Chapter 11

Contaminants from Four New Pervious and Impervious Pavements in a Parking-lot

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A previous account (Thompson and James, 1994) described the design, construction and instrumentation of four different pavements - asphalt (AS), concrete brick (CP), and three -inch and four-inch thick concrete paver stones with infiltration cells (E3 and E4) - in both a typical parking-lot and in a laboratory. Sampling of runoff from both sets of four pavements was subsequently carried out, and the analytical results used to estimate the flux of 23 contaminants including heat (Thompson, 1995). This chapter reports the interim conclusions obtained from the parking-lot pavements for the first year after installation.

11.1 Introductory Background

Impervious paving such as asphalt, when it replace a previously pervious surface, increases contaminant loads to receiving waters, especially pollutants arising from highway pavement, vehicular traffic, air deposition, surrounding land-uses and heated surfaces. Asphalt paving, concrete curbs and impervious gutters are efficient collectors and conveyors of contaminants and stressors to stormwater systems - they may appeal to some people but are generally bad for aquatic ecosystems. Appropriately-designed permeable concrete block pavers, on the other hand, and other infiltration practices, reduce the quantity of these pollutants that reach receiving waters, by filtering stormwater through the upper soil zones.

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Contaminants of interest include oils and greases, heavy metals, nutrients, bacteria, suspended material and elevated temperatures. But the altered flow regime itself is an important stressor: increased impervious surfaces lead to increased flood flows and depleted low flows, because of reduced infiltration and reduced groundwater replenishment. Increased frequencies of these flow rates at both extremes degrade natural riparian habitats and aquatic ecosystems.

The purpose of the present study is a comparison of the performance of four different pavements, denoted AS, CP, EC3 and EC4, from the perspective of surface water pollution control. It forms part of a continuing study on permeable pavements, current details of which may be found on the Web at <http://www.eos.uoguelph.ca/~james>, under "Research". Abstracts of dissertations, eleven of which form the backbone of this work, may be found at the web site.

Furthermore, a long list of literature on this topic is also available at the web site, by searching under "Biblio96". Using Netscape's "Find" facility, for example, keywords in context such as title words, authors, and sources can be located. Abstracts are not included in that list.

11.2 Previous Work

Short reviews are given by the authors in previous volumes in this series (Xie and James, 1993; Thompson and James, 1994) and elsewhere (James and Verspagen, 1996; Kresin and James, 1996). These focus on roads and parking lots, which make up the largest percentage of man-made impervious surfaces (Hade, 1987). Compared to asphalt, permeable paving reduces runoff (see e.g. Thalen et al., 1972) and contaminants reaching receiving waters (Nawang and Saad, 1993; Pratt et al., 1989). When downstream impacts and aesthetic benefits are included, permeable pavement has been found to be more economical than conventional roads (Thalen et al., 1972).

Runoff from asphalt parking lots has been studied at several places, including Sweden by Spangberg and Niemcynowicz (1993), who found increased turbidity, pH, conductivity and concentrations of adverse chemicals, compared to natural areas. Being a petroleum product, the types of substances found in runoff and adjacent areas, from the asphalt, range from polyaromatic hydrocarbons to benzopyrene, and heavy metals (Munch, 1992). There is the potential, but incomplete evidence, that asphalt is carcinogenic to humans (International Agency for Research on Cancer, 1985).

Xie and James (1994) discuss the importance of solar thermal enrichment of stormwater by heated pavement, and further relationships have since been developed by James and Verspagen (1996). Evidently the thermal enrichment of small rivers by modest parking lots can be some 5°C, sufficient to degrade cold water fisheries.

Collectively the literature provides a case for careful environmental review of our current pavement practices, and for these reasons the test pavements were installed and instrumented at the University of Guelph. Readers are referred to the earlier publication (Thompson and James, 1994) for details of the installations. Kresin and James (1996) discuss the long-term performance of permeable concrete pavers in another chapter in this book.

11.3 Pollutants in Pavement Runoff and their Pathways

Snodgrass et al. (1994) found that particulates in the form of heavy metals comprise a large component of the particulate matter found in highway runoff. Friction and automobile deterioration are significant contributors of heavy metals, and deicing salts may contribute to the deterioration of automobiles and highway structures. Fossil fuels contribute petroleum hydrocarbons (PHCs) and incomplete combustion can contribute to the formation of polycyclic aromatic hydrocarbons (PAHs). In fact the most significant pollution loads are due to the use of petroleum-based fuels and lubricants in vehicles. Even though they are weakly volatile, they remain on paving until washed into the drainage system to the receiving waters (Barnes et al., 1979).

The buildup and removal of pollutants is a continuous process occurring over both dry and wet periods, with rainfall washing off the pollutants that have built up. Also, rainfall deposits its own pollutants including low pH (high acid levels). Rainfall also transfers particulates from adjacent pervious areas, and this runoff contains high levels of bacteria, phenols (from insecticides), total and suspended solids, etc. During dry periods, pollutants accumulate until they are blown away.

Contributing factors to a mass balance include the following:

- atmospheric deposition, AD (includes rain)
- vehicle input, VI
- pavement degradation, PD
- pavement leachates, PL
- population input, PI
- vegetation input, VeI
- biological removal, BR
- vehicle removal, VR
- wind removal, WR
- intentional removal, IR.

Net accumulation *NAC* is:

$$NAC = AD + VI + PD + PL + PI + VeI - BR - VR - WR - IR \quad (11.1)$$

Atmospheric Deposition, AD: The analysis of atmospheric deposition or atmospheric fallout is beyond the scope of this study. It is, however, an important consideration. Atmospheric deposition deals with the dust fall over the area and depends primarily on climatic and physiographic conditions (James and Boregowda, 1986). Pollutants in rain are also important.

Vehicle Input, VI: Highway runoff pollutants include metals, nutrients and hydrocarbons that are contributed by motor vehicle traffic. Common sources of origin and pathways include parking lots, streets and highways, industrial areas, construction sites, and unpaved roads. Traffic by-products include: petroleum products, vehicle exhaust, tire and brake wear and metallic corrosion (James and Boregowda, 1986). The quantities of vehicle input can be quantified:

$$L_v = NPLM \quad (11.2)$$

where:

- L_v = mass of dust and dirt produced by vehicles,
- N = number of vehicle axles active each day in a subcatchment,
- P = population to vehicle ratio,
- L = mass of dust and dirt produced per vehicle per km travelled,
- M = total length of road in subcatchment.

Pavement Degradation, PD: Pavement degradation is the deterioration of the pavement surface over time. This is dependent on the vehicles, pavement, weather, environment and pollution input conditions.

Pavement Leachates, PL: Pavement leachate is the removal of material through percolation of water as it infiltrates through the pavement surface and percolates through the bedding material. The rate and amount of pavement leachate depends on: (i) bedding material, (ii) slope, (iii) nature of surface material, (iv) impact energy of raindrop as it hits the surface, (v) rain chemistry, and (vi) air temperature.

Population Input, PI: Population input includes litter such as solid wastes deposited on surfaces, animal and bird faecal droppings and other deposits. Deposits depend upon number of personal or individual littering or amount of animals (and birds) found within the area. For humans:

$$L_p = PL \quad (11.3)$$

where:

- L_p = total mass of dust and dirt due to population,
- P = total population in a subcatchment,
- L = per capita mass of pollutants (James and Boregowda, 1986).

Vegetation Input, VeI: Adjacent to the study area used in this study is a vegetated area. For most of the study period, the area was vegetated with weeds and shrubs. During the month of August, the weeds and shrubs were removed and part of the area was seeded with grass and fertilized. Most of the area was left with fertilizer and mulch. Vegetation input rate depends on the time of year and vegetation density. Vegetation contributes solids, nutrients, and chemicals (James and Boregowda, 1986).

Biological Removal, BR: With the exception of nitrates and phosphates, organic pollutants decompose into simple substances with or without oxygen. This reduces the quantity of pollutants at the time of washoff. Nitrates and phosphates normally increase with the addition of decomposed end-products (James and Boregowda, 1986). Removal of solids by biological decomposition may be estimated:

$$R_b = PF(1 - e^{-kt}) \quad (11.4)$$

where:

- R_b = total mass of dust and dirt removed by biological decomposition,
- P = average mass of dust and dirt available on the surface,
- F = fraction of decomposable dust and dirt,
- k = decay coefficient,
- t = number of days.

Vehicle Removal, VR: Eddies generated by vehicles transport pollutants to ineffective areas from where they may not be washed off during storm events (James and Boregowda, 1986). This results in a reduction of solids being washed off.

Wind Removal, WR: Natural wind transport process reduces the amount of solids being washed off. Contributing factors to this include wind speed, curbs, and adjacent pervious areas which act as a pollutant sink (James and Boregowda, 1986).

Intentional Removal, IR: Main sources of intentional removal include various types of street cleaning. For this study, street cleaning was conducted only during the month of March 1994.

Net Accumulation, NAC: Calculation of net accumulation is the combination of all the above input and removal processes. At the scale of this study, the equation is considered at only an empirical level.

11.4 Contaminants Examined

Runoff was sampled and samples analyzed using methods documented in Thompson (1995) for the chemical, biological, and physical parameters shown in Table 11.1.

Table 11.1 Contaminants investigated.

Physical Properties:		
	Conductivity	
	Solids	Residue, Total (Total Solids)
		Residue, Particulate (Suspended Solids)
	Temperature	
Chemical Constituents:		
Inorganic	Heavy Metals	Copper
		Nickel
		Lead
		Zinc
		Iron
		Cadmium
		Chromium
		Chloride
		Phosphorus
		Phosphates
	Chlorides Nutrients	Nitrogen, Total Kjeldhal
		Ammonium, Total
		Nitrates
		Nitrite
		Phenolics
Organic:	Refractory	
	Biodegradable:	BOD
		COD
		E.Coli
		Solvent Extractable (Oils & Grease)

11.5 Results

Results are presented under two headings: *temperature* and *contaminants*. Temperatures were measured continuously from June 22 to October 2, 1994. As summarized in Table 11.2, contaminants were measured for a total of nine rainfall events.

11.5.1 Temperature

Xie (1993) stated that the level of watershed development had the single greatest anthropogenic influence on the temperature regime of urban, headwater streams. As the urban landscape heats up on warm summer days, it tends to impart a great deal of heat to any runoff passing over it. Because base and sub-base temperatures were lower than surface temperatures, infiltrated water would be affected by this lower temperature as it passed through a porous pavement. Infiltration is the foremost urban BMP for temperature reduction (Galli, 1990).

Table 11.2 Collected event summary.

Location	Event 1 Jul. 15	Event 2 Jul. 21	Event 3 Jul. 29	Event 4 Aug. 9	Event 5 Sep. 15	Event 6 Sep. 25	Event 7 Sep. 27	Event 8 Sep. 28	Event 9 Sep. 30
Rain	T,F,CE	T,F,C	F,CE	F,C	T,F,C	T,F,C	T,F,CE	T,F,C	T,F,C
AS Surface	T,F,C	T,FE,C	F,C	FE,C	T,FE,C	T,FE,C	T,F,C	T,FE,C	T,F,C
AS Base	T,FO	T,FO	N/A	N/A	T,FO	T,FO	T,FO	T,FO	T,FO
AS Sub-base	T,FO	T,FO	N/A	N/A	T,FO	T,FO	T,FO	T,FO	T,FO
CP Surface	T,F,C	T,F,C	C,F	FE,C	T,F,C	T,F,C	T	T,FE,C	T,F,C
CP Base	T,FO	T,FO	N/A	N/A	T,FO	T,FO	T	T,FO	T,FO
CP Sub-base	T,FO	T,FO	N/A	N/A	T,FO	T,FO	T	T,FO	T,FO
E4 Surface	T,FO	T,F,C	C,FE	FE,C	T,FO	T,F,C	T	T,FE,C	T,F,C
E4 Base	T,FO	T,FO	C,FE	FE,C	T,FO	T,FO	T	T,FE,C	T,F,C
E4 Sub-base	T,FO	T,FO	N/A	N/A	T,FO	T,FO	T	T,FO	T,F,C
E3 Surface	T,FO	T,FO	C,FE	FE,C	T,FO	T,FO	T	T,FE,C	T,F,C
E3 Base	T,FO	T,FO	C,FE	N/A	T,FO	T,FO	T	T,FE,C	T,F,C
E3 Sub-base	T,FO	T,FO	N/A	N/A	T,FO	T,FO	T	T,FO	T,FO

Note:

Locations

AS - Asphalt
 CP - Hollandstone paver
 E4 - Uni eco-stone 4"
 E3 - Uni eco-stone 3"

Data

T - Temperature data collected
 F - Flow data collected
 FE - Flow data not collected but estimated
 FO - No water entered the collection system
 C - Contaminant data available
 CE - Rainfall contaminant data based on average concentration of available samples collected
 N/A - No temperature, flow or contaminant data collected

Temperature data was collected from twelve thermocouples, one for each pavement and layer. Data for temperature was collected from the pavements between May and October 1994 and may be compared to short wave radiation, which is the amount of direct sunlight. At night the incoming short wave radiation is zero. Short wave radiation also decreases during periods with cloud cover. Our short wave radiation sensors measured photosynthetically active radiation (PAR) in the 400 to 700 nm waveband where PAR is in units of micromoles per second per square metre ($\text{mmol s}^{-1}\text{m}^{-2}$) (Pettit, 1994).

A comparison of the three layers for the asphalt (AS) pavements is shown in Figure 11.1 for the period of September 21 to October 2, 1994. Air temperature was measured by a shielded sensor designed to attempt to reduce the influence from the adjacent greenhouse. The surface layer recorded the highest and lowest temperatures as well as the greatest variations in maximum and minimum temperature for that pavement. The black top of the AS pavement allows the absorption of short wave radiation from the sun on clear sunny days, so the AS surface temperature is the greatest of all the pavements. During clear, dry nights, the AS surface pavement temperatures drop below the observed air temperature, due to back short wave radiation from the pavement. Figure 11.1 also shows that sub-base temperatures had very little diurnal variation for that period. Sub-base temperatures for AS also had the lowest average temperatures compared to the other pavements for that period. Temperatures from the base level had greater ranges (higher maximum and lower minimum) than the sub-base, but had less range than the surface for that period. Average temperatures from the base layer were greater than the sub-base and less than the surface. This statement is true till September 23, when the asphalt sub-base average daily temperature becomes the greatest temperature of the three levels. This is due to two factors: the average air

Figure 11.1 Temperatures of layers in the asphalt pavement.

temperature has been decreasing and rainfall occurred almost daily which affected the surface temperatures. Visually, PAR values are evidently related to surface temperatures. This relation decreased at the base and decreased even further at the sub-base level.

Surface temperatures from the asphalt were higher than all the other pavements for the period.

Maximum, minimum and average daily temperatures for the duration of the study are summarized by Thompson (1995). During days with direct sunlight, the AS reached the highest surface temperature. During the night, AS tended to have the lowest temperature, compared to the other pavement surfaces. Average surface temperatures were generally similar. The three porous surfaces tended to have the same temperatures at any time of the day. Results from the comparison of the four surface temperatures show that asphalt generated higher temperatures than concrete pavements. This is probably due to the low albedo of the AS pavement compared to the other paving materials.

Rainfall occurring during daylight hours affected the asphalt surface temperatures more than the other surfaces. This was observed on September 27, where PAR values decreased rapidly during rainfall. AS temperatures dropped to a low of 10.6°C from a high of 20.3°C as rainfall occurred during the daylight hours.

For the period, temperatures at the base of the pavements displayed less temperature difference between each pavement and at almost any time of the day. Asphalt consistently had the lowest minimum base temperatures. Base temperatures also had lower average temperatures than other layers. Temperatures from the four sub-base levels showed minor variations in temperature statistics.

11.5.2 Contaminant Load Results

Loads are based on both flow rates and concentrations. This section discusses the results from the individual flow and concentrations, then summarizes the computed loads. Table 11.3 summarizes the rain events sampled showing the storm duration, volume, and intensities.

11.5.3 Flow Results

Surface runoff flow rates were collected for the nine events from June 22 to October 2, 1994. The product of flow and contaminant concentrations produced load results. Information was collected from the tipping bucket runoff gages (TBRGs) and covered containers in the instrumentation chamber. As flow was not measured for all events due to instrumentation errors, missing flow data was estimated. Estimates of flows were based on results from laboratory experiments on infiltration rates and capacities for each pavement.

Table 11.3 Rainfall volume summary.

Event	Date	Duration (min)	Vol (mm)	Peak Intensity (mm/hr)	Antecedent Period (hours)
1	Jul 14	20.0	1.6	12.0	118.0
2	Jul 21	95.0	5.3	18.0	122.0
3	Jul 29	220.0	19.0	51.6	65.0
4	Aug 9	45.0	6.6	21.6	105.0
5	Sept 15	125.0	10.9	18.0	38.3
6	Sept 25	600.0	4.0	12.0	257.0
7	Sept 27	90.0	8.7	18.0	4.0
8	Sept 28	100.0	14.5	45.6	12.0
9	Sept 30	L/A	787.0	L/A	L/A

Note: L/A Data Not Available

Table 11.4 is a comparison of surface runoff as a percentage of rainfall from Event 9. It shows that AS had the greatest percentage of surface runoff relative to the rainfall. E4 and E3 produced less surface runoff than the other pavements.

Table 11.4 Runoff as percentage of rainfall.

Location	Pavement			
	AS	CP	E4	E3
Surface	100	80	61	38

AS = asphalt; CP = concrete brick paver; E = Ecostone;
 3 and 4 denotes thickness in inches of base course.
 CP, E3 and E4 are concrete products.

11.5.4 Contaminant Results

Samples for the various contaminants were collected for nine events over the four month period from June 22 to October 2, 1994. Storm event data were collected from the automatic samplers, containers and the TBRGs. Events were of various sizes, volumes and peak intensity.

11.5.5 Contaminant Load Analysis

Tables 11.5 and 11.6 summarize the results, based on total loads from the nine events. Table 11.5 is a summary of the total surface runoff loads generated for the nine events as well as loads from rainfall. For most of the contaminants, AS generated the greatest surface total load. Pavements E4 and E3 generated the least total load for most of the contaminants. This is due to the asphalt surface being almost 100% impervious. Reductions in surface discharge due to porous pavement show a reduced pollutant load leaving the site as noted by Pratt et al. (1989).

Table 11.5 Surface load summary.

Contaminant	Unit	Pavement				
		Rain	AS	CP	E4	E3
Chloride	mg	0.00e+00	2.65e+04	1.27e+04	2.00e+03	8.82e+02
Copper	mg	8.95e+01	1.17e+02	6.03e+01	3.97e+01	2.08e+01
Nickel	mg	0.00e+00	1.81e+00	2.12e-01	0.00e+00	0.00e+00
Zinc	mg	3.22e+02	7.88e+02	3.31e+02	1.06e+02	1.35e+02
Cadmium	mg	1.02e+00	1.21e+01	1.89e-02	0.00e+00	0.00e+00
Chromium	mg	0.00e+00	4.94e+01	6.42e+00	2.66e+00	2.68e-01
Lead	mg	2.98e+01	2.39e+02	5.11e+01	2.28e+01	2.56e+01
Iron	mg	0.00e+00	4.95e+03	1.51e+03	5.29e+02	3.87e+02
COD	mg	3.09e+04	5.25e+05	1.39e+05	4.58e+04	3.69e+04
Phenolics	µg	9.06e+03	1.41e+04	8.05e+03	2.34e+03	1.57e+03
BOD	mg	0.00e+00	3.57e+04	1.58e+04	3.74e+03	3.69e+02
Solvent Extractable	mg	6.60e+02	1.36e+04	8.92e+03	1.51e+03	1.35e+03
Ammonium	mg	2.25e+03	2.58e+03	6.91e+02	4.84e+02	3.01e+02
Nitrite	mg	5.97e+01	2.55e+02	1.64e+02	3.92e+01	4.81e+01
Nitrate	mg	4.88e+03	3.65e+03	2.47e+03	9.72e+02	6.77e+02
Phosphate	mg	9.30e+00	7.91e+02	7.22e+01	1.50e+01	2.04e+01
Phosphorus	mg	5.58e+01	3.31e+03	1.13e+03	1.59e+02	2.72e+02
TKN	mg	3.11e+03	8.23e+04	5.02e+03	1.19e+03	7.91e+02
E.Coli	CFU	3.64e+04	2.88e+08	7.49e+07	3.18e+07	1.89e+06
Residue Total	mg	6.29e+04	3.04e+06	5.06e+05	1.55e+05	1.10e+05
Residue Particulate	mg	2.25e+04	2.69e+06	3.18e+05	8.72e+04	6.82e+04

Infiltration and percolation loads from the base and sub-base levels were generated only for E3 and E4 due to their perviousness and the results are shown in Table 11.6. No runoff was generated from the base layer of the CP during the course of this study. At the start of this study, before the catchment system was installed, it was observed that runoff was generated from the base layer but the runoff volume decreased till no runoff was generated from the base layer. Properties of the CP are such that it is expected to go to 100% impervious as the voids between the stones lock together with sand and dust (King and Smith, 1991). Because the base and sub-base runoff sampled was a very small (even insignificant) part of the infiltration, estimates of their pollutant loads are likely to be very inaccurate.

Table 11.6 is a summary of the calculations of the estimated loads for the sub-surface. The results are not considered reliable enough to form a major finding.

Table 11.6 Total sub-surface load summary.

Contaminant	Unit	Pavement		
		E4 Base	E4 Sub-base	E3 Base
Chloride	mg	2.54e+04	4.70e+03	1.99e+04
Copper	mg	6.09e+01	9.76e+00	4.92e+01
Nickel	mg	3.29e+00	0.00e+00	8.15e+00
Zinc	mg	7.77e+02	1.40e+02	8.62e+02
Cadmium	mg	5.87e+00	0.00e+00	0.00e+00
Chromium	mg	2.20e+01	3.11e+00	1.08e+01
Lead	mg	1.96e+02	2.81e+01	1.79e+02
Iron	mg	2.03e+03	2.20e+02	1.63e+03
COD	mg	1.16e+05	1.49e+04	1.20e+05
Phenolics	µg	7.45e+03	0.00e+00	8.16e+03
BOD	mg	8.84e+03	0.00e+00	1.72e+04
Solvent Extractable	mg	7.59e+03	5.49e+02	9.28e+03
Ammonium	mg	2.08e+03	0.00e+00	1.94e+03
Nitrite	mg	3.55e+02	2.20e+01	3.69e+02
Nitrate	mg	4.42e+03	9.64e+02	3.77e+03
Phosphate	mg	7.08e+02	4.88e+01	2.61e+02
Phosphorus	mg	1.28e+03	1.34e+02	1.73e+03
TKN	mg	8.55e+03	3.66e+02	4.33e+03
E.Coli	CFU	2.28e+08	6.10e+05	6.54e+07
Residue Total	mg	5.15e+05	2.57e+05	1.71e+06
Residue Particulate	mg	5.60e+05	7.81e+04	1.44e+06

Loads generated from porous pavements discharged partly through the sub-surface which reduced the amount of direct runoff from the surface to receiving waters. More contaminant loads infiltrated below the surface, therefore, the surface runoff had less contaminants, showing that porous pavement exhibits excellent performance with respect to runoff reduction and pollution abatement (Sztruhar and Wheeler, 1993). Of course there remains the potential contribution to groundwater contamination, especially by soluble metals and pesticides.

Rainfall contaminant data “washoff” was collected from the wet portion of the wet/dry collector. In the case when contaminant data was not available (events 1, 3 and 7), the average of all the available contaminant data was taken and this value was used with the rainfall volume collected for that event. For events which did not have available contaminant data, Table 11.7 shows the ratio of the individual rainfall volume to all the rainfall volume. This table indicates the relative size of the individual estimated loads.

Table 11.7 Ratio of event rain to total rainfall.

Source	Volume (L)	Event/Total Rainfall
Total Rainfall (9 Events)	7340.0	1.00
Event 1	130.0	0.0177
Event 3	1540.0	0.210
Event 7	705.0	0.0960

Atmospheric dryfall was collected from the dry portion of the wet/dry collector. Analysis of the atmospheric dryfall was not conducted; however, the mass of the accumulation was examined. Between July 21 and September 16, 1994, 5.01 g of atmospheric dryfall was collected. Between September 16 and September 27, 1994 0.70 g was collected.

Between September 27 and September 29 1994, only 0.01 g of atmospheric dryfall was collected. Total atmospheric dryfall for the length of the study was 5.71 g or 0.147 g/day. Results from the wet/dry collector show that additional work is necessary on the atmospheric dryfall collected.

11.6 Conclusions

Very little previous work has been done to compare pollutant-generation of impervious asphalt to various permeable concrete block pavers in a parking lot. Four instrumented pavements were constructed at the University of Guelph in

1993, and after the first year of runoff sampling, we tentatively draw the following conclusions:

1. pavement surface temperatures are directly related to weather conditions, asphalt showing the highest maximum and lowest minimum daily temperatures;
2. average daily summer temperatures were similar for all four pavings;
3. subgrade temperatures measured about 150 mm below the surface showed a lower diurnal range and lower daily maxima than the surface temperatures;
4. subgrade temperatures measured about 600 mm below the surface showed little diurnal temperature fluctuation;
5. for the 23 contaminants examined, loads from the asphalt surface were always greater than from the other pavings, mostly because the asphalt was 100% impervious; and
6. permeable pavement, particularly Uni-Ecostone (a commercial concrete paver), significantly reduces surface runoff contaminant loads.

Postscript: We add the following comments in response to an anonymous and helpful reviewer.

Heat transmission through pavement is clearly related to the thermal characteristics of the sub-base, as well as the paving surface. In particular the moisture content of the sub-base is expected to play an important role. This of course begs the larger question of the changed thermal behaviour of the earth's urbanized areas, whereby the seasonal heat sink arising from infiltrating water has been compromised. Our work did not determine these effects (see the chapter by James and Verspagen).

We have not considered an important variable for pollutant interactions and mobilities, the pH/redox gradient. We understand that even 0.5 unit changes can be significant within 150 mm depth profiles, particularly for metals. Our work should be seen as merely a start on the problem of estimating the temperature effects of various processes.

Our focus has been on the reduction of surface runoff, and the trapping of pollutants associated with particulates in the upper permeable paving surface, and not the contentious question of the effective retention of soluble metals, herbicides and PAH fractions. We do not expect permeable pavement to retain dissolved pollutants unless the sub-base and top layers have been especially designed and treated for this purpose, which is clearly necessary where important groundwater resources are of concern. The provision of permeable parking lots as sand filtration facilities for removal of stormwater pollutants is an interesting idea, especially for areas of water scarcity, but clearly requires scheduled maintenance operations. Our further research will move in this direction.

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