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Long-term stormwater quantity and quality performance of permeable pavement systems

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Abstract

This study examined the long-term effectiveness of permeable pavement as an alternative to traditional impervious asphalt pavement in a parking area. Four commercially available permeable pavement systems were evaluated after 6 years of daily parking usage for structural durability, ability to infiltrate precipitation, and impacts on infiltrate water quality. All four permeable pavement systems showed no major signs of wear. Virtually all rainwater infiltrated through the permeable pavements, with almost no surface runoff. The infiltrated water had significantly lower levels of copper and zinc than the direct surface runoff from the asphalt area. Motor oil was detected in 89% of samples from the asphalt runoff but not in any water sample infiltrated through the permeable pavement. Neither lead nor diesel fuel were detected in any sample. Infiltrate measured 5 years earlier displayed significantly higher concentrations of zinc and significantly lower concentrations of copper and lead.

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1. Introduction

Impervious surfaces have long been implicated in the decline of watershed integrity in urban and urbanizing areas [1–3]. Most of these surfaces serve automobile travel, but a significant portion of these impervious areas, particularly parking lots, driveways, and road shoulders, experience only minimal traffic loading [4,5]. Parking lots are typically sized to accommodate peak traffic usage, which occurs only occasionally, leaving most of the area unused during a majority of the time [6,7]. Other large parking areas, such as those for businesses and schools, may be used to full capacity nearly every day but with only once-in and once-out traffic that imposes little long-term wear.

The creation of any large impervious surface commonly leads to multiple impacts on stream systems. These impacts include higher peak stream flows which cause channel incision, bank erosion, and increased sediment transport [8–11]. Another impact is a reduction of infiltration which lessens groundwater recharge and potentially lowers stream base flows [1,12,13]. Runoff from impervious areas may also increase pollutant loads to streams [14–17].

Permeable pavements offer one solution to the problem of increased stormwater runoff and decreased stream water quality associated with automobile usage. Permeable pavement systems are commonly made up of a matrix of concrete blocks or a plastic web-type structure with voids filled with sand, gravel, or soil. These voids allow stormwater to infiltrate through the pavement into the underlying soil, which in turn can play a significant role in mitigating the impacts of stormwater runoff caused by urban development [18–21].

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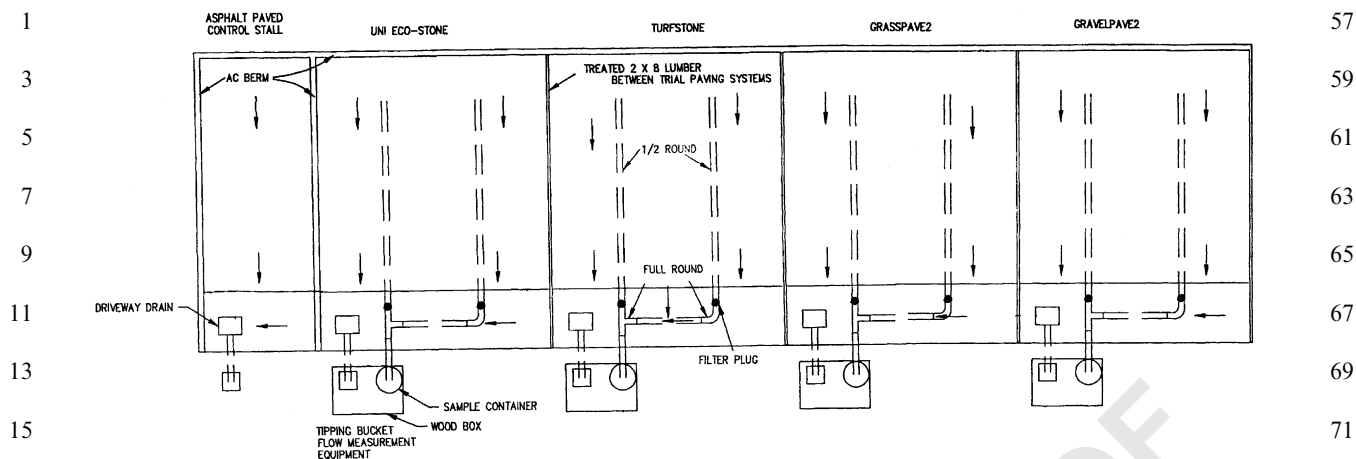


Fig. 1. Plan view of the nine test parking stalls. Each permeable pavement type had two parking stalls paired into one instrument station.

The purpose of this study was to evaluate the long-term effectiveness of permeable pavements as a stormwater management strategy, expecting that if they can infiltrate stormwater reliably without creating a new set of water-quality problems then they present an attractive adjunct or replacement for the current structural requirements for stormwater management. This investigation was made by evaluating the water-quality and water-quantity performance of four permeable pavement systems in an intensively monitored parking lot after 6 years of constant use. Our intention was to address commonly raised questions about permeable pavement systems:

- Is permeable pavement structurally durable, and can it withstand long-term use as well as asphalt?
- Do permeable pavements remain permeable or does particulate matter and grease reduce infiltration over time?
- What is the water quality of the infiltrate through permeable pavement, and how does it compare to runoff from asphalt?

2. Project history

This work follows the study of Booth and Leavitt [22], which presented the results of a preliminary test of a field installation of permeable pavement systems as a means of improving stormwater management. That study was conducted in the first year following construction of the site, using the same facility as the present evaluation.

The field site used for both studies was constructed in 1996. It is located in Renton, Washington, 20 km south of Seattle, and includes nine parking stalls, eight of

which are constructed of four pairs of different permeable pavement systems. The ninth stall is covered with asphalt and used as the control (Fig. 1).

The study site was chosen for several reasons. It has very deep permeable soil that is well suited for infiltration, good security for monitoring equipment, and frequent use. A site with intrinsically good infiltration properties was selected to ensure that the permeable pavements systems were not hindered by poor infiltration in the underlying soil. The site is used for employee parking at the King County Public Works facility, with once-in, once-out daily usage. Stalls were presumed clear of cars at night and on weekends, although this was directly verified only sporadically during the study. Occupancy of the nine stalls during working hours was typically 90–100%.

The initial study by Booth and Leavitt [22] examined both hydrologic and water-quality characteristics of the site. Their results showed no measurable surface runoff from the permeable pavement areas. In samples of infiltrate collected during three storms, concentrations of several priority pollutants (copper, lead, and zinc) were generally low and not significantly different from runoff from the asphalt surface; hardness and conductivity were significantly higher in all subsurface infiltration samples.

3. Methods

The experimental methods used for the present work followed those established in the earlier study [22]. Eight stalls were constructed with four types of commercially available permeable paving systems, with two neighboring stalls covered with each of the four permeable paving

1 systems. The permeable pavement systems used in this
2 study were:

- 3 ● Grasspave^{2®}, a flexible plastic grid system with
4 virtually no impervious area, filled with sand and
5 planted with grass.
- 6 ● Gravelpave^{2®}, an equivalent plastic grid, filled with
7 gravel.
- 8 ● Turfstone[®], a concrete block lattice with about 60%
9 impervious coverage, filled with soil and planted with
10 grass.
- 11 ● UNI Eco-Stone[®], small concrete blocks with about
12 90% impervious coverage, with the spaces between
13 blocks filled with gravel.

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16 Each test parking stall was 3 m wide by 6 m long. A
17 series of gutters and pipes, discussed in detail by Booth
18 and Leavitt [22], were used to collect both surface runoff
19 and subsurface infiltrate. Surface runoff and subsurface
20 infiltration from each pair of stalls were measured with
21 tipping-bucket gauges for each of the four types of
22 permeable pavements and the impervious asphalt stall.
23 Precipitation and runoff rates were recorded in a data
24 logger at 15-min intervals. Durability of the permeable
25 pavement systems was assessed by qualitative visual
26 comparison with the asphalt control stall.

27 During rainfall events, composite samples were
28 collected from surface runoff from the asphalt and from
29 infiltrated water at each of the four pairs of instrumen-
30 ted stalls. Following the guidelines outlined in Wa-
31 shington State Department of Ecology [23], a “rainfall
32 event” was considered to be at least 13 mm of
33 precipitation in 24 h, preceded by at least 24 h of no
34 rain. Flow splitters at each tipping bucket were adjusted
35 to yield about 21 of sample for 10–15 mm of rain for
36 both the permeable (subsurface) and asphalt (surface)
37 runoff collectors. Samples were collected from the field
38 and held for less than 24 h on ice before being taken to
39 the laboratory, where they were analyzed for hardness,
40 conductivity, dissolved metals (lead, copper, and zinc),
41 diesel fuel, and motor oil. Analysis of the samples was
42 done by Aquatic Research, Inc., Seattle, WA, USA, a
43 state-certified laboratory.

47 4. Results

49 4.1. Durability

51 Visual inspection of the permeable pavement systems
52 showed varying, but generally minor, signs of wear and
53 tear after 6 years. In two small areas, the interlocking
54 sheets of the Grasspave^{2®} and the Gravelpave^{2®} plastic
55 matrix had shifted slightly and partly lifted out of the
soil in the area where the rear wheels of the parked cars

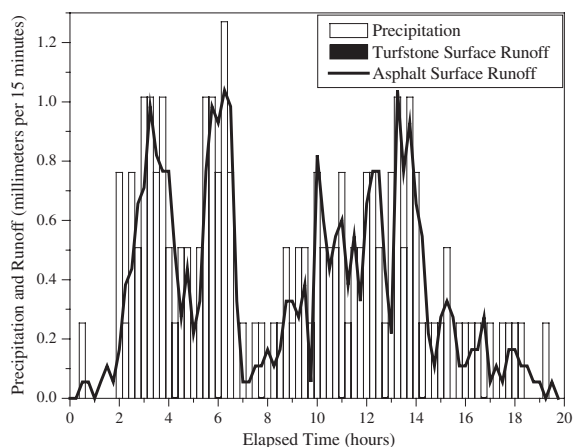
57 typically rest. The Turfstone[®] and UNI Eco-Stone[®]
58 showed no areas of rutting, settling, or shifting. Grass
59 was growing uniformly across the Turfstone[®] surface,
60 but more spotty (and locally quite sparse) in the
61 Grasspave^{2®} stalls.

65 4.2. Runoff and infiltration

66 Surface runoff and infiltration rates were measured at
67 the site throughout November 2001 and from the
68 beginning of January until early March 2002. During
69 the period of measurement, rainfall at the site totaled
70 570 mm. A total of 15 distinct precipitation events were
71 measured during the study period.

72 Runoff from the asphalt stall closely followed
73 precipitation rates during all rain events (Fig. 2). Any
74 delay between the onset of rainfall and the runoff of
75 water was less than the 15-min time step of the data
76 logger, and there was no measurable continuation in
77 runoff after precipitation stopped. This response was
78 dramatically different from any measured “runoff” (see
79 below) from the permeable stalls.

80 For the permeable stalls, virtually all water infiltrated
81 for every observed storm. Measurable surface runoff did
82 occur during several of the precipitation events, but this
83 resulted primarily from observed leaks through the
84 cover of the troughs used to capture surface runoff.
85 These leaks typically resulted in one to three tips (200–
86 600 ml) of the gauge per hour; during the same interval,
87 rainfall events delivered up to several hundred times this
88 volume onto each pair of stalls. These results were
89 therefore deemed insignificant.



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Fig. 2. A comparison of precipitation rates and surface runoff
from a permeable pavement stall and the asphalt stall during a
storm beginning at 16:00 on 6 January 2002. Minor surface
runoff from the permeable Turfstone[®] stall occurring around 4,
6, 8, 11, 13, 14, and 17 h is attributed to leaks in the piping used
to capture water.

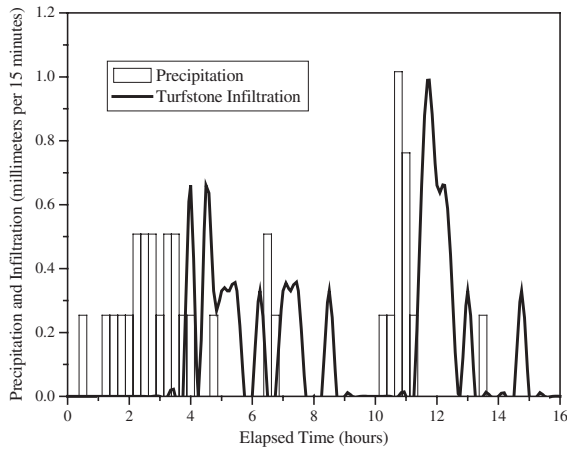


Fig. 3. A comparison of precipitation and subsurface infiltration during a storm beginning at 2 pm on 20 November 2001.

During six of the 15 distinct precipitation events, however, surface runoff from a single pair of stalls was greater than could be attributed to leakage into the trough. Five of these six cases occurred from the Grasspave^{2®} surface and the 6th event was from the Gravelpave^{2®} surface. In four of the six cases, surface runoff occurred during working hours and so cars almost certainly covered the pavement area. Presumably, water sheeting off the roofs and hoods of the cars temporarily saturated the exposed permeable areas, resulting in local surface runoff.

In two cases, substantial surface runoff occurred from the Grasspave^{2®} surface during non-business hours when parked cars were unlikely. One of these runoff events occurred during the most prolonged period of high-intensity rainfall seen during the study. In that storm, 42 mm of rain fell in 14 non-business hours and yielded 1 mm of surface runoff from the Grasspave^{2®} surface during that period. The entire storm lasted 72 h, produced 121 mm of rainfall, and yielded 4 mm of surface runoff in total, the most voluminous example of surface runoff (3% of total precipitation) during the entire study.

Measured infiltration in the permeable pavement stalls followed the trends of precipitation but with a significant lag-to-peak due to subsurface flow rates (Fig. 3). Though the flow path was quite short (<10 cm through soil, plus a few meters along the gravel-filled buried gutter) it imposed delays of up to about an hour.

4.3. Water quality

Composite water samples for entire storms were collected from the asphalt runoff and the infiltrated water passing through each of the pervious pavement systems. Because surface water runoff from the perme-

able pavement was extremely limited and overwhelmingly due to leakage, water quality was not tested for this fraction.

Nine storms were sampled for water quality (Table 1 and Fig. 4). Of the nine, seven fully met the Washington State Department of Ecology definition of a “rainfall event” (13 mm of rain within the first 24 h proceeding at least 24 h of no precipitation). Though two sets of samples did not meet these storm criteria, they were included in the water quality analysis because they “failed” only minimally: in the first case, more than 30 mm of rain fell in 36 h; in the second case, 12.4 mm fell in 48 h. Water quality data were log-transformed for statistical tests and for determining mean concentrations, following the well-established observations that constituent event mean concentrations in urban stormwater follow a log-normal distribution [24]. Paired *t*-tests on the log-transformed data were used to compare the quality of the infiltrated water from the pervious surfaces with the asphalt runoff. In samples where concentrations were below the minimum detection limit, a concentration of one-half the detection limit was assumed [25,26]. The minimum detection limits for sample constituents were as follows: motor oil, 0.10 mg/l; diesel fuel, 0.05 mg/l; copper, 1.0 µg/l; zinc, 5 µg/l; lead, 1 µg/l.

Overall, surface runoff from the asphalt showed significantly higher concentrations than the infiltrated water of most measured constituents, namely motor oil, copper, and zinc. No samples from any surface had detectable diesel fuel or lead. Both hardness and conductivity had significantly higher concentrations in the subsurface infiltrate than in the asphalt runoff samples ($P < 0.01$) (Table 1 and Fig. 4). Among the permeable systems, these parameters were also significantly higher from the concrete-based systems (Turfstone[®] and UNI Eco-Stone[®]) than from the plastic systems (Grasspave^{2®} and Gravelpave^{2®}).

Concentrations for zinc and copper were significantly lower in the infiltration samples than in the asphalt runoff ($P < 0.01$) (Table 1 and Fig. 4). In all cases, the asphalt samples had measurable concentrations of copper and zinc, with the highest measured concentrations being 12.1 and 34 µg/l, respectively. Moreover, all samples from asphalt runoff exceeded Washington State surface water-quality standards for copper at both acute and chronic toxicity levels [27]. For zinc, asphalt runoff exceeded the surface water-quality standard in all but one case at both the acute and chronic levels.

In contrast, 72% (copper) and 22% (zinc) of the infiltrated water samples from the permeable systems were below the minimum detection limit (Table 1 and Fig. 4). Only one sample (from UNI Eco-Stone[®]) exceeded state levels for chronic toxicity for copper. Zinc concentrations were exceeded once for acute level and three times at the chronic level. Note that metal toxicity

Table 1

Mean concentrations of detected constituents from storm samples in 2001–2002 (1996 results from Booth and Leavitt [22] in square brackets). Nine storms sampled in 2001–2002; three in 1996

	Hardness (mg CaCO ₃ /l)	Conductivity (µmhos/cm)	Copper (µg/l)	Zinc (µg/l)	Motor oil (mg/l)
<i>Infiltration samples</i>					
Gravelpave ² [®]	22.6 [20.3]	47 [63]	0.89 (66% <MDL) [1.9 (67% <MDL)]	8.23 (22% <MDL) [2.0 (67% <MDL)]	<MDL
Grasspave ² [®]	14.6 [22.8]	38 [94]	<MDL [21.4 (33% <MDL)]	13.2 [2.5 (67% <MDL)]	<MDL
Turfstone [®]	47.6 [49.4]	114 [111]	1.33 (44% <MDL) [1.4 (67% <MDL)]	7.7 (33% <MDL) [<MDL]	<MDL
Uni Eco-Stone [®]	49.5 [23.0]	114 [44]	0.86 (77% <MDL) [14.3 (33% <MDL)]	6.8 (33% <MDL) [7.9 (33% <MDL)]	<MDL
<i>Surface runoff samples</i>					
Asphalt	7.2 [6.1]	13.4 [17.0]	7.98 [9.0 (33% <MDL)]	21.6 [12]	0.164 (11% <MDL)

In parenthesis is the percent of samples that fell below detectable levels. Lead was not detected in 2001–2002 but was present in 5 of 15 samples in 1996; motor oil was not tested in 1996. <MDL = all samples below minimum detection limit. Minimum detection limits listed in text.

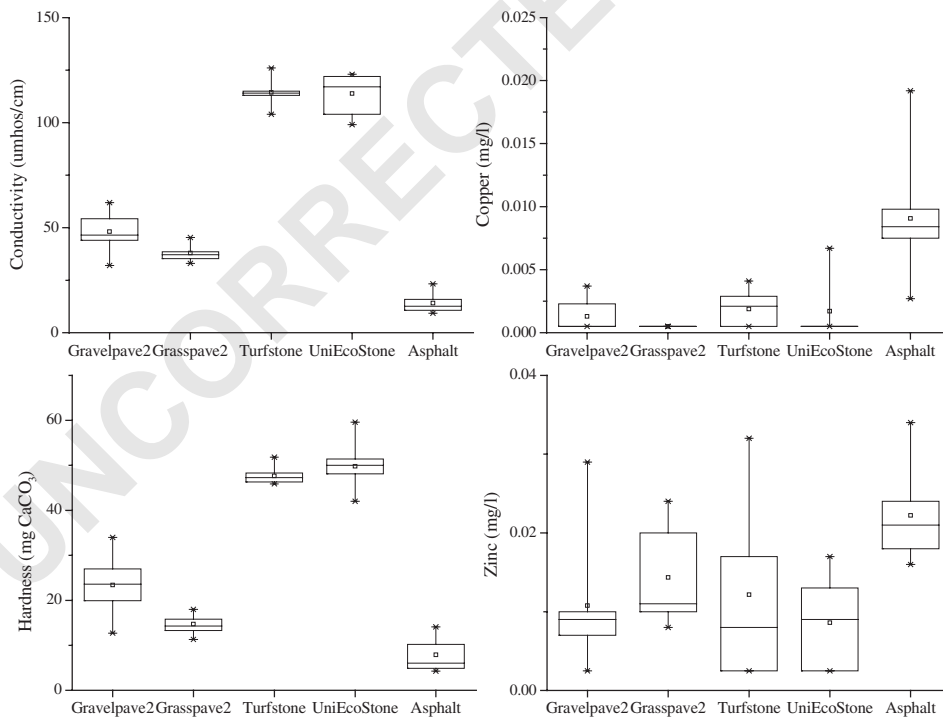


Fig. 4. A comparison of concentrations in composite samples from different paving surfaces collected from nine storms 2001–2002. Samples from permeable pavements were infiltrated water; samples from asphalt were surface runoff. The large box represents the 25th percentile, median, and 75th percentile; the whiskers represent the 5th and 95th percentiles; the small box represents the mean.

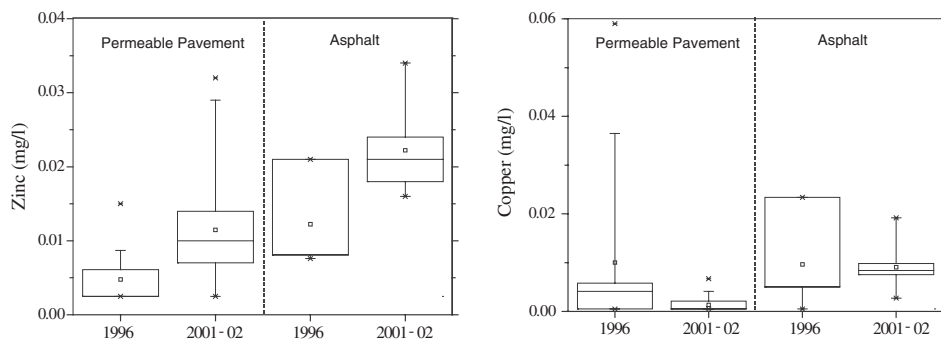


Fig. 5. A comparison of zinc and copper concentrations in samples collected in 1996 and 2001–2002. Concentrations for permeable pavement are averages of infiltrated samples from all four paving systems. For 1996, $n = 12$ from the permeable pavements and $n = 3$ from the asphalt runoff. For 2001–2002, $n = 27$ from permeable pavements and $n = 9$ from asphalt runoff. The large box represents the 25th percentile, median, and 75th percentile; the whiskers represent the 5th and 95th percentiles; the small box represents the mean.

criteria are determined not only by the concentration of the constituent but also by hardness—as hardness increases allowable concentrations for copper and zinc also increase [27].

5. Discussion

Surface durability, infiltration capacity, and water-quality performance of the tested permeable pavement systems all compared well, and in several regards extremely well, with the classic asphalt surface. Structurally, all permeable pavement systems in this study have held up to 6 years of daily usage. Two (Turfstone[®] and UNI Eco-Stone[®]) systems are apparently as durable as the asphalt surface under at least this magnitude and frequency of loading; the flexible plastic systems (Grasspave^{2®} and Gravelpave^{2®}) may have required additional maintenance under heavier or more frequent loads. Under the conditions here, however, the wear was minor and presented no impediment to use.

All four permeable pavement systems infiltrated virtually all precipitation, even during the most intense storms experienced during the study period. A larger parking area covered entirely by permeable pavement would almost certainly have sufficient uncovered areas to make up for any local saturation that may have occurred around individual cars.

While this study demonstrated long-term success for infiltration, it does not assure uniformly good performance everywhere. Pacific Northwest has generally low rainfall intensities. The highest rainfall intensity observed during the study was 7.4 mm/h. Our extremely positive infiltration results may not apply as well in other locales that receive higher rainfall intensities. The site itself was specifically chosen because of good

underlying drainage characteristics, and so infiltration during extended storms would probably not be as effective in areas underlain with less permeable soils. Windblown dust or particulate matter washed off cars could also reduce permeability over time; we observed such deposits, but the infiltration capacity here has not fallen in consequence to levels approaching the rainfall intensities experienced (typically < 5 mm/h).

The water quality results from this study demonstrate clear differences between the subsurface infiltrate and surface runoff from asphalt. For nearly all storms and constituents, water quality of the infiltrated water was significantly different than the surface runoff from the asphalt parking area. For both copper and zinc, infiltration of the stormwater had a dramatic effect on water quality (Table 1): toxic concentrations were reached in 97% of the asphalt runoff samples; but in 31 of 36 infiltrate samples, concentrations fell below toxic levels and in a majority of samples below even detectable levels.

The long-term degradation of water-quality performance may be a modest, but probably not problematic, phenomenon of permeable pavement systems (Fig. 5). Zinc concentrations in both permeable pavement infiltrate (Student t -test, $P = 0.002$) and asphalt runoff (Student t -test, $P = 0.01$) exhibited significant increases during the 6-year study period. Yet two of the systems, Grasspave^{2®} (Student t -test, $P = 0.007$) and UNI Eco-Stone[®] (Student t -test, $P = 0.08$), showed simultaneous decreases in copper concentrations. Lead, present in a third of the 1996 samples, was not detected during the current survey. Conductivity and hardness remained relatively constant between the two studies.

These results suggest both positive and negative changes in runoff water quality after 6 years. Subsurface flow paths for this experimental system, however, were

less than 10 cm, a far shorter path to groundwater tables than would occur in most field installations. Longer flow paths would presumably lead to greater attenuation of pollutant loads and a corresponding decrease in the potential for long-term groundwater impacts.

6. Conclusions

This study evaluated the performance of four permeable pavement systems from the perspectives of mechanical durability, infiltration, and water quality after 6 years of daily use. We found generally positive, and in several aspects very positive, performance in comparison to a traditional asphalt surface.

Runoff performance was very good. All four permeable pavement systems infiltrated virtually all precipitation, even during the most intense storms experienced during the study period. The water quality of the resulting infiltrate was significantly different from, and generally much better than, the surface runoff from the asphalt parking area. For both copper and zinc, the infiltrated stormwater usually had concentrations below detectable levels and, in all but four samples, below toxic levels; in contrast, these constituents had near-uniform toxic concentrations in the asphalt runoff. Motor oil was also consistently much lower in the infiltrate than in the surface runoff; hardness and conductivity were generally higher, and neither lead nor diesel fuel were detected in any sample.

Over a 5-year period, concentrations of some infiltrated constituents have increased while others have stayed the same or decreased. Zinc concentrations in both infiltrated and surface runoff exhibited marked increases; copper concentrations decreased substantially in two of the infiltrating systems. Lead was detected in one-third of the samples in 1996 but not in the present study; conductivity and hardness were relatively constant.

Despite these generally quite favorable results, uniformly good performance cannot be guaranteed everywhere. The experimental site has particularly favorable soil conditions, and rainfall intensities in the Pacific Northwest United States are typically quite low, masking any potential consequences of reduced infiltration of the surfaces over time. The study site had no weather conditions requiring snow removal or extended periods of sub-freezing weather, so this study is not a comprehensive evaluation of the suitability of such systems for all climate zones. Financial considerations, either the cost of installing permeable pavement systems or the cost savings from reduced stormwater management facilities, will play a major role in determining the feasibility of any given project. Despite these acknowledged limitations, we believe that these results provide clear indication of the value of permeable pavement

systems and their long-term suitability for broad expanses of the built environment.

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References

- [1] Klein RD. Urbanization and stream quality impairment. *Water Resour Bull* 1979;15(4):948–63.
- [2] Schueler T. Site planning for urban stream protection. Silver Spring, MD, USA: Center for Watershed Protection; 1995.
- [3] Booth DB, Jackson CJ. Urbanization of aquatic systems—degradation thresholds, stormwater detention, and limits of mitigation. *Water Resour Bull* 1997;33(5):1077–90.
- [4] City of Olympia. Impervious surface reduction study. Department of Public Works, Olympia, WA, USA, 1995.
- [5] Washington State Department of Transportation. Design manual. M22-01, Olympia, WA, USA, 2001.
- [6] Willson RW. Suburban parking requirements. *J Am Plann Assoc* 1995;61(1):29–42.
- [7] Albanese B, Matlack G. Environmental auditing: utilization of parking lots in Hattiesburg, Mississippi, USA and impacts on local streams. *Environ Manage* 1998;24(2):265–71.
- [8] Whipple W, Dilouie JM, Pytler T. Erosional potential of streams in urbanizing areas. *Water Resour Bull* 1981;17(1):36–45.
- [9] Trimble SW. Contribution of stream channel erosion to sediment yield from an urbanizing watershed. *Science* 1997;278(5342):1442–4.
- [10] Nelson EJ, Booth DB. Sediment budget of a mixed-land use, urbanizing watershed. *J Hydrol* 2002;264:51–68.
- [11] Konrad CP, Booth DB, Burges SJ, Montgomery DR. Partial entrainment of gravel bars during floods. *Water Resour Res* 2002;38(7):9-1–9-16.
- [12] Simmons DL, Reynolds RS. Effects of urbanization on base flow of selected south-shore streams, Long Island, New York. *Water Resour Bull* 1982;18(5):797–805.
- [13] Finkenbine JK, Atwater JW, Mavinic DS. Stream health after urbanization. *J Am Water Resour Assoc* 2000;6(5):1149–60.
- [14] Van Hassel JH, Ney JJ, Garling DL. Heavy metals in a stream ecosystem at sites near highways. *Trans Am Fish Soc* 1980;109(6):634–6.
- [15] Jones RC, Clark CC. Impact of watershed urbanization on stream insect communities. *Water Resour Bull* 1987;23(6):1047–55.

- 1 [16] Horner RR, Skupien JJ, Livingston EH, Shaver HE. Fundamentals of urban-runoff management-technical and
3 institutional issues. Washington, DC, USA: Terrene
Institute; 1994.
- 5 [17] Winter JG, Duthie HC. Effects of urbanization on water
quality and invertebrate communities in a southern
7 Ontario stream. *Can Water Resour J* 1998;23(3):245–57.
- 9 [18] Pratt CJ, G, Mantle JD, Schofield PA. Urban stormwater
reduction and quality improvement through use of perme-
able pavements. *Water Sci Technol* 1989;21(8/9):769–78.
- 11 [19] Fujita S. Infiltration structures in Tokyo. *Water Sci
Technol* 1994;30(1):33–41.
- 13 [20] Pratt CJ. A review of source control of urban stormwater
runoff. *Water Environ Manage* 1995;9(2):132–9.
- 15 [21] Watanabe S. Study on storm water control by permeable
pavement and infiltration pipes. *Water Sci Technol*
1995;32(1):25–32.
- [22] Booth DB, Leavitt J. Field evaluation of permeable
pavement systems for improved stormwater management. *J Am Plann Assoc* 1999;65(3):314–25. 17
- [23] Washington State Department of Ecology. Stormwater
management manual for the Puget Sound Basin, Olympia,
WA, USA, 1990. 19
- [24] Novotny V, Olem H. Water quality prevention, identifica-
tion and management of diffuse pollution. New York, NY,
USA: Van Nostrand Reinhold; 1994. p. 484–90. 21
- [25] Gilbert RO. Statistical methods for environmental pollu-
tion monitoring. New York, NY, USA: Van Nostrand
Reinhold; 1987. p. 177–8. 23
- [26] Kayhanian M, Singh A, Meyer S. Impact of non-detects in
water quality data on estimation of constituent mass
loading. *Water Sci Technol* 2000;45(9):219–25. 25
- [27] Washington State Department of Ecology. Water quality
standards for surface waters of the State of Washington.
WAC, Olympia, WA, USA, 1997 [chapter 173–201A]. 27
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