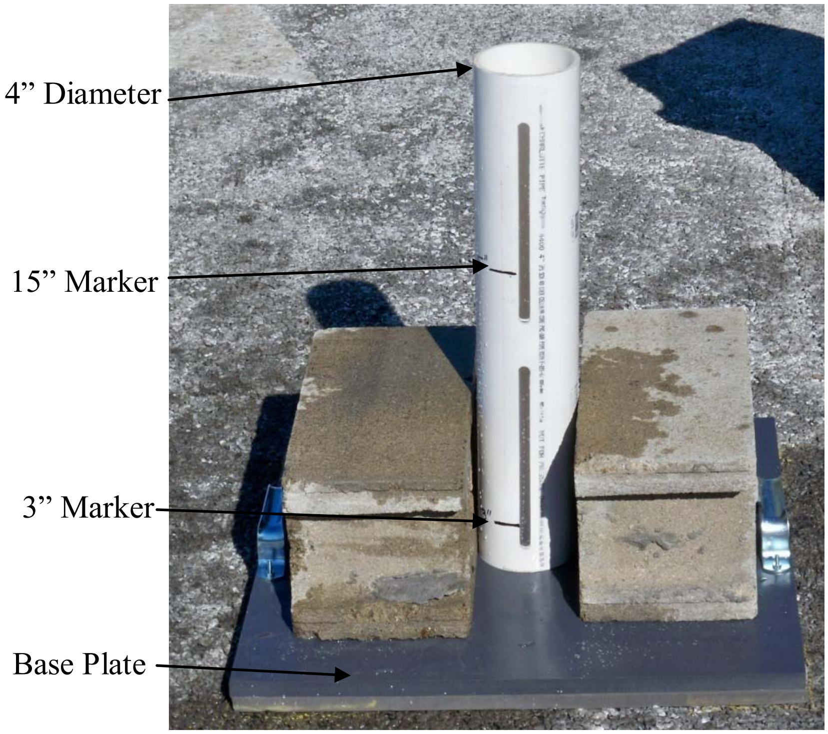
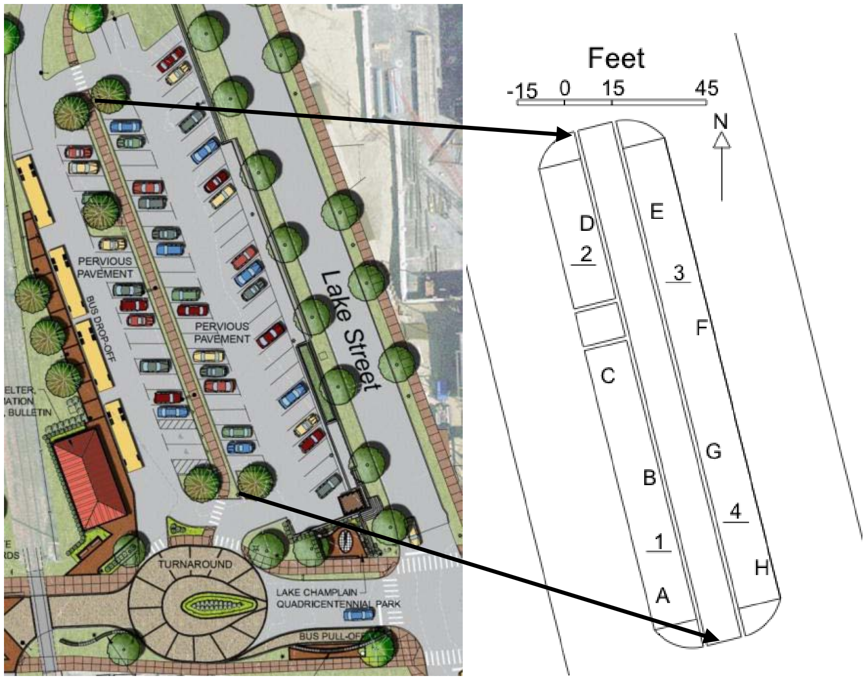


FIGURE1 Falling head infiltrometer in use.

Field Facilities

Infiltration testing was performed at two PCP facilities. The first facility is located at College Street in Burlington, Vermont, and was constructed in June 2009. PCP is used in the central portion of the parking area, with the remainder traditional asphalt. Figure 2 shows an outline of the site with infiltration monitoring sites listed alphabetically and cleaning locations listed numerically. The site is graded to direct water to the central PCP section. Below the pavement surface is a 34-inch layer of gravel used as storage reservoir and perforated pipes that remove the collected stormwater. No cleaning operations were performed on the facility prior to this investigation. Winter maintenance consisted of plowing with little use of sand or salt; however, both were used on a nearby road with runoff from the road entering the facility.

The second facility is located at Heritage Flight in South Burlington, Vermont, and was constructed in September 2009. The lot is solely PCP. An outline of the facility is shown in Figure 3, with infiltration monitoring sites and cleaning sites shown as in Figure 3. The area is primarily a parking facility; however, a small amount of truck travel occurs due to fuel deliveries. The facility is graded flat with minimal runoff from the adjacent impervious surfaces. The PCP overlays a gravel base 32-inches (81.2 cm) thick with water infiltrating into native soils. The facility was cleaned by street sweeping bi-annually, once in the fall after foliage had dropped and once in the spring after winter maintenance ended. Winter maintenance consisted of plowing with a rubber tipped blade with no application of sand or salt.



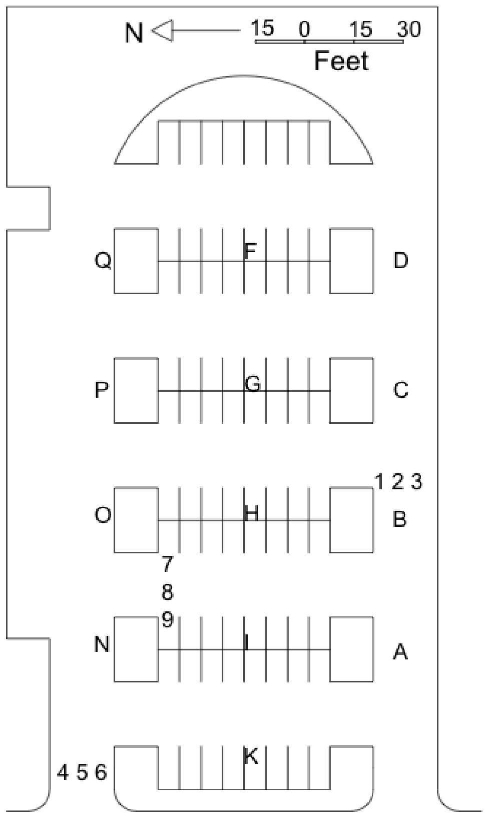
A) B)

FIGURE 2 College Street PCP facility, (a) Overview of facility, and (b) Location of testing sites.

Long-term Field Monitoring

The infiltration rate was measured at eight locations at the College Street facility, with sites A, C, F and H located near the PCP/asphalt divide and sites B, D E and G located near the inner island. Fourteen locations were selected at the Heritage lot, with sites at areas: (i) outside the wheel path experiencing little traffic (A, C, N, and P), (ii) inside the wheel path experiencing traffic (B, D, O, and Q), (iii) in parking areas not under tires (E, G, and I), and (iv) in parking areas under tires (F, H, and K). Infiltration measurements were in August 2010 at both locations, with subsequent measurements taken every month. Although infiltration data immediately after construction is not available, infiltration rates of slabs created in the laboratory using an identical mix design and similar placement methods were used to estimate a range of post-construction infiltration rates.

(a)



(b)

FIGURE 3 Heritage PCP parking facility, (a) Photograph of the facility, and (b) Location of testing sites.

Infiltration Recovery Methods

Cleaning operations were separated into two categories: (i) facility wide cleaning operations; which included street sweeping and vacuum truck cleaning; and (ii) spot cleaning methods such as vacuuming by hand, pressure washing and a combination of the two methods. Street sweeper cleaning was performed using a Elgin Whirlwind air sweeper that brushed material from pores and carried it to a central vacuum. This vacuum removed material; however, it did not form a tight seal with the pavement surface. Vacuum cleaning was performed using a Tymco 500x regenerative air vacuum truck. This system utilized a vacuum system providing a better seal to the pavement surface and included pressurized air to dislodge material from the pores and remove it from the surface. Street sweeping was performed as part of regular maintenance at the Heritage facility in September of 2010 and vacuum truck cleaning was conducted at both facilities in October 2011. To determine the effectiveness of these maintenance operations infiltration rates were measured before and after cleaning at eight locations per facility. Handheld methods were tested to determine their effectiveness at restoring infiltration at four locations at the College Street facility and ten locations at the Heritage facility. Sites selected for vacuuming were cleaned by a 5-hp wet-dry vacuum; an area measuring 2'x2' (61cm x 61cm) was vacuumed for 30 seconds in one direction, then another 30 seconds in the perpendicular direction. Locations selected for pressure washing were cleaned with a 3,500-psi pressure washer; the method of cleaning was identical to the vacuuming procedure. The combined method was used at sites by first pressure washing then vacuuming. Pre and post cleaning infiltration rates for all methods were determined using the falling head infiltrometer.

RESULTS AND DISCUSSION

Long-term Field Monitoring

Results of long-term monitoring of the College Street facility are presented in Figure 5. Figure 5a shows monitoring sites along with the infiltration rate (in/hr) at the beginning and end of monitoring period (August 2010 to July 2011), and the percent decrease. Infiltration values reported as CLG indicated complete clogging. Infiltration rate likely ranged from 1,400 to 2,800 in/hr (1.0 to 2.0 cm/sec) immediately after construction.

Initial infiltration rate of sites near the inner island are significantly lower than other locations, with sites B, D, and G having the lowest infiltration rates at the start of testing. The initial infiltration of other sites was higher, ranging from 574 to 1,442 in/hr (0.41 to 1.03 cm/sec). Figure 5b shows areas where clogging from sand or organic matter was visible at the end of the monitoring period; clogging was identified by standing water after storm events. Clogging primarily occurred at locations near the inner island and was present on both sides of the facility. Clogging near site G consisted mostly of sand, whereas near sites D and B clogging consisted of a combination of organic matter and sand. Visibly clogged areas covered approximately 15% of the facility. Figure 5c shows locations that appeared to be raveling during the monitoring period, these locations closely matched areas of severe clogging. These observations support previous laboratory studies indicating that clogging can accelerate freeze-thaw damage in PCP (*12*). Due to the high initial clogging, these sites do not show significant change over the testing period. Other locations showed decreases in infiltration rates of 42% to 64%. Average infiltration values determined at each location are presented in Figure 5d. Infiltration measurements were not recorded in December and May due to poor weather conditions. Infiltration rates generally decreased continually throughout the monitoring period with infiltration rates at sites A, C, and E decreasing by the largest amount. This gradual decrease suggests that clogging material is constantly being transported to the site with little variation over the year long period.

Results of long-term monitoring at the Heritage facility are presented in Figure 6. Clogging at the beginning of monitoring was observed at sites B, and D as seen in Figure 6a.

Delivery trucks, that can compact sand and other materials into pores, regularly travel these sites. Infiltration rates at sites in a similar location but not experiencing truck traffic (A and C) were an order of magnitude higher. This difference was not as drastic in the sites with a similar distribution inside and outside of the travel lane, but did not regularly experience truck traffic (N though Q), indicating that not only vehicle traffic but the type of vehicle can impact the clogging of PCP. Sites located in the parking areas showed the highest initial and final infiltration values, with little difference between sites inside or outside the travel lane. Figure 6b shows visible clogging located near entrances to the facility. Clogging material was found to consist mostly of asphalt particles from the nearby road. Raveling, shown in Figure 6c, was not correlated with clogging at the Heritage facility and was observed to be more random in location. Both clogging and raveling were observed on less than 5% of the surface. As with the College Street facility, unclogged areas showed similar reductions to infiltration rate; most sites decreased 10% to 30% over the testing period. Figures 6d and 6e show the range of infiltration rates observed in travel lanes and parking areas respectively. All sites with the exception of C showed a gradual decrease over time with infiltration values remaining high at the end of testing. Differences existed between infiltration rates of sites located within the wheel track and sites outside the wheel track as seen in Figure 6d. Several sites presented in Figure 6e show infiltration rates above the range of initial infiltration values. These results are likely due to variability of the construction, specifically low compaction resulting in higher infiltration rates. In the parking areas there was little difference between the sites inside the wheel track and sites outside the wheel track.

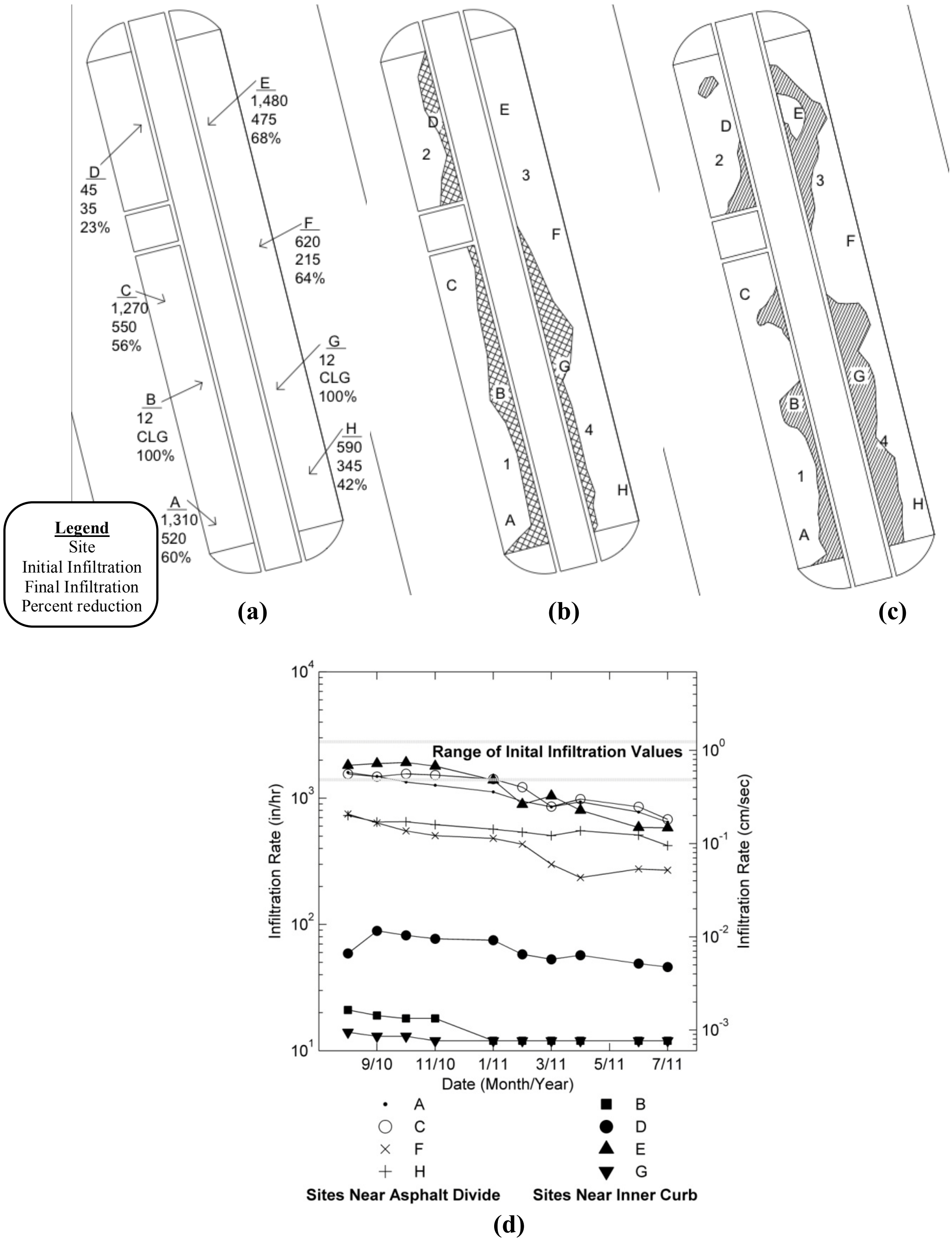


FIGURE 5 Results of field monitoring at College Street facility. (a) Infiltration sites, (b) Visual signs of clogging, (c) Visual signs of raveling, and (d) Infiltration measurements.

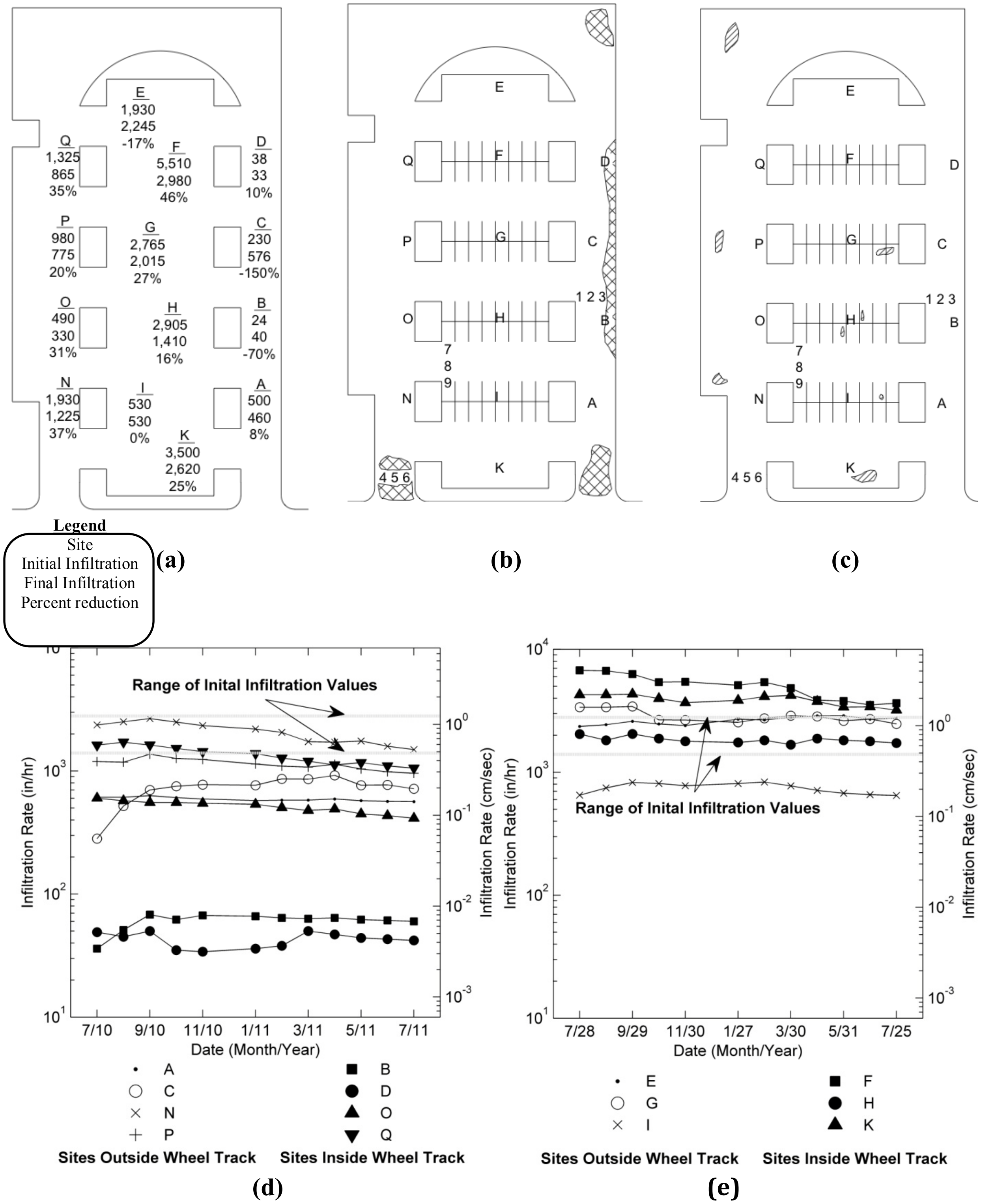


FIGURE 6 Results of field monitoring at Heritage facility. (a) Infiltration sites, (b) Visual signs of clogging, (c) Visual signs of raveling, (d) Infiltration measurements in travel lanes, and (e) Infiltration measurements in parking areas.

Infiltration Recovery Methods

Facility Wide Cleaning

The effects of facility wide maintenance practices are presented in Figure 7. Bars show the initial infiltration value measured at the beginning of the monitoring period with measurement before and after cleaning by both street sweeper and vacuum truck. For each cleaning method the absolute increase to infiltration rate (in/hr) and percentage increase are presented above the bar plots. A range of estimated post construction infiltration values and the infiltration rate associated with the 100-year, 24-hour storm event for the region are shown. Cleaning by sweeper was only performed at the Heritage facility and is shown in Figure 7a. Sweeping primarily collected dislodged aggregate and cement paste along with large inorganic and organic material on the PCP surface. The average increase to infiltration values was 28% due to cleaning. However, this value includes results from clogged sites that showed large increases to infiltration rate due to low pre cleaning infiltration rates. These sites do not accurately represent the average conditions of the facility and inflate the average recovery value. Removing these sites (B and D) from the analysis results in an average increase to infiltration rate of 21%, which more accurately represents the effect on non-clogged areas. During post cleaning observations material was still present in the pore structure indicating that cleaning was incomplete.

Vacuum truck cleaning was performed on both sites with differences in effectiveness. At the Heritage facility vacuum truck cleaning was found to be more effective than sweeping. The average increase to infiltration rate was 89% considering all sites and 30% when sites B and D were removed from analysis. Both of these numbers are greater than the increase due to sweeper cleaning. The addition of pressurized air resulted in additional material being removed from the pores, increasing infiltration recovery rates. As compared to the Heritage facility, at the College Street facility vacuum truck cleaning was less effective, only restoring infiltration rates at three of the six sites with an average increase to infiltration rates of 17%. During post cleaning observations of the site, material was observed to still be trapped in the PCP, indicating that there was a limit to the extent that vacuum truck cleaning can be used on clogged PCP.

Based on the results from the Heritage facility, it can be concluded that cleaning using a vacuum truck results in a better restoration of infiltration rates than a sweeper. It appears though that regular (bi-annual) sweeping at the Heritage facility reduced areas of clogging, allowing for increased restoration. Likewise, severe clogging at the College Street facility was likely due to the lack of regular cleaning. This clogging reduced the effectiveness of vacuum truck cleaning. These observations indicate that it would be beneficial to clean PCP facilities regularly; twice a year (in spring and in fall) preferably using a vacuum truck. If that is not feasible, cleaning with a sweeper is expected to be better than no cleaning at all.

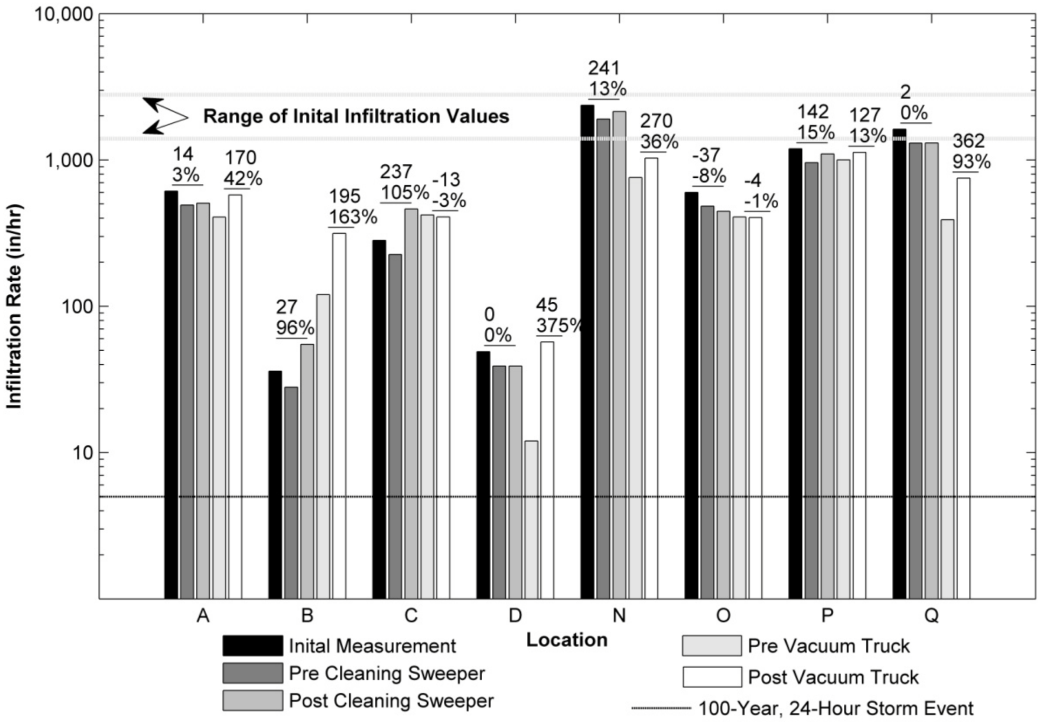
Spot Cleaning

Results of spot cleaning methods performed at the College Street and Heritage facilities are presented in Figures 8 and 9, respectively. Sites are reported with their numerical identifier, pre-cleaning infiltration rate, post-cleaning infiltration rate and percentage restoration, all infiltration rates are in in/hr. Figures have been modified for the Heritage facility to better show the area where cleaning was performed.

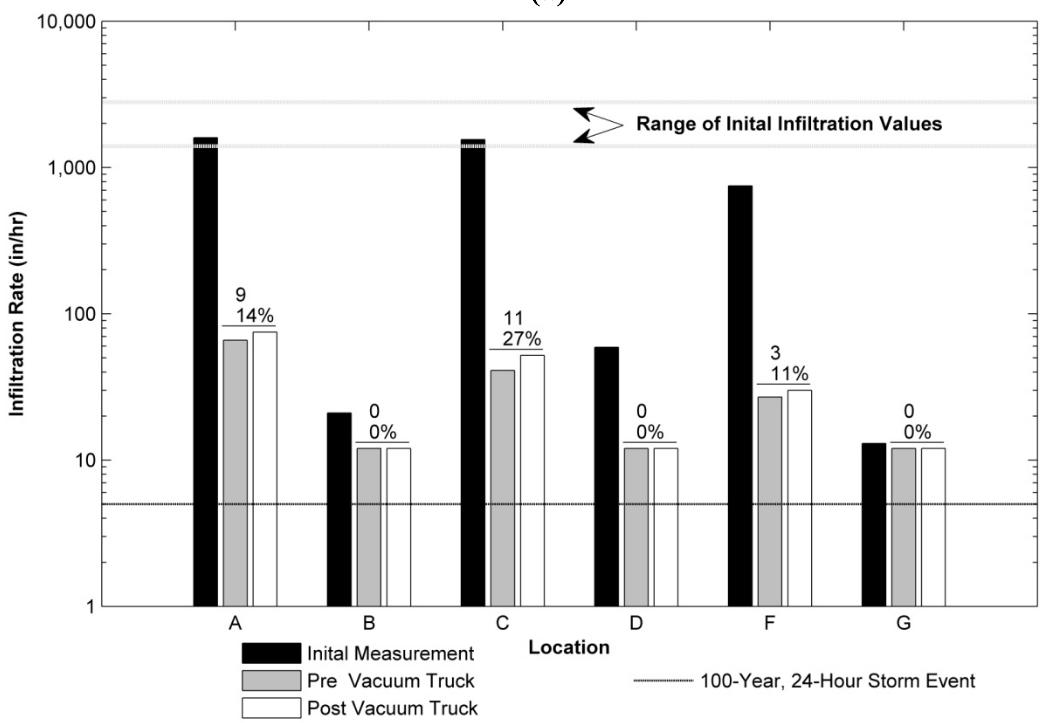
Pre-cleaning infiltration rates at a given site are generally similar for all cleaning methods. The largest variation was observed at College Street at site 2 which ranged from 700 to

1,120 in/hr (0.53 to 0.83 cm/sec). At the Heritage facility the largest variation in pre-cleaning infiltration rates was found at site 3, ranging from 42 to 1,000 in/hr (0.03 to 0.72 cm/sec). Sites at both facilities were found to vary greatly with pre-cleaning infiltration rates ranging from 82 to 1,160 in/hr (0.006 to 0.83 cm/sec). These values indicate that cleaning procedures were tested on a wide variety of clogging conditions.

Pressure washing increased infiltration rates at all sites except for site 1 at the Heritage facility, with increases of 4% to 591% and an average increase of 85%. The largest increases to infiltration rates were observed in areas such as College Street 4 and Heritage 4-6 indicating that pressure washing can restore areas of severe clogging. At site 8 pressure washing was observed to cause a small amount of raveling; however at all other sites no such raveling was observed. Vacuuming was also found to restore infiltration rates from 4% to 28% with an average value of 10%. However, College Street sites 2 and 4 and Heritage sites 4 and 6 showed no increase, indicating that vacuuming alone cannot remediate severe clogging. Combined pressure washing and vacuuming resulted in restoration of infiltration rates at all sites including severely clogged sites with increases to infiltration rate ranging from 6% to 1,070% and averaging of 100%. Results of spot cleaning indicate that different methods result in different treatment efficiencies. Although these methods are impractical for facility wide cleaning operations pressure washing and combined pressure washing and vacuuming were found to successfully remediate severely clogged areas that street sweepers and vacuum trucks could not clean. Pressure washing followed by vacuuming would be ideal to prevent the migration of material into PCP; however, pressure washing alone can be effective if small areas (compared to the overall site) are to be cleaned.

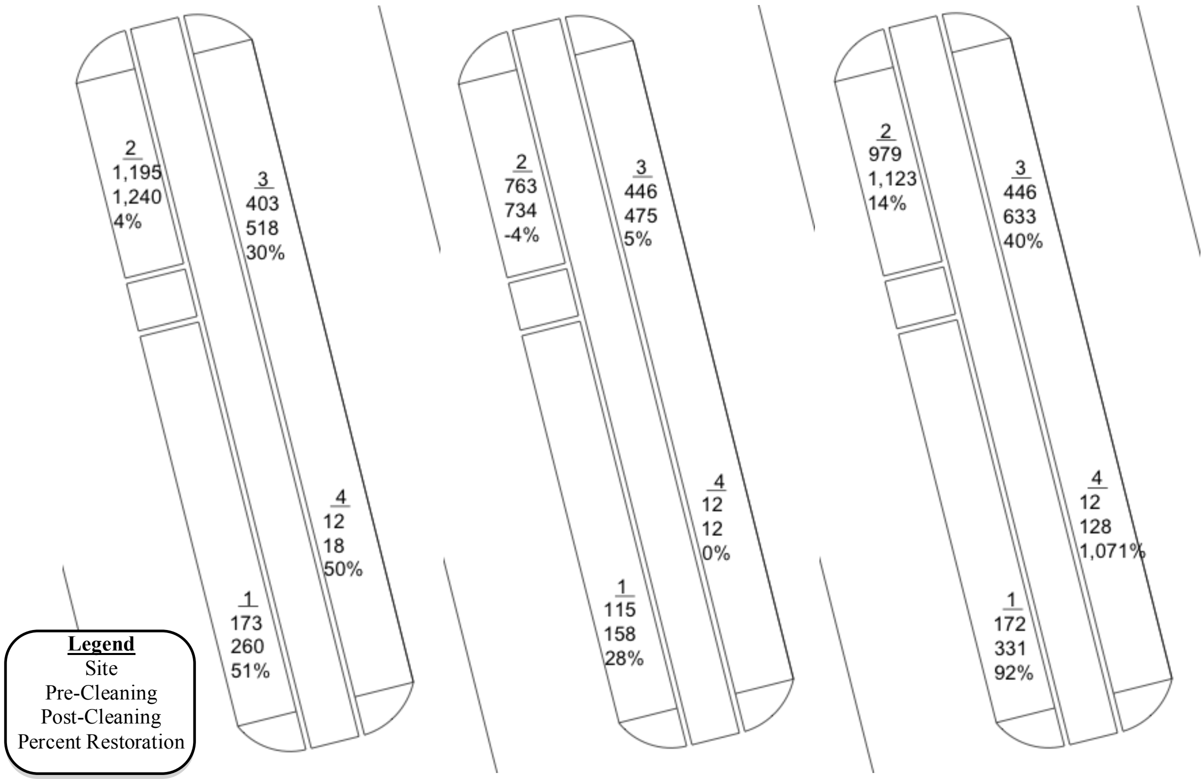


(a)



(b)

FIGURE 7 Results of Maintenance operations (b) Heritage lot, (b) College street lot



A) B) C)

FIGURE 8 Effects of various cleaning methods on infiltration rate at the College Street facility A) Pressure washing, B) Vacuuming and C) Combined

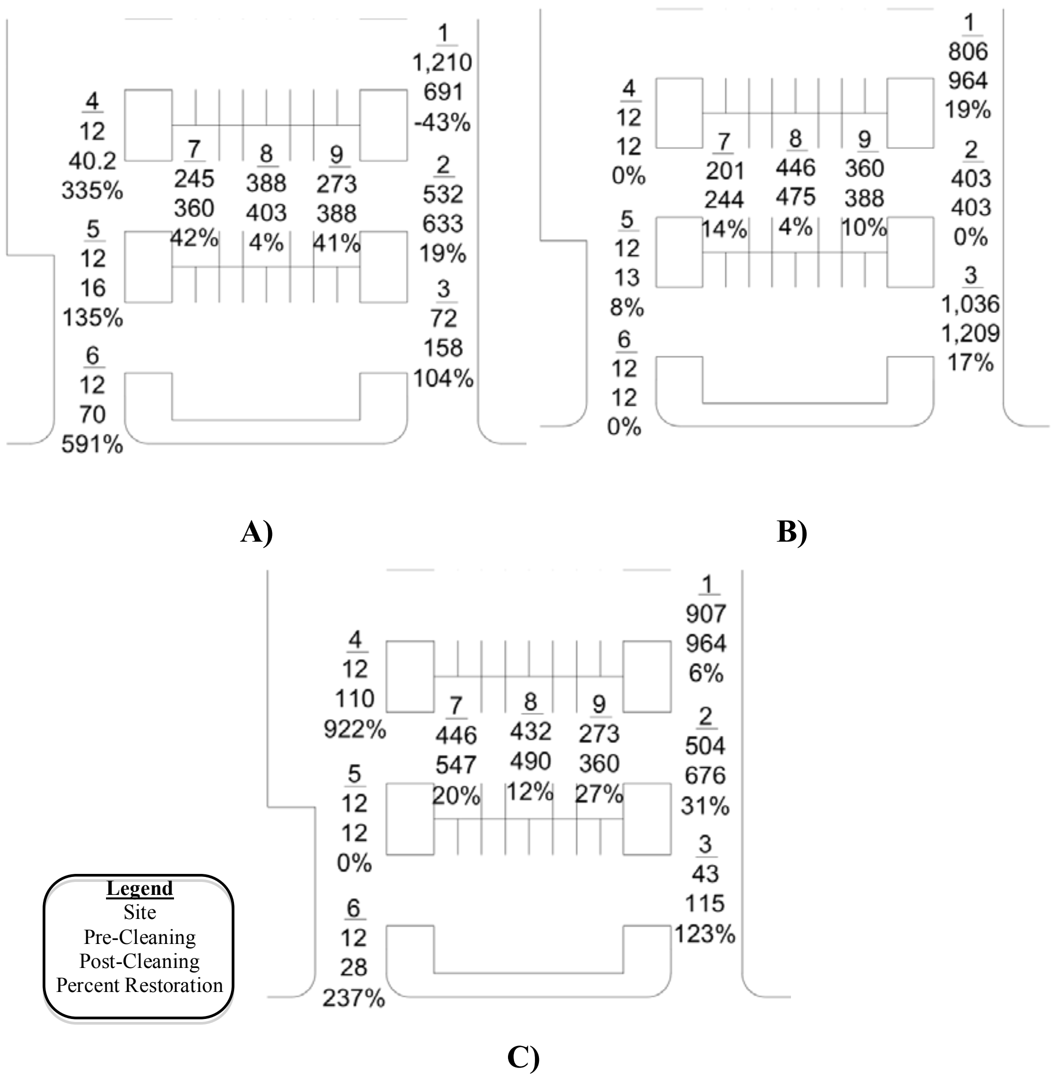


FIGURE 9 Effects of various cleaning methods on infiltration rate at the Heritage facility. A) Pressure washing, B) Vacuuming and C) Combined.

Comparison to Previous Studies

Long-term Monitoring

Reduction in infiltration rate of 87% in the field observed Henderson et al. (*6*) compare reasonably well with values observed in this study with the College Street and Heritage facilities showing 59% and 26% reductions, respectively. Laboratory reductions were observed to be approximately 40% and 30% in specimens exhibiting clogging (*9, 10*). Both of these results fall within the range of field observations indicating that laboratory studies can be used to estimate field performance of PCP.

Infiltration Recovery Methods

Field testing of vacuum cleaning performed by Henderson et al. (*6*) showed post-cleaning infiltration rates were 100 times greater than pre-cleaning infiltration rates. In another study (*7*) cleaning increased infiltration rates 10, 56 and 66 fold for vacuuming, pressure washing and combined methods respectively. These increases to infiltration rate were considerably larger compared to the results of this study; with vacuuming restoring infiltration rates by 1.1 times original value on average, pressure washing restoring infiltration rate by 1.85 times original value and combined methods 2 times original value. This difference between the efficiency of cleaning methods is significant. In results reported by Henderson et al. (*6*) cleaning was performed one year after construction, whereas in this study cleaning was not investigated until after the second year of operation. The additional time between construction and cleaning in this study likely allowed material to be forced into the PCP, resulting in reduced cleaning efficiency. Different hydraulic testing conditions (saturated hydraulic conductivity vs. unconstrained infiltration) make direct comparisons with the second study difficult and could explain the observed difference; however, the effectiveness of each cleaning method compared to one another (vacuum vs. pressure washing) is similar for both studies.

CONCLUSIONS AND DISCUSSION

The objectives of this study were to observe the performance of PCP in the field; determine the effectiveness of cleaning methods to restore infiltration rates, and compare field observations to available laboratory results when possible. This was accomplished by monitoring two PCP sites in Vermont over about a year long period and testing various cleaning methods at these sites. At each site, several locations were monitored and tested.

Infiltration rates measured at the PCP facilities decreased over the one year period with average reductions of 59% for the College Street facility and 26% for the Heritage facility. Reductions to infiltration rate over time were gradual, indicating that the clogging process occurred consistently over both sites irrespective of the season. Differences were observed between sites within and outside of the wheel track of vehicles, clogging was also observed to be more severe in locations where trucks regularly traveled. Previous studies that simulated clogging in laboratory found infiltration rates decreasing in a more or less linear fashion as the clogging material was added, with final reductions ranging from 20% to 40%. This suggests that the real world clogging of PCP can be simulated in laboratory studies.

Facility wide cleaning operations included street sweeping and vacuum truck cleaning, which resulted in increases to infiltration rate of 21% and 30%, respectively, and both methods are recommended for regular cleaning operations. Spot cleaning methods were also investigated with increases of 85% after pressure washing, 10% after vacuuming and 100% after pressure washing followed by vacuuming. Cleaning by pressure washing was found to be effective at restoring infiltration rates in areas of severe clogging, however the method forces material into the gravel subbase potentially clogging it in the future. Vacuuming along with pressure washing is preferred as it is able to restore infiltration rate and remove material from PCP. These field results of infiltration rates were found to yield substantially less recovery of infiltration rates compared to previous laboratory studies. Nonetheless, less than 15% of the total PCP area was clogged in both facilities, and in general the infiltration rate of the PCPs remained greater than the infiltration needed to accommodate a 100-yr storm event, except in the severely clogged regions.

ACKNOWLEDGEMENTS

This work was funded by the United States Department of Transportation through the University of Vermont Transportation Research Center along with the Vermont Agency of Transportation (VTrans). The authors are grateful to the VTrans Materials & Research Section for their assistance in sample preparation. Additional thanks go to Ian Anderson, Bradford Berry and George McCain who provided assistance on this project.

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