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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.

Keywords: Impervious surfaces; Permeable pavement; Stormwater; Urban runoff; Water quality

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].

The purpose of this study was to evaluate the long-term effectiveness of permeable pavements as a

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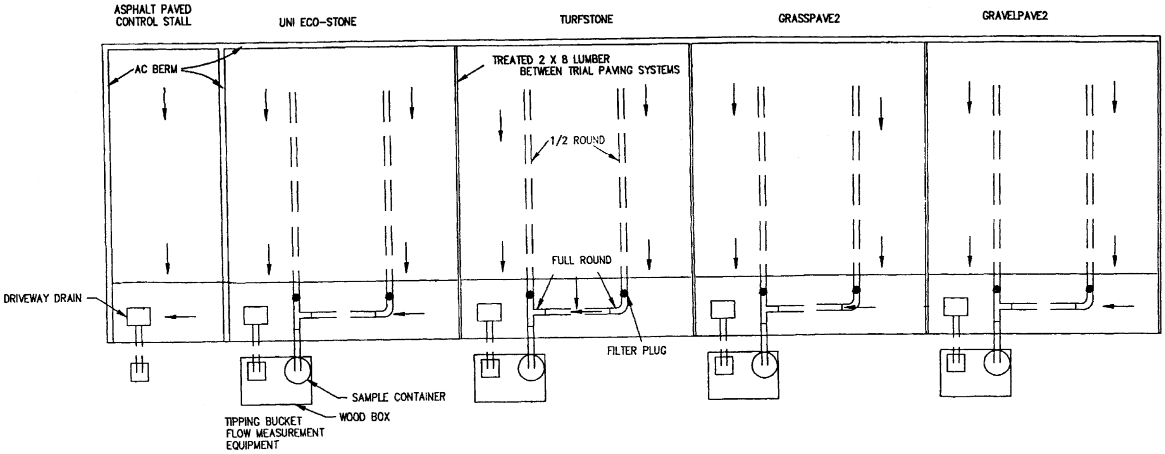

Fig. 1. Plan view of the nine test parking stalls. Each permeable pavement type had two parking stalls paired into one instrument station.

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

- Grasspave$^{2®}$, a flexible plastic grid system with virtually no impervious area, filled with sand and planted with grass.
- Gravelpave$^{2®}$, an equivalent plastic grid, filled with gravel.
- Turfstone®, a concrete block lattice with about 60% impervious coverage, filled with soil and planted with grass.
- UNI Eco-Stone®, small concrete blocks with about 90% impervious coverage, with the spaces between blocks filled with gravel.

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

During rainfall events, composite samples were collected from surface runoff from the asphalt and from infiltrated water at each of the four pairs of instrumented stalls. Following the guidelines outlined in Washington State Department of Ecology [23], a "rainfall event" was considered to be at least 13 mm of precipitation in 24 h, preceded by at least 24 h of no rain. Flow splitters at each tipping bucket were adjusted to yield about 2 l of sample for 10–15 mm of rain for both the permeable (subsurface) and asphalt (surface) runoff collectors. Samples were collected from the field and held for less than 24 h on ice before being taken to the laboratory, where they were analyzed for hardness, conductivity, dissolved metals (lead, copper, and zinc), diesel fuel, and motor oil. Analysis of the samples was done by Aquatic Research, Inc., Seattle, WA, USA, a state-certified laboratory.

4. Results

4.1. Durability

Visual inspection of the permeable pavement systems showed varying, but generally minor, signs of wear and tear after 6 years. In two small areas, the interlocking sheets of the Grasspave$^{2®}$ and the Gravelpave$^{2®}$ plastic matrix had shifted slightly and partly lifted out of the soil in the area where the rear wheels of the parked cars typically rest. The Turfstone® and UNI Eco-Stone® showed no areas of rutting, settling, or shifting. Grass was growing uniformly across the Turfstone® surface, but more spotty (and locally quite sparse) in the Grasspave$^{2®}$ stalls.

4.2. Runoff and infiltration

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

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

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

During six of the 15 distinct precipitation events, however, surface runoff from a single pair of stalls was

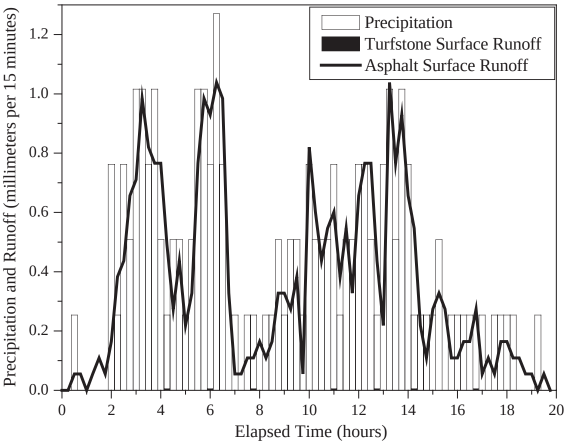

Fig. 2. A comparison of precipitation rates and surface runoff from a permeable pavement stall and the asphalt stall during a storm beginning at 16:00 on 6 January 2002. Minor surface runoff from the permeable Turfstone® stall occurring around 4, 6, 8, 11, 13, 14, and 17 h is attributed to leaks in the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

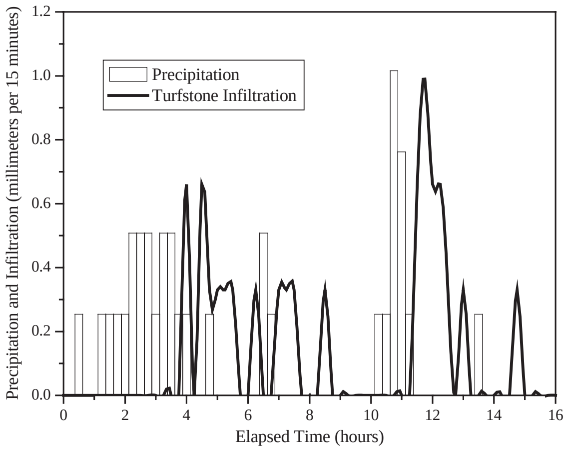

Fig. 3. A comparison of precipitation and subsurface infiltration during a storm beginning at 2 pm on 20 November 2001.

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 permeable 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 then 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)
Infiltration samples					
Gravelpave$^{2®}$	22.6	47	0.89 (66% <MDL)	8.23 (22% <MDL)	<MDL
	[20.3]	[63]	[1.9 (67% <MDL)]	[2.0 (67% <MDL)]	
Grasspave$^{2®}$	14.6	38	<MDL	13.2	<MDL
	[22.8]	[94]	[21.4 (33% <MDL)]	[2.5 (67% <MDL)]	
Turfstone$^{®}$	47.6	114	1.33 (44% <MDL)	7.7 (33% <MDL)	<MDL
	[49.4]	[111]	[1.4 (67% <MDL)]	[<MDL]	
Uni Eco-Stone$^{®}$	49.5	114	0.86 (77% <MDL)	6.8 (33% <MDL)	<MDL
	[23.0]	[44]	[14.3 (33% <MDL)]	[7.9 (33% <MDL)]	
Surface runoff samples					
Asphalt	7.2	13.4	7.98	21.6	0.164 (11% <MDL)
	[6.1]	[17.0]	[9.0 (33% <MDL)]	[12]	

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.

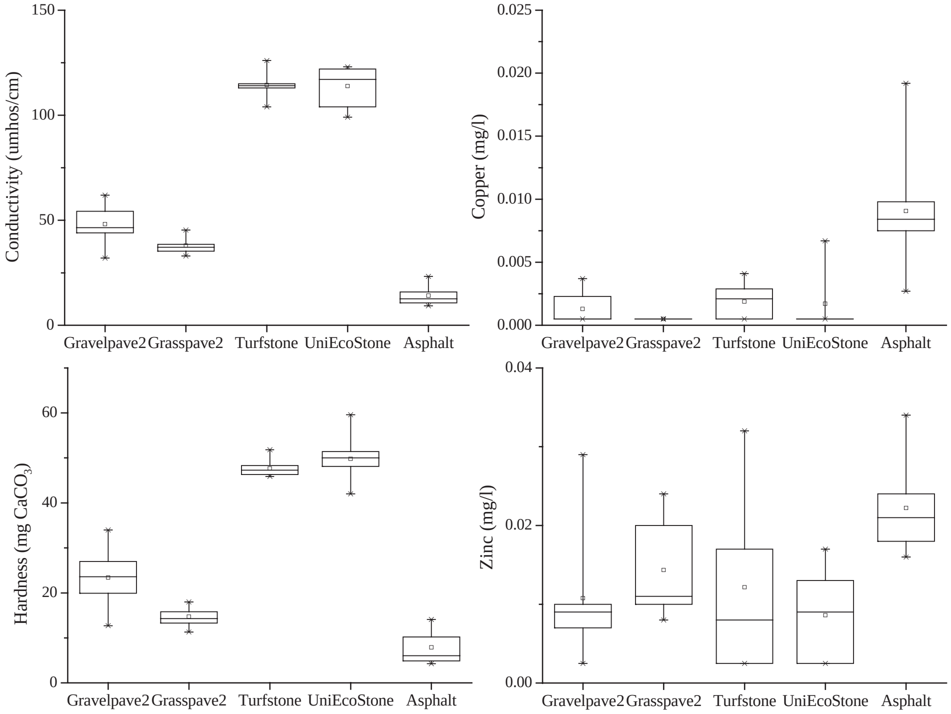

Fig. 4. A comparison of concentrations in composite samples from different paving surfaces collected from nine storms 2001–2002. Samples from permeable pavements were infiltrated water; samples from asphalt were surface runoff. The large box represents the 25th percentile, median, and 75th percentile;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

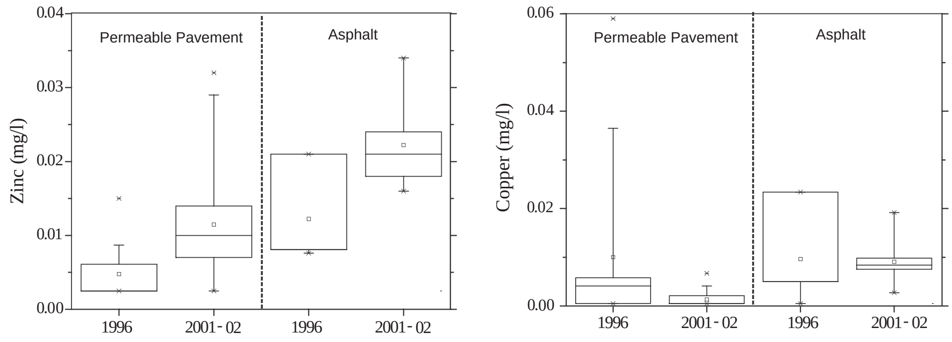

Fig. 5. A comparison of zinc and copper concentrations in samples collected in 1996 and 2001–2002. Concentrations for permeable pavement are averages of infiltrated samples from all four paving systems. For 1996, $n = 12$ from the permeable pavements and $n = 3$ from the asphalt runoff. For 2001–2002, $n = 27$ 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 (Grasspave2® and Gravelpave2®) 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, Grasspave2® (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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