Chapter 17

A Laboratory Examination of Pollutants Leached from Four Different Pavements by Acid Rain

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Part of a series of studies on the effects of pervious and impervious pavement on urban runoff, this chapter describes a laboratory investigation of pavement leachate. Previous literature is reviewed and the leaching processes described. To determine the effect of free-draining porous pavement as an alternative to conventional impervious surfaces, independent of traffic and land-use, four types of pavements were installed in the engineering laboratory at the University of Guelph. They were: asphalt, interlocking concrete blocks, and two versions of an infiltrating concrete paving stone. Real (acid) rainwater was collected and used in the laboratory. Runoff volume, pollutant load, and the quantity and quality of pollutants in water percolating through these pavements under different simulated rainfall durations and intensities, were studied. Results are compared to data collected from four similar test pavements in the university's parking lot. In this present study, the only contaminants of interest were phenols, pH, zinc, iron and oils and grease, as most contaminants originated in the rainwater. It was found that pH of rain is a significant factor, with asphalt having the least buffering, and that infiltrating pavers reduced both runoff and contaminants most, while asphalt produced most of both.

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17.1 Introduction

Reported here is just one component of a larger study conducted at the University of Guelph on the impacts of pervious and impervious pavement on urban runoff. Other findings have been reported by Thompson and James (1995), Kresin et al., (1997), James and Thompson, (1997), and James and Verspagen, (1997). Our main purpose here was to investigate the contribution of pervious and impervious pavements themselves to the chemical and physical alteration of urban runoff, by eliminating the effects of the environment and traffic. Only the changes in water quality strictly due to the pavement matrix were studied.

Urbanization increases the flux of stormwater and its pollutants to receiving waters. Various stormwater practices can mitigate these concerns. Recent approaches have focused on detention and retention of excess runoff. However, the best solution is to restore as far as practicable the natural drainage system in urban settings by increasing infiltration and groundwater recharge. *Re-naturalization* can be done by various means including using porous pavement, thereby reducing or even eliminating direct surface runoff from the receiving water. By using porous pavements such as permeable concrete blocks and concrete grids for parking lots and low-traffic roads, the total area of impervious surface can be effectively reduced.

We compared the quantity and the quality of runoff from three porous concrete pavers to that from an impervious asphalt pavement (deemed to be the most widely-adopted alternative in Canada). Laboratory apparatus was built to reflect rainfall conditions likely to be experienced in reality, but without the influence of traffic and contiguous land-uses. Rain was collected in bulk from a large, clean, glass roof nearby, mixed and applied to the laboratory pavements by a rainfall-simulating rig. Water samples were collected from: an outside wet/dry rain sampler nearby; the glass roof; and the laboratory pavements: at the surface, immediately below the surface, at the base, the sub-base, and from the bottom drain. Flow rates were measured and the water analyzed for 26 constituents:

1. Chemical oxygen demand (COD)	14. Iron
2. Biological oxygen demand (BOD)	15. Lead
3. Conductivity	16. Nickel
4. Oils and Grease	17. Zinc
5. Total phenols	18. Bacteria
6. Total kjeldahl nitrogen (TKN)	19. pH
7. Ammonium	20. Turbidity
8. Nitrates	21. Chloride
9. Nitrites	22. Sodium
10. Phosphates	23. Total Solids
11. Cadmium	24. Total Suspended Solids
12. Chromium	25. Sulfate
13. Copper	26. Phosphorus

17.2 Background Review

Regional maps of extreme rainfalls show that maximum rainfall intensities in 35 Canadian urban areas in the last 10 years has been only 64mm/hr (Hogg and Carr 1985). However, rainfall intensity measured in short durations, such as 1 minute, has reached a maximum value of 84mm/hr (Haro, 1984). In this study a maximum theoretical rainfall intensity of 200mm/h was used, for wider application to all geographic regions. Precipitation has the attribute of cleansing the atmosphere. Rain is not pure water, or even like tap water; it certainly cannot be compared to distilled water, which contains very little dissolved or suspended materials. Data shows that there are considerable differences in chemical composition of various rainfalls (Faust and Aly, 1981). Rainwater has a complex chemical composition that varies from location to location as well as from storm event to storm event and from season to season (Casimiro et al., 1990). For this reason, rain and snow contain many pollutants in quantities that may be harmful to terrestrial and aquatic ecosystems. Pollutants included in wet precipitation are acidity, toxic metals, organic chemicals, phosphates, and nitrogen compounds (Novotny and Olem, 1993).

There is evidence that there has been a significant change in the pH value of precipitation from the mid-1950s in the northeastern U.S. and Canada (Faust and Aly, 1981). In this region, concern has been expressed in recent years about the acidic nature of precipitation (pH values less than equilibrium value of 5.65 for "pure" rain saturated with CO₂). Acid rainfall leaches cations from soils and from urban infrastructure, damaging concrete and corroding metals (Novotny and Olem, 1993). From our analysis of rainwater quality in Guelph, the interdependency between air and water seems to be an important concern regarding the quality of pavement leachate. For example, wind temperature and mixing patterns of the atmosphere both and a body of water influences the concentrations of pollutants. Air pollution sources are international, and do not necessarily originate near the experimental area. Emitted pollutants may travel long distances and deposition occur over a large scale - or it may be localized.

Previous work has shown that relatively high concentrations and substantial mass loadings of oil and grease occur in stormwater runoff draining urban areas, and have a substantial impact on receiving waters (Silverman and Strenstorm, 1988). In general, pollutant concentrations are known to range between 0.1 and 300 mg/L, and levels of biochemical oxygen demand (BOD), suspended solids and turbidity have also been monitored (Spangberg and Niemczynowicz, 1992).

Constituents found in highway stormwater runoff may be attributed to: traffic deposition (e.g. tire wear, brake linings, and leakage of oil and lubricants), dustfall from the surrounding environment, pavement wear (the breakdown of asphalt and/or concrete surfaces), maintenance operations (e.g. application of deicing compounds, pesticides and herbicides), accidental spills, and littering

(Thomson et al., 1994). When considering urban runoff from roadways and other traffic areas, it is important to note that pollutants may also originate from the paving material itself. This largely uninvestigated source is the main focus of this chapter.

Porous pavement

Types of porous pavements include: *porous asphalt*, which increases the amount of voids available and contains no fine materials; *concrete grid*, which contains large openings filled with a mixture of joint sand and topsoil (examples: 'Turfstone' or 'Grasscrete'); and *infiltration-enhanced concrete block paver*, which allows infiltration between the joints. The latter contain higher values of permeability than natural soils due to larger voids (example: UNIECO-STONE®).

Use of porous pavement is limited by the lack of long-term data on its capabilities to remove pollutants, as well as the need for subsoils with sufficient permeability to infiltrate the runoff stored in the pavement reservoir. Design and engineering of porous pavement requires careful consideration of these limitations. Other disadvantages are the potential for clogging by sediments or ice (Lorant, 1992). Porous pavements are not suitable for high-volume highways or heavy vehicular traffic because of potential structural problems resulting from saturation of subgrade. With maintenance precautions, clogging is evidently not a major problem, and if the pavement becomes sediment-clogged, it may be cleaned by street sweeping or flushing. Ice is considered to have low potential for clogging the pavement (Lorant, 1992). On the other hand, porous pavements can have several advantages (Lorant, 1992) such as attenuation of runoff, improved erosion control, minimal water quality degradation, less need for curbs and storm sewers, retention of natural drainage patterns and vegetation, improved road safety, and ground water recharge.

Porous pavements infiltrate rain by temporarily retaining all or a portion of the inflow until it infiltrates, percolates, or evaporates away. There is no outflow until the storage capacity is exceeded. Pollutant removal efficiencies (in terms of surface runoff) are therefore 100% up to maximum storage capacity. Soil material bedded in the pavement plays a major role in cation exchange of organic matter, pH and soil structure. Pollutant removal processes that the porous pavement undergoes are chemical and biological, involving adsorption, filtration, precipitation and decomposition (Lorant, 1992). Virginia Polytechnic Institute and State University conducted a study on the quality of surface runoff from concrete grid pavements, compared to concrete slabs (Smith et al., 1984). Results showed that grid pavements greatly reduce surface runoff volume. Ten pollutants found in the surface runoff from slabs were greater than those in the surface runoff from the grid pavements. Soils beneath the grid pavements effectively removed significant quantities of pollutants from the water that infiltrated. Heavy metal removal appeared to be especially good. Nitrate/nitrite was a notable exception, and tended to increase because of leaching from the soil.

Silverman and Strenstrom (1988) noted that the use of porous pavements has numerous advantages. Biological degradation of oil through soil cultivation is well documented as an effective treatment practice (Kincannon, 1972); capturing oil and grease in pavement and subgrade, or in soils surrounding and underlying paving blocks, appears to present analogous opportunity for degradation. Inorganic pollutants such as heavy metals may sorb to soil and underdrain particles, and are thus removed from stormwater discharge. Once the water penetrates through the base material, water can drain vertically into the ground or into the subgrade.

Natural filtration of runoff water by the soil removes most contaminants. Most pathogenic bacteria and many chemicals are filtered out within 0.9 to 3 m of vertical percolation and 15 to 60 m of lateral movement (Jackura, 1980). However, soil and underlying strata characteristics are highly site-specific, making accurate predictions of pollutant filtration difficult. Soil properties generally considered important for filtration and retention of pollutants are pH, cation exchange capacity, clay mineral content, organic matter content, pore space and structure (Lorant, 1992). There are many factors that affect the permeability of the material, including effective grain size, percent passing the No. 200 sieve and porosity.

Pavements which provide permeability by means of enlarged joints or openings must be designed in such a way that filler material in conjunction with joint and drainage openings will allow drainage corresponding to an average coefficient of permeability of $k = 2 \times 10^{-2}$ m/s (Muth, 1992).

Galli (1990) reported that pervious pavement is the best practice in reducing urban temperature fluctuations. He also reported that infiltration was the best of the urban best management practices (BMPs), outperforming other BMPs by a wide margin. Furthermore, he concluded that urbanization had a detrimental effect on the water temperature downstream of cities. Muth (1992) performed an experiment on UNI Eco-Stone® paver (EC) at Karlsruhe University of Engineering in Germany. It was found that with increasing slope or increasing storm intensity, surface runoff was significantly reduced. In addition, it was determined that the rate at which the water will flow through the EC surface will depend on the specific materials used to fill the drainage voids and on the slope of the pavement (Rollings and Rollings, 1993).

Schueler et al. (1992) prepared a study on porous pavement for the Metropolitan Washington Council of Governments. They state that porous pavement required the slope to be less than 5%, and was generally best suited for parking lots and other light traffic areas such as access roads. Tests were done on EC for slopes of 0% to 10% at Northeastern University, Boston. A 100-year design storm, of 5-minute duration with an intensity of 300 mm/hr was shown to be absorbed by the EC on slopes of 0% to 5% (Sargo, 1993, citing others).

Field et al. (1982) found that porous pavement is practical and cost-effective for watersheds ranging from 0.1-4.0 ha. Silverman and Strenstrom (1988) noted that the initial cost of porous asphalt pavement has been estimated to be about 50% greater than for impervious asphalt pavements, although much of the high estimate may reflect unfamiliarity with construction requirements since materials and techniques do not appear inherently more expensive.

Rollings and Rollings (1993) stated that EC will permit land-use planning, allowing more efficient use of property for greater economic value. This makes EC cost-effective, as it will provide more usable property than otherwise would be developed, due to requirements for stormwater retention or by limitations on how much permeable area is allowed on site.

Asphalt pavements

Pluhowski (1970) analyzed the effect of anthropogenic changes on the stream temperature and thermal patterns of five streams on Long Island, New York. He found that widespread alterations in the natural environment have sharply reduced infiltration capacity of soils, thereby increasing storm runoff to streams in urban areas. Not only was the volume of runoff increased, but there was a reduction in the arrival time of runoff to watercourses. The first-flush phenomenon on a small asphalt surface was documented (Spangberg et al., 1993). After a spell of dry weather, a significant part of the pollution wash-off occurs during the initial stage of the runoff process, just before the runoff peak. Wash-off of measured pollution variables is strongly correlated with the rainfall intensity. According to Spangberg and Niemczynowicz, 1992, importance of intensity and pollutants seem to decrease over time.

Galli (1990) noted that imperviousness together with local meteorological conditions had the largest influence on urban stream temperatures. In general, the average water temperature of the urban stream increased in a linear fashion with increasing levels of watershed imperviousness. Results indicated that the average rate of increase was 0.08°C per % increase in imperviousness. Xie (1993) noted that with increasing imperviousness, the size of storm needed to produce large stream temperature fluctuations decreased. At 12% watershed imperviousness level, over 1.8 mm of rainfall was generally required. By contrast, at 60% imperviousness, less than 0.5 mm of precipitation was needed to produce a comparable temperature change. It should be noted that the impact stormwater runoff on receiving streams increased as the runoff to receiving stream flow ratio increased.

Summarizing, the literature indicates that physical alterations of a watershed associated with asphalt paving of urban areas has been recognized as a source of increased stormwater, hydrologic and water quality impacts. Utilization of porous pavement provides a control strategy capable of mitigating the detrimental aspects of urban runoff. Advantages of porous pavement outweigh

the disadvantages. Initial cost of constructing porous pavement is slightly higher than constructing an impervious pavement, but if costs of environmental impacts were to be included, porous pavement is clearly very much less expensive; in the long run, the costs for both types of pavements may be similar.

17.3 Processes at the Pavement

Rainwater undergoes many processes at the pavement, e.g. energy conversion at raindrop impact, splash distribution, chemical reactions, erosion of loose particles, particulate wash-off throughout the pavement, surface infiltration, percolation, solution of pavement chemicals and clogging of pores.

Three important characteristics of natural rainfall that need to be simulated in the laboratory are:

1. raindrop size distribution,
2. raindrop impact velocity, and
3. appropriate rainstorm intensities.

These are key factors in soil surface sealing, and the resulting runoff (Lal, 1988). Kinetic energy of the simulated storms can be calculated by using the method outlined by Tossell et al. (1990). As rainfall intensity increases, energy density flux (EDF) increases. Differences in simulated and natural energies were due to the drop velocities of the simulated rain, and the interaction of drop size distribution and the drop velocity distribution (Tossell et al., 1990). It was found that the EDF of simulated rainfall was always lower than the EDF of natural rainfall. Differences were not constant for all rainfall intensities, the ratio of simulated rain EDF to the natural rain EDF increasing with increase in the rainfall intensity (Tossell et al., 1990).

In this chapter, the term *erosion* is used to describe the detachment of loose particles and their transport. Generally, very low rainfall intensities are not of major interest for erosion and hydrologic studies; on the other hand, very high intensities are rare but do occur. Scouring at the surface of pavements usually occurs as a result of high storm intensity. Irvine (1989) determined that the most important factor affecting erosion rate was surface cover. Aggregate surfaces typically had the highest erosion rates while surfaces protected by grass had lower erosion rates. Factors including slope length, slope gradient and in situ particle size distribution accounted for the differences in erosion rates from plots with similar surface cover (Irvine, 1989). Several studies and analyses have suggested that erosion is approximately proportional to the square of the intensity (Lal, 1988). Detachment is almost entirely by raindrop impact. Rate of particle detachment by raindrop impact is time dependent even for a constant rainfall intensity. The pattern is not consistent, and generally the time effect must be ignored until further research defines the relationship (Haan et al., 1982). When

high storm intensity occurs, it usually has high impact energy on the pavement, and scours the surface. Sediment yield will be high. For porous pavements, scouring will take place at the joints, where the fillings are loose. With high storm intensity, the filling material is dislocated from its original position, and washed off. Scouring will also take place over time on asphalt pavements with high rain impact energy. It depends on the storm events that the pavement experiences. The highest sediment yield will take place during the first flush, but the sediment yield will be very low after the surface is cleaned.

Slope is a major factor affecting downhill erosion. With large pervious pockets, the rain will hit the filling material at an angle, and cause the particles to be washed off with the water more easily. However, with most porous pavement, the flow of the runoff is reduced; water velocity is slowed down before it hits the next pavement or rill.

Total solid content is the main pollutant carrier in highway runoff (Lorant, 1992). It exhibits the highest degree of association with other pollutants. Closely correlated is the suspended solid content. Suspended solid concentrations are markedly increased at high flow rates as scouring of the pavement surface takes effect. Solid mobilization is dependent on flow velocities. The first flush is not a common feature of all storms thus although high suspended solid levels are normally encountered during the initial stages of the event, peak levels generally coincide with either peak flow rate or peak rainfall intensity (Lorant 1992).

For many watersheds, infiltration is the most important hydrologic component determining the shape of the runoff hydrograph (Haan et al., 1982). Major controlling factors are: soil type, surface crusting, season of the year, antecedent moisture conditions, rainfall hyetograph and subsurface moisture conditions. In this study, no surface crusting occurred. In the real world, factors affecting the surface crust include: dustfall, pavement degradation, vegetation and local land-use practices. Season of the year also affects infiltration since these affect the presence or absence of frozen ground. It is possible for frozen ground to have non-zero infiltration (Haan et al., 1982). Freezing will normally decrease the rate of infiltration, but some water will usually infiltrate. Seasons will also affect the runoff quality (Lorant, 1992). Moisture content in the soil at the beginning of the storm event and the rainfall hyetograph itself will influence the infiltration rate. It may well be that the rate of rainfall at an instant is less than the infiltration capacity of the soil. Water cannot infiltrate into the soil faster than the rate at which it is being supplied (Haan et al., 1982). Soil type is the prime factor to consider when modeling infiltration. As the water is absorbed by the soil, the wetting front advances by filling up all the air pores in the soil. After the wetting front has reached its maximum capacity, water moves through the transmission zone. Once the maximum water content is reached, the soil becomes saturated and the infiltration rate becomes constant.

In porous pavements, the openings in the pavement surface where water infiltrates are here called *pores*. Infiltration is dependant on the pore size, the depth of the jointing material and the type of jointing material. Pore size the product of the joint size per plot area and the void size. Theoretically, the larger the pore size on the surface, the higher the infiltration rate; the larger the depth of the jointing material, the longer the water has to infiltrate. One of the factors that affects permeability is the age of the pavement, i.e. dependent on type of traffic over the pavement and type of waste collected in the pores. This causes clogging of the pores in porous pavements. Clark stated in his study that it is widely accepted but unsubstantiated, that the pavement surface of compressed concrete blocks become impermeable to water, as detritus and debris accumulate on the surfaces and in the joints. A current assumption is that a pavement has an initial permeability which decreases to near zero with time (Clark, 1980).

Another factor that affects permeability is the type of joint filling material. Water movement through the soil depends on many factors. Of these, the major factors are the soil type and the water content. Each soil type has its own hydraulic conductivity, which is a measure of the soil's ability to transmit water and is primarily dependant on the pore volume, pore size and bulk density of the material (Evans, 1989). In addition, temperature, air content of the water and the biological activity of the sample will all affect the hydraulic conductivity (Evans, 1989).

Porous pavement surfaces have joints which are filled with a soil material through which water will infiltrate before percolating into the subsurface. At the onset of a storm, the matrix potential is highly negative and thus infiltration is high but unsaturated conductivity is low. Complications are introduced by closed water films which entrap air. Additionally, fine material may form at the surface in real outdoor pavements, and act as a capillary block (Ostrowski, Manfred. Pers. Comm. 1997).

Percolation refers to the movement of water in the subgrade, influenced by (Evans, 1989) the prior experience of the pavement, the slope of the pavement, the weather and temperature, and the type of bedding material. After the water infiltrates, it percolates through the sand and crushed stone in the sub-base and base. With sand, percolation acts in the same manner as the infiltration process. With the crushed stone, there is no water absorption, and the stone acts as a free-draining subgrade. Clark conducted a study in 1980 on newly laid pavements with free-draining subgrade. He concluded that the amount of water penetrating to the subgrade depends on the volume of the water applied and not the rate of application (Clark, 1980). He also stated that on newly-laid pavement with a freely draining subgrade, up to 25% of rainfall penetrated the pavement. Evans argued that at rainfall intensities lower than the hydraulic conductivity of the joints, the infiltration rate will be rainfall-intensity dependent (Evans, 1989). Evans seemed to be correct for sandy soil as bedding material. For stone, the

water penetrates through the stones without absorption i.e. for stone, the higher the rainfall intensity, the more water percolates through the pavement. If the subgrade is more permeable than the pavement, then the water travels vertically down through the pavement and the subgrade (Evans, 1989).

Depth of the material also affects the permeability: if the material is deep, the water has a greater distance to percolate. Other factors are slope, temperature and pH. If pavements experience a temperature change, the water quality data will likely be completely different, as many chemicals, such as acidity and conductivity, tend to change with temperature. If the rainwater is very acidic, it will pick up more chemicals as it travels through the pavement. If less acidic and more neutralized, it will not. Hence the runoff will have lower concentrations of contaminants. However, not all contaminants will react with the water as it percolates through the pavement. Some chemical reactions will take place within the surface and subsurface bedding material itself.

Transformation of nitrogen in the soils of the surface waters and the subsurface bedding material of the pavements, and its pathways from soil to surface waters are numerous, and can be represented by a typical nitrogen cycle. Since the mobile components NH_4^+ and NO_3^- are carried by soil water, downward or lateral N movement occurs only if the moisture content is above that for gravitational water (0.3 bar tension). Maximum movement occurs when soil moisture content is near saturation, and decreases rapidly with decreasing moisture content (Novotny and Olem, 1993).

Sulfates are formed from the oxidation of sulfides (S) to give sulfites (SO_3), which is then oxidized to give sulfates (SO_4). Sulfides are common in sediments and have been found in sediments with sand and gravel (Novotny and Olem, 1993). Under anaerobic conditions SO_4^{2-} may be reduced by the action of bacteria to some form of an insoluble sulfide salt. Sulfate ion in water may come from a number of different sources. It may be leached from minerals, particularly gypsum, $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$, or from the oxidation of sulfide minerals such as pyrite, FeS_2 (Manahan, 1975). As noted earlier in the literature, rainwater also contains a high concentration of sulfate ion.

Summarizing, of the many processes that take place at the surface of the pavements and through the subgrade, the rainfall intensity, nature and appearance of the surface, slope, temperature and pH of the water are all important.

17.4 Laboratory Experiments

Equipment built to conduct leaching tests on laboratory pavements comprised four major components: rainfall collector, rainfall simulator, pavements and their bedding materials, and the samplers.

Laboratory rainwater

To reflect natural rainfall conditions, rainfall herein denoted LABR was collected for use in the laboratory. A polyethylene tank (5 ft in height and 5 ft in diameter) was connected to the gutter of a University greenhouse. To reduce the amount of particulates reacting with the rainwater, the glass roof and the gutter were hosed down every other day. Furthermore, the laboratory container was washed with phosphorous-free soap and acid-dipped with concentrated hydrochloric acid prior to pumping in this rainwater. A stirrer was installed to prevent particulates from settling in the water. Previous studies (Abrahamsen et al., 1986) indicated that stored rainwater tends to vary in chemical composition with time, i.e. stored rainwater will not retain the same concentrations as when first collected. This in turn degrades the accuracy of the runoff quality samples. Hence the time-variation of the pH of the stored rain under a constant temperature (25°C) was measured. To determine whether LABR was similar to natural rain, fresh rainwater (denoted WDSR herein) was collected and analyzed using a Wet/Dry Sampler (WDS) placed on the roof of the Engineering building. Water quality parameters were measured and the difference between laboratory rainwater and fresh rainwater determined. The WDS used two buckets, one collecting “wet” rain and the other “dry” rain. During wet weather, the “dry” bucket is automatically covered, and vice versa. Rainwater was collected and analyzed in the Engineering Laboratory. Also, 200 ml of rain was collected from a wet/dry sampler (denoted WDSR) half an hour after the cessation of rain.

The rainfall simulator

Rainfall simulation equipment and techniques for assessing soil erosion, particle detachment, overland flow, and chemical runoff are described by Kresin et al., 1997.

Test pavements

Four test pavements were installed in parking lot P10 at the rear of the School of Engineering, at the University of Guelph, and four similar laboratory pavements were also built simultaneously in the engineering laboratory of the school, as described by Thompson. Pavement boxes were designed for collecting runoff through the porous subgrade. The four pavement samples tested were:

1. asphalt (AS),
2. rectangular concrete paver (PC),
3. UNI Eco-stone® with 3 inch base and joints filled with washed stone (EC3), and finally
4. UNI Eco-stone® with 4 inch base and joints filled with a mixture of washed stone and sand.

For the four sub-base materials, a soil mixture of granular *A* was used. Base materials differed for some of the pavements: For the AS and PC pavements, the base material consisted of granular *A* material. For the EC3 pavement, the base

material consisted of 3 in. of clear washed stone, and for EC4 the base consisted of 4 in. mixture of clear washed stone and granular *A* sand. PC had voids filled with sand. EC3 had joints filled with clear washed stone, and EC4 had voids filled with a mixture of washed stone and granular *A* sand. Sampling points were: immediately beneath the pavement, in the base, and in the sub-base. In the sub-base layer, a perforated 4 in. plastic pipe was placed, with a plastic sheet with washed stone, since the bottom of the pipe was pervious. In the base layer, another plastic sheet with washed stone was placed across the pavement. The top outlet hole was placed half-way down the blocks to capture surface runoff, and a row of concrete blocks were removed. To allow separate collection of runoff from each layer, outlet pipes of different sizes were attached to these holes, and drained towards the ground. Plastic sheeting was placed over the pipes to prevent runoff from splashing into the collectors while sampling. Finally, a hole was placed underneath the boxes to drain the water. This hole remained open throughout the experiments. For the impervious asphalt pavement (AS), runoff was generated only from the surface. Around the rainfall simulator, a curtain was hung, to contain the water.

Sampling

Pavements were set at slopes ranging from 1% to 10%, and rainfall intensities from 21 to 200 mm/hr. In addition, an experiment using tap water instead of LABR rain was conducted at an intensity of 90 mm/hr. Samples were collected over a 1 hour duration and analyzed within 24 hrs, at most. For periods longer than that time limit, they were stored at -4°C. Chemical analyses were performed in our laboratory on the runoff from all the tests, and chemical analyses were performed by the Ontario Ministry of the Environment and Energy (MOEE) on the runoff collected from a 5% gradient. Water samples were subjected to the following analyses in the Engineering Laboratory: pH, BOD, transmittance, sodium, chloride, sulfates, phosphorous. The rest of the analyses were performed at the MOEE laboratories. Water samples were analyzed and preserved in accordance with "Standard Methods" (17th ed., 1989).

17.5 Results

Rainwater quality

When fresh rainwater first falls, it usually has an average pH of as low as 3.4, due to industrial pollution in the air. It was found that pH of approximately 3.4 lasts for a maximum of 2 hours, as shown in Figure 17.1. After 2 hours, the rainwater released more carbon dioxide and caused the pH to increase to an average of 5.5, when it stabilized and for some time before it changed rapidly once again. The LABR rainwater used in the laboratory to perform the experiments was slightly more polluted than the fresh rainwater samples. Differences in

quality between LABR and WDSR rain were determined. Parameters such as total ammonium (NH_3^+), total phenols, TKN, nitrates and nitrites, total phosphorous, sulfates, and trace metals, differed slightly or not at all. No statistical analysis was performed on these data because of the very small sample sizes, but it is recommended that future studies incorporate more quantitative analyses.

Figure 17.1 pH of LABR rain vs. time.

Volume

Runoff volumes collected from each pavement at four simulated rainfall intensities and three different slopes showed that the greater the slopes, the more surface runoff is generated. Furthermore, the higher the rainfall intensity, the sooner the pavements became saturated, and the more runoff is generated at each level. In comparison with the other porous pavements, PC generated the largest volume of surface runoff for the 5% and 10% slopes. The amount of surface runoff was always less than the applied rain, due to wetting, splash and ponding.

Water quality

All samples were composite samples of runoff at each level, from each pavement. Some chemicals in the LABR rain remained constant after the rain came in contact with the pavement: TKN, cadmium, copper, and chromium. Other chemical concentrations were very low, although some differences were observed. Selected parameters have been compared in four ways:

1. behavior of the pollutants within the pavement itself,
2. difference in chemicals between different pavements at different levels,
3. difference in water quality parameters obtained at different slopes from each pavement,
4. difference in the quantity of pollutants.

Pollutant concentrations

A range of pHs were obtained from the four pavements, at different levels in the pavement. All the pavements had the capacity to neutralize the acid rain. pH seemed to become more alkaline as it percolated deeper into the porous pavements. The sub-base runoff of all the pavements had the same pH average of 8.8. The provincial objective for protection of the aquatic habitat set by the Ontario Ministry of Transportation (MTO) for BOD and COD concentrations is between 4 - 8 mg/L. In the case of the porous pavements and AS pavement, the BOD and COD parameters did not differ much from the LABR rainwater to which they were exposed. AS surface runoff contained a higher concentration of oil and grease than did the PC, EC3 and EC4 surface runoff. In the laboratory, the oil and grease concentrations varied up to 1.3 mg/L for all the pavements. AS pavement usually contained concentrations over 1 mg/L. Under parking lot conditions, the concentrations in AS surface runoff varied between 0.8 mg/L to 12.9 mg/L, and the porous pavements varied between 0.6 mg/L to 5.9 mg/L (Thompson, 1994). Total kjeldahl nitrogenous (TKN) and total ammonium (NH_3^+) decreased when the simulated rainwater reached the pavements, while nitrates and nitrites seemed to increase while percolating through the soil. AS had the largest range of nitrates and nitrites in the surface runoff, (ranging from 0.002 to 1.61 mg/L), larger than the EC3 and EC4 pavements (ranging from 0.9 to 2.0 mg/L) at all levels, and the PC pavement (ranging from 0.95 to 1.3 mg/L) at all levels. Total phosphorus and phosphates did not seem to change. Concentrations of phenols should not exceed 1 mg/L to protect against tainting of edible fish flesh (Lorant, 1992). The results indicate that AS surface runoff contained an average concentration of approximately 2.5 mg/L. The EC3 surface runoff had an average value of 1.6 mg/L. The PC and EC4 pavements never had sufficient volume of surface runoff to measure phenols. However, the subgrade runoff was analyzed, and showed that as the water percolated deeper into the pavement, the concentration of phenols decreased. Concentrations were always lower than the concentration of phenols from the AS surface runoff. In all cases, the concentrations for all the pavements exceeded the objective needed to protect aquatic habitat. Sodium decreased in concentration once the rainwater hit the surface of the porous pavements. The sodium ion (Na^+) in this case did not precipitate into the water, but rather was adsorbed by the filling materials in the joints and between the edges of the porous pavements. As the water percolated to the base materials of the PC, EC3 and EC4 pavements, the range of concentration for the Na^+ increased. The base runoff concentrations of sodium in the EC3 and EC4 pavements increased, and then when the water percolated to the sub-base, the concentration in both pavements decreased again. For chloride ion (Cl^-), the concentration increased as the water percolated deeper and deeper into the pavements. However, the Cl^- concentration in the AS surface runoff maintained a higher range than the porous pavements (5 to 18 mg/L). The EC3 surface runoff

maintained the lowest Cl^- concentration range (0.1 to 0.3 mg/L). Provincial water quality objectives state that chlorine should not exceed 0.002 mg/L. Data on lead, zinc, iron, chromium, copper, cadmium and nickel are shown in Appendix C. No metal concentrations were different from the LABR rainwater. The values were almost undetectable. The highest concentrations were in the zinc, iron, copper and lead. All metal concentrations were almost similar to concentrations in the LABR rain. The pavements generated surface runoff with metal concentrations exceeding the MOEE objectives for the protection of aquatic habitat, with the exception of three trace metals: chromium (Cr), lead (Pb) and nickel (Ni). These metal concentrations were below the objectives required by the MOEE to protect aquatic habitat. AS surface runoff had the highest concentrations in lead, zinc and copper. In summary, the following contaminants were found to remain unchanged through the pavements: BOD, COD, TKN, phosphorous and phosphates, oils and grease, total phenols, cadmium, chromium, nickel and copper. These parameters might have changed in concentration within the pavement, but the change was very small and almost negligible. The rest of the parameters also did not change by much, but the changes were detectable. These changes are summarized in Table 17.1. It should be noted that even though the percent of change for some of the chemicals was high ($> 100\%$), the actual change was very low because of their low initial concentrations in the applied rain.

Comparison between LABR rain leachate and tap water leachate

The biggest difference between tap water and LABR rain was the pH, which was 7.00 compared to 5.5. It was found that the concentrations of the parameters leaching from tap water in most cases had lower concentrations than that leached using LABR rainwater, as shown in Table 17.2. This proves that the pH of the water has an impact on the pavement leachate.

Mass of pollutants

In order to determine the pollution control effect of the pavements, mass was calculated for chemicals that showed a significant difference in the runoff concentrations. During the one-hour duration of simulated rainfall, some levels did not become fully saturated. Thus not enough runoff was generated and collected to perform some of the water quality analyses. In others, the concentrations of some chemicals were very small, below the detection limits. Only a sufficient amount of surface runoff was collected from the surface of EC3 and AS at a rainfall intensity of 200 mm/hr, mass of chemicals from surface runoff was calculated only for these surfaces. Loads of the subgrade runoff are shown in Table 17.3.

Table 17.1 Change in pollutants (%).

	PC (1)	PC (2)	PC (3)	EC3 (1)	EC3 (2)	EC3 (3)	EC4 (1)	EC4 (2)	EC4 (3)	AS (1)
pH	+49	+49	+50	+24	+43	+49	+49	+43	+50	+30
NH ₃ ⁺	-6	-72	-69	NA	-66	-72	NA	+33	+53	+3
NO ₃ ⁻	-6	+81	+81	+13	+19	+100	NA	+75	+162	+29
Cl ⁻	+500	+100	+700	+200	+350	+3200	+2700	+120	+900	+650
Na ⁺	-24	-7	-11	-55	-15	-41	+34	+59	-9	+20
SO ₄ ²⁻	-2	-26	-73	-18	-21	-73	-29	-25	-29	-51
Fe	+386	+950	+7480	+1040	+1410	+252	NA	+520	+590	+240
Pb	+76	+167	+2030	+1620	+51700	+933	NA	-116	+56	-50
Zn	+77	+4	+192	+148	+89	+60	NA	-16	-12	+2270

Where: (1) = surface (2) = base (3) = sub-base (+) = increase (-) = decrease

Where NA = not available.

Table 17.2 Difference between average concentrations of leachate from surface runoff.

Parameters	With Tap Water	With LABR Rainwater
pH	7.13	5.56
Sodium	19.2 mg/L	29.2 mg/L
Chloride	5.1 mg/L	7.5 mg/L
BOD	2.0 mg/L	2.0 mg/L
Sulfate	22.5 mg/L	39.5 mg/L

Table 17.3 Mass of chemicals from surface runoff.

PARAMETER	LABR RAIN	EC3	AS
TS (mg)	5800	282.8	13392.2
TSS (mg)	475	53.6	1176.8
Total phenols (mg)	0.1	0.0	0.2
Oils and Grease (mg)	180	3.2	0
TKN (mg)	150.6	1.6	172.4
NH ₄ (mg)	65.8	0.3	640
P (mg)	3.2	0.1	4.0
Cl (mg)	146	3.7	464.1
Cd (mg)	1.4	NA	0.3
Cu (mg)	7.4	0.1	14.1
Fe (mg)	11.2	1.0	33.1
Pb (mg)	1.2	NA	1.2
Ni (mg)	0.4	NA	0.0
Zn (mg)	18.2	NA	38.1

Where NA = Not Available

17.6 Discussion

17.6.1 Difference between LABR and WDSR Rain

Parameters that showed a difference in quality between the LABR and WDSR rain were: pH, COD, TS, TSS, conductivity, sodium and sulfate. Pure water in equilibrium with the atmosphere would have a pH of 5.6. The principal factor in rainfall's acidity is carbon dioxide. WDSR rain had a pH lower than 5.6, most likely due to the reaction with sulfur dioxide and nitrogen oxides in the atmosphere. COD is a measure of the oxygen equivalent of the organic matter

present in the sample. LABR rain collected from the greenhouse roof contained dead leaves and dead insects (despite regular cleaning). This likely increased the organic content of the rain, whereas the WDSR rain contained no organics. Total solids and total suspended solids did not differ significantly. This small difference is probably again due to the collection system of both rainwaters; the LABR rain most likely picked up solids from the greenhouse gutter and (perhaps) the pump that was used to transfer the water to the laboratory tank. Conductivity is a numerical expression of the ability of an aqueous solution to carry an electric current. This depends on many factors, including the amount of salt in solution. Differences in conductivity between LABR and WDSR rain were not significant, indicating that the salt content was not very different. Sodium and chloride concentrations for instance confirmed that the difference is very small. Finally, the main source of sulfate is the air itself; sulfuric acid is a main component of acid rain. Both LABR and WDSR rainwaters are acidic, and it was found that both had similar values of sulfate. As the sulfate comes in contact with the pavement, it will react with other chemicals resulting in a change in its concentration.

17.6.2 Surface Percolation

Of the porous pavements, EC3 generated most subsurface runoff. In our case, the surface area of all the pavements were the same (1 m²). Having a larger joint size does not necessarily mean that it has a more voids. The decrease in pore size in the EC4 is due to the sand that filled its joints, in addition to the stone. Hence, the EC3 pore size was larger than the EC4. Since the joint was filled with both sand and stone, the water percolation process was slowed down more in EC4 than the PC pavement also, which had only sand as the filling material. Due to the sand, water did not percolate far in the one hour duration. This slowed down the infiltration process through the surface, and in turn through the subgrade. When the slope changed from 1% to 5%, the surface and subsurface runoff increased. However, for a 10% gradient, water did not penetrate through the porous pavement voids as much; the water traveled down the surface slope, and penetrated through the edges of the blocks. Thus the higher gradient allowed the water to penetrate to the collection hole faster. The steep slope allowed the water to percolate at an angle rather than vertically downwards. As far as infiltration is concerned, at 10% water did not infiltrate, but rather flowed across the pavement towards the outlet hole.

As noted earlier, infiltration depends on the rate of water application, the soil conditions and the rate of deep percolation (or water discharge from the box). Infiltration rate was constant when the amount of water applied was equal to the amount of water leaving the pavement, as illustrated in Figure 17.2. Infiltration rate decreased as time increased. Figure 17.2 explains the physical processes that apparently occurred in the pavement. Total volume applied (V), is equal to the

sum of the volumes collected from the surface (V1), from the base (V2), from the sub-base (V3), from the drain at the bottom (D) and finally the evaporation (E) taking place at the surface. In the laboratory, since temperature was kept constant, evaporation was less likely to occur over a duration of 1 hour. Hence, E can be assumed to be negligible. Within the pavement, adsorption (SA) and desorption (SD) take place between the soil and water. Each individual volume collected from each surface (Vn), is equal to the sum of the volume of water adsorbed (SAn) and desorbed (SDn) in each respective layer. Hence, whenever Vin was equal to Vout, infiltration rate was observed to be constant.

Figure 17.2 Volume balance in the pavement.

17.6.3 Water Quality

Concentrations of the chemicals changed as water percolated deeper and deeper through the pavement. In some cases the concentrations increased, and in others they decreased, depending on the reactions that took place.

pH

The surface of the AS pavement comprises bitumen, which is obtained by evaporating petroleum products. One of the gases likely to be emitted is hydrogen sulfide (H_2S), and its concentration depends on the AS surface. Since the pH of the surface runoff was almost 7.00 at all times, it means that either little metal sulfides (such as iron sulfide) was present in the surface, or sufficient calcium carbonate ($CaCO_3$) was available to neutralize the sulfuric acid and the acidic

metal. With all the porous pavements, the surfaces most likely contain sufficient limestone (CaCO_3), and the pH of the surface runoff was alkalized sharply. Limestone is commonly found in local soil and stone and is the usual primary chemical compound causing reduction of acid rain i.e. carbonates such as magnesium carbonate (MgCO_3) and CaCO_3 produce metal compounds and less acidic precipitates. One of the more important functions of soils is the exchange of cations that takes place between the soil and water and it depends on the type of soil and the type of water interacting with it. Since the PC and EC3 gave subsurface runoff pH of over 8.5, there must have been more anions available in the soil to react with the hydrogen ions (H^+), leaving some hydroxide ions (OH^-) free to be given off in runoff. Similarly, the deeper the water percolated into the pavements, the more metal carbonates reacted with the water, causing the pH to alkalize even more.

Oxygen demand parameters

Little change was observed in the oxygen parameters in the surface and subsurface runoff of all the pavements, likely due to the low concentrations of organic matter in the laboratory. The objectives set by MTO to protect aquatic habitat are between 4 and 8 mg/L for both BOD and COD. BOD concentrations measured in the surface and subsurface runoff were always below this range, and COD concentrations were always above it.

Solids

Measured concentrations of TS and TSS indicated no distinct relationship between the pavements. With time, the LABR rainwater cleared whatever dust and other pollutants that collected on the pavement surface, leading to a reduction in concentration of TS and TSS towards the end of the hour. This was obvious from the clarity of the runoff samples collected. Generally, the surface of the pavements were covered by PVC sheeting and were not exposed to solid particle build-up on the surface between experiments. Our data indicated that the deeper the water percolated, the higher the concentrations of TS and TSS. This is due to entrainment of solid particles captured through the pavements. Conclusions over the long term cannot be drawn, since the laboratory pavements were not been exposed to rain for long.

Conductivity and transmittance

Conductivity depends on many factors. Two of them are salt concentration and temperature. In previous research, porous pavement has been known to reduce the temperature of stormwater runoff (Galli, 1990). However, the relationship between conductivity and temperature cannot be derived from our laboratory results, since temperature was not measured or varied. Secondly, the conductivity obtained from each pavement were different, and no relationship was established. In the porous pavements, the surface runoff always had a low

transmittance at the start of the experiment, and increased. The data indicated that as the leachate traveled to the subsurface layers in the porous pavements, transmittance decreased. Another factor that affected transmittance was time of water contact with the particles. As rainfall intensity increased, the transmittance of surface and subsurface runoff also increased. Similarly, the steeper the slope, the less time the water probably remained in contact with the particles before running off. Therefore, fewer soil particles were desorbed and higher transmittance was observed.

Oils and grease

With the porous pavements, the concentrations of oil and grease were always below detection limits. Infiltration through the porous surface will contribute to this: if there were oil and grease at the surface, it probably adhere to solid particles and be filtered by the filling material in the joints. Under laboratory conditions, oil and grease was only found in the AS surface runoff probably due to the bitumen, which contains oil. However, the AS surface runoff concentrations were also low, since the main source of oil and grease is from industrial effluents and vehicles lubricants, as discussed earlier. In our parking lot experiments, oil and grease concentrations were higher than the laboratory results, as expected. Also, the AS surface runoff always had higher concentrations of oil and grease than the porous pavement surface runoff, consistent with laboratory results. Both laboratory and parking lot data therefore demonstrated that porous pavement reduced oil and grease in the surface runoff. The data also showed that with higher rainfall intensity, the concentration of oil and grease decreased in the AS surface runoff. This was probably related to the *first flush* phenomenon.

Nutrients

Nitrates (NO_3^-) and nitrites (NO_2^-) increased as the water percolated to the sub-base. The behavior of the nutrients in the pavement can be explained as follows: with deeper percolation into the pavement, the gravitational water pressure was higher, and at saturation, NO_3^- and NO_2^- were increased and collected in the runoff. Another reason was most likely due to the oxidation of ammonia (NH_3^+) to produce NO_2^- , and this in return was oxidized by the minerals originating in the soil to produce NO_3^- . For this reason, NH_3^+ decreased as the leachate percolated deeper into the pavement, while NO_2^- and NO_3^- increased. As for the remaining nutrients (TKN, phosphorous and phosphates), the transformation is a slow process, and for the increase in concentration to take place, the pavements would need more time. As Novotny and Olem (1993) stated, between rains, nitrogen movement is slow or nonexistent. Furthermore, the pH of the subsurface layers of the porous pavement was above 8.00, and the rate of the nitrification process was likely to be slow, leading to a reduction in the concentrations of TKN and NH_4^+ as the water traveled down through the

pavement. This is also probably the reason why the AS surface runoff had the highest range of concentrations in nutrients. Phosphorus (P) and phosphates (PO_4) did not change in concentration from the LABR rain that was applied at all times. The source of P and PO_4 is mainly from rock weathering and roadside fertilizer. Under laboratory conditions, these sources did not exist.

Total phenols

The AS surface runoff had the highest concentration of total phenols. The sources of phenols are mainly from automobiles, combustion of coal and industrial effluents, and the bitumen itself. In our tests there was no other obvious source of phenols. For the EC3 surface, no phenols were detected. However, when the leachate reached the sub-base, the phenol concentration increased, indicating that some phenol could have adhered to the granular A sand or been present in the soil itself, and hence either mechanically washed out as runoff or desorbed and dissolved in the runoff.

Sodium and chloride

As the leachate traveled through the porous pavement, the sodium concentration in the runoff decreased. This was likely due to the Na^+ ion reacting with the chloride from the bedding material, and thus allowed the Na^+ to dissolve in the water in the form of a salt (NaCl). However, in the case of EC3 and EC4, the concentration increased in the base runoff and decreased once again in the sub-base runoff. Most likely, the Na^+ reacted with chlorides from the clear washed stone and was released in the base runoff in the form of sodium chloride. As for the sub-base runoff, the Na^+ concentration decreased again, probably due to being absorbed by the soil and not desorbing into the leachate. The AS surface runoff maintained almost the same concentration range in Na^+ as the LABR and WDSR rain (35 to 69 mg/L). This might have been due to the AS surface being washed many times, leaving no particulates for the water to come in contact with at the surface. In reality, however, the surface will never be free of particulates, due to pollution from the urban environment. Hence, the concentration of Na^+ is bound to increase as well. Chloride concentration (Cl^-) increased as leachate traveled through the porous pavements. This was likely because the Cl^- has a tendency to precipitate and diffuse in water, hence increasing its concentration in the runoff. EC3 had the lowest concentration in Cl^- , probably due to the following reason: when the water leached past the clear washed stone, most of the Cl^- in the water reacted with other cations that had adhered on the stone from previous leachates, or rather had already existed in the stone.

Sulfates

When the LABR rain made contact with the surfaces of all the pavements in the laboratory, the SO_4^{2-} decreased. This was likely due to the SO_4 ion reacting with the soil on the surfaces and the subsurface bedding material and adhering to

the sediments in the form of calcium sulfate or another salt. Hence, the SO_4 compound formed was not leached out with the runoff. In addition, the acidity of the rain had a major effect on the leaching rates and leaching concentrations. If the LABR rain contained a high concentration of H_2S and sulfuric acid (H_2SO_4), then more SO_4 ion is likely to leach out with the surface and subsurface runoff. Thus, the laboratory results in this study show that the SO_4 concentration is less than when the pH is more acidic. The AS surface runoff always had a pH close to 7 and an average concentration of SO_4 of 17 mg/L, whereas, the PC surface runoff had a pH of 8.9, and concentration of 30 mg/L. Furthermore, when the pH was less alkaline, as in the surface runoff of the EC3 and EC4 (8.7), the average concentrations of SO_4 were 36 mg/L and 37 mg/L respectively. Hence, as the pH increased, the SO_4 concentration decreased. The SO_4 concentration increased when the water reached the base material of EC3 and EC4. This may be due to the water reacting with pyrite (FeS_2) in the rock to form sulfuric acid, and thus increasing the concentration of SO_4 .

Metals

The only metals that showed a significant change in concentration from the LABR rainwater were: lead (Pb), zinc (Zn), iron (Fe), chromium (Cr) and nickel (Ni). The Fe increase was likely due to the added iron leached out from the soil. The Zn increase was probably leached from the pipes of the rainfall simulator, the submersible pump and the stirrer in the water tank. Generally, Pb and Zn concentrations are strongly enriched in parking lots as a result of vehicular traffic (Lorant, 1992), and under laboratory conditions, would be expected to have low concentrations. The results show that the AS pavement had the highest concentration in Zn. Metal precipitation with water is greatly affected by the pH. Since metals are cations, they have a strong tendency to react with acidic water. Hence, the more acidic the water, the more metal ions are likely to dissociate from the soil and produce metal precipitates in the leachate. This was the case in this study. The acidic LABR rainwater had been alkalized by the surface before it leached through the porous pavement. Hence, metals were less likely to be desorbed from the soil and given out as runoff. Due to the low concentrations, no distinct relationship can be made between metal concentration and the surface runoff, except that AS had the highest surface runoff concentration in Zn, Pb and Cu.

Bacteria counts

The types of bacteria that were investigated were fecal coliform and *Escherichia coli* (E.coli). Bacteria counts were very low for all the pavements - bacteria counts from the runoff generated in the parking lot were almost 100 times more than in the laboratory. Roadway surfaces can become periodically seeded with debris containing bacteria (Lorant, 1992). In the laboratory, there was no source for coliforms, and it was to be expected that the bacteria counts would be negligible.

Rain-pavement interaction

Figure 17.3 summarizes conceptually the rain-pavement interaction. Many factors affect the rate of change in pavement leachate under laboratory conditions, including:

- Soil type and structure - what the soil comprises, the chemicals it contains (such as iron, calcium carbonate, etc.), adsorption capacity.
- pH of the water and the soil. With most of the parameters, it seems that the higher the pH, the less likely the dissolution of cations and anions in the leachate, and hence the concentrations of many contaminants changed.
- Season. For instance, in the case of sodium and chloride, in the winter, the concentration of sodium chloride in surface runoff is likely to increase due to the contribution of de-icing salts. Furthermore, this will contribute to the addition of total solids and total suspended solids.
- Nature of the surface. If the surface is pervious, the water will penetrate through the joints, through the filling material which will slow down the process of surface runoff, as well as in most cases filter out (such as oil and grease) or add more contaminants from the leachate (such as sulfate).

Figure 17.3 Conceptual diagram of the rain-pavement interaction system.

- The duration of the rainfall. For processes such as nitrification, a longer duration of rain is required.

Mass balance

Figure 17.4 summarizes the procedure for calculating the mass balance. As shown in Table 17.3, the EC3 pavement reduced almost all the chemicals measured in this study. AS always had a higher load in the surface runoff. Physical phenomena that affected the mass balance include the absorption and desorption of the various leachates by the pavement. Chemical reactions that took place between the pavement and LABR rain are shown in Figure 17.4.

Figure 17.4 Conceptual diagram for mass balance of the laboratory pavement

17.7 Conclusions

- In Guelph rainwater is initially very acidic, having a pH of approximately 3.4. Almost 2 hours after collection, CO_2 is released into the atmosphere and the stored water reaches a pH of 5.5. After a further 72 hours (at least) it neutralizes to a pH of 7.
- For similar rainfall intensities and durations, impervious asphalt pavements produce large amounts of surface runoff, compared to porous pavements. For areas such as parking lots, normally paved with asphalt, porous pavement is evidently an effective way of reducing the quantity of stormwater runoff.

- The total void size in the porous pavement surfaces is one of the main factors that affects its permeability. Of the four pavements tested, Eco-stone® reduced surface runoff volume the most due to its large voids at the surface and subsurface layers.
- Where washed stone is used as the bedding material, water drains faster through the subgrade than it does for subgrades which are a mixture of sand and stone, or sand alone.
- Runoff collected from porous pavement in the laboratory showed very low concentrations of all water quality parameters, especially oils and grease, phenols, heavy metals and bacteria. Of the three pavements tested, Eco-stone® showed the lowest concentrations in these parameters.
- Percolation through the surface and underlying media of porous pavements slowed the water flow. The process allowed more time for oxidation; and more time to react with other chemicals, such as chlorides, nitrates and nitrites. Also, the pavement apparently filtered suspended solids and some contaminants, such as sodium and sulfates.
- Heavy metal removal through percolation appeared to be good, even though the concentrations were very low. The biggest reduction was observed with zinc and iron.
- Porous pavement surface runoff had pH values more alkaline than the asphalt surface. The asphalt pavement gave pH values that were almost neutral.
- Surface runoff from asphalt contained a higher mass of all the parameters investigated compared to the mass measured in the surface runoff from Eco-stone®.
- Surface runoff from the asphalt surface contained a concentration of phenols higher than the concentrations found in the porous pavement surface and subgrades.
- Leachate from the pavements contained contaminants mainly from rainwater in the atmosphere. Hence, the processes that take place at the surface of the pavements are mainly due to the processes of rainfall as it falls on the ground.
- Water is generally not contaminated by the surfaces of porous concrete pavements or their bedding materials, but rather from the external environment, as proven by the parking lot runoff analyses. Asphalt surfaces are made from the combustion of petroleum products, and hence some pollutants such as oils, grease and phenols, will originate from that surface.

- Porous pavement appears to have significant long term benefits compared to conventional asphalt pavements in terms of its ability to reduce the quantity of stormwater pollutants. Eco-stone® reduced the amount of stormwater pollutants more than did the other porous pavement.

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