This paper is a summary of the Eco-Stone research and studies that have been done to date and includes a general design overview and other information that may be helpful to the designer. For a copy of any of these reports, theses, or articles call UNI-GROUP U.S.A. at 1-800-872-1864 or contact us via e-mail at info@uni-groupusa.org.

The information included in this report is intended to provide guidance and recommendations for the design and construction of UNI Eco-Stone® interlocking concrete permeable pavements. Recommendations are guidelines only and will vary with local regulations, specifications, environmental conditions, materials, and established construction methods for an area. It is not intended to replace the judgement or expertise of professional engineers or landscape architects, who should be consulted in the design and construction of permeable pavements.

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INTRODUCTION

As open land is developed and covered with impervious surfaces such as asphalt roadways, concrete parking decks, and buildings, there is an increase in stormwater runoff that may result in downstream flooding, streambank erosion, and excessive strain on existing drainage facilities. Numerous studies indicate that stormwater runoff is also the primary source of pollutants found in surface waters and often contains a toxic combination of oils, pesticides, metals, nutrients, and sediments. Approximately 40% of America’s surveyed waterways are still too polluted for fishing or swimming and 90% of our population lives within 10 miles of these bodies of water.

With the implementation of the United States Environmental Protection Agency’s National Pollutant Discharge Elimination System (NPDES) stormwater regulations in the early 1990s, state agencies, municipalities, and regional authorities began searching for new options in stormwater management. Effective management of stormwater runoff offers a number of benefits, including improved quality of surface waters, protection of wetland and aquatic ecosystems, conservation of water resources, and flood mitigation. Traditional flood control measures that rely on detention of peak flow are typical of many stormwater management approaches, but generally do not target pollutant reduction, and often cause unwanted changes in hydrology and hydraulics. The EPA recommends an approach that integrates control of stormwater flows and the protection of natural systems to sustain aquatic habitats.

Effective stormwater management is often achieved through a comprehensive management systems approach instead of individual practices. Some individual practices may not be effective alone, but may be highly effective when used in combination with other systems. The EPA’s Phase II rule encourages system building to allow for the use of appropriate situation-specific practices that will achieve the minimum measures. Ordinances or other regulations are used to address post-construction runoff from new development or redevelopment projects. In addition, it is important to ensure adequate long-term operation and maintenance of BMPs. Governing authorities must develop and implement strategies that include a combination of structural and/or non-structural best management practices (BMPs) appropriate for their communities. Non-structural BMPs are preventative actions that involve management and source controls. Structural BMPs include storage practices, filtration practices, and infiltration practices that capture runoff and rely on infiltration through a porous medium for pollutant reduction.

Permeable pavements are considered structural BMPs under infiltration practices. From an engineering viewpoint, permeable pavements are infiltration trenches with paving over them to support pedestrian and vehicular traffic. Much of the design and construction is derived from experience with infiltration trench design, which has been used for years as a way to reduce stormwater runoff and recharge groundwater. Permeable pavements should be designed by civil engineers, architects, or landscape architects familiar with stormwater management concepts, especially the Soil Conservation Service (SCS) method, (now know as the National Resources Conservation Service or NRCS method). For years, porous pavements consisted of cast-in-place asphalt or concrete comprised of coarse aggregate, which had earned a poor reputation due to their tendency for clogging, and there was no way to renew porosity. Today, permeable interlocking permeable pavements offer a better solution.

UNI Eco-Stone® is a permeable interlocking concrete pavement system designed to mitigate stormwater runoff through infiltration, thereby reducing volume flows, improving water quality, and recharging groundwater. UNI Eco-Stone® is a true interlocking paver that offers the structural support and stability of traditional concrete pavers, combined with the environmental benefit of stormwater management. Eco-Stone® has a minimum compressive strength of 8000 psi, maximum 5% absorption, and meets or exceeds ASTM C-936 and freeze-thaw testing per section 8 of ASTM C-67. ECOLOC® features the same infiltration benefits as Eco-Stone®, but offers increased structural strength and stability for industrial pavement applications.
LOW IMPACT DEVELOPMENT AND ENVIRONMENTAL DESIGN

In addition to the EPA, other agencies and organizations are addressing the issue of development and the impact of stormwater runoff on the environment and society. According to the National Resources Defense Council, Low Impact Development (LID) has emerged as an attractive approach to controlling stormwater pollution and protecting watersheds. LID attempts to replicate pre-development hydrology to reduce the impacts of development. By addressing runoff close to the source, LID can enhance the environment and protect the public, while saving developers and local municipalities money. One of the primary goals of LID design is to reduce runoff volume by infiltrating rainwater into groundwater and finding beneficial uses for water as opposed to pouring it down storm sewers. Some of LID runoff control objectives include reducing impervious cover, preserving and recreating natural landscape features, and facilitating infiltration opportunities. LID principles are based on the premise that stormwater management should not be seen as stormwater disposal, but instead that numerous opportunities exist within a developed landscape to control stormwater close to the source. This allows development to occur with low environmental impact. LID is much more than the management of stormwater - it is about innovation in the planning, designing, implementing, and maintaining of projects. Permeable pavers, such as Eco-Stone®, are listed as one of the ten common LID practices.

Increasing numbers of municipal green building programs are offering incentives for sustainable landscape architecture and development. Programs that require LEED (Leadership in Energy and Environmental Design, a national green building assessment system developed by the U.S. Green Building Council) certification to achieve benefits, come the closest to a comprehensive approach for sustainable projects. While private sector participation is voluntary, many municipalities are requiring that city-owned or funded projects achieve LEED objectives. Many municipalities nationwide already have local programs in place and are forming departments dedicated to sustainable building. LEED is a self-assessing, voluntary building system for rating new and existing commercial, institutional, and high-rise residential buildings. It evaluates environmental performance from a “whole building” perspective over a building’s life cycle, providing a definitive standard for what constitutes a “green building”. It is a feature-oriented system where credits are earned for satisfying each criteria. UNI Eco-Stone® permeable pavers may qualify under a number of sections:

- **Credit 5** (1 to 2 points) - Local Regional Materials specifies a minimum of 20% building materials that are manufactured regionally within a radius of 500 miles. An additional point can be earned if 50% of the regionally manufactured materials are extracted, harvested, or recovered within this radius. Most pavers will meet these standards.

- **Credit 6** - Stormwater Management - The intent of Credit 6 is to limit the disruption of natural water flows by minimizing stormwater runoff, increasing on-site infiltration, and reducing contaminants and pervious pavements are recommended. Credit 6.1 provides 1 point for building sites where the existing impervious area is greater than 50%. The LEED requirement is that runoff rate and quantity be reduced by at least 25%. Eco-Stone permeable pavements can reduce runoff to zero under many design storms. Credit 6.2 provides 1 point for treatment systems designed to remove 80% of the average annual post development total suspended solids (TSS), and 40% of the average annual post development total phosphorous (TP). Permeable pavements have been shown to reduce these pollutants in even greater percentages, with reductions as high as 95% of TSS and 70% of TP.

- **Credit 7** - Landscape and Exterior Design to Reduce Heat Islands. Credit 7.1’s (1 point) intent is to reduce heat islands (thermal gradient differences between developed and undeveloped areas) to minimize impact on microclimate and human and wildlife habitat - light-colored, high-albedo materials (a reflectance of at least 0.3 for 30% of the sites non-roof impervious surfaces) and open grid paving are recommended. Since concrete pavers can be manufactured in a wide range of colors, they can be made to register an albedo of at least 0.3. Higher values can be achieved by using white cement or light-colored aggregates (where available).

Many local municipalities, regional authorities, and state agencies such as Departments of Environmental Protection are now recommending or requiring best management practices for the mitigation of stormwater and are providing information to residents and the business community about BMP practices and stormwater solutions. The City of Toronto, for example, promotes stormwater pollution education to residents and industry through advertising and their website. Among other suggestions, they recommend replacing impermeable surfaces with materials that allow for infiltration. The city has approved Eco-Stone® for parking pads in residential applications.

Please visit our website at www.uni-groupusa.org for more information and references of interest.
UNI ECO-STONE® PERMEABLE INTERLOCKING CONCRETE PAVEMENTS

FEATURES AND BENEFITS OF THE UNI ECO-STONE® PAVEMENT SYSTEM

• The unique, patented design features funnel-like openings in the pavement surface, which facilitate the infiltration of rainwater to reduce or eliminate stormwater runoff and maximize groundwater recharge and/or storage
• Mitigates pollution impact on surrounding surface waters and may lessen or eliminate downstream flooding and stream bed and bank erosion
• Improves water quality by infiltrating water through the base and soil, and also reduces runoff temperatures
• Decreases project costs by reducing or eliminating drainage and retention systems required by impervious pavements and reduces the cost of compliance with many stormwater regulatory requirements
• Permits better land-use planning, allowing more efficient use of available land for greater economic value
• Provides a highly durable, yet permeable pavement capable of supporting vehicular loads

Permeable interlocking concrete pavements do require greater initial site evaluation and design effort. They require a greater level of construction skill, inspection during construction and after installation, and attention to detail. In addition, maintenance is a critical aspect to help ensure long-term performance. It is recommended that a qualified professional engineer with experience in hydrology and hydraulics be consulted for permeable interlocking concrete pavement applications. This guide is intended as an overview of construction guidelines and research conducted to date. Please see the research and reference sections for detailed guidance and additional information.

Eco-Stone® provides an attractive pavement surface that can be used for residential, commercial, and municipal pedestrian and vehicular pavement applications. It can be used for parking lots, driveways, overflow parking and emergency lanes, boat ramps, revetments, bike paths, sidewalks and other pedestrian areas, low-speed roadways, storage and loading facilities, and depots (see page 9 for exclusions and site selection guidelines).

MUNICIPAL REGULATIONS, INFILTRATION PRACTICES, AND OBJECTIVES

Municipal policy, design criteria, and local experience usually govern the use of infiltration systems such as permeable pavements. Design criteria and regulations vary nationwide, as rainfall amounts, geography, climate, and land-use development patterns can vary widely. Most BMPs are designed for a specific design storm, for example a 2-year, 24-hour storm of 1.5 in./hr (33 mm/hr) or volume from the first 1/2 to 1 in. (13 to 25 mm). Though initial infiltration rates can be quite high with UNI Eco-Stone® permeable pavements, a few studies have shown that long-term infiltration rates for permeable interlocking pavements in general range between 1.0 and 2.5 in./hr (25 and 65 mm/hr). Though higher rates may be possible with optimal construction and regular maintenance, designers may wish to use this conservative range as a guideline. This range would be able to infiltrate frequent, short duration rainstorms, of which 70-80% of North America storms are comprised.

Some municipalities regulate both water quality and quantity. They may require a criteria for reducing specific types of pollutants, such as phosphorous, metals, nitrogen, nitrates, and sediment, and water quality regulations are often written to protect lakes, streams, and rivers from problems associated with runoff. An increasing number of municipalities are limiting the use of impervious surfaces and many have created stormwater utilities to help cover the increasing costs of constructing, managing and maintaining stormwater drainage systems.

Selection of base, bedding, and joint/drainage opening fill materials will be guided by local stormwater management objectives. Generally, for runoff control, regulations try to meet one or more of four management objectives.
Capture and infiltrate the entire stormwater volume so there is zero discharge from the drainage area. Costs for infiltrating or capturing all the runoff through the use of permeable pavements may be offset by reducing or eliminating pipes and other drainage appurtenances.

Infiltrate the increased runoff generated by development and impervious surfaces. The goal is to attain runoff volumes equal to or near those prior to development. Volumes are estimated prior to and after development, and the difference is to be infiltrated or stored, and then slowly released. Permeable pavements, vegetated swales, or rain gardens, among other BMPs, can accomplish this.

Infiltrate a fixed volume of runoff from every storm. This fixed amount of infiltrated water often is indicative of a large percentage of the region's storms. The volume is usually expressed as depth in inches (or mm) of runoff over the catchment area. Permeable interlocking concrete pavements are usually capable of infiltrating the first inch (25 mm) or more of runoff, which helps reduce the “first flush” of pollutants in this initial runoff volume. Grass swales and sand filters provide additional filtering and removal of some pollutants in rainwater, and designers may want to consider using them in conjunction with permeable pavements for added benefits.

Infiltrate sufficient water to control the peak rate of discharge. Many municipalities establish a maximum rate of peak discharge (in cubic feet/second or liters/second) for specific storm sewers or bodies of water. This approach favors detention ponds rather than infiltration as a means to control downstream flooding. Permeable interlocking concrete pavements can be used as a means of detention, especially in densely-developed areas where ponds are not feasible, by combining the benefits of a parking area with sub-surface detention.

Depending upon the amount of exfiltration (the downward movement of water through the crushed stone base into the subgrade soil), UNI Eco-Stone® can meet most of these stormwater management objectives.

GENERAL CONSTRUCTION GUIDELINES

UNI-GROUP U.S.A. provides design professionals with a variety of tools for designing Eco-Stone® permeable interlocking concrete pavements. Please refer to the research section of this guide for information on designing the Eco-Stone® pavement system. In addition, we offer Lockpave® Pro structural design software and PC-SWMM™ Permeable Pavement software for the hydraulic design of Eco-Stone® permeable pavements. The computational engine is the Runoff module of the USEPA’s Stormwater Management Model. It allows the user to develop a simple model of a permeable pavement design, run the model with a specified design storm, and analyze the results. A successful design is assumed in the program to be one in which the entire volume of runoff is captured by the pavement (i.e. no surface runoff occurs). Though this model is based on this zero runoff scenario, design parameters can be adjusted to meet other stormwater management objectives. PC-SWMM™ for Permeable Pavements software is a tool to aid design professionals and provides general guidance. It is intended for use by professional civil engineers and is not a substitute for engineering skill and judgement and in no way is intended to replace the services of experienced, qualified engineers.

DESIGN OPTIONS - FULL, PARTIAL OR NO EXFILTRATION

Permeable interlocking concrete pavements are typically built over an open-graded or rapid-draining crushed stone base, though a variety of aggregate materials, including free-draining and dense-graded, may be used depending on design parameters. In all cases, fines passing the No. 200 sieve should be less than 3%. In addition to runoff reduction, permeable pavements may be designed to filter pollutants, treat the “first flush”, lower runoff temperature, and remove total suspended solids (TSS). Because it provides for infiltration and partial treatment of stormwater, it is considered a structural BMP (Best Management Practice). The most optimal installation is infiltration through the base with complete exfiltration into a permeable subgrade. However, the design of the pavement can be very flexible. Perforated drainage pipes can provide drainage in heavy, overflow conditions or provide secondary drainage if the base loses some of its capacity over time. For installations where slow-draining subgrade soils are present and only partial exfiltration will occur, perforated pipes can drain excess runoff. Often, these pipes are sized smaller than typical drainage pipes in traditional pavement applications. If no exfiltration will occur due to site limitations, all the stored water would need to be directed to drains, though the flow rates would be reduced by the infiltration through the system.
In addition, if high levels of pollutants are present, the pavement can be designed to filter and partially treat the stormwater. In some cases an impervious liner may need to be placed between the base and the subgrade. According to the EPA, there are four cases where permeable interlocking concrete pavements should not exfiltrate and where an impervious liner might be used.

- When the depth from the bottom of the base to the high level of the water table is less than 2 ft (0.6 m), or when there is not sufficient depth of the soil to offer adequate filtering and treatment of pollutants.
- Directly over solid rock, or over solid rock with no loose rock layer above it.
- Over aquifers where there isn’t sufficient depth of soil to filter the pollutants before entering the groundwater. These can include karst, fissured, or cleft aquifers.
- Over fill soils, natural or fill, whose behavior may cause unacceptable performance when exposed to infiltrating water. This might include expansive soils such as loess, poorly compacted soils, gypsiferous soils, etc.

Even if these situations are not present, some soils may have a low permeability. As a result, water is usually stored in the base to slowly infiltrate into the soils. In some cases, there may be a more permeable soil layer below a low or non-permeable layer, where it may be cost effective to drain the water with a french drain or pipes through this layer into the soil with greater permeability.

SITE SELECTION GUIDELINES

Eco-Stone® permeable interlocking concrete pavers can be used for a wide variety of residential, commercial, municipal and industrial (ECOLOC®) applications. In addition to some of the guidelines previously described, permeable pavements should be at least 100 ft (30 m) from water supply wells, wetlands, and streams, though local regulations may supercede this requirement.

There are however, certain circumstances when permeable pavements should not be used. Any site classified as a stormwater hotspot (anywhere there is risk that stormwater could infiltrate and contaminate groundwater) is not a candidate for permeable pavements. This might include salvage and recycling yards; fueling, maintenance, and cleaning stations; industrial facilities that store or generate hazardous materials; storage areas with contents that could damage groundwater and soil; and land uses that drain pesticides and/or fertilizers into permeable pavements. In addition, permeable pavements may not be feasible when the land surrounding and draining into the pavement exceeds a 20% slope, or the pavement is downslope from buildings where the foundations have piped drainage at the footers.

INfiltration RATE DESIGN AND CONSIDERATIONS

One of the most common misconceptions in designing permeable pavements is the assumption that the amount or percentage of open surface area is equal to the percentage of perviousness. For example, a designer might incorrectly assume that a 20% open area is only 20% pervious. The permeability and amount of infiltration are dependent on the infiltration rates of the joint and drainage opening material, bedding layer, and base materials. Compared to soils, Eco-Stone® permeable interlocking concrete pavements have a very high degree of infiltration. The crushed aggregate used for the joints, drainage openings, and bedding has an initial infiltration rate of over 500 in./hr (over 10^{-3} m/sec), much greater than native soils. Rapid-draining and open-graded base materials offer even higher infiltration rates of 500 to over 2000 in./hr (over 10^{-3} to 10^{-2} m/sec).

Though the initial infiltration rates for these aggregate materials are very high, it is important to consider the lifetime design infiltration of the entire pavement cross-section, including the soil subgrade. As this may be difficult to predict, designers may want to use a conservative approach when calculating the design infiltration rate. Limited research has shown that permeability decreases with the age of the pavement, rainfall intensities, and the conditions under which it is used and maintained. This holds true for infiltration trenches as well. Therefore, engineers should account for these factors when designing infiltration rates for permeable interlocking concrete pavements and should encourage the establishment of a maintenance program to ensure long-term performance.
CONSTRUCTION MATERIALS AND INSTALLATION GUIDELINES

The objective of permeable pavements is to infiltrate and store the runoff and drain it into the subgrade, or if the subgrade is impermeable, into a drainage system. Proper construction of permeable interlocking concrete pavements is crucial to the long-term performance and success of the system. It is very important that sediment be prevented from entering the base and pavement surface during construction, as this will greatly reduce permeability of the system. It is highly recommended that the designing engineer inspect the site during the construction of permeable pavements (as is the case with infiltration trenches). This will help ensure the specified materials and design parameters selected by the engineer are followed. Though a range of materials may be used for the joint and drainage opening, bedding, and base layers, some general guidelines have been included here. Consult the UNI Eco-Stone® design manuals and the PC-SWMM™ program for more information on designing Eco-Stone® permeable pavements.

A professional engineer with soils experience should assess the site’s subgrade soils for design strength, permeability, and compaction requirements. The Unified Soils Classification System provides general guidance on the suitability of soils for the infiltration of stormwater and bearing capacity. To help maximize infiltration, the subgrade should have less than 5% passing the No. 200 (0.075 mm) sieve, though other soils may drain adequately depending on site conditions and specific characteristics. A minimum tested infiltration for full exfiltration subject to vehicular traffic is 0.52 in./hr (3.7 x 10^-6 m/sec), though some areas may require higher or lower rates. With virtually all pavements, including permeable pavements, compaction of the subgrade soil is required to ensure adequate structural stability and to minimize rutting. However, compaction does reduce the infiltration rate of soils. Therefore, this should be considered in the drainage design calculations for the project. Typically, the soil subgrade should be compacted to at least 95% standard Proctor density for pedestrian pavements, and to a minimum 95% modified Proctor density for vehicular applications. Some native soils, typically silty sands and sands, have enough strength (a soaked CBR of at least 5%) that compaction may not be required.

For years, engineers tried to design pavements that kept water out of the base and subgrade layers, as water in a typical “impervious” pavement structure was recognized as a primary cause of distress. However, over the last 15 years, the Federal Highway Administration (FHWA), American Association of State Transportation and Highway Officials (AASHTO), and the Corps of Engineers (COE) have given the subsurface drainage of pavements much consideration. They have found that the use of rapid-draining or open-graded aggregate materials in base/drainage layers in many pavement designs can result in longer pavement life (see Additional Reference section for more information).

For the base layer, a hard, crushed stone, open-graded or rapid-draining aggregate is generally recommended, though as discussed earlier, other aggregate materials may be used depending on design parameters and objectives. The base must be designed and constructed to prevent the pavement from becoming saturated and losing its load-bearing capacity in the presence of water, and stability will be enhanced if nonplastic materials are used. The thickness of the base depends on the amount of water storage required, the permeability and strength of the soil subgrade, and susceptibility to frost, as well as anticipated traffic loads. The water infiltration capacity of the base will vary with its depth and the percentage of void spaces in it (void space of a certain material can be supplied by the quarry or determined by testing). Please see the UNI-GROUP U.S.A. Eco-Stone® design manuals for additional information on base material selection and contact your local UNI® manufacturer for guidance on recommended materials for your region. The base is installed in 4 to 6 in. (100-150 mm) lifts and is compacted. If an open-graded material with larger size aggregates creates an uneven surface when compacted, a 2 in. (50 mm) layer of ASTM No. 8 or No. 9 crushed aggregate may be “choked” into the top of the material to stabilize the surface and help meet filter criteria. In some cases, open-graded bases may be stabilized with asphalt or cement to increase structural capacity. However, this may reduce storage capacity of the base and must be carefully monitored during construction. The Asphalt Institute and Portland Cement Association provide guidelines on constructing these types of bases.

For the bedding layer, testing has shown that a 2-5 mm clean, hard, crushed aggregate containing no fines provides the best performance in satisfying both structural and infiltration requirements. It should be screeded to a uniform depth of 1 to 1.5 in. (25-45 mm). This material is also recommended for the joints and drainage openings for
the Eco-Stone® pavement. ASTM C-33 sand, which is used in traditional interlocking concrete pavement bedding layer construction, is not recommended for permeable pavement installations as it reduces infiltration rates. In addition, we do not recommend sweeping a fine sand into the joints after the pavers are installed.

If filter criteria between the layers of the pavement (subgrade, base, and bedding) cannot be maintained with the aggregate materials selected for the project, or if traffic loads or soils require additional structural support, geotextiles or geogrids are often used. They are almost always used between the subgrade and the base. Consult the FHWA and AASHTO for information on geotextile filter criteria.

Edge restraints are required for all permeable interlocking concrete pavements. Cast-in-place, precast concrete, or granite curbs should be a minimum of 6 in. (150 mm) wide and 12 in. (300 mm) deep.

The UNI Eco-Stone® pavers are installed on the screeded bedding layer and are compacted with a plate compactor. After initial compaction, the joints and voids are filled with the 2-5 mm aggregate material and the pavers are compacted again. For vehicular areas, proof rolling may be preferable. UNI Eco-Stone® and UNI ECOLOC® pavers can be installed manually or mechanically. Mechanized installation can offer substantial cost savings on larger-scale installations.

COLD CLIMATE DESIGN CONSIDERATIONS

In northern climates the pavement must be designed for freeze-thaw conditions. For cold climates in the northern U.S. and Canada, the lowest recommended infiltration rate for the subgrade is 0.5 in./hr. (3.5 x 10^-4 m/sec). Designers may wish to incorporate a 1-2% slope and catch basins as a safety factor for over-flow should the system not be able to infiltrate all runoff under winter conditions. Snow can be plowed from Eco-Stone® pavements using standard equipment. Deicing salts are not recommended, however, as salt will infiltrate into the base and subgrade. The use of sand also should be avoided as it will reduce infiltration of the system. However, the Eco-Stone® surface, made up of joints, openings, and the paving units (as opposed to a continuous area of slick pavement) may help provide traction under snowy conditions.

MAINTENANCE

One of the most important aspects of permeable interlocking concrete pavements is proper maintenance. Any type of permeable pavement can become clogged with sediment over time, reducing infiltration and storage capacity. When properly constructed and maintained, permeable interlocking concrete pavements should provide a minimum service life of 20 to 25 years. If base or utility repairs become necessary, Eco-Stone® may be taken up and reinstalled after the repairs are made. Traffic levels and type of usage, as well as sources that may wash sediment onto the paver surface often dictate how quickly the pavement might experience reduced infiltration levels. It is highly recommended that sediment from areas surrounding permeable pavements be controlled or stabilized and prevented from getting onto permeable pavements. The property owner plays an important role in the maintenance of permeable pavements. Many local municipalities and regional governing authorities require a maintenance agreement to help ensure long-term performance of all types of BMPs.

Testing conducted from 2001 to 2002 at the University of Guelph in Ontario, Canada on Eco-Stone® parking lot pavements installed in 1994 indicated that trafficked areas with high clogging potential had lower permeability values than areas with low clogging potential such as parking stalls and areas near vegetated medians. Tests demonstrated that it was possible to regenerate infiltration rates for most areas of the pavement by removing some of the drainage void material (10-25mm) and refilling the openings with fresh material. It should be noted that these pavements had only been cleaned once a year using standard street sweeping (brush, not vacuum) vehicles, yet much of the pavement still infiltrated sufficient amounts of stormwater as per design storm requirements. Numerous research studies done over the years at this site have found that the Eco-Stone® pavements were capable of substantially reducing contaminants in stormwater and exhibited reduced thermal impact loads. Please see the research section of this guide for additional information.
It is strongly recommended that interlocking permeable pavements be inspected and cleaned at regular intervals to ensure optimum performance. Depending on the amount and type of traffic on the pavement and its potential for clogging, cleaning may be needed from twice a year to every 3 or 4 years. An indication that the pavement needs to be cleaned is when surface ponding occurs after rain storms, though it would be prudent to clean pavements on a cycle that prevents ponding. Vacuum street sweepers can be used to remove any encrusted sediment on the surface of the drainage openings. As street sweeping is a BMP under EPA guidelines, this also satisfies other criteria in a comprehensive stormwater management program. More aggregate material may be added to refill the drainage voids, if necessary, after cleaning. In addition, the incorporation of vegetated areas around permeable pavements should be encouraged to help filter runoff.
RESEARCH AND TESTING
UNI ECO-STONE® PERMEABLE PAVEMENT SYSTEM

DESIGN CONSIDERATIONS FOR THE UNI ECO-STONE® CONCRETE PAVER
Raymond and Marion Rollings - 1993

GENERAL SUMMARY

This 32-page manual reviewed testing information from the U.S. and Germany and extrapolated from existing design practice to provide basic design guidance on the development of designs for the UNI Eco-Stone® pavement system. Numerous references are included as well as tables on infiltration test and rates, permeability values, filter criteria, potential drainage void gradations, and more. Sample design cross sections are also included. A 4-page addendum of updated research was added in 1999.

OUTLINE

• INTRODUCTION
  • Purpose
  • Description
    Subgrade and Base Course
    Surfacing Materials
• DESIGN CONSIDERATIONS
  • Structural Considerations
  • Water Impact on Design
    Wearing Course and Bedding Layer
    Base and Subbase Courses
    Subgrade
  • Hydraulic Design
  • Filter Requirements
  • Special Considerations
• SPECIFICATIONS
• APPLICATIONS
• CONCLUSIONS
• REFERENCES
• SAMPLE DESIGN DRAWINGS
GENERAL SUMMARY

The information provided in this report, based on testing begun in 1994 at the Department of Civil Engineering at Texas A & M University under the direction of professor Dan Zollinger, serves as a guideline for the design of concrete paver block pavement systems using UNI Eco-Stone®. The guidelines are organized to give the reader a brief review of basic hydrological concepts as they pertain to the design of pavements and the benefits of using UNI Eco-Stone® in pavement construction projects. Information is provided on how runoff infiltration can be controlled in the pavement subsurface and its interaction with the performance of the pavement system. A method is provided to determine the amount of infiltration and the storage capacity of a permeable base relative to the time of retention and degree of saturation associated with the characteristics of the base. The guidelines contain a simple step-by-step process for the engineer to select the best pavement alternative in terms of base materials and gradations for the given drainage, subgrade strength conditions, and the criteria for maximum allowable rutting.

OUTLINE

- INTRODUCTION
  - Advantages of Using UNI Eco-Stone® Pavement
  - The Considerations for Water
  - The Purpose of This Report
- GENERAL HYDROLOGY CONCEPTS
  - Rainfall
  - Intensity-Frequency Duration Curve
  - The Depth of Rainfall
  - Storm Water Runoff Volume
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- SURFACE DRAINAGE SYSTEM
  - Computation of Runoff
- SUBSURFACE DRAINAGE DESIGN
  - Introduction
  - General Considerations
    - Properties of Material
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- PERFORMANCE OF PERMEABLE BLOCK PAVEMENT SYSTEMS
- REFERENCES
- APPENDIX A
  - Design Procedure for Drainage and Base Thickness for UNI Eco-Stone®
  - Paver Block Pavement Systems
- APPENDIX B
  - UNI Eco-Stone® Pavement Design and Drainage Worksheet
- APPENDIX C
  - Storm Frequency Data
- APPENDIX D
  - Permeability and Gradation Data
INFILTRATION AND STRUCTURAL TESTS OF PERMEABLE
ECO-PAVING
B. Shackel, J.O. Kaligis, Y. Muktiarto, and Pamudji

GENERAL SUMMARY

In laboratory tests conducted on UNI Eco-Stone® and UNI Eco-Loc® in 1996 by Dr. Brian Shackel at the University of New South Wales in Sydney, Australia, measurements of water penetration under heavy simulated rainfall were studied, and the structural capacities of the paver surfaces were evaluated. A range of bedding, jointing, and drainage void materials was tested, ranging from 2mm to 10mm aggregates. The best performance was achieved with a clean 2mm-5mm aggregate containing no fines. The use of ASTM C-33 grading was found to be inappropriate where water infiltration is the primary function of the pavement. The experimental data showed that it was possible to reconcile the requirements of obtaining good water infiltration (capable of infiltrating rainfall intensities similar to those in tropical conditions) with adequate structural capacity that is comparable to that of conventional concrete pavers.

OUTLINE

• CONCEPTS, BENEFITS, AND BACKGROUND OF ECO-PAVING
• BEDDING, JOINTING, AND DRAINAGE MATERIALS
  • Infiltration Tests
  • Structural Tests
• SUMMARY AND CONCLUSIONS
  1. Pavements laid using 4mm to 10mm gravels as the bedding, jointing, and drainage medium could accept rainfall intensities of up to about 600 l/ha/sec, with the best performance being given by a clean 2mm-5mm basalt aggregate containing no fines.
  2. Increase in the fines present in the jointing and drainage material led to a reduction in the ability of the pavements to accept rainfall.
  3. Blinding the pavements with a conventional laying sand reduced the amount of water penetrating the pavement by nearly 50% at moderate rainfall intensities.
  4. There was little significant difference in water infiltration in pavement blinded by sand from that observed for pavements using a sand complying with ASTM grading C33, as the bedding, jointing, and drainage medium.
  5. The use of ASTM grading C33 appears inappropriate where water infiltration is the prime function of the pavement.
  6. At crossfalls below 2%, the type of Eco-paver and the laying pattern did not significantly affect the infiltration of water into the pavement.
  7. At a cross fall of 10%, the Eco-Loc® pavers accepted water more readily than Eco-Stone®.
  8. It was not possible to obtain any significant structural capacity in pavements where the joints were left unfilled, and where the mechanism of load transmission between the pavers was solely via the spacer nibs.
  9. In pavements using a 10mm basalt aggregate as the bedding, jointing, and drainage material, the joints were only partially filled when normal construction practices were followed. This did, however, impart some load-bearing structural capacity to the pavements.
  10. Good load-bearing capability was achieved using gravels with a maximum particle size of about 4mm-5mm. The values of mat modulus measured were then comparable to those reported for conventional pavers tested in the same way using normal sand jointing materials.
  11. Sand blinding a pavement, using basalt as the laying medium, gave little improvement in structural capacity. This can be explained in terms of the difficulty of getting sand into joints that were already partially filled with aggregate.
  12. There was no structural problem associated with closely spaced continuous joints running through the Eco-Loc® cluster pavements. Such joints are a severe simulation of the situation encountered when machine laying paving clusters. In other words, in the tests described here, there was no intrinsic problem associated with cluster laying.

Overall, the test results indicated that permeable eco-paving may be able to fulfill many of the roles now served by conventional pavers, even under significant traffic loads. This opens up new marketing opportunities for permeable eco-paving once suitable design and specification procedures are established and verified.
ONGOING RESEARCH AT GUELPH UNIVERSITY

Professor William James

In 1994, laboratory and site testing of the UNI Eco-Stone® Paving System was begun at Guelph University in Ontario, Canada, under the direction of William James, Professor of Environmental Engineering and Water Resources Engineering. The research has generated several graduate theses with a focus on environmental engineering and stormwater management. Summaries of the theses are to follow.

THE LEACHING OF POLLUTANTS FROM FOUR PAVEMENTS USING LABORATORY APPARATUS

Reem Shahin - 1994

GENERAL SUMMARY

This 180-page thesis describes a laboratory investigation of pavement leachate. Four types of pavements were installed in the engineering laboratory: asphalt, conventional interlocking pavers, and two UNI Eco-Stone® pavements, to determine the effect of free-draining porous pavement as an alternative to conventional impervious surfaces. Runoff volume, pollutant load, and the quantity and quality of pollutants in actual rainwater percolating through or running off these pavements under various simulated rainfall durations and intensities were studied. UNI Eco-Stone® was found to substantially reduce both runoff and contaminants. The report includes tables and charts documenting volumes of runoff collected on various slopes, water penetration testing, water quality characteristics of the surface runoff – including trace metals, pH, phenols, sodium, nitrates, and concentrations of pollutants at all levels within the pavements. Numerous references are also included.

OUTLINE

1.0 INTRODUCTION
   1.1 Objectives of the study
   1.2 Scope of the study

2.0 LITERATURE REVIEW
   2.1 Nature of Water
      2.1.1 Properties of water
      2.1.2 Acidity
      2.1.3 Rainwater
      2.1.4 Behaviour of rainwater in the environment
      2.1.5 Water pollution
   2.2 Urbanization Effects
      2.2.1 Effects of urban storm water on aquatic ecosystems
   2.3 Nature of Pollutants
      2.3.1 Atmospheric sources of water pollution
      2.3.2 Man-made sources of water pollution
   2.4 Porous pavement
      2.4.1 Types of porous pavements
      2.4.2 Advantages and disadvantages
      2.4.3 Porous pavement as an infiltration system
      2.4.4 Previous research
   2.5 Asphalt pavement
   2.6 Temperature effects

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   3.2 Splash distribution
   3.3 Chemical reactions with the water
   3.4 Erosion of loose particles
   3.5 Particulate wash-off throughout the pavement
3.6 Surface infiltration
   3.6.1 Infiltration equations
   3.6.2 Infiltration process
   3.6.3 Infiltration zones
3.7 Water percolation
3.8 Solution of chemicals in the pavement
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   4.2 The rainfall simulator
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   4.3 Test pavements
   4.4 Instrumentation for sampling
   4.5 Sampling in the field
   4.6 Laboratory analyses
      4.6.1 Laboratory apparatus
   4.7 Mass balance
5.0 RESULTS
   5.1 Simulated rainwater calibration
   5.2 Rainwater quality
   5.3 Volume
      5.3.1 Rate of removal
   5.4 Water quality
      5.4.1 Pollutant concentrations
      5.4.2 Comparison between LAB rain leachate and tap water leachate
      5.4.3 Mass of pollutants
6.0 DISCUSSION
   6.1 Difference between LAB and WDS rain
   6.2 Dynamics of water movement
      6.2.1 Water movement within the soil
      6.2.2 Surface percolation
      6.2.3 Water movement in the subgrade
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      6.2.5 Ponding
   6.3 Water quality
      6.3.1 pH
      6.3.2 Oxygen demand parameter
      6.3.3 Solids
      6.3.4 Conductivity and transmittance
      6.3.5 Oils and grease
      6.3.6 Nutrients
      6.3.7 Total phenols
      6.3.8 Sodium and chloride
      6.3.9 Sulphates
      6.3.10 Metals
      6.3.11 Bacteria counts
   6.4 Rain-pavement interaction
   6.5 Mass balance
7.0 CONCLUSIONS
   1. Rainwater is very acidic in the city of Guelph, having a pH of approximately 3.4 when it first makes contact with the ground. It takes almost 2 hours after collection to release CO₂ into the atmosphere and reach a pH of 5.5. At this pH, it takes at least 72 hours before it neutralizes to a pH of 7.
2. Impervious asphalt pavements produce large amounts of surface runoff, compared to porous pavements, for similar rainfall intensities and durations. Porous pavement is evidently a very effective way of reducing the quantity of stormwater runoff from areas such as parking lots that are normally paved with asphalt.

3. For all gradients, EC3 (UNI Eco-Stone® with 3” base and joints filled with washed stone) performed the best at reducing surface runoff from all the pavements studied.

4. The total void size on the porous pavement surfaces is one of the main factors that affects permeability, and not the pore size in the joints. EC3 reduced the most surface runoff volume due to the large voids available at the surface and at the subsurface layers. Hence more water infiltrated through the pavement.

5. In these experiments, EC3, EC4 (Eco-Stone® with 4” base and joints filled with a mixture of washed stone and sand), and PC (regular concrete pavers) pavements did not clog, due to the short duration of all the experiments. In addition, the pavements were placed in the laboratory, and hence, no dust or any other particulate accumulated on the surface and in the joints.

6. PC, EC3, and EC4 performed well in reducing volume of surface runoff at 1%, 5%, and 10% gradients with rainfall intensities lower than 55.6mm/hr. At higher rainfall intensities, ponding occurred at the joints and at the outlets, which slowed down the infiltration process to the subsurface layers.

7. Since the EC3 had washed stone as its bedding material, the water drained faster through its subgrade than it did for the EC4 and PC subgrades, which had a mixture of stone and sand in one, and sand alone in the other, respectively.

8. The runoff collected from porous pavement in the laboratory showed very low concentrations in all water quality parameters, especially in oils and grease, phenols, heavy metals, and bacteria counts. Eco-Stone® pavements showed the lowest concentrations in these parameters of the three pavements.

9. Percolation through the porous pavements surface and underlying media slowed the water flow. The process allowed more time for oxidation; the water had 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 sulphates.

10. 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 in the surface runoff from the porous pavements, which had lower concentrations than the surface runoff from the asphalt surface (AS).

11. The porous pavement surface runoff had pH values more alkaline than the asphalt surface gave pH values that were almost neutral.

12. The surface runoff from asphalt contained a higher mass of all the parameters investigated compared to the mass measured in the surface runoff of EC3.

13. Surface runoff from the AS surface contained a concentration of phenols higher than the concentrations found in the porous pavement surface and subgrades.

14. The 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 process of rainfall as it falls on the ground (i.e., raindrop distribution, rainfall energy, and acidity of the rainwater).

15. The laboratory experiments on porous pavement generally proved that the water is not being contaminated from the surface of these pavements or their bedding materials, but rather from the external environment, as proven by the parking lot runoff analyses. With AS, the surface is made from the combustion of petroleum products, and hence, some of the pollutants will originate from the surface, as in oil, grease, and phenols.

16. 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. EC3 reduced the amount of stormwater pollutants more than the other porous pavement.

8.0 RECOMMENDATIONS

Based on the data gathered and conclusions reached in this study, recommendations that may be made include:

1. In addition to the ability to reduce runoff, the porous pavements will have lower surface runoff temperature, as the water penetrates through the pavement. Hence, an experiment to examine temperature of runoff under laboratory conditions will be valuable. The water quality analyses were performed at a constant temperature (25°C). Temperature changes will have a great impact on water quality, since many parameters were found to be related to pH, and pH changes with temperature.

2. Tests should be performed to determine long-term effects of maintenance and potential for clogging.

3. When performing tests on water quality of stormwater runoff, some parameters remained almost constant. The contaminants that need not be examined in detail include TKN, NH₄, BOD, COD, and some metals such as cadmium and chromium.
4. On the other hand, some parameters exhibited very interesting behaviour, particularly pH, phenols, oils and grease, sulphate, sodium and chloride, nitrates and nitrites, zinc, lead, nickel, and copper.

5. From the data obtained in this study, although the pH of runoff from asphalt seemed to be more neutral than the porous pavement pH, more investigation of the pH is needed in order to reach a more definite conclusion on the performance of AS vs porous pavement in terms of pH.

6. Since hydraulic conductivity is mainly dependent on temperature, when examining temperature, hydraulic conductivity will be an important parameter.

7. The rising cost of petroleum-based asphalt is diminishing the price difference between asphalt pavement and porous pavement. Relative long-term predictions for the future cost of using asphalt and porous pavement would be an interesting study.

8. Porous pavements should be used in many applications of low traffic volume to effect significant reductions in stormwater runoff. Qualitative and quantitative experiments should be carried out on porous pavement on lightly used roads.

9. Future experiments can be conducted using different conditions to give a more complete and detailed characterization of the performance of porous pavements.
GENERAL SUMMARY

This 173-page study examines the thermal enrichment of surface runoff from an impervious asphalt surface and a UNI Eco-Stone® permeable paver surface. The pavement samples were heated and a rainfall simulator was used to generate rainfall and cool the pavement samples. Thermocouples monitored the temperature in the subgrade and at the surface and inlet and outlet water temperatures were monitored. The primary objective of the research was to measure the thermal enrichment of surface runoff from the two types of pavement. The study revealed that the UNI Eco-Stone® pavement produced very little surface runoff and exhibited less thermal impact than the asphalt surface. The environmental advantage with the Eco-Stone® permeable pavement is its ability to allow rainfall to infiltrate the surface and thereby reduce total thermal loading on surrounding surface waters. Tables include surface runoff observations, sample and instrumented pavement comparison and temperature differences, and surface temperature data. Figures include the impact of urbanization on stream temperature, surface runoff temperature comparisons for asphalt and Eco-Stone® pavements, surface energy budgets under various conditions, and surface runoff impact on receiving rivers. Many references are sited.

OUTLINE

1.0 INTRODUCTION
   1.1 Study Objective
   1.2 Study Scope

2.0 BACKGROUND
   2.1 Impacts of Thermally Enriched Urban Stormwater Runoff
   2.2 Surface Energy Budgets
   2.3 Heat Transfer
   2.4 Application of Energy Budget and Heat Transfer Equations
   2.5 Rainfall Simulation

3.0 THEORETICAL DEVELOPMENT
   3.1 Sensitivity Analysis of Surface and Heat Transfer Equations
   3.2 Thermal Enrichment of Surface Runoff

4.0 LABORATORY EQUIPMENT
   4.1 The Test Pavements
   4.2 The Rainfall Simulator
   4.3 Rainfall Calibration and Intensity Selection
   4.4 Data Collection and Sources
   4.5 Heating the Test Samples
   4.6 Comparison to Outdoor Conditions

5.0 RESULTS
   5.1 Surface Temperature Observations
   5.2 Low and Medium Intensity Rainfall (25mm-hr⁻¹ & 115mm-hr⁻¹)
   5.3 High Intensity Rainfall (190mm-hr⁻¹)
   5.4 Regression Analysis

6.0 DISCUSSION
   6.1 Accuracy of the Proposed Equations
   6.2 Sensitivity Analysis of the Thermal Enrichment Relationship
   6.3 Comparison of Asphalt and Paving Stone Surfaces
   6.4 Applicability

7.0 CONCLUSIONS AND RECOMMENDATIONS
Several conclusions may be inferred from the information presented in this study:
1. Both the asphalt surface and the porous paving stone surface used for the experiments conducted in this study caused increases in the temperature of the surface runoff, the paving stone surface less so than the asphalt surface.
2. Very little surface runoff was observed from the porous paving stone sample.
3. The rainfall intensity, thermal conductivity of the pavement, initial surface runoff temperature, and initial rainfall temperature are the dominant parameters in a surface runoff thermal enrichment relationship.
4. The expression \( \Delta T_{sr} = Aln(t) + B \) may be used to determine the thermal enrichment of surface runoff from either impervious asphalt or porous paving stone (known as Eco-Stone® and produced by UNI-GROUP U.S.A. producers where:

\[
A = 0.0047 \times i - 5.18 \times k_s - 0.13 \times T_{is} + 0.15 \times T_{ir} - 1.55 \\
B = -0.0294 \times i - 2.26 \times k_s + 0.52 \times T_{is} + 0.07 \times T_{ir} - 14.62
\]

where \( i \) is the rainfall intensity [mm/hr]; \( k_s \) is the thermal conductivity of the surface [kW.m⁻¹.°C]; \( T_{is} \) is the initial surface runoff temperature[°C]; \( T_{ir} \) is the initial rainfall temperature[°C]; and \( t \) is the time after the start of the rainfall [min].
5. The accuracy of the relationship is ± 4.0 °C in the first 10 minutes after rainfall begins and ± 1.5 °C when averaged over the entire duration of the rainfall event.
6. Research should continue to improve the accuracy of the relationship and further validate the relationship over a range of rainfall intensities.

Consideration of these conclusions and the information presented in this study leads to the following recommendations:
1. That thermal enrichment of urban stormwater runoff be considered when new developments are proposed.
2. That thermally-sensitive pavement materials be used more extensively than in current applications.
3. That the relationship presented in this study be used to estimate the magnitude of the thermal enrichment of a new development on receiving waters.
4. That the relationship proposed in this study be used in a stormwater model to provide an estimate of the thermal enrichment resulting from specific catchments.
5. That further research be conducted using different surface materials (e.g. roofing materials or concrete).
6. That further research be conducted into the cooling of stormwater in underground pipe networks leading to receiving waters.
7. That monitoring of subgrade temperatures continue in the instrumented parking lot to obtain a database with respect to initial surface runoff temperatures.
8. That infrared thermometers be installed to monitor the surface temperature of the instrumented parking lot.
DESIGN AND INSTALLATION OF TEST SECTIONS OF POROUS PAVEMENTS FOR IMPROVED QUALITY OF PARKING LOT RUNOFF

Michael Kaestner Thompson, P.Eng. - 1995

GENERAL SUMMARY

This 162-page thesis examines the design, construction, and instrumentation of four test sections of parking lot pavement (one conventional interlocking paver, two UNI Eco-Stone® using two different filter materials, and one conventional asphalt) to assess alternatives to the impervious pavements commonly used in parking areas and low speed roadways. Appropriately designed Eco-Stone® pavements could reduce impacts from runoff and reduce pollutant load on surrounding surface waters by infiltrating storm-water. Preliminary results showed reductions in surface contaminants and temperatures when compared to impervious pavements. Figures include cross sections of pavement design and instrumentation, subsurface drainage system grading, laboratory test pavement apparatus, longitudinal and lateral flow paths, collection system orientation, thermocouple details, and drainage pattern. Photographs include the subbase drainage system, base drainage system, surface inlet drains, connecting pipes, thermocouple, and wet/dry precipitation sampler. The tables include a pollutant summary for highway runoff, pavement thickness and materials used, collected event summary, temperature results, rainfall volume summary, surface and sub-surface load summary, contaminant analysis and investigation, and concentrations and total loads. Results are presented under two categories – temperature and contaminants. Once again, numerous pollutants were analyzed including heavy metals such as lead, zinc, iron, cadmium, and nickel, phenols, nitrates and nitrates, chromium, chloride, phosphates, ammonium and E.coli. References are included.

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7.0 CONCLUSIONS AND RECOMMENDATIONS
7.1 Conclusions
The purpose of this study was to construct instrumented pavements for a study of porous pavement as an alternative to impermeable pavement for use in parking lots where traffic speed is less than 50km/hr. Four instrumented test pavements were built in parking lot P10 at the University of Guelph. A materials budget was developed for the contributing variables at the scale of a parking lot. This study is only a preliminary step for continuous work necessary to delineate the processes involved in a parking lot system. In this chapter, conclusions are drawn related to the design, construction, and instrumentation of the facility. Recommendations are then made for improvements to the work.

The following conclusions can be made:
1. No previous experimental work has examined the effectiveness of porous pavements as an alternative to impervious pavements. This study prepared a facility for future porous pavement research for application in North America.
2. The materials budget that was developed provides a preliminary background on the build-up and wash-off processes that are involved. The constructed and instrumented test pavements provided the information necessary in understanding the materials budget.
3. Pavement temperatures were recorded between the months of June to September, 1994. Surface temperatures are directly related to the meteorological conditions; the greatest temperature ranges were generated in the asphalt surface. In fact, for most of the time, the asphalt surface generally had the highest maximum daily temperatures and lowest minimum daily temperatures. Asphalt pavements show more adverse results than the other pavements.
4. In the summer, average daily temperatures were generally similar for all the pavement surfaces. Average temperatures for one pavement can be applied to all pavements.
5. Base temperatures measured approximately 15 cm below the surface, showed a lower diurnal range than the surface temperatures. Maximum base temperatures were less than the surface temperatures, at least in early summer.
6. Sub-base temperatures, measured up to 600 mm below the surface, showed little diurnal temperature fluctuation. In early summer, sub-base temperatures were lower than surface temperatures.
7. Contaminant loads from asphalt surface were always greater than the other pavements and surfaces. This is mostly due to the asphalt being 100% impervious, which increases the amount of runoff and pollutants reaching the sewers and ultimately the receiving waters.
8. UNI Eco-Stone® effectively reduces the amount of surface runoff. Runoff was only generated from the surface when the rainfall intensity exceeded the infiltration rates of the pavement. UNI Eco-Stone® proved to be an adequate porous pavement for reducing surface contaminant runoff loads.

7.2 Recommendations
1. Improvements are necessary in the flow measurement. The use of a datalogger is recommended to adequately record flows. However, the TBRGs require further improvement or replacement. A proposed simple alternative to the TBRG could be large barrels located in the instrumentation chamber under each of the catchments. This system would be inspected frequently to determine the best size barrel for each of the catchments.
2. The present system is designed to measure ground temperatures and not runoff temperatures. Additional work is necessary for reliable measurement of runoff and precipitation temperatures. A system is necessary to accurately measure the runoff water temperature as it passes through the layers. This would allow a better understanding of the role of temperatures, runoff, and pavements.
3. The asphalt surface thermocouple requires constant observation due to the damage originally sustained. Continuous monitoring of the temperature from the asphalt is necessary to ensure accurate measurement of temperature. This is also true for all the pavements and layers.
4. Particular work is necessary in the heat transfer process between the pavement and water. Appropriate instrumentation is necessary to accurately assess these water temperatures.
5. With the long-term continuation of this work, care must be taken to ensure minimal settling of the pavements. Additional work is necessary in improving surface drainage. Improvements are necessary to ensure adequate drainage of the surfaces. Adequate drainage of the system can be effectively accomplished by removing two of the pavements, i.e., the CP and the E3 pavements could be removed. CP would then be replaced with E4, this doubling the size of the E4 surface. E3 would be replaced with the AS, thereby doubling the size of the AS pavement. These changes would effectively reduce the drainage problems, as well as provide the appropriate grading necessary for future use.

6. It is recommended that additional locations and other materials be investigated for porous pavement research.

7. More detailed observation of the effect of vehicles parking on the test pavements must be made to monitor vehicle pollutant contribution.

8. Consideration must be given to the removal and restoration of the pavement in the long term when the study is completed.
LONG-TERM STORMWATER INFILTRATION THROUGH CONCRETE PAVERS

Christopher Kresin - 1996

GENERAL SUMMARY

This 188-page study investigates the infiltration capacity of porous concrete paver installations of various ages. Using a rainfall simulating infiltrometer, several test plots at four UNI Eco-Stone® installations were subjected to a total of 60 tests comprising two simulated rainfalls of known intensity and duration. The first rainfall provides initial moisture losses to wetting the drainage cell material, while data collected during the second rainfall is used to calculate effective infiltration capacity. Long-term stormwater management modeling was reviewed and suggestions made to enhance the modeling capabilities of the United States Environmental Protection Agency's Storm Water Management Model. These changes will permit simulation of long-term responses of surfaces paved with permeable concrete pavers.

The study showed that although the infiltration capacity of the UNI Eco-Stone® pavements decreased with age and degree of compaction (traveled versus untraveled), it could be improved with removal of the top layer of the drainage cell aggregate material. The report also noted that all but two of the sites studied were constructed with improper drainage cell material, which restricted the potential infiltration. The thesis strongly recommends that Eco-Stone® installations be constructed and maintained as per the manufacturers' specifications to ensure adequate performance. The tables include simulated rainfall intensities, effective infiltration rates and capacities, grain-size analysis results, drainage cell material analysis, and SWMM run times. Figures show typical permeable pavement structure, soil moisture zones, SWMM program organization, uniformity coefficients and intensities at various pressures, grain-size distribution curves for previous research and test sites, and porous pavement water balance. Photographic documentation includes various trash, oil deposits, and vegetation in drainage cells, the test plot delineator, test plot under rainfall conditions, rainfall simulator, drainage cell material extraction and crust removal, stormwater runoff, and test site locations.

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  1. Infiltration capacity of UNI Eco-Stone® MICBEC pavers decreases as the installation ages.
  2. Infiltration capacities at UNI Eco-Stone® 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 initial $f_{Eo}$, by street sweeping/vacuuming the
     Eco-Stone® surface.
  5. $f_{Eo}$ is affected to a greater extent by EDC fines content than organic matter content.
  6. Most fines are trapped near the surface of the EDC material.
  7. Except for Sites 1A and 1B, UNI Eco-Stone® installations are constructed with improper EDC material,
     which restricts potential $f_{Eo}$.
  8. $f_{Eo}$ values of the magnitudes presented in this study would not provide infiltration of the smallest storms
     common to the Toronto area.
  9. SWMM currently can not simulate the response of permeable pavement.
 10. SWMM can be modified to model systems that include permeable pavements, over a long-term, efficiently
     and effectively.
  7.2 Conclusions Based on Literature Review and Observations
  1. Infiltrating stormwater is environmentally beneficial.
  2. Permeable pavement is an effective infiltration BMP.
  3. Eco-Stone® offers limited benefits when used for small surface areas as stormwater does not have adequate
     time to infiltrate the porous pavement.
  4. Porous and conventional asphalt pavement has a greater potential to contaminate stormwater and the
     adjacent environment than concrete pavers.
5. MICBEC pavements will always reduce stormwater runoff volumes through depressions storage.

7.3 Recommendations

From the conclusions, the following is recommended:

1. UNI Eco-Stone® installations must be constructed and maintained to manufacturer’s specifications to ensure adequate performance.
2. Permeable pavement installations should be constructed with minimal slope and to provide surface detention so that greater volumes of stormwater may be captured and infiltrated.
3. Eco-Stone® should be installed in parking lots to detain stormwater on the surface and should be swept/vacuumed every spring, which provides the required site maintenance.
4. Every effort should be made to maximize runoff to pervious areas.
5. SWMM coding must be updated to FORTRAN 90 syntax and the RUNOFF block modified to allow better catchment discretization.

Future research should be conducted to determine:

1. How deep into the permeable pavement do fines propagate and whether there is an optimal gradation of EDC material that will capture fines as the surface, as well as provide adequate f/Eo.
2. How well UNI Eco-Stone® performs under freezing conditions.
3. An appropriate Eco-Stone® maintenance frequency.
FEASIBILITY OF A PERMEABLE PAVEMENT OPTION IN THE STORM WATER MANAGEMENT MODEL (SWMM) FOR LONG-TERM CONTINUOUS MODELING

Craig Kipkie - 1998

GENERAL SUMMARY

The purpose of this 134-page project was to examine the feasibility of, and attempt to develop computer code for the United States Environmental Protection Agency's Storm Water Management Model (SWMM). The code would allow planners and designers to simulate the response of permeable pavements in long-term modeling applications. The infiltration capacity of the permeable pavement was determined from past studies of UNI Eco-Stone® and accounts for degradation over time and regeneration by mechanical means. Various simulations run with the proposed new code indicated that using permeable pavements could greatly reduce flows when compared to impervious surfaces. Figures include types of permeable pavers, typical permeable pavement structure, SWMM program structure, SWMM RUNOFF subcatchment schematization, porous pavement water balance, and hydrographs for various dates from 1971 to 1981. The tables include Kresin's experimental results, subcatchment surface classification, RUNOFF block input data, sample calculations, and description of permeable pavement parameters for various tests. Also included is a potential source code for a subroutine PERMPAV.FOR containing the calculations for the permeable pavement option for SWMM. Numerous references also are included.

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7.0 CONCLUSIONS AND RECOMMENDATIONS
7.1 Conclusions
   1. It is possible to insert new source code into SWMM to simulate the long-term hydrologic response of permeable pavement.
   2. Various simulations, with the proposed new source code, indicated that the model produces reasonable results under a generalized set of input conditions.
   3. As expected, simulations showed that using permeable pavement can greatly reduce flows when compared to impervious surfaces.
   4. Difficulties can arise in receiving programming support with SWMM because of the size and complexity of the code and numerous authors over the past 30 years.

7.2 Recommendations
   1. The validity of the new source code must be tested using observed data from permeable pavement installations.
   2. Test should be conducted using shorter time steps (1 minute).
   3. Modifications should be made to connect the permeable pavement subroutine to the groundwater routine.
   4. Clarification of the water depth in the reservoir of the permeable pavement structure should be made.
   5. Possible modifications to the new source code should be made after further alpha and beta testing.
   6. Further research must be conducted on the degradation of the infiltration capacity.
   7. Appropriate guidelines for maintenance frequency must be established to ensure that the flow reducing qualities of permeable pavement remain effective.
   8. Modifications to the SWMM code should be made to incorporate the water quality aspects of permeable pavement for long-term, continuous simulations.
   9. Proper documentation must be prepared to support the proposed new code.
   10. Instructional material should be developed and distributed for instruction in the use of the proposed new code.
GENERAL SUMMARY

This study investigated the infiltration capacity of UNI Eco-Stone® permeable pavers at a research test section located at the University of Guelph that was installed in 1994. The objectives were to determine how infiltration capacity, volatile organic matter, heavy metal concentration, and particle size analysis of the drainage void material vary with average daily traffic use and surface ponding. Using a rainfall infiltrometer, 110 test plots were subjected to 420 tests comprising two simulated rainfall events of known intensity and duration. Data collected during the second rainfall was used to calculate effective infiltration capacity. Preliminary results yielded different results for infiltration capacity and particle size analysis of the drainage void material for the different average daily traffic uses. The purpose of the research was to test the hypothesis that UNI Eco-Stone® infiltration capacities decrease with age and traffic use, and that the infiltration capacities could be improved by street sweeping/vacuuming. The tests plots with a coarser gradation of aggregate materials had higher infiltration rates than the section with a greater percentage of fines in the base and bedding materials. The greatest infiltration rates were found in areas with low average daily traffic and regeneration could be easily accomplished. In areas of medium to heavy average daily traffic usage, infiltration rates were lower and regeneration was limited, indicating a need to establish a periodic cleaning program to ensure optimum infiltration levels.

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7.0 CONCLUSIONS
7.1 Conclusions
1. Since no previous experimental work has examined the regeneration of the infiltration capacity of permeable pavement installations, this study will serve as a guideline for future permeable pavement research in North America.
2. The infiltration capacity tested between May and September, 2001, was determined to be spatially variable and dependent on the average daily traffic use, percentage of fine matter in the EDC, and the test installation subbase specifications. The infiltration capacity was also found to be dependent, to a lesser degree, on the percentage of volatile organic matter within the EDC.
3. The infiltration rates were found to be greatest in the low ADT area and regeneration to the maximum infiltration capacity could be accomplished by removing as little as 15mm of EDC material.
4. The infiltration rates in the medium ADT area were found to be less than the low ADT area. Although regeneration to the critical infiltration capacity could not be reached by removal of 25mm of EDC material, but results suggest that this could be possible with removal of more EDC material. Some degree of regeneration was noted at all excavation depths.
5. The infiltration rates in the high ADT areas were found to be the lowest, and only a minimal amount of regeneration could be obtained.
6. The infiltration rates were higher, and regeneration could be reached by removing less EDC matter, in the Eco-Stone® 3" installation. The infiltration rates within the Eco-Stone® 4" installations were much lower initially and regeneration to the critical infiltration capacity was not obtained for any test plot.
7. The infiltration rates are very spatially variable, as illustrated by the large coefficients of variation obtained.
8. The percentage of fine matter within the EDCs, measured up to 25mm from the top of the paver, was much higher in the Eco-Stone® 4" installation. The percentage of fine matter was also found to be inversely proportional to the infiltration rate.
9. The infiltration rate was found to be lower for the plots that have water ponded on them for a period of greater than one hour after a storm event, than plots where the water does not pond. The percent of fine matter in the EDCs was found to be slightly greater within the first 5mm and approximately equal for all other depths. The percent of VOC was found to be significantly higher in the frequently flooded plots, for all depths, not just the upper 5mm.
10. The percentage of volatile organic matter within the EDCs was found to be similar for both installations and all traffic uses. The percent VOC was found to be much greater for the vegetated plots, underneath the large coniferous tree along the grass verge. The infiltration rate was not found to be greatly affected by the percent VOC, with the exception of plots where the percent VOC was significantly greater than the average VOC percent. In this case, the infiltration rate was found to be an order of magnitude greater than the unvegetated area.
11. The concentrations of heavy metals within the EDCs were found to be less than the Ontario Ministry of the Environment's Guideline Concentrations for Selected Metals in Soils. All of the metals tested were below the MOE guideline level, and, with the exception of zinc, below the expected value for Ontario soils.
7.2 Recommendations

1. It is necessary to minimize the amount of fine matter accumulating within the EDC. This can best be done by periodically cleaning the permeable pavement installation to keep the EDCs clear of fine matter. The frequency of cleaning will be dependent on the ADT, as well as land use practices on and adjacent to the test installation.

2. The percent VOC within the cells helped to keep fine matter from accumulating within the EDCs. Whenever possible, coniferous trees should be encouraged to grow along permeable pavement installations and on any islands or verges within the parking lot. Coniferous trees were found to be useful because the needles falling off of the trees, into the EDCs, helped to maintain high infiltration capacities. Vegetation of any kind should not be discouraged from growing within the EDCs.

3. Future permeable pavement installations should be constructed so that drainage is in the direction of the highly vegetated areas near the curb.

4. Fine matter should not be used when installing the subbase material, as it decreases the infiltration capacity and the ability to regenerate the infiltration capacity.

5. It is recommended that additional testing be done on other permeable pavement installations in order to better identify the frequency of cleaning required to maintain and optimal infiltration rate.

6. Further studies should be aimed at testing permeable pavement installations on a larger scale. This would allow for better estimation of the installation as a whole and lessen the spatial variability of testing at such a small scale.

8.0 REFERENCES
THE RATE OF CLOGGING OF CONCRETE PAVERS
Matthew Wilson - 2002

GENERAL SUMMARY
This study investigates the changes in permeability of porous pavement resulting from clogging with street dust and dirt. Changes in permeability are assessed experimentally through the artificial application of sediment and rainfall to a test section of pavement surface. The primary objective is to determine the quantity of sediment and the number of rain events that cause the pavement to become functionally clogged. Data is obtained from approximately 50 experimental runs for concrete pavers. The results of the experiment are used to suggest a maintenance schedule for this type of porous pavement system. This work, coupled with a sequence of ongoing similar experiments on porous pavement with different design specifications (selection of base, bedding, and joint/drainage opening fill materials) should help to tailor construction guidelines and site selection to maintenance schedules and provide optimal long-term performance. Conclusions from this experiment also may be incorporated into the development of software such as Lockpave® Pro and PC-SWMM™ for UNI Eco-Stone permeable pavers.

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11.0 CONCLUSIONS
11.1 Conclusions
1. Change in the performance (infiltration rates) of the porous pavement as a result of the sediment application did not begin immediately.
2. The quantities of sediment that can be applied without causing a decline in performance of the pavement is determined by the porosity of the drainage cell fill material.
3. Results from this experiment, using a fill with 34% porosity, suggest the possibility of fewer maintenance visits than have been recommended in other studies on clogging of porous pavement.
4. After the application of 1.4 kg of sediment to 1 m² of porous pavement, the average infiltration rate at the pavement surface may decline to a rate below the inflow rates (1/25-year design storm of 5-minute duration with an intensity of 230mm/h). More frequently observed rainfall events with lower rainfall intensities may produce different results.
5. After the accumulation of 3.9 kg of sediment on 1 m² of porous pavement, the drainage cell material may become functionally clogged. However, over a large section of porous pavement, heterogeneity of the infiltration rates over different sections may uphold the performance of the pavement for some time.
6. To determine whether results of this experiment over-estimate the rate of clogging, the time-dependent rate of restoration of infiltration capacity should be determined through experimentation. If infiltration capacity is restored over time between rainfall events, this effect should be included, after every rainfall simulation, to make this experiment more realistic.

12.0 RECOMMENDATIONS
12.1 Recommendations
1. Uni Eco-Stone® MICBEC permeable pavers should be maintained with mechanical or vacuum sweepers when the surface is affected by partial clogging. Using the design specifications given in the appendix, this should correspond to the accumulation of between 1.4 to 3.9 kg of D&D on 1 square meter of pavement.
2. The results of this experiment should be compared to similar experiments using different drainage cell and base materials of varying porosity. This will provide a basis for determining the relative average infiltration rates and performance of these materials and the corresponding maintenance required by these different materials.
3. The results of this experiment should be compared to similar experiments using different rainfall intensities and duration. It would be useful to gather baseline data on the performance of porous pavement for more
commonly observed storm events, such as the one-hour/one-year or one-hour/two-year frequency storm.

4. A similar experiment to that described in this report should be performed but for various intervals of time elapsed between sequences of experimental runs. Allowing different periods of time to elapse between series of experimental runs should provide a useful description of time-dependent restorative processes that counteract clogging of the pavement.

5. To encourage the integration of this technology as a technical standard in the urban drainage profession, a standardization of design procedures and maintenance programs should be developed.

6. Where porous pavement is installed, the use of a carefully-worded maintenance agreement that provides specific guidance, including how to conduct routine maintenance, should help to protect the capital investment.

13.0 REFERENCES

14.0 APPENDICES

A. Design Specifications
B. Checks for Continuity
C. Diskette Directory
GENERAL SUMMARY

This series of experiments is a continuation of the procedure described by Wilson (2002). All experiments were performed outdoors in the School of Engineering parking lot at the University of Guelph during the summer of 2002. An experimental pavement comprising paver blocks and a base layer of aggregate about 200mm thick was installed in an apparatus rig with a surface area of 0.93m² at a slope of 2%. Artificial rain was generated using a rainfall simulator. Uni Eco-Stone® pavers were placed in position on the aggregate base. In real pavements, the base is laid over the subgrade, but in these experiments the base aggregate was laid over the impervious steel invert of the rig, fitted at the downstream edge with three 0.5 inch diameter drain pipes. The work reported in the present two volumes consisted of four experiments, each experiment having a specific base, bedding and fill aggregate. Each application of total suspended solids (TSS) and rain is a run. Each run was subject to TSS applied at a fixed rate, and a specified intensity of artificial rain applied for a duration of 305 seconds. TSS as used in this report denotes a mix of particulates applied to the paver surface. Flow was sampled over a duration of 20 seconds twice a minute for the first 6 minutes, and thereafter once a minute until a minimum flow rate was reached. Results of Experiment 1 were conducted and compiled by Wilson (2002), but the particle size analyses of (a) cell fill aggregate with its in-washed TSS and (b) base aggregate with its trapped TSS, for Experiment 1, were conducted by ul Haq, and are presented in Chapter 5 of this report.

OUTLINE

1.0 INTRODUCTION
2.0 EXPERIMENT 2
   2.1 Setup
   2.2 Rainfall
   2.3 Wet/dry Porosity
   2.4 TSS Application
   2.5 Experiment Run
   2.6 Trapping of TSS
3.0 EXPERIMENT 3
   3.1 Setup
   3.2 Rainfall
   3.3 Wet/dry Porosity
   3.4 TSS Application
   3.5 Experiment Run
   3.6 Trapping of TSS
4.0 EXPERIMENT 4
   4.1 Setup
   4.2 Rainfall
   4.3 TSS Application
   4.4 Experiment Run
5.0 SIEVE ANALYSIS FOR EXPERIMENT 1
6.0 SUMMARY

A series of four experiments with multiple runs was performed. During each experiment, a specific paver structure was tested for clogging under a specific TSS build-up during a designed rainfall. Results of the four experiments suggest that permeable pavers are capable of maintaining high infiltration rates over a long period of time. Most of the fines from the TSS applied during the experiments were trapped in the top 10mm of the drainage cell fill material. The HPB-base aggregate did not accumulate any fines, but they accumulated on the drain filter fabric. Similar phenomenon was not observed during the experiments using Milton Granular-A type of base. In one experiment, where the TSS application rate was reduced to 25%, results suggest that the clogging of drainage cells may also be associated with the total number of rains and/or total depth of rainfall rather than cumulative total build-up of TSS alone. This may need to be further investigated. Once the paver is clogged, all the TSS washes off. Clogging seems to be exclusively in the upper 10mm. In this type of pavement, only dissolved or extremely small particles will pass through. The pavement should easily meet the 80% retention requirement, depending on the grain size distribution and the total amount applied. Measuring TSS in the outflow, was and is not cost-effective
(it is slow and expensive to collect the number of outflow samples required and to analyze them in the laboratory - and would have required considerably more time and money).

7.0 APPENDICES
   A. Design of Experimental Rig
   B. Specifications of Aberfoyle-HPB Aggregate
   C. Specifications of Milton Granular A Aggregate
   D. Glossary

Additional testing relating to the Clogging Studies:

MEASUREMENT OF INFILTRATION RATES THROUGH ECO-STONE® PERMEABLE PAVERS IN A PARKING LOT AT THE UNIVERSITY OF GUELPH, 12 MONTHS AFTER PREVIOUS WORK

William James - 2003

Infiltration through Eco-Stone® permeable pavers was measured in the parking lot at the back of the School of Engineering at the University of Guelph. Shows results of infiltration experiments for low, medium and high traffic usage areas.
The following synopses are all edited by William James of Guelph University and are Proceedings of the Stormwater and Water Quality Management Modeling Conferences, Toronto, Ontario 1994-2000. They are based on the research conducted at Guelph University described on the previous pages.

PROVISION OF PARKING-LOT PAVEMENTS FOR SURFACE WATER POLLUTION CONTROL STUDIES
William James and Michael K. Thompson - 1994

This study prepared a facility for future research on porous pavement for application in North America with comparative test sections of UNI Eco-Stone® concrete pavers, traditional concrete pavers and asphalt in the laboratory and in a parking application. The purpose was to investigate porous pavement as an alternative to impervious pavement for parking lots. A large number of contaminants were investigated, including, heavy metals, chlorides, nutrients, phenolics, solids, and solvents. Preliminary results showed that contaminant loads from the asphalt surface were always greater than the other pavement surfaces. The Eco-Stone® pavement was shown to effectively reduce the amount of surface runoff, with runoff generated only when rainfall intensity exceeded infiltration rates. However, this is likely to be a rare occurrence due to high infiltration rates of the pavement.

CONTAMINANTS FROM FOUR NEW PERVIOUS AND IMPERVIOUS PAVEMENTS IN A PARKING LOT
William James and Michael K. Thompson- 1996

While the previous study described the design, construction, and instrumentation of four pavements in the laboratory and parking lot, this study reports on the interim conclusions obtained from the parking-lot pavements for the first year after installation. In addition to investigation of contaminants, temperature studies also were conducted. The Eco-Stone® pavement continued to show significant reductions in surface runoff contaminant loads.

THERMAL ENRICHMENT OF STORMWATER BY URBAN PAVEMENT
William James and Brian Verspagen - 1996

This study covers the thermal enrichment of surface runoff from impermeable asphalt and the Eco-Stone® porous concrete paver. Though more research was required, it was found that thermal enrichment of urban stormwater runoff should be considered when new development is proposed, and thermally-sensitive pavement materials should be used more extensively. The asphalt paving surface was found to increase the temperature of the runoff more than the Eco-Stone® pavement.

OBSERVATIONS OF INFILTRATION THROUGH CLOGGED POROUS CONCRETE BLOCK PAVERS
William James, Christopher Kresin and David Elrick - 1997

The purpose of this research was to test the hypothesis that, for a particular permeable paver (Eco-Stone®), infiltration capacities may be improved by simply street sweeping and/or vacuuming the surface. The research used data collected at several Eco-Stone® installations in the area. While studies showed infiltration capacity was reduced as the pavement aged, it was found that infiltration could be improved with removal of the top layer of drainage cell material. It was found that very little surface water runs off new installations of UNI Eco-Stone®, and that maintenance was recommended to renew infiltration capacity. Research also found that fines in the drainage cell material affected infiltration to a greater extent than organic material, which reinforces proper material specification guidelines be followed during installation.

A LABORATORY EXAMINATION OF POLLUTANTS LEACHED FROM FOUR DIFFERENT PAVEMENTS BY ACID RAIN
William James, Reem Shahin - 1998

In this study, the contaminants investigated were phenols, pH, zinc, iron, oils and grease. It was found that pH of rain is a significant factor, with asphalt having the least buffering, and that Eco-Stone reduced both runoff and contaminants.
the most. Percolation through the permeable pavement surface and underlying media slowed the water flow, allowing
more time for oxidation. It also was shown to filter suspended solids and some contaminants such as sodium and sulfates.
Heavy metal removal through percolation appeared to be good. Surface runoff from asphalt contained a higher mass of
all the parameters investigated compared to the Eco-Stone runoff. It was found that generally, while water is not
contaminated by the surface of the porous pavement, asphalt surfaces are made from petroleum products and some
pollutants such as oils, grease, and phenols would be generated from the surface. It was found the Eco-Stone 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.

FEASIBILITY OF A PERMEABLE PAVEMENT OPTION IN THE STORMWATER
MANAGEMENT MODEL (SWMM) FOR LONG-TERM CONTINUOUS
MODELLING

William James, Craig William Kipkie - 1998-9

This project focused on examining the feasibility of inserting new FORTRAN computer code into the USEPA's SWMM,
such that it would allow designers to simulate the hydrological response of permeable pavements in long-term modelling
applications. It was found that it was possible to insert new code, and the model produced reasonable results under a
generalized set of input conditions. Simulations showed that using permeable pavements can greatly reduce flows
compared to impervious surfaces.

STORMWATER MANAGEMENT MODEL FOR ENVIRONMENTAL DESIGN OF
PERMEABLE PAVEMENTS

William James, W. Robert C. James, and Harald von Langsdorff - 2000

This monograph details the underlying method and function of a free-ware program that uses the USEPA Stormwater
Management Model (SWMM) for the design of permeable pavement installations - PC-SWMM. The program allows
quick implementation of a BMP in SWMM and is very user-friendly. The SWMM code for groundwater and infiltration
has not been comprehensively tested against a specific permeable pavement field program due to lack of field testing to
date. PC-SWMM is a tool to aid designers and is intended for use by civil engineers that are competent in evaluation of
the significance and limitations of the computations and results. It is not a substitution for engineering judgement, nor is
it meant to replace the services of professional qualified engineers.

MAINTENANCE OF INFILTRATION RATES IN MODULAR INTERLOCKING
CONCRETE PAVERS WITH EXTERNAL DRAINAGE CELLS

William James and Christopher Gerrits - 2003

This report examines the effectiveness of methods used to restore the infiltration capacity of permeable pavers. The
decrease in infiltration capacity with age and increased traffic use was tested, and the possibility of street sweeping/
vacuuming the surface to maintain infiltration capacities of permeable pavers was investigated. The infiltration capacity
was dependent on the pavement usage, percentage of fine matter in the external drainage cell material and the bedding
layer gradation. Control of the amount of fine matter accumulating in the drainage cell material was found to be of
prime importance. This can be accomplished by periodic cleaning to keep the drainage cell material clear of fine matter.
Frequency of cleaning will be dependent on the pavement usage, as well as land-use practices on and adjacent to the
pavement. Tests indicated that the infiltration capacity of the pavement could be significantly improved by removing 10-
20mm (0.4-0.8 inches of drainage cell material). It was found that vegetation actually helped keep fine matter from
accumulating in the drainage cell material and that vegetation (especially coniferous trees) should be encouraged to grow
along side permeable pavements.
STUDIES ON THE ENVIRONMENTAL DESIGN OF PERMEABLE CONCRETE PAVING BLOCK PAVEMENT FOR REDUCING STRESSORS AND CONTAMINANTS IN AN URBAN ENVIRONMENT

William James - 2002

This paper discusses the impacts of urbanization - increased flow and contaminant loads to receiving waters and thermal enrichment. It states that BMPs for quantity control are being replaced by techniques that combine both stormwater quantity and quality control such as permeable pavements. Recent studies by the author on Eco-Stone® permeable pavements are reviewed. Discussion on construction, materials, and maintenance is included. Rates of infiltration reduction are discussed in relation to type of traffic usage.
ADDITIONAL UNI ECO-STONE® RESEARCH AND TESTING

FIELD EVALUATION OF PERMEABLE PAVEMENT SYSTEMS FOR IMPROVED STORMWATER MANAGEMENT

Professor Derek B. Booth and Graduate Research Assistant Jennifer Leavitt - 1999

This project (detailed in the report below) explored some practical implications of alternative stormwater management practices, with a focus on manufactured permeable pavers in parking areas. This report issued at a later date found differences in runoff responses between the permeable and impermeable surfaces to be quite dramatic and that permeable pavements are very successful at managing runoff from small and moderate storms. It found all permeable pavements studied accomplished the basic hydrological goal of infiltration well. However, they did differ in the ability to handle high traffic volumes and in appearance.

THE UNIVERSITY OF WASHINGTON PERMEABLE PAVEMENT DEMONSTRATION PROJECT

Professor Derek B. Booth, Jennifer Leavitt and Kim Peterson – Research Assistants - 1996

This project was initiated to review the types and characteristics of permeable pavements in the Pacific Northwest to provide potential users of these systems with information. They constructed a well-instrumented full-scale test site in a section of a new employee parking lot at the King County Public Works facility in Renton, WA, to evaluate the durability, infiltratability, and water-quality benefits of four types of permeable pavements - UNI Eco-Stone®, Grasspave2®, Gravelpave2® and Turfstone™. An additional section of impervious asphalt was constructed as a control. The intent of the project is to evaluate the long-term performance of the systems over a number of years. The study is being conducted in conjunction with King County, the City of Olympia, Washington State Department of Ecology, and the City of Renton. Initial results of this study showed the use of permeable pavements dramatically reduced surface runoff volumes and attenuated peak discharge and though there were significant structural differences in the systems, the hydrologic benefits were consistent. In addition, it was found that a significant contribution of permeable pavements is the ability to reduce effective impervious area, which has a direct connection to downstream drainage systems. As a result, it can be used to control runoff timing, reduce volume, and provide water quality benefits.

EXPERT OPINION ON UNI ECO-STONE® - PEDESTRIAN USE

Professor Burkhard Bretschneider - 1994

This report tested UNI Eco-Stone® for safety and walking ease under a pedestrian traffic application in the parking lot of the Lenze Company in Aerzen, Germany. Bicycles, wheel chairs, baby carriages, and foot traffic were tested. Ladies high heel shoes were tested for penetration depth in the drainage cell aggregate materials. The findings showed that proper filling and compaction of the drainage cell materials was important for good overall performance.

EXPERT OPINION - IN-SITU TEST OF WATER PERMEABILITY OF TWO UNI ECO-STONE® PAVEMENTS

Dr. Soenke Borgwardt - Institute for Planning Green Spaces and for Landscape Architecture - University of Hannover - 1994

Tests were performed on two UNI Eco-Stone® pavements of various ages at two different locations in Germany. A parking lot at the train station in Eldagsen was installed in 1992, while the Lenze Company parking lot in Gross Berkel was installed in 1989. The results showed that the Eldagsen site was capable of infiltrating 350 l/sec/ha, and even after 60 minutes, absorbed more than 200 l/sec/ha. At the Lenze site, the Eco-Stone® pavement was capable of infiltrating 430 l/sec/ha, and even after 60 minutes, a rainfall amount of 400 l/sec/ha was absorbed. Although the comparison shows that the older test area had a higher permeability than the newer installation, laboratory tests showed the lesser permeability values of the Eldagsen site were the result of the existence of fines. This reconfirms the recommendation for selecting proper gradation of drainage cell and bedding materials in the 2mm to 5mm range and that ASTM C-33 grading should not be used if infiltration is the primary function of the pavement.
DRAINAGE WITH INTERLOCKING PAVERS
Professor W. Muth – Research Institute for Water Resources - Karlsruhe University - 1994

The institute tested UNI Eco-Stone® pavers in comparison to traditional pavers for water permeability. Surface runoff and the associated drainage were measured under a variety of rainfall amounts and intensities.

DEVELOPMENT OF DESIGN CRITERIA FOR FLOOD CONTROL AND GROUNDWATER RECHARGE UTILIZING UNI ECO-STONE® AND ECOLOC® PAVING UNITS
Professor Thomas Phalen, Jr. – Northeastern University - 1992

The purpose of this research was to develop the technical data related to the paving system's permeability characteristics. This early research was expanded on in the Rollings and Texas A&M design manuals.

STRUCTURAL DESIGN SOFTWARE

LOCKPAVE® PRO
Dr. Brian Shackel

The LOCKPAVE® PRO computer program has been developed to assist design professionals in the structural design of interlocking concrete block pavements for a variety of applications, including streets, airport, and industrial projects. It provides a choice of mechanistic or empirical design methodology and offers the ability to select, analyze, and compare alternative pavement types. It also includes UNI Eco-Stone® permeable pavement hydraulic modeling based on the USEPA's SWMM model.

FEATURES OF PC-SWMM™ FOR PERMEABLE PAVEMENTS

- Allows user to develop a simple model of permeable pavement design, run the model with a specified design storm, and analyze the results of the model
- An Input Wizard interface guides the user through the required parameters
- Model results include graphs of the input function (design storm), surface runoff (if any), depth of water in the base material, and drainage of the base material for the duration of the model run
- A summary report includes user-defined input and tabulation of numerical results
- Features support for Run-On - flow contributions from adjacent impervious and pervious surfaces
- Incorporates new regeneration data from research studies
- The model accepts an arbitrary rainfall hyetograph and provides a step-by-step accounting (conservation of mass) of water movement through the permeable pavement installation, including surface detention, overland flow, infiltration, subsurface storage, and subsurface drainage

When designing Eco-Stone® pavements, please use LOCKPAVE® PRO first to establish the minimum requirements for the structural performance of the pavement. The program defaults to the most conservative parameters - very poor drainage conditions and saturation of the base more than 25% of the time - for its structural analysis. Then run PC-SWMM™ to see if your drainage design parameters are met. If the minimum base thickness established by LOCKPAVE® PRO is inadequate for your storage/drainage requirements, increase the base layer thickness step-by-step until your hydraulic parameters are met.
ECO-STONE® POWERPOINT PRESENTATION

This comprehensive slide/computer PowerPoint presentation is oriented to the design professional. It includes basic design guidance, hydraulic information, research information, and project references and is based on the Design Considerations for the UNI Eco-Stone® Concrete Paver by Rollings and Rollings.

CASE STUDIES

RIO VISTA WATER TREATMENT PLANT

*Case Study – 2-page*

Case study on the Castaic Lake Water Agency of Santa Clarita, CA project - Water Conservatory Garden and Learning Center Parking Lot. Features 27,000 sq ft parking lot installation of UNI Eco-Stone® permeable pavers.

MICKEL FIELD AND HIGHLANDS PARK

*Case Study – 2-page*

Case study on Mickel Field/Highlands Park of Wilton Manors, FL project - Renovation of community parks’ walkways and parking lots. Features over 37,000 sq ft of UNI Eco-Stone® permeable pavers.

JORDAN COVE URBAN WATERSHED STUDY

*Case Study – 4-page*

Case study is on an innovative research project funded in part by the Connecticut Department of Environmental Protection through the USEPA’s National Monitoring Program Section 319. Other participants in the project include the University of Connecticut Natural Resources Management and Engineering Dept., the town of Waterford, CT, and the developer John Lombardi. Over 15,000 sq ft of UNI Eco-Stone® pavers were used for the street cul-de-sac and driveways of some homes in the “paired watershed” development. A variety of BMPs have been incorporated into the site for long-term monitoring and comparison with traditional subdivision construction.

*Private Residence, Long Island, NY*
ADDITIONAL REFERENCES


Booth, D., J. Leavitt, and K. Peterson, 1995. *The University of Washington Permeable Pavement Demonstration Project - Background and First-Year Field Results*, University of Washington, Department of Civil Engineering, Seattle, WA.


The Asphalt Institute, 1989. The Asphalt Handbook, MS-4, Lexington, KY.


STORMWATER MANAGEMENT INSPECTION FORM
WATERSHED MANAGEMENT INSTITUTE AND USEPA

INfiltrATION PAVING CONSTRUCTION INSPECTION REPORT

DATE: ___________________________  INDIVIDUAL CONTACTED: ___________________________

PROJECT: ___________________________________________________________________________

LOCATION: ___________________________________________________________________________

SITE STATUS: _______ ACTIVE ________ INACTIVE ________ COMPLETED

<table>
<thead>
<tr>
<th></th>
<th>Satisfactory</th>
<th>Unsatisfactory</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Pre-construction</td>
<td>Runoff diverted</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Area stabilized</td>
<td></td>
</tr>
<tr>
<td>2. Excavation</td>
<td>Size and location conforms to plans</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Side slopes stable</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Soil permeability</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Groundwater/bedrock</td>
<td></td>
</tr>
<tr>
<td>3. Geotextile/Filter Fabric Placement</td>
<td>Fabric specification</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Placement conforms to specifications</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sides of excavation covered</td>
<td></td>
</tr>
<tr>
<td>4. Aggregate Base Course</td>
<td>Size as specified, sieve analysis conforms to spec</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Clean/washed material</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Thickness, placement, and compaction meets spec</td>
<td></td>
</tr>
<tr>
<td>5. Permeable Interlocking Concrete Pavers</td>
<td>Meets ASTM or CSA standards as applicable</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Elevations, slope, pattern, placement and compaction</td>
<td></td>
</tr>
<tr>
<td></td>
<td>as per specifications</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aggregate joint materials conform to specification</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Drainage or bio swales, vegetated areas for emergency runoff</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Overflow or pre-treatment for filtering runoff</td>
<td></td>
</tr>
<tr>
<td>6. Final Inspection</td>
<td>Elevation and slope conform to drawings</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Transitions to impervious pavement separated with</td>
<td></td>
</tr>
<tr>
<td></td>
<td>edge restraints</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Stabilization of soil in areas draining onto pavement</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(vegetative strips recommended)</td>
<td></td>
</tr>
</tbody>
</table>

Action to be taken:

No action necessary. Continue routine inspections

Correct noted site deficiencies by

1st notice ________________ 2nd notice ________________

Submit plan modifications as noted in written comments by

Notice to Comply issued ________________  Final inspection, project completed ________________
**STORMWATER MANAGEMENT INSPECTION FORM**  
**WATERSHED MANAGEMENT INSTITUTE AND USEPA**  
**INfiltration paving maintenance inspection report**

**DATE:** ___________________________________________ **TIME:** ___________________________

**PROJECT:**  

**LOCATION:**  

**Individual Conducting Inspection:** ___________________________ **“As built” plans available** Y/N

*Inspection frequency shown in parentheses*

<table>
<thead>
<tr>
<th>Inspection Item</th>
<th>Satisfactory</th>
<th>Unsatisfactory</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Debris on infiltration paving area (Monthly)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Vegetation areas (Monthly)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mowing done when needed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fertilized per specifications</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No evidence of erosion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Dewatering (Monthly)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Infiltration paving dewaters between storms</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Sediments (Monthly)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Area clean of sediments</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Area vacuum swept on a periodic basis as needed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Structural condition (Annual)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No evidence of surface deterioration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No evidence of rutting or spalling</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Inspection Frequency Key: Annual Monthly After major storm*

**Action to be taken:** ___________________________________________

If any of the answers to the above items is checked unsatisfactory, a time frame shall be established for their corrective action or repair.

*No action necessary. Continue routine inspections* ___________________________________________

Correct noted facility deficiencies by ___________________________________________

*Facility repairs were indicated and completed. Site reinspection is necessary to verify corrections or improvements.*

Site reinspection accomplished on ___________________________________________

Site reinspection was satisfactory. Next routine inspection is scheduled for approximately: ________________________

Signature of Inspector ___________________________________________