# Chapter 10

# Observations of Infiltration Through Clogged Porous Concrete Block Pavers

**Christopher Kresin, William James and David Elrick**

James and Verspagen (1996), Thompson and James (1995), and Shahin (1994) have observed low runoff volumes from porous concrete paver laboratory test blocks used in their respective research. However, the laboratory test blocks were not subjected to wear or the deposition of pollutants over time on the surface and, therefore, perform under optimum conditions. The purpose of this research is to test the hypothesis that, for a particular permeable paver hereinafter called Uni-ecostone (see acknowledgements at end for trademarks), infiltration capacities decrease with age and certain land uses, and that infiltration capacities may be improved by simply street sweeping and/or vacuuming the surface. The research uses data collected at several Uni-ecostone porous concrete paver installations.

Permeable pavement helps reproduce the pre-development hydrologic regime at urbanized sites (Schueler, 1987). In achieving this, the key is to provide a surface infiltration capacity which allows an adequate volume of stormwater runoff to be captured by the facility. Such an infiltration capacity is dependent upon factors such as surface slope, and surface ponding. There is little difficulty in designing and constructing a system to provide appropriately high infiltration capacities; however, maintaining these infiltration capacities over several years has proven to be challenging.

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## 10.1 Introductory Background

Permeable pavements, meaning the complete pavement structure from the porous pavement surface to the underlying native soil, provide control of both stormwater quantity and stormwater quality. Stormwater runoff volumes may be reduced by as much as 80% (Schueler, 1987) and peak flow rates lowered. Quality parameters controlled include suspended solids, nutrients, BOD, turbidity, and temperature (Schueler, 1987; James and Verspagen, 1996); however, seasonal effectiveness is low due to higher springtime runoff volumes and constituent concentrations. Schueler (1987) and Pitt (1996) report that the potential for groundwater contamination as a result of stormwater infiltration is slight. Along with providing the advantages associated with stormwater infiltration, permeable pavement installations reduce land consumption and down-size stormwater conveyance systems.

Urbonas and Stahre (1994) describe the following three types of porous pavements: 1. porous asphalt pavement (PAP), 2. porous concrete pavement (PCP), and 3. modular interlocking concrete blocks (MICB) of the internal drainage cell type (MICBIC, e.g. Turfgrass). Not included with the above is the modular interlocking concrete block with external drainage cells (EDCs) (MICBEC, e.g. Uni-ecostone). PAP and PCP may be described as "no fines" asphalt and concrete pavement mixes; they are typically composed of aggregate that has been purged of finer particles; stormwater infiltrates the surface through the resulting voids in the mix (Maryland Department of Natural Resources, 1984; Northern Virginia Planning District Commission, 1992; Marshall Macklin Monaghan, 1994).

The primary disadvantage of a porous pavement is surface clogging. PAP and PCP have been observed (Urbonas and Stahre, 1994) to clog and seal within one to three years of construction. Concrete block paving, however, has overcome the difficulties of surface clogging (Field, 1984, cited in Bedient and Huber, 1992). PAP and PCP are at a further disadvantage in comparison to MICBEC pavements in that once they are sealed they must be replaced in their entirety whereas only the drainage cell material need be replaced in MICBEC installations.

## 10.2 Previous Research

Little investigation into long-term infiltration capacities provided by the Uni-ecostone has been carried out. Four relevant studies utilized rainfall simulators.

Borgwardt (1994) conducted experiments at two Uni-ecostone installations (2 years and 5 years in age), in much the same manner as this study, in an attempt to determine the infiltration capacities of the sites and investigate the effects of age on these capacities. Borgwardt's findings at a 5-year and a 2-year old site provided infiltration capacities of 1.2 and 2.4 mm/hr. Constant rates were observed to occur at rainfall durations between 10 and 30 minutes.

Muth (1988) conducted laboratory investigations using 2 m x 2 m Uni-ecostone plots under varying slopes and rainfall intensities. No surface runoff was observed for rainfall intensities up to 72 mm/hr at a 0% slope and for rainfall intensities up to 36 mm/hr at a 2.5% slope. After 20 minutes an infiltration capacity of 1.8 mm/hr was observed. Clark (1980) also found, in his investigation of standard porous (e.g. turfstone) pavers, that a change in slope from 1 to 2% has little effect on runoff volumes.

Phalen (1992) investigated permeabilities of different Uni-ecostone drainage cell material types. Phalen's results for sand alone (33.0 - 68.6 mm/hr) compare well with Muth's sand-covered test plot result (71.1 mm/hr); from this it may be concluded that the finer-grained sand controls infiltration capacity (Rollings and Rollings, 1993). Tests of increasingly coarse drainage cell material result in permeabilities ranging from 475.0 to 4368.8 mm/hr (Phalen, 1992).

Shackel (1995) conducted laboratory tests into the suitability of the Uni-ecostone for rainfall intensities higher than those common in Europe. Infiltration under different combinations of five bedding, jointing, and drainage cell materials, ranging from 2 mm sand to 10 mm gravel, was investigated. Results show that uniform and clean 2-5 mm gravel provides the highest infiltration capacities (216 mm/hr) and ensures joint-filling. The addition of fines or sands to the drainage material was also found to substantially reduce infiltration capacities.

## 10.3 Surface Crusting

The hydraulic conductivity of a soil is often more than that of the surface layer, due to crusting at the surface and its limiting affect on infiltration rates (Bosch and Onstad, 1988; Ferguson, 1994). Mohamoud et al. (1990A) also conclude that surface effects (e.g. residue cover and crusting) are more significant than soil hydraulic properties when considering infiltration capacities. Surface crusts are fine-textured in comparison to the texture of the underlying soil, thus creating larger matric forces. These matric forces may be large enough that flow into the relatively larger pores of the underlying soil is not permitted. Under conditions of large head excepted, the underlying layer does not become saturated due to the limiting effect of the surface crust (Ferguson, 1994).

Crusts are created when soil aggregates break down and enter the soil matrix with infiltrating water, or fine particles are deposited on the surface by runoff and subsequently compacted. Interaggregate macropores become filled as deposition continues; however, once a crust is established, further decline in infiltration capacity is not observed (Behnke, 1969; Norton et al., 1986). Typically, crusts are less than 2 mm thick, appear slick in comparison to the underlying soil (Ferguson, 1994) and consist of a compact skin (0.1 mm thick) and a region of compacted fines (Ahuja and Swartzendruber, 1992). Ferguson (1994) describes two types of soil crusts:

1. the formation of *structural crusts* is affected by soil clay content, mineralogy, organic matter content as well as the chemical constituents in the soil water, and
2. *depositional crusts* form through sediment deposition by surface water flow (Shainberg, 1992).

Of particular importance in the latter process is the deposition of clay particles. Soils are also subject to biological clogging (Allison, 1947); the presence of decomposable organic matter assists this process. Duley (1939), while investigating the effects of surface cover on infiltration capacity, observed an infiltration capacity of 3.05 cm/h decrease to one fifth of this value when the soil surface was exposed to compaction from falling raindrops. A 1 mm thick surface crust had formed which, when removed, returned the soil's infiltration capacity to 4.09 cm/h. In urban settings crust formation is affected by increased mechanical wear and the deposition of rubber, brake dust, and petroleum products due to automobile traffic. To summarize, according to the literature reviewed here, crust formation is influenced by:

- soil composition (e.g. clay content);
- antecedent moisture conditions;
- structural state of the soil;
- rainfall characteristics;
- surface slope;
- surface roughness;
- soil wetting and drying cycles; and
- soil freeze-thaw cycle.

## 10.4 Spatial Variability and Scale Effects

Spatial variability is inherent in many hydrologic processes; simply stated, a spatially variable parameter is one which differs from point to point. An understanding of spatial variability and scale effects is imperative when investigating hydrologic processes. Thus, it is important to recognize that representing a spatially variable parameter with a value obtained from a point reading or measurement is likely to be incorrect. Several factors jointly affect infiltration capacity making it a highly variable parameter spatially (Smith, 1982). Such parameters must be represented as spatially averaged means (SPAMs). Examples of SPAM parameters used in hydrologic calculations are hydraulic conductivity (K) and rainfall intensity (i). Representing variables as SPAMs should be done carefully. Spatial variations which affect SPAMs at MICBEC installations include compaction (e.g. wheel ruts), vegetative growth, and heavier sediment deposition in low lying areas.

Scale effects are grouped into three sources by Song and James (1992): *Variabilities* include weather, topography, and geology; *discontinuities* amplify the variabilities at boundaries such as those separating soil types; and *processes* (e.g. infiltration) further amplify variabilities. The above sources of scale effects lead to a correlation between scale and heterogeneity; greater heterogeneity requires smaller optimal scales. Scale may be defined as either *laboratory*, *hillslope*, *catchment*, *basin*, or *continental/global* (Song and James, 1992). When considering infiltration capacities at the test plot scale, the scale must be such that effects of the characteristics of individual plots at each MICBEC installation are not directly reflected in the result; thus, test plots must be randomly assigned. Usual scale effects at the test plot scale relate to processes occurring at the plot boundary and inhomogeneities in the upper soil mantle. Boundary processes include leakage from the test plot and the lateral flow component of infiltration which results during flow from a ponded source. Inhomogeneities typically result from sediment deposition, vegetation, desiccation cracks, as well as structural and thermal deformations.

## 10.5 Experimental Methodology

Infiltration capacity was measured at a number of plots at installations of different ages. A portable rainfall simulator (shown in Plates 10.1 and 10.2) was used to apply two constant rate rainfalls to 0.7 $m^2$ test plots (similar to Borgwardt, 1994); 2 cm of head was allowed to pond during both events. Following the second event, observations of decline in head over time were recorded. Applying two rainfalls accounts for initial losses to soil wetting, saturating the drainage cell material. These tests are point measurements; thus, they are highly spatially variable. In an attempt to provide for spatial variabilities and their effect on infiltration capacities, test plots at two plot types were targeted. Travelled (compacted) and untravelled (not compacted) plots were differentiated from each other by qualitatively evaluating the test installations. In order to investigate the potential for regenerating infiltration capacity, the top five mm of EDC material was removed from each EDC within several test plots and the tests repeated. A total of 60 tests were completed at four sites, results from two of the test sites are presented in this chapter.

At Site 1 (Parking lot P10, University of Guelph) adjacent land use consists of asphalt parking areas as well as a small grassed area from which red pine trees overhang the test sites depositing their needles on the MICBEC surface. Site 2 is the Belfountain conservation area parking lot in Belfountain, Ontario. This

**Plate 10.1** Portable rainfall simulator, horizontal surface.

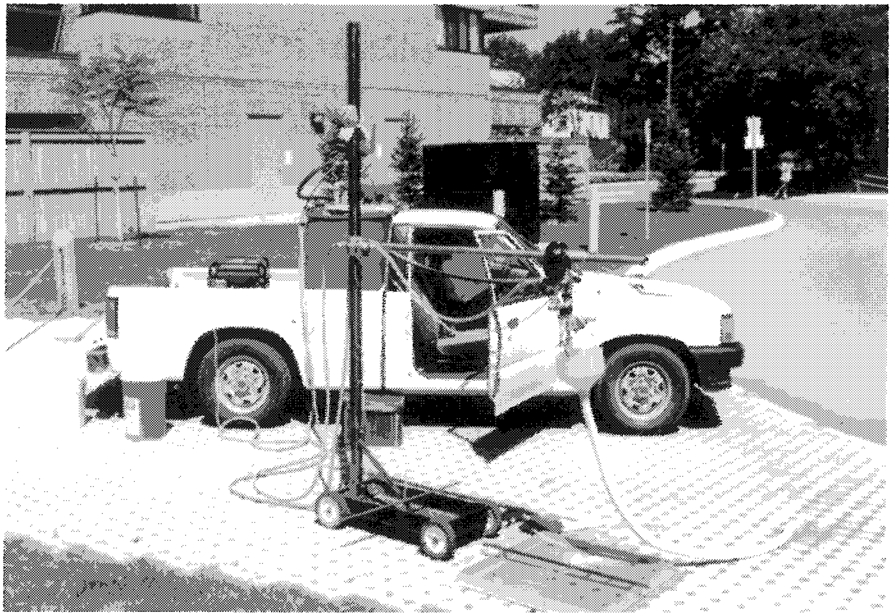

**Plate 10.2** Portable rainfall simulator, sloping surface.

parking lot is not utilized in the winter and is therefore not subjected to a rigorous winter maintenance program or winter deposition from automobiles. Adjacent land use at this site consists of green space, which includes grass and tree areas, mulch-covered planting beds, and a gravel parking area up-slope from the MICBEC installation. Site 1 was in service for three years and Site 2 for one year.

Infiltration into a porous pavement constructed of Uni-ecostone is limited by the infiltration capacity of the finest layer of material. "*If all sediments are uniform or the deeper sediments are more permeable than those near the surface, and the water table is at considerable depth, the infiltration rate is controlled by the sediments near the surface.*" (Hannon, 1980). Inevitably, EDCs will clog. This is due mainly to surface deposition and the fact that most filtering occurs in the top 50 mm of soil (Ferguson and Debo, 1990). With no maintenance practice in place, a cap which may become impervious, will eventually form. In these cases, it is most likely that the infiltration capacity of the installation will be governed by the infiltration capacity of the EDC cap.

EDCs are delineated by the MICBEC pavers which form them. The MICBEC pavers themselves are impervious; thus, water which infiltrates the EDCs flows vertically through the pavement layer. Therefore, the lateral flow component is considered to be negligible and flow through the EDCs is considered to occur vertically downward. Percolation may be slowed at textural interfaces such as that between the EDC and subgrade materials. However, under saturated and ponded conditions, these effects are accounted for. Once water has percolated through the EDC material and enters the subgrade material it is no longer restricted to vertical flow only, a lateral flow component is introduced. Since the infiltration capacity in this case is limited by material where the flow is vertical, the lateral flow component need not be considered. In order to ensure that the effects of the subgrade are not a factor, the test plot must be either vertically isolated to a depth into the subgrade material or the pavers removed with the drainage cell material kept in-place. Isolating the plot to a depth into the subgrade is not practical as a large area must be excavated and removing a test plot of pavers is inherently risky as the drainage cell material may be disturbed.

Using the data obtained during the field investigations (head versus time) Darcy's infiltration theory was applied to determine infiltration capacities. In order to apply Darcy's theory the following assumptions are made:

- excess rainfall is assumed to act as a storage volume, having uniform depth, over the test plot (Mohamoud et al., 1990);
- matric forces within the drainage cell material are negligible. Prill and Aronson (1978) observed that the moisture content below infiltration basins stabilizes after small ponding periods and Day (1978) employed saturated test plots to ensure baseline soil moisture contents;
- since soil matric forces are negligible, the total hydraulic gradient results from the hydraulic head caused by water ponded on the surface;

- the drainage cell material is assumed to have a homogeneous, stable profile which allows for steady, gravity-induced vertical infiltration approaching a rate equal to Ks. Mein and Larson (1973) and White et al. (1982) assumed similar one dimensional infiltration in the development of their models; and
- flow in the subgrade has a negligible affect on infiltration through the EDCs.

A key factor in this investigation is that the simulated rainfall be applied at a rate greater than the initial infiltration capacity of the test plot, thus ensuring an excess water supply at the surface. Also, since infiltration capacity of the surface crust is assumed to be limiting, the model interprets the crust thickness as the depth of the EDC material. Temperature effects are assumed to be negligible over the ranges encountered throughout the test periods.

Darcy (1856) showed that the specific discharge (flow rate over the cross sectional area of soil through which the flow is occurring) of water through a porous soil media is directly proportional to the difference in hydraulic head over a defined length of soil sample. Darcy also observed that, for different soil types, the specific flow rate differed. This required the introduction of a proportionality constant which essentially provides for matric forces affecting infiltration. Hydraulic conductivity (K) is that constant. Darcy's law is manipulated to reflect falling head infiltration:

$$Ks = [\ln(\frac{(L + Ho)}{(L + H)}) \times \frac{L}{(t - to)}] \tag{10.1}$$

where:

$L$ = crust thickness (length)
$H$ = head at time of concern (length)
$Ho$ = head at previous time (length)
$(t\text{-}to)$ = length of time step (time)
$Ks$ = saturated hydraulic conductivity (length per time)

Ensuring 100% saturation in field studies is difficult as, inevitably, air is trapped within the soil matrix and air flows in an upward direction against the infiltrating water. Thus, Ks is termed the field-saturated hydraulic conductivity (Elrick, 1996), or effective infiltration capacity (*f*e).

## 10.6 Results and Discussion

Values of *f*e determined for the recession period of each individual test plot should, in theory, be equivalent; assumptions of soil homogeneity and saturated flow imply this. Therefore, mean *f*e values for the recession period are determined for each test plot (these values better represent the effective infiltration capacity of a site during a rainfall event) in order to subsequently determine the overall *f*e values (*f*E) for each plot type. Once *f*E values for each plot type have been determined they are used to produce a value approximating the overall *f*E (*f*Eo) for each site. To do so, the percent travelled and percent untravelled areas at each site must be evaluated so that a weighted average of *f*E-travelled (*f*t) and *f*E-untravelled (*f*u) may be produced. At Site 1, 25 from a total of 81 1 m square grid squares were evaluated during site characterization. Of these grids, thirteen were defined as travelled and twelve as untravelled. Using this information, Site 1 is characterized as 52% travelled and 48% untravelled, similarly Site 2 is characterized as 51% travelled and 49% untravelled. Using the above, *f*Eo for Site 1 is 5.8 mm/h and that for Site 2 is 14.9 mm/h.

Evaluation of EDC material is done so as to provide a comparison of EDC hydraulic conductivities as well as to determine the EDC material installed during construction. This is achieved based on grain-size distribution plots of the EDC material extracted from randomly assigned plots. Bowles (1992) details the methodology used to produce grain-size distribution plots with reference to the American Society for Testing and Materials (ASTM) and the American Association of State Highway and Transportation Officials (AASHTO) standard methods (ASTM D421 and D422 and AASHTO T87 and T88). Prior to grain-size analysis, organic matter (OM) in the EDC material was burned off using a muffle furnace.

Attempts at regenerating infiltration capacities were made by removing the top 5 mm of EDC material (literature suggests that most clogging occurs in the top thin layer of soil), termed the EDC crust, from each EDC within several test plots. The computational methods previously described here also applied to the test data from the regenerated plots. Table 10.1 provides a summary of relevant values for both sites.

**Table 10.1** Summary of test results.

| Site # | *f*Eo | EDC % passing #200 | EDC % OM | Regenerated *f*Eo | Crust % Passing #200 | Crust % OM |
|---|---|---|---|---|---|---|
| 1 | 5.8 | 6.6 | 0.19 | 7.7 | 15.9 | 0.58 |
| 2 | 14.9 | 1.9 | 0.39 | 40.0 | 5.5 | 0.62 |

Only Borgwardt (1994) has focused on the effects of aging on *f*Eo at Uni-ecostone installations. Borgwardt's findings are in Table 10.2. Both sites targeted by Borgwardt were parking lots,

Comparing these sets of results, it is evident that *f*Eo is more a function of the fines content of the EDC material than of the age of the site. Borgwardt (1994) attributes the lower *f*Eo of the 2 year old site to the higher percent passing the

**Table 10.2** Summary of Borgwardt's (1994) findings.

| Site Age (yr) | EDC Organic Matter (%) | % Passing #200 Sieve (%) | /Eo (mm/h) |
|---|---|---|---|
| 2 | 0.9 | 7.0 | 1.2 |
| 5 | 0.5 | 3.5 | 2.4 |

number 200 sieve. Thus, sources of fine materials (e.g. adjacent land uses and winter maintenance practices) are important factors in the decay of /Eo. Also of importance is the grinding and crushing action of traffic as this increases fine materials at the surface and the potential for clogging. From Table 10.1 it may also be assumed that, since both the OM content and the percent passing the number 200 sieve for Site 1 are less than those values for Site 2, compaction of the EDC material (increased compaction with increasing age) also affects /Eo.

A two-way analysis of variance (ANOVA) of the data from this study may be used to strengthen this assumption. As Table 10.3 indicates, /Eo at sites of different ages and different degrees of compaction (travelled and untravelled) differ significantly (6.69 and 6.54 > 4.75). Since the interaction between age and compaction is not significant (2.22 < 4.75), the decrease in /Eo is completely explained by the main effects (age and compaction).

**Table 10.3** ANOVA table for /Eo's at sites 1 and 2.

| Source of Variation | Sum of Squares | Degrees of Freedom | Mean Square | Fo | Fcrit* |
|---|---|---|---|---|---|
| Age | 543.39 | 1 | 543.39 | 6.69 | 4.75 |
| Compaction | 531.19 | 1 | 531.19 | 6.54 | 4.75 |
| Interaction | 180.52 | 1 | 180.52 | 2.22 | 4.75 |
| Error | 974.39 | 12 | 81.20 | | |

* Fcrit taken at the 0.05 level (95%)

Results presented by both Muth (1988) and Phalen (1992) may be used to compare /Eo's based on the grain-size distribution of the EDC material. Grain-size distribution plots show similar trends, seemingly coinciding with Muth's and Phalen's results where coarser materials are concerned but containing more fines. Thus, values for /Eo are lower than those found by the previous researchers. This is also consistent with Shackel (1995) who concluded that the addition of fines or sands to the EDC material reduces *f*Eo. Grain-size analysis in this study suggests that EDC materials used in construction were not to manufacturer specifications.

Knowing where fines collect in the permeable pavement is important. If fines settle in any location other than the top layer of the EDC material (the crust), any degradation in *f*Eo is permanent as efforts to remove fines in other locations is not likely due to expense. Grain-size analyses of the crust material removed from Sites 1B and 2 reveal that this material has both a higher OM and fines content than the EDC material. Plotting these results (Figure 10.1) with those found by Muth (M) (1988) and Phalen (P) (1992), an excellent agreement between P: 33.02 mm/h and Site 2 whereas the higher fines content of Site 1B's crust material obviously affects *f*Eo.

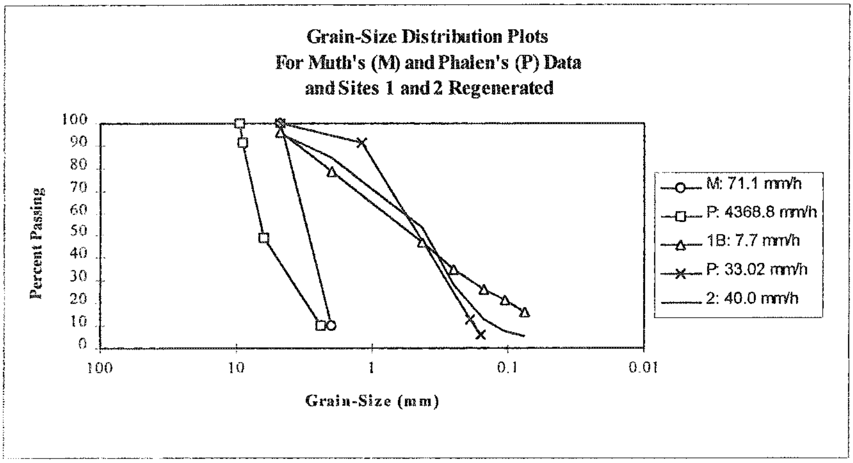

**Figure 10.1** Grain-size distribution for various sites.

Similarly, a two-way ANOVA was carried out using the data from the test plots with EDC crusts removed. Table 10.4 identifies site age to be significant (15.10 > 4.46) in affecting *f*Eo of EDC crusts whereas plot type and interaction are insignificant (0.38 < 4.46, 1.29 < 3.84). It is not surprising that age is significant as sediment deposition increases with installation age especially when sites (e.g. Site 1) are subjected to winter deposition.

Several researchers conclude that degraded infiltration capacities at PAP/PCP (Schueler, 1987) and MICBEC (Muth, 1988) installations may be regenerated through periodic sweeping and vacuuming of the surface. Schueler (1987) notes that regeneration is not possible if the PAP/PCP surface is clogged with large sediments as sweeping and vacuuming is unable to pull these particles from the pores. Results from this study support reports by Uni-group USA (1993) that sediment accumulation reduces the infiltration capacity provided by Uni-ecostone

**Table 10.4** ANOVA table for test plots with EDC crusts removed.

| Source of Variation | Sum of Squares | Degrees of Freedom | Mean Square | Fo | Fcrit* |
|---|---|---|---|---|---|
| Age | 3088.02 | 1 | 3088.02 | 15.10 | 4.46 |
| Compaction | 77.52 | 1 | 77.52 | 0.38 | 4.46 |
| Interaction | 264.14 | 1 | 264.14 | 1.29 | 3.84 |
| Error | 1636.89 | 8 | 204.61 | | |

* Fcrit taken at the 0.05 level (95%)

installation (see Table 10.1). Uni-group recommends that the surface be swept and vacuumed on a 4 year cycle; this maintenance procedure has met with success in Germany. Results presented herein show that *f*Eo is able to be regenerated. However, at Site 1 it is evident that the EDC's are clogged to a point where only a fraction of the original *f*Eo could be regenerated, raising questions as to an appropriate maintenance frequency. It should be noted that this site was not constructed according to current (1996) drainage cell material specifications.

## 10.7 Conclusions

The nationwide urban runoff program (NURP), in the United States, identified the extent of impervious surfaces directly connected to the drainage system as the most important factor affecting runoff volumes after volume of rain (Pitt, 1996). In urban settings runoff volumes are ten-fold those in predevelopment areas (Madison et al., 1979), directly reflecting the NURP findings. Thus, in order to reduce stormwater runoff volumes in urban areas, impervious area must be reduced. The application of permeable pavement is one method. Results from this study show that a significant relationship exists between overall effective infiltration capacity (*f*Eo) and age; as Uni-ecostone installations age, *f*Eo decreases. Also significant is the relationship between *f*Eo and the degree of compaction (defined as travelled or untravelled). *f*Eo can be improved by removal of the top layer of external drainage cell (EDC) material, the EDC crust. Conclusions drawn from the results include:

1. Very little surface water runs off newly laid Uni-ecostone permeable paving. Infiltration capacity of Uni-ecostone modular interlocking concrete blocks with external cells (MICBEC) decreases as the installation ages.
2. Infiltration capacity at Uni-ecostone installations decreases with increased compaction.

3. Infiltration capacity of the EDC crusts, found to be significantly affected by age, limits *f*Eo.
4. *f*Eo may be regenerated, most probably to some fraction of the initial *f*Eo, by street sweeping/vacuuming the Uni-ecostone surface.
5. *f*Eo is affected to a greater extent by EDC fines content than OM content.

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Uni-ecostone is correctly written UNI ECO-STONE®, a registered trademark of F. Von Langsdorff Licensing Ltd. Canada.

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