

UNI ECO-STONE®

FAMILY OF PERMEABLE INTERLOCKING CONCRETE PAVERS

DESIGN GUIDE & RESEARCH SUMMARY



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This manual is a summary of the Eco-Stone® family of permeable concrete pavers research and studies that have been conducted 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, articles or our new multi-project case study, call UNI-GROUP U.S.A. at 1-800-872-1864 or visit our web site at www.uni-groupusa.org.

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

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UNI® PERMEABLE PAVING PROJECTS

- Buckingham Fountain, Chicago, IL - 236,000 sf
- Triangle Parking Lot, Stone Mountain, GA - 160,000 sf
- US Cellular Field, Chicago White Sox, Chicago, IL - 265,000 sf
- Jordan Cove - Glen Brook Green Residential Development Waterford, CT - 15,000 sf
- Broadway West Retail Center, Forest Lake, MN - 43,000 sf
- McKinney Green Building, Platinum LEED® certified McKinney, TX - 80,000 sf
- Citi Field, Flushing, NY - 80,000 sf
- Whole Foods, Naperville, IL - 165,000 sf
- Stonehill College, Easton, MA - 20,000 sf
- White Mountain National Forest Headquarters, Campton, NH - 25,000 sf
- RI Para-Transit Maintenance Facility, Providence, RI - 40,000 sf
- Center Street Village, Mentor, OH - 110,000 sf
- Aurora Police Station, Chicago - 92,000 sf
- Morton Arboretum, DuPage County, IL - 173,000 sf
- Westmoreland Street, Portland, OR - 19,000 sf
- City of Grand Rapids Water Systems Offices, MI - 11,000 sf
- Goodbys Marina, City of Jacksonville, FL - 24,000 sf
- Evergreen State College, Olympia, WA - 47,000 sf
- Autumn Trails Residential Development, Moline, IL - 39,000 sf
- Anchorage Inn, York, ME - 20,000 sf
- Rio Vista Water Treatment Plant Castaic Lake Water Agency, Santa Clarita, CA - 27,000 sf
- Ash Avenue Park & Ride, Marysville, WA - 30,600 sf
- East Gwillimbury Go Commuter Train Station, New Market, ON - 30,000 sf
- The College School of Webster Groves, St. Louis, MO - 20,000 sf
- Springbrook Prairie Market, Naperville, IL - 150,000 sf
- City of Tacoma Parking Lot Test Project, Tacoma, WA - 9,000 sf
- Dow, Howell, Gilmore Associates, Inc., Midland, MI - 12,000 sf
- Waubensee Parking Lot W, Sugar Grove, IL - 77,000 sf
- Mickel Field & Highlands Park, Wilton Manors, FL - 37,165 sf
- State Ave. Parking Lot, Marysville, WA - 13,000 sf
- Earth Rangers Centre, Woodbridge, ON - 8,800 sf
- Orland Park Police Headquarters, Orland Park, IL - 80,000 sf
- Minnesota Landscape Arboretum, Chanhassen, MN - 2,000 sf
- Couch Place, Green Alley in Theatre District Chicago, IL - 3,000 sf
- Wilcox Lake Park, City of Richmond Hill, Oakridges, ON - 8,000 sf
- The Marina Grande, Riviera Beach, FL - 10,000 sf
- Medina Development, Spanaway, WA - 18,000 sf
- Tri-Met Merlo Road Development, Beaverton, OR - 18,000 sf
- Aquascapes Parking Lot, St. Charles, IL - 50,000 sf
- City of Ankeny, IA - 8,000 sf
- Cascades Park, Bloomington, IN - 40,000 sf
- Tacoma Community College, Tacoma, WA - 85,000 sf
- Annsville Creek, Peekskill, NY - 20,000 sf
- Lake Forest High School, Lake Forest, IL - 45,000 sf
- Calvary Chapel, Olympia, WA - 9,000 sf
- Job Corp Service Center, Grand Rapids, MI - 9,000 sf
- Maxwell Market Improvements, Chicago, IL - 45,000 sf
- Private Residence, Mercer Island, WA - 6,000 sf
- Bioline, Portland, OR - 4,000 sf
- Whole Foods Market, Chicago, IL - 29,000 sf
- SWT and Associates, St. Louis, MO - 8,000 sf
- Bethel University, Minneapolis, MN - 50,000 sf
- Snoqualmie Fire Station, Snoqualmie, WA - 1,800 sf
- 7th District Police Station, Chicago, IL - 41,000 sf
- Homestead Village VI, Dallas, TX - 3,000 sf
- West Seattle High School, Seattle, WA - 2,200 sf
- Humberwood Development Center, Etobicoke, ON - 9,000 sf
- Drake Hill Commons, North Hampton, NH - 15,000 sf
- South Lake Union Streetcar Maintenance Facility, Seattle, WA - 5,500 sf
- Warrenville Road, Warrenville, IL - 40,000 sf
- Amtrak Station, Grand Rapids, MI - 4,000 sf
- Kean Design, Winter Park, FL - 3,000 sf
- Crazy Crab Restaurant, Hilton Head, SC - 900 sf
- Olympia School District Facility, Olympia, WA - 3,400 sf
- Geneva Water Treatment Facility, Geneva, IL - 29,000 sf
- Hopworks Urban Brewery, Portland, OR - 6,000 sf
- Minneapolis Animal Shelter, MN - 10,000 sf
- Lake Hills Farmer's Market, Bellevue, WA - 1,500 sf
- Kane County Cougars Stadium, Geneva, IL - 210,000 sf
- Conservation & Restoration NW Railway Parking Lot Snoqualmie, WA - 9,000 sf
- The Streeter Building, Chicago, IL - 7,700 sf
- Twin County Credit Unit, Lacey, WA - 80,000 sf
- Montgomery Village Hall, IL - 14,000 sf
- Mason Brown & Associates, Auburn Hills, MI - 6,000 sf
- Golf View Plaza, Carpentersville, IL - 22,000 sf
- Auburn Way S. Safety Improvements, Auburn, WA - 5,000 sf
- Howland Hook, Port of New York/New Jersey, Staten Island, NY - 15,000 sf
- City Escapes Parking Lot, Chicago, IL - 17,000 sf
- Vineyard Lanes, Bainbridge Island, WA - 16,000 sf
- Easy Street, Ann Arbor, MI - 15,000 sf
- Terra Springs, Stillwater, MN - 48,000 sf
- Lowes/Safeway Parking Lot - Lacey, WA - 27,000 sf
- Residential Housing Development, Hilton Head Island, SC - 1,800 sf
- Queenquay Community Center - Toronto, ON - 3,000 sf
- City of Anna Maria, FL - 3,000 sf
- Southgate Market, Chicago, IL - 15,200 sf
- Development, Costa Mesa, CA - 8,000 sf
- Wynnsong Cinemas, Savannah, GA - 10,000 sf
- Tanglewood Park, Batavia, IL - 14,000 sf
- Redwood Village Condominiums, Woodinville, WA - 8,000 sf
- Private Residence, Winter Park, FL - 14,000 sf
- Regent Court Apartments, Vero Beach, FL - 5,500 sf
- Parkside at Cabrini, Chicago, IL - 13,000 sf
- Seattle Center Mural Stage, Seattle, WA - 2,000 sf
- Harbourfront Fire Station No. 9, Toronto, ON - 7,000 sf
- Jurgens Park, Tualatin, OR - 4,500 sf
- Ground Effects, Yorkville, IL - 12,000 sf
- Rail Road Avenue, Bellingham, WA - 6,000 sf
- Wayne Road Apartment Complex, Detroit, MI - 3,000 sf
- Sherwood Island State Park, Westport, CT - 32,000 sf
- 4th Street Parking Lot, La Center, WA - 40,000 sf
- Corkscrew Swamp State Park, Naples, FL - 2,500 sf
- Kane County Government Center, Geneva, IL - 9,000 sf
- Gorman/Fitchburg, Fitchburg, WI - 5,500 sf
- Choix Nursery, Marysville, WA - 5,700 sf
- Trinity United Church, Grimsby, ON - 10,000 sf
- Commercial Parking Lot, Nantucket, MA - 23,000 sf
- Holbrook Avenue, Everett, WA - 6,000 sf
- Newark International Airport, Newark, NJ - 262,000 sf
- Ford Canada Corporation, Oakville, ON - 2,500 sf
- Bloomfield Township Residences, Bloomfield, MI - 3,000 sf
- Lewis County Parking Lot, Chehalis, WA - 5,700 sf
- Suave Island Boat Ramp Parking Lot, Suave Island, OR - 2,000 sf
- City of Clear Lake, IA - 5,000 sf
- Highpoint Development, West Seattle, WA - 11,000 sf
- Villa Park Police Station, Villa Park, IL - 6,000 sf
- Multnomah Arts Center - Portland, OR - 10,500 sf
- Sand Dollar Resort & Time Share, Sanibel Island, FL - 28,000 sf
- Bed, Bath & Beyond, Hyannis, MA - 19,000 sf
- Snoqualmie Train Museum, Snoqualmie, WA - 4,000 sf
- Dominican University, River Forest, IL - 120,000 sf
- Tualatin Police Station, Tualatin, OR - 2,500 sf
- Artesia Condominium, Cape Canaveral, FL - 4,500 sf
- Lewis Wetlands Stewardship Project, La Center, WA - 20,000 sf
- Wings of Imagination Parking Lot - Key West, FL - 2,400 sf
- Macomb County Road Commission Headquarters, MI - 1,000 sf
- Lucky Labrador Brew Pub, Multnomah, OR - 3,800 sf
- Private Residence, Mercer Island, WA - 2,700 sf
- CVS Parking Lot, Yarmouth, MA - 4,500 sf
- Seneca College, Toronto, ON - 3,150 sf
- Wedge Park Phase II, Fife, WA - 3,600 sf

For updated project lists visit www.uni-groupusa.org.

DEVELOPMENT, IMPERVIOUS COVER AND THE IMPACTS OF STORMWATER RUNOFF

With ever-increasing levels of development, natural, undisturbed land is rapidly being replaced with impervious surfaces such as asphalt roadways, parking lots, and buildings. As a result, the management of increased levels of stormwater runoff and its impact on the environment has become a major issue for all levels of government throughout the country. Numerous studies indicate that stormwater runoff is the primary source of pollutants found in surface



Drake Hill Commons, North Hampton, NH

waters and contains a toxic combination of oils, pesticides, metals, nutrients, and sediments. Additionally, research has shown that once a watershed reaches just 10% impervious surface cover, water resources are negatively impacted. 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.

Increasing stormwater runoff levels also are negatively impacting aging and outdated storm sewer systems across the country, particularly in urban areas. Municipalities will either be forced to replace and update their sewer systems at enormous cost to their residents or manage their stormwater runoff in other ways.

In the early 1990s, the United States Environmental Protection Agency (EPA) established the National Pollutant Discharge Elimination System (NPDES) stormwater regulations to comply with the requirements of the Clean Water Act. Compliance with federal, state, and local stormwater programs involves the use of "best management practices" (BMPs) to manage and control stormwater runoff. 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 approaches that integrate control of stormwater and protection of natural systems.

In 1999 and 2001, the International City/County Managers Association (ICMA) and the EPA released the framework for "Smart Growth" policies that communities around the country could adopt to meet environmental, community, and economic goals. Simultaneously, organizations such as the Low Impact Development Center and the Center for Watershed Protection began advocating low impact development (LID) as a way to preserve and protect the nation's water resources. They promote comprehensive land planning and engineering design, watershed planning and restoration, and stormwater management approaches that protect water resources and attempt to maintain pre-existing hydrologic site conditions. Their goal is to achieve superior environmental protection, while allowing for sustainable development.

The EPA began working with these organizations in 2006 to promote the use of LID and Smart Growth as a way to manage stormwater runoff. The goal is to protect water resources at the regional level by encouraging states and municipalities to implement policies that consider both growth and conservation simultaneously. These approaches are quickly gaining favor across the country and are being incorporated into local development regulations to help meet stormwater runoff requirements and provide more livable, sustainable communities. One of the primary goals of LID design is to reduce runoff volume by infiltrating rainwater on site and to find beneficial uses for the water as opposed to utilizing storm drains. LID objectives include the reduction of impervious cover, preservation of natural landscape features, and the maximization of infiltration opportunities. Infiltration helps recharge groundwater, reduces urban heat island effects, and reduces downstream erosion and flooding. This allows development to occur with much less environmental impact.

In addition, the EPA is working with the U.S. Green Building Council to incorporate more stormwater aspects into its Leadership in Energy and Environmental Design (LEED®) green building assessment system. The LEED® system is increasingly being adopted by cities and states across the country that now require municipal buildings to meet minimum certification standards.



Buckingham Fountain, Chicago, IL

As the end of the EPA's NPDES permit cycle is approaching for many municipalities, the EPA will be focusing on transitioning into fully implementing and improving the operational phase of the program. The EPA may begin to establish ordinances to move the program in the direction of preferred design and best management practices and provide additional guidance for municipalities. The EPA already offers extensive information and guidance manuals such as *National Menu of BMPs*, *National Urban Management Measures Guidance*, *Using Smart Growth Techniques as Best Management Practices*, *Protecting Water Resources with Higher Density Development*, and *Parking Spaces/Community Places, Finding the Balance Through Smart Growth Solutions*.

The EPA also is developing a comprehensive guide for Phase II communities on post-construction practices in conjunction with the Center for Watershed Protection. This will include detailed guidance on program setup, creating ordinances, Smart Growth, LID, and more. For more information and links to these manuals, please visit our web site at www.uni-groupusa.org.

THE UNI ECO-STONE® FAMILY OF PERMEABLE PAVERS... THE SOLUTION TO STORMWATER RUNOFF PROBLEMS

Permeable interlocking concrete pavements (PICPs) are becoming increasingly popular as more cities and states are faced with meeting stormwater runoff regulations, increased impervious cover restrictions, and the adoption of LID or LEED® practices.

The Eco-Stone® family of permeable interlocking concrete pavers is comprised of a number of paver designs that mitigate stormwater runoff through infiltration. This allows for reduction of volume and peak flows, improved water quality, filtering of pollutants, mitigation of downstream flooding and erosion, and recharge of groundwater. UNI® permeable pavers, Eco-Stone®, Ecoloc®, Eco-Optiloc®, and Eco-Priora®, feature true interlocking designs that offer the structural support, durability, and beauty of traditional concrete pavers, combined with the environmental benefit of permeability. The permeability is achieved through the drainage openings and joints in the pavement surface. Measurements of the original UNI Eco-Stone® paver and physical characteristics are shown in Figure 1.



Physical Characteristics - UNI Eco-Stone®	
Height/Thickness	3 1/8" = 80 mm
Width	4 1/2" = 115 mm
Length	9" = 230 mm
Pavers per sq ft	= 3.55
Percentage of drainage void area per sf	= 12.18%
Flow rate through Eco-Stone voids	= 1872 in./hr
Composition and Manufacture	
Minimum compressive strength - 8000psi	
Maximum water absorption - 5%	
Meets or exceeds ASTM C-936 and freeze-thaw testing per section 8 of ASTM C-67.	

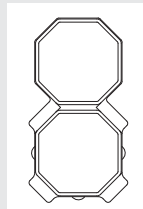


Figure 1

The drainage openings in an UNI® permeable pavement are created when the pavers are installed (Figure 2). This is what distinguishes the Eco-Stone® family of permeable pavers from traditional interlocking concrete pavers. The drainage openings are filled with a clean, hard crushed aggregate that is highly permeable, allowing for rapid infiltration of stormwater (Figure 3).

ECO-STONE® PERMEABLE PAVEMENT AS AN EPA BEST MANAGEMENT PRACTICE

The EPA encourages "system building" to allow for the use of appropriate site-specific practices that will achieve the minimum measures under Phase II of NPDES. Governing authorities must develop and implement strategies that include a combination of structural and/or non-structural BMPs appropriate for their communities. Structural practices include storage practices, filtration practices, and infiltration practices that capture runoff and rely on infiltration through a porous medium for pollutant reduction. Infiltration BMPs include detention ponds, green roofs, bioswales, infiltration trenches, and permeable pavements. Non-structural practices are preventative actions that involve management and source controls. Many states and municipalities have incorporated the EPA regulations into their stormwater design manuals as to deal with increased impervious cover, stormwater runoff, and over-taxed drainage and sewer systems.

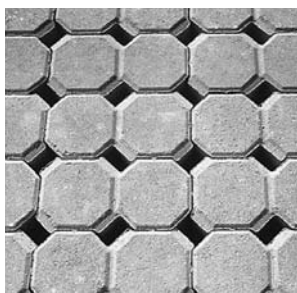


Figure 2

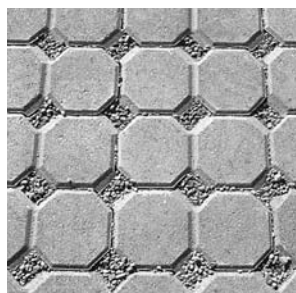


Figure 3



Mickel Field/Highlands Park, Wilton Manors, FL

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. 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.

PICPs are considered structural BMPs under infiltration practices. From an engineering viewpoint, permeable pavements are essentially infiltration trenches with paving on top that supports pedestrian and vehicular traffic. By combining infiltration and retention, Eco-Stone® permeable interlocking concrete pavements offer numerous benefits over other types of structural

infiltration systems. Permeable pavements work well in conjunction with other recommended BMP infiltration practices such as swales, bioretention areas, and rain gardens.

ECO-STONE® FAMILY OF PERMEABLE PAVERS AND LID, LEED® AND GREEN BUILDING

LID has emerged as an attractive approach to controlling stormwater pollution and protecting watersheds. With reduction of impervious surfaces a major tenant of Low Impact Development, permeable and porous pavements, such as UNI® permeable pavers, are promoted as one of the ten most common LID practices. The use of site-scale technologies, such as PICPs that control runoff close to the source, closely mirror the natural process of rainwater falling onto undeveloped areas and infiltrating into the earth. With many areas of the country experiencing severe droughts, groundwater recharge issues, and increasing water pollution, LID and Smart Growth approaches will not only help alleviate these problems, but also create cities that are more energy efficient, environmentally sustainable, and cost effective. Recently, several areas in the United States have experienced the worst drought conditions in recorded history. The drought is so severe in some cases, that potable water supplies for many cities are being impacted. Infiltration technologies advocated by LID and green building, such as PICPs, offer a way to help filter precious rainwater back into the earth and recharge groundwater.

The LEED® green building assessment system has become increasingly popular with the North American design community since its inception in 1998. This voluntary building system for rating new and existing commercial, retail, institutional, educational, neighborhood, and residential buildings evaluates environmental performance from a “whole building” perspective over the project’s life cycle. The minimum number of points or credits for a project to be LEED® certified is 26, though silver (33-38 points), gold (39-51 points), and platinum (52-69 points) ratings also are available. The Eco-Stone® Family of Permeable Pavements may qualify for up to 14 points under the Sustainable Sites (SS), Material and Resources (MR), and Innovation and Design Process (ID) credits. While traditional concrete pavers also may qualify under some of the credits, PICP can earn LEED® points via Sustainable Sites stormwater management credits by meeting water quality and runoff treatment criteria. Some of the most easily attainable credits include:

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



Aurora Police Station, IL

• **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).

For additional LEED® credits, please see our web site or ask your UNI® manufacturer for a copy of the Interlocking Concrete Pavement Institute's Tech Spec 16 - *Achieving LEED® Credits with Segmental Concrete Pavements*.

For many years, most home builders and developers were wary of green building practices. However, with impervious cover restrictions, increasing costs of energy, and concern over environmental impacts now beginning to affect residential projects, the National Association of Home Builders is encouraging the use of "green" products in single and multi-family developments. They have developed a comprehensive guide on green building that promotes mixed-use developments, cluster housing, green technologies and materials, and alternative stormwater approaches. UNI® permeable pavements offers an attractive solution to meeting impervious cover restrictions and is a green technology that offers added beauty, durability, and value to residential projects.



Highpoint Development, West Seattle, WA

ECO-STONE® AND MUNICIPAL STORMWATER MANAGEMENT OBJECTIVES

Municipal regulations for managing stormwater runoff vary across the country due to rainfall amounts, geography, climate, and land-use development patterns. Water quality and/or quantity may be regulated, with criteria for reducing water pollutants such as nitrogen, phosphorous, nitrates, metals, and sediment. Municipal policy, design criteria, and local experience usually govern the use of infiltration systems such as permeable pavements. Many municipalities now restrict the amount of impervious surfaces for virtually all types of construction, including private residences. In addition, thousands of municipalities have created stormwater utilities to fund the increasing costs of managing stormwater. These fees vary, but are usually based on runoff volumes and percentage of impervious cover on a lot. Regional authorities, counties, and municipalities may use a number of design objectives for managing stormwater runoff from a site. These may include:

- Limiting impervious cover to reduce stormwater runoff and pollutants from developments
- Capturing the entire stormwater volume so there is zero or no discharge from the drainage area
- Capturing and treating stormwater runoff to remove a stated percentage of pollutants - this will become increasingly important for managing Total Maximum Daily Loads (TMDLs)
- Capturing and treating a fixed volume of runoff, typically 0.75-1.5 in. (18-40 mm), which usually contains the highest level of pollutants
- Maintaining runoff volumes generated by development at or near pre-development levels
- Maintaining groundwater recharge rates to sustain stream flows and ecosystems and recharge aquifers
- Mitigating streambank erosion and enhancing stream channel protection by infiltration and detention of runoff volume from a given design storm
- Reducing downstream flooding by keeping the post-development peak discharge rate equal to the pre-development rate for a given design storm

The Eco-Stone® family of permeable interlocking concrete pavements may offer solutions for attaining all of these goals and design objectives. PICP can reduce runoff volumes and flows, mitigate downstream erosion and flooding, and recharge groundwater where existing site soils are suitable for infiltration. It also can filter pollutants with removal rates of up to 95% total suspended solids, 70% total phosphorous, 51% total nitrogen, and 99% zinc. Reducing runoff also may offer property owners reductions in stormwater utility fees where municipalities have established them to fund increasing costs due to stormwater runoff.

FEATURES AND BENEFITS OF THE UNI ECO-STONE® FAMILY OF PERMEABLE PAVERS

UNI® permeable pavers are attractive, yet durable pavements that can be used for residential, commercial, institutional, and recreational pedestrian and vehicular applications. Eco-Stone® permeable pavements are a site-scale infiltration technology that is ideal for meeting the EPA's NPDES regulations, LID and Smart Growth objectives, LEED® certification, municipal and regional impervious cover restrictions, and green building requirements.

- Can be designed to accommodate a wide variety of stormwater management objectives
- Runoff reductions of up to 100% depending on project design parameters - 100% permeable surface utilizes natural infiltration through aggregate-filled openings and joints to reduce runoff
- Maximizes groundwater recharge and/or storage and can be used with rainwater harvesting technologies for the retention and storage of stormwater for re-use for irrigation or other non-potable applications
- Can be used with underground stormwater storage systems over slow-draining soils
- Reduces nonpoint source pollutants in stormwater, thereby mitigating impact on surrounding surface waters, and may lessen or eliminate downstream flooding and streambank erosion
- Treats stormwater by slowing runoff velocities to allow for sedimentation and filtering by aggregates in the openings/joints and base and bioremediation.
- Minimizes impacts and stress on existing storm sewer systems through reduced peak discharges - can reduce peak flows by as much as 89% and delay timing of peak runoff flow from several hours to several days
- Allows better land-use planning and more efficient use of available land for greater economic value, especially in high-density urban areas, and may decrease project costs by reducing or eliminating drainage and retention/detention systems and lower stormwater utility fees
- May reduce heat island effect and thermal loading on surrounding surface waters

Examples of pollutant removal rates for Eco-Stone® are shown here. This data is from the Jordan Cove Urban Watershed Project Annual Report by the University of Connecticut (see research section of this manual), which conducted monitoring on this EPA Section 319 National Monitoring Project. According to the Jordan Cove Urban Watershed web site, the stormwater runoff volume from the LID subdivision after construction was *42% less* than runoff from the site *prior to development*. In virtually all cases, development typically creates more runoff from the site. For more information on Jordan Cove, visit our web site at www.uni-groupusa.org.

Variable	Asphalt	Eco-Stone Pavement	Crushed Stone
Runoff depth, mm	1.8 a	0.5 b	0.04 c
Total suspended solids, mg/l	47.8 a	15.8 b	33.7 a
Nitrate nitrogen, mg/l	0.6 a	0.2 b	0.3 ab
Ammonia nitrogen, mg/l	0.18 a	0.05 b	0.11 a
Total Kjeldahl nitrogen, mg/l	8.0 a	0.7 b	1.6 ab
Total phosphorous, mg/l	0.244 a	0.162 b	0.155 b
Copper, ug/l	18 a	6 b	16 a
Lead, ug/l	6 a	2 b	3 b
Zinc, ug/l	87 a	25 b	57 ab

Table 1. Mean weekly pollutant concentration in stormwater runoff from asphalt, Eco-Stone® and crushed stone driveways
 Note: Within each variable, means followed by the same letter are not significantly different at $\alpha = 0.05$

The manufacturers of UNI-GROUP U.S.A. were the first interlocking concrete paver producers to introduce permeable pavers to North America in 1989. As leaders in the industry for more than 35 years, we have been at the forefront of new product development, technologies and advancements to meet the needs of an ever-changing marketplace. We have millions of square feet of PICP projects throughout North America, including residential, commercial, municipal, and even industrial applications, and we offer unmatched expertise in the field.

ECO-STONE® DESIGN AND GENERAL CONSTRUCTION GUIDELINES

UNI-GROUP U.S.A. offers a variety of tools for designing the Eco-Stone® family of permeable pavements. Research on UNI® permeable pavers has been conducted at major universities such as Texas A&M, University of Washington, and Guelph University, and pollution monitoring has been conducted at EPA Section 319 National Monitoring Program sites Jordan Cove Urban Watershed Project in Connecticut and Morton Arboretum in Illinois. We offer design manuals, case studies, and Lockpave® Pro structural interlocking pavement design software, featuring PC-SWMM™ PP for the hydrologic design of UNI® 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



Rainwater Runoff Model - Minnehaha Creek Watershed District, MN

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™ PP software is a tool to aid design professionals and provides general hydrologic design guidance that is not intended to supercede a professional engineer's site-specific project design.

Eco-Stone® and Ecoloc® are featured in the book *Porous Pavements* by Bruce Ferguson, a national authority on stormwater infiltration. And, as members of the Interlocking Concrete Pavement Institute, our manufacturers can offer additional design and reference information, such as ICPI's *Permeable Interlocking Concrete Pavements* manual, which offers detailed design specification guidance, Tech Specs™ and CAD digital files.

It is recommended that a qualified civil engineer with knowledge in hydrology and hydraulics be consulted for applications using permeable interlocking concrete pavement to ensure desired results. Information provided in this guide is intended for use by professional designers and is not a substitute for engineering skill or judgment. It provides an overview of construction guidelines and research to date and is not meant to replace the services of experienced, professional engineers

Permeable interlocking concrete pavements require greater initial site evaluation and design effort compared to traditional concrete paver installations. They require a greater level of construction skill, inspection during construction and after installation, and attention to detail. In addition, maintenance is an important design aspect to help ensure long-term pavement performance.



Testing infiltration at the Rainwater Runoff Model

Design Options - Full, Partial and No Subgrade Soil Infiltration

The Eco-Stone® family of permeable pavements can be designed with full, partial, or no infiltration into the soil subgrade. Optimal installation is infiltration through the base aggregate, with complete exfiltration into a permeable subgrade. This allows for not only runoff and pollutant reduction, but also groundwater recharge. For full subgrade soil infiltration under vehicular loads, the minimum soil infiltration rate is typically 0.52 in./hr (3.7×10^{-6} m/sec). For maximum infiltration, subgrade soils should have less than 5% passing the No. 200 (0.075 mm) sieve, though up to 25% passing may be adequate for drainage depending on site conditions and other characteristics. PICP may be used over clay or other low-permeability soils through the incorporation of drainage pipe or with stormwater storage systems that allow slow exfiltration into the soils. However, the soils must be stable while saturated, especially under vehicular loading.

Where soils have extremely low or no permeability, a high water table, poor soil strength, or in areas over aquifers where there isn't sufficient depth of the soil to filter pollutants, no subgrade soil infiltration should occur, and an impermeable liner and perforated pipe is utilized to drain all stored water to an outfall pipe. This design still allows for infiltration of stormwater and some filtering of pollutants and slows peak rates and volumes, so it still can be beneficial for managing stormwater.

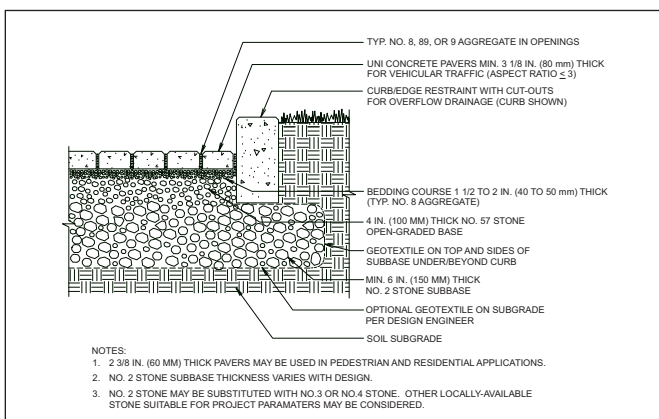


Figure 4 - Typical Cross-Section of an Eco-Stone® Permeable Pavement Full Infiltration into Subgrade Soils

It may also be possible to collect this water for further treatment. 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 pipe extended through this layer into the soil with greater permeability. For extreme rainfall events, if any overflow occurs, it can be controlled via perimeter drainage to bio-retention areas, grassed swales, or storm sewer inlets.

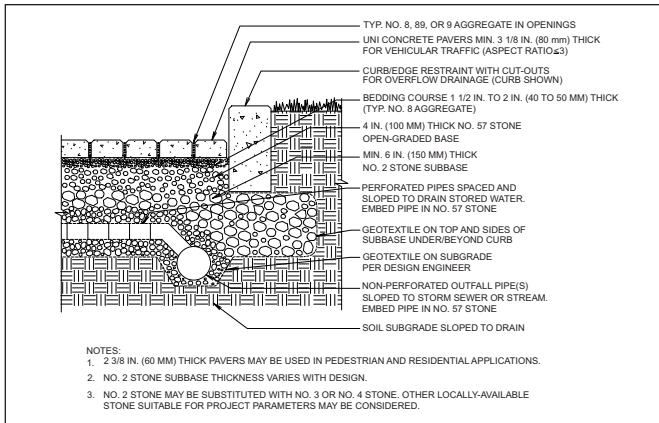


Figure 5 - Typical Cross-Section of an Eco-Stone® Permeable Pavement Partial Infiltration into Subgrade Soils

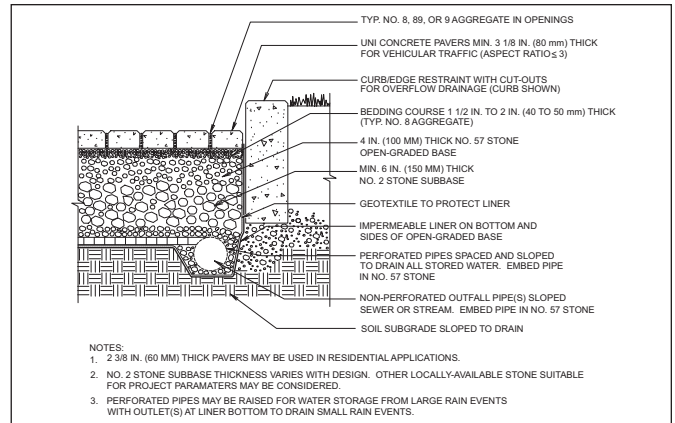


Figure 6 - Typical Cross-Section of an Eco-Stone® Permeable Pavement No Infiltration into Subgrade Soils

Site Selection Guidelines

UNI® permeable interlocking concrete pavers can be used for a wide variety of residential, commercial, municipal and industrial (Ecoloc® and Eco-Optiloc®) applications. They can be used for parking lots, driveways, overflow parking, emergency lanes, boat ramps, walkways, low-speed roadways, and storage facilities. Permeable or porous pavements should not exceed 5% slope for maximum infiltration. In addition to some of the guidelines previously described, permeable pavements should typically be sited at least 100 ft (30 m) from water supply wells, streams, and wetlands, though local jurisdictional regulations may supercede these guidelines. The minimum estimated depth from the bottom of the pavement base to the high level of the water table should be greater than 2 ft (0.6m) to allow for filtration of pollutants through the soils.

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.



Snoqualmie Fire Station, WA



Residential Development, Costa Mesa, CA

Infiltration Rate Design

Permeable interlocking concrete pavements are typically designed to infiltrate frequent, short duration storms. Well-maintained PICP can reduce runoff volumes from intense rainstorms, typically by 70-90%. It may be possible to manage runoff volumes from larger storms, including 100-year storms, through engineering design and the use of complementary best management practices, such as bio-retention areas and vegetated swales.

One of the most common misconceptions when designing or approving permeable interlocking concrete pavement is the assumption that the amount or percentage of open surface area of the pavement is equal to the percentage of perviousness. For example, a designer or municipal agency might incorrectly assume that a 15% open area is only 15% pervious. In 1992, Professor Thomas Phalen, Jr. tested the flow-through rate of the drainage openings in Eco-Stone® pavements at 1872 in./hr. While this is very high, the permeability and amount of infiltration are also dependent on the infiltration rates of the aggregates used for the joint and drainage openings, the bedding, base, and subbase, and ultimately, the subgrade.

Compared to soils, the materials used in Eco-Stone® permeable pavement systems have very high infiltration rates – from 500 in./hr (over 10⁻³ m/sec) to over 2000 in./hr (over 10⁻³ to 10⁻² m/sec). This is far more pervious than any existing site soils.

Though initial infiltration rates are very high, it is important to consider *lifetime* design infiltration of the entire pavement cross-section, including the soil subgrade when designing PICPs. As lifetime design infiltration rates may be difficult to predict, designers may want to use a conservative approach when calculating the design infiltration rate. Based on research to date, a conservative design rate of 10 in./hr (25 cm/hr) can be used as the basis for the design surface infiltration rate over a 25-year pavement life in case the pavement is not maintained.

Approximate Particle Size	Permeability (k) in./hr (m/s)
ASTM No. 8 (2 to 10 mm)	4000 to 1400 (3 x 10 ⁻¹ to 1 x 10 ⁻²)
ASTM No. 9 (2 to 5 mm)	1400 to 140 (1 x 10 ⁻² to 1 x 10 ⁻³)
ASTM No. 10 (1 to 3 mm)	140 to 14 (1 x 10 ⁻³ to 1 x 10 ⁻⁴)

Table 3. Permeability ranges of joint fill aggregates for permeable pavers (after Borgwardt 2006)

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. Infiltration tests conducted by Dr. Soenke Borgwardt in 2006 demonstrated that newly installed pavements, with an approximate 12% open surface area and a 2-5 mm drainage void fill aggregate, infiltrated approximately 62 in./hr (1300 l/s ha). After 10 years, the infiltration rate was approximately 16 in./hr (1300 l/s ha). His data showed that even with minimal maintenance, the pavements were capable of infiltrating virtually any design storm. 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 optimal long-term performance. With optimal construction and maintenance, longer-term infiltration rates of 50 in./hr (1270 mm/hr) or more are possible.

A number of design methods may be used for sizing of the open-graded base. The *ICPI Permeable Interlocking Concrete Pavement* manual uses a design method adapted from the state of Maryland's *Standard Specifications for Infiltration Practices* and *Maryland Stormwater Manual*. You may obtain a copy of ICPI's manual from your local UNI® manufacturer. The method assumes familiarity with NRCS TR 55 method for calculating stormwater runoff.

For designers who use Natural Resources Conservation Service (NRCS) curve numbers in determining runoff calculations, the curve number for PICP can range from 45-80 depending on soil type - by comparison, impervious asphalt or concrete ranges from 95-98. Other design professionals may use coefficient of runoff for calculating peak runoff discharges. These values depend on existing soil infiltration rates, base storage capabilities, and area design storms, though in all cases, they are significantly less than impervious pavements. Research to date has shown PICP has a C value range of 0.00-0.30. For peak runoff calculations, the coefficient of runoff, C for the design life of permeable interlocking concrete pavements can be estimated with the following formula:

$$C = \frac{I - \text{Design infiltration rate, in./hr}}{I}$$

where I = design rainfall intensity in inches per hour. The formula should not be used in water quality calculations however, as it does not account for volume.

Other quantitative models such as HEC-1 and EPA SWMM may be modified to include permeable interlocking pavements. The PC-SWMM™ PP software program included with our Lockpave® Pro structural design software is based on the EPA's model and also may be used for calculations.

Construction Materials and General Installation Guidelines

It is preferable and highly recommended that site subgrade soils not be compacted if structural strength is suitable, as compaction reduces infiltration rates. Design procedure typically assumes a soil CBR (minimum 96-hour soaked per ASTM D 1883 or AASHTO T 193) strength of at least 5% or an R-value of 24 to support vehicular traffic. Low CBR soils (<5%) may require compaction and/or stabilization for vehicular traffic applications. Perforated pipe also would typically be required to drain excess water in the base in applications over low CBR soils. Applications subject to strictly



The College School of Webster Groves, St. Louis, MO

pedestrian traffic should not require compaction of the subgrade. *If soils must be compacted, the reduced infiltration rates must be factored into the design.* Care should be taken during excavation and tracked vehicles should be used to minimize inadvertent compaction.

A civil or geotechnical engineer experienced in local site conditions and stormwater management should be consulted to ensure all project parameters and objectives are met and to determine the suitability of the site for permeable pavement installation. 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. *It is of utmost importance to prevent sediment from entering the base and pavement surface during construction of permeable interlocking concrete pavements.* Use of construction controls such as silt fences and drainage swales is encouraged and care should be taken to stabilize the surrounding areas that will drain on to the pavement prior to the pavers receiving runoff.



Mechanical Installation of Ecoloc® Permeable Pavers

PICPs are frequently built over open-graded aggregate bases consisting of washed, hard, crushed stone, though successful installations have utilized other aggregate materials, including dense-graded, when infiltration rates and storage capacities are suitable (see helpful design tools Lockpave® Pro and PC-SWMM™ PP on page 56). Generally, stone materials used for PICP bases should have less than 1% fines passing the No. 200 sieve. Geotextiles may be used in some PICPs, but are optional when using a No. 2 or 3 aggregate subbase as described below. If filter criteria between the pavement layers (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 may be used. Consult AASHTO for information on geotextile filter criteria. Curb cut-outs and/or catch basins are typically incorporated into permeable pavement designs to handle emergency overflow of stormwater under extreme storm conditions. As noted earlier, perforated drainage pipe is usually included in designs with partial or no infiltration into the subgrade. Perforated drainage pipes can provide drainage in heavy, overflow conditions or provide secondary drainage if the base loses some of its capacity over time.



White Mountain National Forest Service Headquarters, NH

Typically, ASTM No. 2 or 3 (or equivalent) open-graded aggregate is used for the subbase at a minimum thickness of 6 in. (150 mm) for pedestrian applications and 8 in. (200 mm) for vehicular applications. This makes it easier for contractors to construct the base and add structural stability. A base layer of open-graded aggregate (typically ASTM No. 57 or equivalent) is then installed over the subbase. This helps meet filter criteria between the layers. The recommended thickness for this layer is 4 in. (100 mm). It may be possible, however, to use a single material for the base and subbase depending on project design parameters and contractor experience. The thickness of the base/subbase 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). The open-graded materials described here typically have an in-situ porosity of at least 0.32 for void space for water storage. This translates to a water storage capacity in the void spaces between the aggregates of 20-40%. A 40% void space means that the volume of the base will need to be 2.5 times the volume of water that will be stored.

The No. 2 or 3 subbase aggregate should be spread in 4 to 6 in. (100-150 mm) lifts and compacted with a static roller. The No. 57 base layer can be spread and compacted in a single 4 in. (100 mm) lift. Aggregate materials should be moist when compacting. Initial passes of the roller can be with vibration to consolidate the stone, however, final passes should be without vibration. When all lifts are installed and compacted, the bedding layer can be installed. Material equivalent to ASTM No. 8 stone is recommended for the bedding layer, which is screeded and leveled to a thickness of 1 1/2-2 in. (25-50 mm) to provide a setting bed for the pavers. The No. 8 material should be moist to facilitate chinking into the No. 57 base material. The UNI® pavers are then installed on this bedding layer. No. 8 aggregate also is typically used to fill the drainage openings and joints.



East Gwillimbury Go Commuter Train Station, Newmarket, Ontario

If desired, material equivalent to No. 87, 89, 9 or 10 stone also may be used to fill the smaller joints between the pavers. *Bedding and jointing sand used in the construction of traditional interlocking concrete pavements should not be used for PICP.* Once the drainage openings and joints are filled, the surface is swept and then compacted with a plate compactor. After the initial compaction, refill the joints and openings, sweep clean and compact again. Repeat if necessary to completely fill the joints and openings. For vehicular pavements, proof-rolling may be considered with at least 2 passes of a 10T rubber-tired roller. The Eco-Stone® family of permeable pavers can be installed manually or mechanically and may be trafficked immediately after final compaction, unlike other types of porous or pervious pavements that require cure time. Like traditional interlocking concrete pavements, PICP uses edge restraints to secure the edges of the pavement. Cast-in-place and precast concrete curbs are recommended for these types of installations.

In cases where it may be necessary to increase the structural capacity of the pavement either due to existing site soil strength or traffic loads, bases may be stabilized with asphalt or cement prior to installation. Just enough asphalt or cement to coat the aggregate is required, though care must be taken during construction not to fill the void spaces with asphalt or excess paste, as this may reduce storage capacity of the base. The Asphalt Institute and Portland Cement Association provide guidelines on constructing these types of bases.

Permeable interlocking concrete pavement conforms to current ADA requirements that surfaces be firm, stable, and slip/skid resistant. It is important to keep the joints/openings filled with aggregate. If the openings in the surface are not desirable, solid pavers can be installed in areas used by disabled persons, or a paver such as Eco-Priora®, with its minimal chamfers and smaller joints may be used. If ADA design requirements change in the future, UNI® permeable interlocking paver designs can be adapted to meet new guidelines.

Unlike pervious concrete and porous asphalt, the Eco-Stone® family of permeable pavers can be installed in virtually any climate and can be utilized immediately upon installation and compaction, with no cure time. They are not affected by temperature extremes and are not subject to binder drain-down. UNI® high-quality permeable interlocking concrete pavers can withstand turning forces, which can lead to degradation and raveling with other types of pervious pavements.

Cold Climate Design Considerations

In northern climates the permeable interlocking concrete pavement must be designed for freeze-thaw conditions. PICP has been used successfully for many years throughout North America and can withstand repeated freeze/thaw in northern climates due to adequate space for ice to expand within the open-graded base. For cold climates in the northern U.S. and Canada, the lowest recommended infiltration rate for the subgrade is 0.25 in./hr. (2×10^{-6} m/sec).

Snow can be plowed from UNI® permeable pavements using standard snow removal equipment. The use of sand should be avoided as it will reduce infiltration, however, a small aggregate may be used for traction if needed. Deicing chemical use should be minimized, as it is not possible to remove chlorides found in these materials, though this problem is universal to all types of pavements. It is preferable not to stockpile snow on permeable pavements, if at all possible.



NYS Parks Office, Staatsburg, NY

Experience to date with permeable interlocking concrete pavement in winter conditions has shown that melting snow and ice drain through the pavement surface, thereby reducing icing hazards. A cold climate permeable pavement study, begun in 2004 at Seneca College in Ontario for the Toronto and Region Conservation Authority has shown that the Ecoloc® pavement has performed well in a severe winter climate. The college's maintenance department reports that little, if any salt has been needed to keep the pavers clear of ice. This may reduce the amount of deicing materials needed and minimize the impact on the environment.



McKinney Green Building, McKinney, TX

Maintenance

All permeable pavements, including porous asphalt and pervious concrete, require periodic cleaning to maintain high infiltration rates, and care must be taken to keep sediment off the pavement during and after construction. Studies and field experience have shown that infiltration rates may be maintained by street sweeping/vacuuming. The frequency of cleaning is typically dependent on traffic levels. It is generally recommended to vacuum the pavement surface at least once or twice a year, though some low-use pavements may not need cleaning as often. Periodic inspections of the site should be conducted for ponding or areas with reduced levels of infiltration.

Vacuum settings on street sweeping equipment may require adjustment to prevent the uptake of aggregate in the pavement openings and joints during routine cleaning. Some types of vacuum systems are capable of removing more aggregate should infiltration rates be reduced after several years and more regeneration is needed. The surface should be dry when cleaning. Replenishment of the joint and opening aggregate can be done, if needed, at the time of cleaning. *It is important to keep the drainage voids and*

joints filled with aggregate. As street cleaning is a BMP under EPA guidelines, this also satisfies other criteria in a comprehensive stormwater management program.

If properly constructed and maintained, PICP should provide a service life of 20 to 25 years. Like our traditional interlocking concrete pavers, the Eco-Stone® family of permeable pavers may be taken up and reinstated, without leaving an unsightly patch, if underground repairs to utilities or the subgrade are needed. If at the end of its design life the pavement no longer infiltrates the required amount of stormwater runoff, permeable interlocking concrete pavement is the only type of permeable or porous pavement that can be taken up, the base and bedding materials removed and new aggregate installed, and the same pavers then reinstalled.

UNI ECOLOC® HEAVY-DUTY PERMEABLE INTERLOCKING CONCRETE PAVERS

Ecoloc® has all the same attributes and features of our Eco-Stone® permeable paver with the added benefit of supporting industrial loads. The angled L-shaped unit provides superior resistance to twisting or tipping under high point loading. It can be used together with our industrial traditional interlocking concrete paver, UNI-Anchorlock®, to provide design professionals with the option of combining solid pavement areas with permeable areas. Like Eco-Stone®, Ecoloc® features funnel-shaped openings that facilitate the infiltration of stormwater runoff. Physical characteristics are described in Figure 7.

Ecoloc® can be mechanically installed and is ideal for larger-scale projects such as parking lots, roadways, storage and depot areas, and ports. Over 173,000 sf of Ecoloc® was used for an EPA Section 319 National Monitoring Permit Project at Morton Arboretum in Illinois. It also is in use at a test site located at Howland Hook Terminal at the Port of New York/New Jersey that is subjected to heavy, containerized loads, port forklifts and cargo carriers. Another 30,000 sf of Ecoloc® was installed at the East Gwillimbury Go Commuter Train Station parking lot in Newmarket, Ontario and over 205,000 sf was used for parking lots at Dominican University in River Forest, Illinois.

Physical Characteristics - Ecoloc®	
Height/Thickness	3 1/8" = 80 mm
Width	8 7/8" = 225 mm
Length	8 7/8" = 225 mm
Pavers per sq ft	= 2.41
Percentage of drainage void area per sf	= 12.18%
Flow rate through Ecoloc voids	= 1872 in./hr
Composition and Manufacture	
Minimum compressive strength -	8000psi
Maximum water absorption -	5%
Meets or exceeds ASTM C-936 and freeze-thaw testing per section 8 of ASTM C-67.	

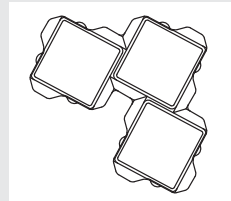
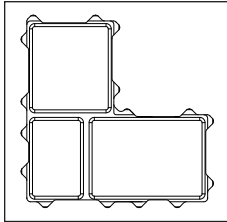


Figure 7

As previously noted, Ecoloc® is undergoing evaluation at Seneca College in Ontario for the Toronto and Region Conservation Authority to study permeable interlocking concrete pavement performance in cold climates conditions (see research section of this manual). In addition, Ecoloc® is part of a comparison study of porous and permeable pavements being conducted at the Tacoma Landfill in Washington.

ECO-OPTILOC® PERMEABLE INTERLOCKING CONCRETE PAVERS

As interest in permeable interlocking concrete pavements continues to increase, the Eco-Stone® family of permeable pavers is adding new shapes and styles to meet demand.



Eco-Optiloc® combines three shapes in a single L-shaped unit for the look of cobblestone with the added benefit of permeability. In this paver design, infiltration is achieved through the joints, as opposed to openings. Like our Ecoloc® paver, it offers superior structural strength under heavy traffic loads. Eco-Optiloc® is well suited to commercial, municipal, and residential applications.

In addition, it can be combined with traditional solid Optiloc® pavers for added design flexibility.

Eco-Optiloc® permeable pavers are gaining in popularity due to their style and durability under vehicular loading. They are ideal for mechanically-installed large-scale areas such as the 265,000 sf parking lot at U.S. Cellular Field in Chicago, IL, the 92,000 sf Aurora Police Station parking area in Illinois, the 40,000 sf Rhode Island Para-Transit Authority maintenance facility in Providence, RI, and the 110,000 sf Center Street Village lot in Mentor, OH.



Center Street Village, Mentor, OH

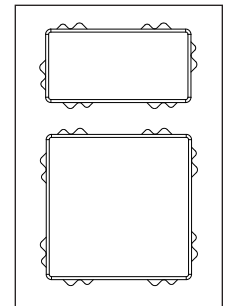
ECO-PRIORA® PERMEABLE INTERLOCKING CONCRETE PAVERS



Montgomery Village Hall, IL

Eco-Priora® is the newest paver in the Eco-Stone® family of permeable pavers. It can be produced in a variety of square and rectangle sizes for true design versatility, including 4" x 8", 8" x 8", 5" x 10" and 10" x 10", as well as other sizes. The shapes can be installed individually in patterns such as herringbone and running bond, or together in a variety of interesting patterns, offering the most design flexibility of any permeable paver on the market.

The flat surface, minimal chamfers, and smaller joint width of Eco-Priora® make it ideal for pedestrian areas and ADA handicap-accessible pavements. Eco-Priora® features unique, patented interlocking spacers that offer superior structural capabilities under vehicular traffic loads compared to other square and rectangular permeable pavers.



Eco-Priora® is quickly becoming one of the most popular UNI® permeable pavers. It was selected for the renovation of the historic Buckingham Fountain plaza in Chicago, IL, where over 236,000 sf was installed in a custom pattern with a specialized finish. It is one of the largest pedestrian permeable interlocking pavements in the country. Stonehill College in Easton, MA utilized 20,000 sf in three custom colors for their science quadrangle, where students gather and events are held. Both of these projects desired an attractive pedestrian permeable pavement featuring customized designs, which could be accessed by vehicles if needed. The Eco-Priora® pavers fulfilled all these requirements.

While UNI Eco-Stone® is available at all UNI® manufacturers in the United States and Canada, please check with your local UNI® producer for availability of Ecoloc® and other permeable pavers such as Eco-Optiloc® and Eco-Priora® in your area. UNI® manufacturers also produce grid pavers such as TurfStone™ for parking or access areas that require green space. Please visit our web site www.uni-groupusa.org for updated information, design references and research, PICP projects, a list of manufacturers, and more.

SECTION 32 14 13.19

UNI PERMEABLE INTERLOCKING CONCRETE PAVEMENT

(1995 MasterFormat Section 02795)

Note: This guide specification is intended for use in the U.S. It describes construction of permeable interlocking concrete pavers on a permeable, open-graded crushed stone bedding layer (typically No. 8 stone). This layer is placed over an open-graded base (typically No. 57 stone) and subbase (typically No. 2 stone). Other aggregate materials also may be suitable depending on specific project parameters. The pavers and bedding layer are typically placed over an open-graded crushed stone base with exfiltration to the soil subgrade. In low infiltration soils or installations with impermeable liners, some or all drainage is directed to an outlet via perforated drainpipes in the subbase. While this guide specification does not cover excavation, liners and drainpipes, notes are provided on these aspects.

The text below must be edited to suit specific project requirements. It should be reviewed by a qualified civil or geotechnical engineer, or landscape architect familiar with the site conditions. Edit this specification term as necessary to identify the design professional in the General Conditions of the Contract.

PART 1 GENERAL

1.01 SUMMARY

A. Section Includes

1. Permeable interlocking concrete pavers.
2. Crushed stone bedding material.
3. Open-graded subbase aggregate.
4. Open-graded base aggregate.
5. Bedding and joint/opening filler materials.
6. Edge restraints.
7. [Geotextiles].

B. Related Sections

1. Section []: Curbs.
2. Section []: [Stabilized] aggregate base.
3. Section []: [PVC] Drainage pipes
4. Section []: Impermeable liner.
5. Section []: Edge restraints.
6. Section []: Drainage pipes and appurtenances.
7. Section []: Earthworks/excavation/soil compaction.

1.02 REFERENCES

A. American Society for Testing and Materials (ASTM)

1. C 131, Standard Test Method for Resistance to Degradation of Small-Size Coarse Aggregate by Abrasion and Impact in the Los Angeles Machine.
2. C 136, Method for Sieve Analysis for Fine and Coarse Aggregate.
3. C 140, Test Methods for Sampling and Testing Brick and Structural Clay Tile, Section 8 – Freezing and Thawing.
4. D 448, Standard Classification for Sizes of Aggregate for Road and Bridge Construction.
5. C 936, Standard Specification for Solid Interlocking Concrete Pavers.
6. C 979, Specification for Pigments for Integrally Colored Concrete.
7. D 698, Test Methods for Moisture Density Relations of Soil and Soil Aggregate Mixtures Using a 5.5-lb (2.49 kg) Rammer and 12 in. (305 mm) drop.
8. D 1557, Test Methods for Moisture Density Relations of Soil and Soil Aggregate Mixtures Using a 10-lb (4.54 kg) Rammer and 18 in. (457 mm) drop.
9. D 1883, Test Method for California Bearing Ratio of Laboratory-Compacted Soils.
10. D 2922 Standard Test Methods for Density and Soil-Aggregate In-Place by Nuclear Methods (Shallow Depth)
11. D 4254, Standard Test Methods for Minimum Index Density and Unit Weight of Soils and Calculation of Relative Density.

B. UNI-GROUP U.S.A.

1. UNI Eco-Stone® Family of Permeable Pavers Design Guide and Research Summary.
2. Lockpave® Pro and PC-SWMM™ PP for structural and hydrologic design

C. Interlocking Concrete Pavement Institute

1. Permeable Interlocking Concrete Pavement manual.

1.03 SUBMITTALS

- #### A. In accordance with Conditions of the Contract and Division 1 Submittal Procedures Section.

- B. Paver Manufacturer's, installation subcontractor's drawing and details: Indicate perimeter conditions, junction with other materials, expansion and control joints, paver [layout,] [patterns,] [color arrangement,] installation [and setting] details. Indicate layout, pattern, and relationship of paving joints to fixtures and project formed details.
- C. Minimum 3 lb (2 kg) samples of subbase, base and bedding aggregate materials.
- D. Sieve analysis of aggregates for subbase, base and bedding aggregate materials per ASTM C 136.
- E. Project specific or producer/manufacturer source test results for void ration and bulk density of the base and subbase aggregates.
- F. Soils report indicating density test reports, classification, and infiltration rate measured on-site under compacted conditions, and suitability for the intended project.
- G. Erosion and sediment control plan.
- H. [Stormwater management (quality and quantity) calculations; structural analysis for vehicular applications] using ICPI Permeable Interlocking Concrete Pavements manual, Lockpave® Pro with PC-SWMM™ PP or [specify] design methods and models.
- I. Permeable concrete pavers:
 - 1. Manufacturer's product catalog sheets with specifications.
 - 2. [Four] representative full-size samples of each paver type, thickness, color, and finish. Submit samples indicating the range of color expected in the finished installation.
 - 3. Accepted samples become the standard of acceptance for the work of this Section.
 - 4. Laboratory test reports certifying compliance of manufacturer's concrete pavers with ASTM C 936.
 - 5. Manufacturer's material safety data sheets for the safe handling of the specified paving materials and other products specified herein.
 - 6. Paver manufacturer's written quality control procedures including representative samples of production record keeping that ensure conformance of paving products to the product specifications.
- J. Paver Installation Subcontractor:
 - 1. Demonstrate that job foremen on the project have a current certificate from the ICPI Paver Installer Certification program.
 - 2. Job references from projects of a similar size and complexity. Provide Owner/Client/General Contractor names, postal address, phone, fax, and email address.
 - 1. Written Method Statement and Quality Control Plan that describes material staging and flow, paving direction and installation procedures, including representative reporting forms that ensure conformance to the project specifications.

1.04 QUALITY ASSURANCE

- A. Paver Installation Subcontractor Qualifications:
 - 1. Utilize an installer having successfully completed concrete paver installation similar in design, material, and extent indicated on this project.
 - 2. Utilize an installer holding a current certificate from the Interlocking Concrete Pavement Institute Concrete Paver Installer Certification program.
- B. Regulatory Requirements and Approvals: [Specify applicable licensing, bonding or other requirements of regulatory agencies.]
- C. Review the manufacturers' quality control plan, paver installation subcontractor's Method Statement and Quality Control Plan with a pre-construction meeting of representatives from the manufacturer, paver installation subcontractor, general contractor, engineer and/or owner's representative.
- C. Mock-Ups:
 - 1. Install a 10 ft x 10 ft (3 x 3 m) paver area.

Note: Mechanized installations may require a larger mock up area. Consult paver installation contractor on the size of the mock up.

- 2. Use this area to determine surcharge of the bedding sand layer, joint sizes, lines, laying pattern(s), color(s) and texture of the job.
- 3. This area will be used as the standard by which the work will be judged.
- 4. Subject to acceptance by owner, mock-up may be retained as part of finished work.
- 5. If mock-up is not retained, remove and properly dispose of mock-up.

1.05 DELIVERY, STORAGE, AND HANDLING

- A. General: Comply with Division 1 Product Requirement Section.
- B. Comply with manufacturer's ordering instructions and lead-time requirements to avoid construction delays.
- C. Delivery: Deliver materials in manufacturer's original, unopened, undamaged container packaging with identification tags intact.
 - 1. Coordinate delivery and paving schedule to minimize interference with normal use of buildings adjacent to paving.
 - 2. Deliver concrete pavers to the site in steel banded, plastic banded, or plastic wrapped cubes capable of transfer by forklift or clamp lift.
 - 3. Unload pavers at job site in such a manner that no damage occurs to the product or existing construction.
- D. Storage and Protection: Store materials in protected area such that they are kept free from mud, dirt, and other foreign materials.

1.06 ENVIRONMENTAL REQUIREMENTS

- A. Do not install in rain or snow.
- B. Do not install frozen bedding materials.

1.07 MAINTENANCE

- A. Extra materials: Provide [Specify area] [Specify percentage] additional material for use by owner for maintenance and repair.
- B. Pavers shall be from the same production run as installed materials.

PART 2 PRODUCTS

Note: Some projects may include permeable and solid interlocking concrete pavements. Specify each product as required.

2.01 PERMEABLE INTERLOCKING CONCRETE PAVERS

- A. Manufacturer: [Specify UNI manufacturer name.]
 - 1. Contact: [Specify UNI manufacturer contact information.]
- B. Permeable Interlocking Concrete Paver Units:
 - 1. Paver Type: [UNI Eco-Stone, UNI Ecoloc, UNI Eco-Optiloc or UNI Eco-Priora, where available.]
 - a. Material Standard: Comply with material standards set forth in ASTM C 936.
 - b. Color [and finish]: [Specify color.] [Specify finish.]
 - c. Color Pigment Material Standard: Comply with ASTM C 979.

Note: Concrete pavers may have spacer bars on each unit. Spacer bars are recommended for mechanically installed pavers. Manually installed pavers may be installed with or without spacer bars. Verify with manufacturers that overall dimensions do not include spacer bars.

- d. Size: [Specify] inches [({Specify}mm)] x [Specify] inches [({Specify}mm)] x [Specify] inches [({Specify}mm)] thick.

Note: When 3¹/₈ in. (80 mm) thick pavers are specified, their compressive strength test results per ASTM C 140 should be adjusted by multiplying by 1.18 to equate the results to that from 2³/₈ in. (60 mm) thick pavers.

- e. Average Compressive Strength (ASTM C 140): 8000 psi (55 MPa) with no individual unit under 7200 psi (50 MPa).
- f. Average Water Absorption (ASTM C 140): 5% with no unit greater than 7%.
- g. Freeze/Thaw Resistance (ASTM C 67): Resistant to 50 freeze/thaw cycles with no greater than 1% loss of material. Freeze-thaw testing requirements shall be waived for applications not exposed to freezing conditions.

2.02 PRODUCT SUBSTITUTIONS

- A. Substitutions: Permitted for gradations of crushed stone jointing material, base and subbase materials. All substitutions shall be approved in writing by the project engineer

2.03 CRUSHED STONE FILLER, BEDDING, BASE AND SUBBASE

- A. Crushed stone with 90% fractured faces, LA Abrasion < 40 per ASTM C 131, minimum CBR of 80% per ASTM D 1883.
- B. Do not use rounded river gravel.
- C. All stone materials shall be washed with less than 1% passing the No. 200 sieve.
- D. Joint/opening filler, bedding, base and subbase: conforming to ASTM D 448 gradation as shown in Tables 1, 2 and 3 below:

Note: No. 89, 9 or 10 stone or that having similar gradations also may be used to fill narrow permeable paver joints.

Sieve Size	Percent Passing
12.5 mm (1/2 in.)	100
9.5 mm (3/8 in.)	85 to 100
4.75 mm (No. 4)	10 to 30
2.36 mm (No. 8)	0 to 10
1.16 mm (No. 16)	0 to 5

Table 2
Grading Requirements for ASTM No. 57 Base

Sieve Size	Percent Passing
37.5 mm (1½ in.)	100
25 mm (1 in.)	95 to 100
12.5 mm (½ in.)	25 to 60
4.75 mm (No. 4)	0 to 10
2.36 mm (No. 8)	0 to 5

Table 3
Grading Requirement for ASTM No. 2 Subbase

Sieve Size	Percent Passing
75 mm (3 in.)	100
63 mm (2½ in.)	90 to 100
50 mm (2 in.)	35 to 70
37.5 mm (1½ in.)	0 to 15
19 mm (¾ in.)	0 to 5

E. Gradation criteria for the bedding and base:

Note: D_x is the particle size at which x percent of the particles are finer. For example, D_{15} is the particle size of the aggregate for which 15% of the particles are smaller and 85% are larger.

1. D_{15} base stone / D_{50} bedding stone < 5.
2. D_{50} base stone / D_{50} bedding stone > 2.

2.04 ACCESSORIES

A. Provide accessory materials as follows:

Note: Curbs will typically be cast-in-place concrete or precast set in concrete haunches. Concrete curbs may be specified in another Section. Do not use plastic edging with steel spikes to restrain the paving units.

1. Edge Restraints
 - a. Manufacturer: [Specify manufacturer.]
 - b. Material: [Pre-cast concrete.] [Cut stone.] [Concrete.]
 - c. Material Standard: [Specify material standard.]

Note: See ICPI publication, Permeable Interlocking Concrete Pavements for guidance on geotextile selection. Geotextile use is optional.

2. Geotextile Fabric:
 - a. Material Type and Description: [Specify material type and description.]
 - b. Material Standard: [Specify material standard.]
 - c. Manufacturer: [Acceptable to interlocking concrete paver manufacturer.]

PART 3 EXECUTION

3.01 ACCEPTABLE INSTALLERS

A. [Specify acceptable paver installation subcontractors.]

3.02 EXAMINATION

Note: The elevations and surface tolerance of the soil subgrade determine the final surface elevations of concrete pavers. The paver installation contractor cannot correct deficiencies excavation and grading of the soil subgrade with additional bedding materials. Therefore, the surface elevations of the soil subgrade should be checked and accepted by the General Contractor or designated party, with written certification presented to the paver installation subcontractor prior to starting work.

A. Acceptance of Site Verification of Conditions:

1. General Contractor shall inspect, accept and certify in writing to the paver installation subcontractor that site conditions meet specifications for the following items prior to installation of interlocking pavers.

Note: Compaction of the soil subgrade should be determined by the project engineer. If the soil subgrade requires compaction, compact to a minimum of 95% standard Proctor density per ASTM C 698. Compacted soil density and moisture should be checked in the field with a nuclear density gauge or other test methods for compliance to specifications. Stabilization of the soil and/or base material may be necessary with weak or continually saturated soils, or when subject to high wheel loads. Compaction will reduce the permeability of soils. If soil compaction is necessary, reduced infiltration may require drainpipes within the open-graded subbase to conform to local storm drainage requirements.

- a. Verify that subgrade preparation, compacted density and elevations conform to specified requirements.

- b. Provide written density test results for soil subgrade to the Owner, General Contractor and paver installation subcontractor.
 - c. Verify location, type, and elevations of edge restraints, [concrete collars around] utility structures, and drainage pipes and inlets.
2. Do not proceed with installation of bedding and interlocking concrete pavers until subgrade soil conditions are corrected by the General Contractor or designated subcontractor.

3.03 PREPARATION

- A. Verify that the soil subgrade is free from standing water.
- B. Stockpile joint/opening filler, base and subbase materials such that they are free from standing water, uniformly graded, free of any organic material or sediment, debris, and ready for placement.
- C. Edge Restraint Preparation:
 - 1. Install edge restraints per the drawings [at the indicated elevations].

3.04 INSTALLATION

Note: The minimum slope of the soil subgrade should be 0.5%. Actual slope of soil subgrade will depend on the drainage design and exfiltration type. All drain pipes, observation wells, overflow pipes, geotextiles (if applicable), and impermeable liner (if applicable) should be in place per the drawings prior to or during placement of the subbase and base, depending on their location. Care must be taken not to damage drainpipes during compaction and paving. No mud or sediment can be left on the base or bedding aggregates. If they are contaminated, they must be removed and replaced with clean materials. Base/subbase thicknesses and drainage should be determined using UNI Manufacturer's specifications, ICPI's Permeable Interlocking Concrete Pavements manual and Lockpave® Pro/PC-SWMM™ PP software.

- A. General
 - 1. Any excess thickness of soil applied over the excavated soil subgrade to trap sediment from adjacent construction activities shall be removed before application of the [geotextile] and subbase materials.
 - 2. Keep area where pavement is to be constructed free from sediment during entire job. [Geotextiles] Base and bedding materials contaminated with sediment shall be removed and replaced with clean materials.
 - 3. Do not damage drainpipes, overflow pipes, observation wells, or any inlets and other drainage appurtenances during installation. Report any damage immediately to the project engineer.
- B. Geotextiles
 - 1. Place on bottom and sides of soil subgrade. Secure in place to prevent wrinkling from vehicle tires and tracks.
 - 2. Overlap a minimum of [12 in. (0.3 m)] [24 in. (0.6 m)] in the direction of drainage.
- C. Open-graded subbase and base
 - 1. Moisten, spread and compact the No. 2 subbase in 4 to 6 in. lifts (100 to 150 mm) lifts [without wrinkling or folding the geotextile. Place subbase to protect geotextile from wrinkling under equipment tires and tracks.]
 - 2. For each lift, make at least two passes in the vibratory mode then at least two in the static mode with a minimum 10 t (10 T) vibratory roller until there is no visible movement of the No. 2 stone. Do not crush aggregate with the roller.
 - 3. The surface tolerance of the compacted No. 2 subbase shall be $\pm 2\frac{1}{2}$ in. (± 65 mm) over a 10 ft (3 m) straightedge.
 - 4. Moisten, spread and compact the No. 57 base layer in one 4 in. (100 mm) thick lift. On this layer, make at least two passes in the vibratory mode, then at least two in the static mode with a minimum 10 t (10 T) vibratory roller until there is no visible movement of the No. 2 stone. Do not crush aggregate with the roller.

Note: At the option of the designer, this supplemental test method noted below can be used to establish a consistent methodology for in-situ density data collection of open-graded aggregate base layer (typically ASTM No. 57 stone). This test method can assist contractors in reaching adequate job site compaction and offer an additional level of confidence for the project owner and designer. This test method is appropriate for pavement subject to consistent vehicular traffic such as parking lots and roads. It is not needed for pedestrian areas and residential driveways.

- 5. Use part of the compacted base area as a control strip for density testing by [Testing Company].
 - a. The [Testing Company] shall supply nuclear moisture/density gauges and ancillary equipment required to conduct density and moisture content measurements for compaction of the No. 57 aggregate drainage layer. Qualified testing laboratory operators/gauges may conduct compaction testing. Each gauge operator shall be trained in the safe operation, transportation and handling of the gauge. The registered owner of the gauge shall have and maintain a valid Radioisotope License for each gauge.
 - b. Each gauge shall have been calibrated within the last 12 months, either by the manufacturer or other qualified agent, against certified density and moisture reference blocks. The density standard count and the moisture standard count shall be within 2 percent and 4 percent respectively, of the most recent calibration values. A certificate of calibration for each gauge shall accompany each gauge.

6. Target Density
 - a. Determine a target density on the control strip during under the following conditions:
(1) after initial placement and compaction of the base aggregate layer, (2) when there is a perceptible change in the appearance or gradation of the aggregate, (3) when there is a change in the source of aggregate.
 - b. Test field density according to ASTM D 2922 Standard Test Methods for Density of Soil and Soil-Aggregate In-Place by Nuclear Methods (shallow Depth). Field density tests shall be performed on compacted base materials to determine within acceptable limits of a target density.
7. Control Strip
 - a. The Testing Company shall construct a control strip for the determination of a target density consisting of a single uniform lift as specified in the contract documents, but not more than 4 in. (100 mm) thick and covering approximately 600 yd² (500 m²) in area. No testing shall be performed within 10 ft (3 m) from any unrestrained outside edge of the work area. The control strip may be incorporated into the project upon acceptance of density measurements by the Testing Company.
 - b. During construction of the control strip, the surface of the aggregate shall be visibly moist and maintained as such throughout construction and compaction.
 - c. After initial placement of the aggregate base material, the compaction equipment shall make two passes over the entire surface of the control strip. Field densities and field moisture contents, using the backscatter/indirect method, shall be determined at five randomly selected locations at least 15 ft (5 m) apart. The dry density and moisture content shall be calculated for each of these locations and the averages shall be used as initial values. The maximum compacted thickness of the aggregate base layer measured for density shall be 4 in. (100 mm).
 - d. The compaction equipment shall then make two additional passes over the entire surface of the control strip. After compaction, three separate, random field density and moisture content determinations shall be made, using the backscatter/indirect method, and a new average dry density and moisture content shall be calculated.
 - e. If the new average dry density exceeds the previous value by more than 1.2 pcf (20 kg/m³) then two additional passes of the equipment shall be carried out as described above. If the new average dry density does not exceed the previous value by more than 1.2 pcf (20 kg/m³), then compaction of the control strip will be considered satisfactory and complete.
 - f. Upon satisfactory completion of the control strip, an additional seven (7) field density and moisture tests, using the backscatter/indirect method, shall be taken at random locations and the dry density and moisture content values shall be determined. The final dry density and moisture content of the control strip shall be the average of these seven values plus the three most recent values obtained upon completion.
8. Compaction Equipment
 - a. Use a smooth dual or single smooth drum, minimum 10 ton (10 T) vibratory roller or a minimum 13,500 lbf (60 kN) centrifugal force, reversible vibratory plate compactor that provides maximum compaction force without crushing the aggregate base.
9. Test Report
 - a. The test report shall include the following:
 - 1) Project description.
 - 2) Sketch of test area and test locations.
 - 3) Aggregate type and layer thicknesses.
 - 4) Aggregate characteristic properties: gradation, void ratio, bulk density.
 - 5) Compaction equipment type and weight.
 - 6) Static or vibratory compaction.
 - 7) Number of passes of the compaction equipment.
 - 8) Test number and location.
 - 9) Individual and average field wet density, moisture content, and dry density values determined after each compaction operation in accordance with ASTM D 2922 Standard Test Methods for Density of Soil and Soil-Aggregate In-Place by Nuclear Methods (Shallow Depth).
 - 10) Calculation of target density.
10. The surface tolerance the compacted No. 57 base should not deviate more than. ± 1 in. (± 25 mm) over a 10 ft (3 m) straightedge.

Note: As an alternative test method, in-place density of the base aggregate may be checked per ASTM D 4254. Compacted density should be 95% of the laboratory index density established for the base layer.

D. Bedding layer

1. Moisten, spread and screed the No. 8 stone bedding material.
2. Fill voids left by removed screed rails with No. 8 stone.
3. The surface tolerance of the compacted surface should not deviate more than $\pm\frac{3}{8}$ in. (± 10 mm) over a 10 ft (3 m) straightedge.
4. Do not subject screeded bedding material to any pedestrian or vehicular traffic before paving unit installation begins.

E. Permeable interlocking concrete pavers and joint/opening fill material

1. Lay the pavers [paving slabs] in the pattern(s) and joint widths shown on the drawings. Maintain straight pattern lines.
2. Fill gaps at the edges of the paved area with cut units. Cut pavers subject to tire traffic shall be no smaller than $\frac{1}{3}$ of a whole unit.
3. Cut pavers to be placed along the edges with a [double-bladed splitter] or masonry saw.
4. Fill the openings and joints with No. 8 stone.

Note: Some paver joint widths may be narrow and not accept most of the No. 8 stone. Use joint material that will fill joints, such as washed ASTM No. 9 or 10 stone.

5. Remove excess aggregate by sweeping pavers clean.
6. Compact and seat the pavers into the bedding material using a low-amplitude, 75-90 Hz plate compactor capable of at least 4,000 lbs (18 kN) centrifugal compaction force. This will require at least two passes with the plate compactor.
7. Do not compact within 6 ft (2 m) of the unrestrained edges of the paving units.
8. Apply additional aggregate to the openings and joints, filling them completely. Remove excess aggregate by sweeping and compact the pavers. This will require at least two passes with the plate compactor.
9. All pavers within 6 ft (2 m) of the laying face must be left fully compacted at the completion of each day.
10. The final surface tolerance of compacted pavers shall not deviate more than $\pm\frac{3}{8}$ in. (± 10 mm) under a 10 ft (3 m) long straightedge.
11. The surface elevation of pavers shall be $\frac{1}{8}$ to $\frac{1}{4}$ in. (3 to 6 mm) above adjacent drainage inlets, concrete collars or channels.

3.05 FIELD QUALITY CONTROL

- A. After sweeping the surface clean, check final elevations for conformance to the drawings.
- B. Lippage: No greater than $\frac{1}{8}$ in. (3 mm) difference in height between adjacent pavers.

Note: The minimum slope of the finished pavement surface should be 1%. The surface of the pavers may be $\frac{1}{8}$ to $\frac{1}{4}$ in. (3 to 6 mm) above the final elevations after compaction. This helps compensate for possible minor settling normal to pavements.

- C. The surface elevation of pavers shall be $\frac{1}{8}$ to $\frac{1}{4}$ in. (3 to 6 mm) above adjacent drainage inlets, concrete collars or channels.

3.06 PROTECTION

- A. After work in this section is complete, the General Contractor shall be responsible for protecting work from sediment deposition and damage due to subsequent construction activity on the site.

END OF SECTION

RESEARCH AND TESTING UNI ECO-STONE® AND ECOLOC® PERMEABLE PAVEMENTS

EXPERIENCE IN THE APPLICATION OF PERMEABLE INTERLOCKING CONCRETE PAVING IN AUSTRALIA

Simon Beecham, Baden Pezzaniti, Brian Shackel, and Alan Pearson - Oct. 18-21, 2009, 9th International Conference on Concrete Block Paving, Buenos Aires, Argentina

GENERAL SUMMARY

This paper reports assessments of a range of permeable interlocking concrete pavements (PICP) that have been in service around Australia for approximately 10 years. Each of the assessments is supported by a critical review of the properties and in-service performance of the pavements based on in-situ measurements and inspections, supplemented by laboratory test data. Factors studied include the infiltration rate, structural properties and performance together with lifespan and physical filtration efficiency. The effects of sediment load and pavement clogging have also been examined. Most of the pavements studied had not been subject to routine or systematic maintenance. Despite this, the study showed that on pavements up to 10 years of age, most were still capable of good infiltration. Sweeping the pavement surface was shown to be beneficial to infiltration and laboratory tests confirmed that most fine sediment was trapped in the upper portions of the jointing materials. Overall, the results tend to indicate that, at least under Australian conditions, the need to routinely sweep permeable paving may not be as necessary as is often assumed in the Northern Hemisphere.

OUTLINE

- **INTRODUCTION**
- **PAVEMENTS SELECTED FOR TESTING**
 - Ecoloc,® Eco-Trihex™ and Formpave®
- **METHODOLOGY**
 - Inspections of structural and surface conditions
 - Double-ring infiltrometer tests at several locations
 - Sampling of jointing materials for subsequent laboratory tests
- **WALKOVER INSPECTIONS**
- **INFILTRATION MEASUREMENTS**
 - Testing and Summary of sites
 - Infiltration rates ranged from 2.76 to 42.5 in./hr per sf (70 to 1080 mm/h.m2 (193 to 3000 l/s.ha))
- **JOINTING MATERIAL**
 1. Typical specification for jointing aggregate in Australia is a clean uniform 2-5mm.
 2. Sieve analyses at sites showed jointing materials generally had a maximum particle size of approximately 6-7mm, with 10% or more passing the 1.18 mm sieve and approximately 5% passing the 0.3 mm sieve size - typical of ASTM #9 grading.
 3. At 10 of the 14 locations, it was found there were more fine particles in the upper 30 mm depth of the jointing material than the lower 30-60 mm depth. In areas known to have been swept, there was no change in fines between the upper and lower jointing depths, indicating that most of the fine clogging materials observed in the upper depths of the jointing material for unswept pavements could be easily removed by sweeping.
- **CONCLUSIONS**
 1. This study investigated the hydraulic conductivity of a number of full-scale field installations of permeable pavements in Australia. Two general types of pavers were tested, namely pavers with drainage openings located along the joints and pavers that had widened joints.
 2. The study showed that clogging was a natural process, but that the majority of the sediment causing clogging was retained in the upper horizons of the jointing material and that this sediment could be removed with sweeping. However, the testing also indicated that frequent sweeping was not required for most pavement installations.
 3. "As new" infiltration rates should not be used for the design of permeable pavements. Instead, a clogging factor needs to be applied to allow for the incremental clogging that occurs with these types of pavements.
 4. Overall, the results demonstrate that, even for pavements that have received little routine maintenance, the infiltration rates 8 to 10 years after construction remain in a serviceable condition.

PERFORMANCE EVALUATION OF PERMEABLE PAVEMENT AND A BIORETENTION SWALE

Tim Van Seters, Derek Smith and Glenn MacMillan, Toronto and Region Conservation Authority, Toronto, ON - 2007

GENERAL SUMMARY

Infiltration stormwater best management practices are gaining in popularity due to reductions in flow volume and temperature related impacts on nearby receiving waters. Permeable pavement and bioretention swales offer some of the most promising potential. With these technologies, runoff is infiltrated into the soil naturally, reducing the need for treatment and eliminating the need for underground or site consuming detention facilities. This study builds and expands on the previous research in evaluating the effectiveness of Ecoloc® permeable concrete interlocking pavers and bioretention swales for stormwater management under climate and soil conditions representative of watersheds in the Greater Toronto Area (cold climate areas). The site for this study is located on a parking lot at Seneca College's King Campus in the Township of King. The parking lot is often full during the school year, but is used less frequently during the summer, except during special events. Water quality and quantity were monitored. In addition, five older permeable pavement sites ranging in age from 3 years to 16 years were surveyed.

OUTLINE

- **INTRODUCTION**
- **STUDY AREA**
 - Study Design and Construction
- **MONITORING METHODS**
- **INTERIM RESULTS AND DISCUSSION**
 - Water Quantity
 - Water Quality
 - Surveys of Older Sites
- **SUMMARY AND CONCLUSIONS**
 1. Results of the study show that the Ecoloc® permeable interlocking pavers and bioretention swales offered significant stormwater management benefits over traditional asphalt pavements.
 2. Base course water levels rarely increased beyond two-thirds of the total base course depth of 60cm.
 3. Though the bioswale overflowed more frequently, a majority of the runoff infiltrated into the ground or was released back into the atmosphere by evapotranspiration.
 4. Both practices were effective in reducing and delaying peak flows.
 5. Infiltrated water would help to recharge groundwater and supplement baseflows in local streams.
 6. The hydrologic properties of these practices help to eliminate the potential for downstream erosion and flooding typically caused by post-development changes.
 7. Water quality results to date indicate that both technologies provide good removal of typical parking lot contaminants, such as zinc, lead and hydrocarbons.
 8. Surveys of older Ecoloc® and Eco-Stone® pavements indicate that most of these contaminants are being captured in the bedding and upper base layers and that long-term accumulation of contaminants in the soils underneath the pavements is probably not of any significant concern.
 9. Additional soil and runoff monitoring is planned for the future.



Seneca College, Toronto, ON

JORDAN COVE URBAN WATERSHED PROJECT

John C. Clausen, Department of Natural Resources Management and Engineering College of Agriculture and Natural Resources, University of Connecticut - 2007

GENERAL SUMMARY

The Jordan Cove Urban Watershed EPA Section 319 National Monitoring Program Project was a ten year study designed to study the water quantity and quality benefits of a urban subdivision development using pollution prevention best management practices. Stormwater runoff was monitored from three watersheds - control, traditional and best management practice (BMP). The traditional watershed had been developed with 'traditional' subdivision requirements, whereas the BMP watershed had been developed using a best management practice approach prior to, during, and post construction. Runoff from these watersheds was compared to an existing control watershed. The goal was to show that by using a BMP approach, pre-development hydrologic conditions could be maintained during and after residential development. The overall objective of the project was to demonstrate water quantity and water quality benefits of developing urban residential subdivisions with BMP nonpoint source controls. Eco-Stone® permeable interlocking pavers were used for a road cul-de-sac and some of the shared driveways. Other practices such as rain gardens, vegetated swales, and gravel driveways were incorporated into the project.

OUTLINE

- **INTRODUCTION**
 - Background
 - Project Description
- **OBJECTIVES**
- **PROJECT ORGANIZATION AND RESPONSIBILITY**
- **METHODS**
 - Study Design
 - Project Schedule
 - Study Area
 - Site Development Waivers
 - Deed Restrictions
 - Monitoring Methods
 - Sample Analysis
 - Maintenance
 - Driveway Study
 - Lawn Nutrient Study
 - Household Survey
 - Statistical Analysis
- **RESULTS AND DISCUSSION**
 - Precipitation
 - BMP Watershed
 - Traditional Watershed
 - Driveway Study
 - Lawn Nutrient Study
 - Household Survey
 - BMP Costs
- **CONCLUSIONS AND RECOMMENDATIONS**
 1. Residential development can have significant adverse impacts on runoff quality and quantity.
 2. The BMP watershed did not demonstrate typical hydrologic changes due to construction, such as increased runoff.
 3. A reduction in stormwater runoff was observed from the BMP watershed during construction.
 4. Runoff reduction continued during the post-construction phase and the project was successful in maintaining pre-development discharge rates.
 5. Concentrations of TSS, NO₃-N, NH₃-N, TKN and TP increased in stormwater runoff at the BMP site during



Jordan Cove Urban Watershed Project, Waterford, CT

construction and remained higher following construction, though this could be related to transport from fertilizer application by homeowners in the grassed swales.

6. It was noted that soil compaction occurred due to heavy equipment using a temporary access road causing problems with infiltration in rain gardens and swales. It is recommended that soil compaction be kept to a minimum, and that hard-surface roads are used for access during construction.
7. Due to the excessive loading of wind-blown and vehicle-tracked fine particles loaded on to the pavers during construction, the infiltration capacity of the roadway was reduced. Therefore, it is recommended that if a pervious surface has high loading of fine particles, the surface should be maintained by vacuum suction and replacement of the infill materials.
8. Stormwater runoff volume from the LID subdivision after construction was 42% less than runoff from the site prior to development.
9. Single ring infiltrometer testing of the Eco-Stone® driveways had rates of infiltration from 4.13 to 4.65 inches per hour (10.5 to 11.8 cm) and Flowing Infiltration tests on the pavement had rates of 4.49 inches per hour (11.4 cm).

THE MORTON ARBORETUM'S GREEN PARKING LOT

Andrew J. Sikich, P.E. and Patrick D. Kelsey, CPSSc/SC - 2005

GENERAL SUMMARY

The Morton Arboretum, located in DuPage County, IL, decided in the late 1990s to undertake a large-scale redevelopment of their 1700-acre outdoor museum. Since the facility had received a grant from the Illinois Environmental Protection Agency's (IEPA) Clean Lakes Program for a complete renovation of Meadow Lake, which lies adjacent to the visitor center and parking lot, an impervious asphalt lot was deemed inappropriate for the "low impact" design parameters of the project. An asphalt lot would produce significant concentrations of pollutants in the stormwater runoff and increase thermal loads in the lake, thereby degrading water quality and negatively impacting bio-diversity of the ecosystem. The designers for the project decided to construct a "green" parking lot that would incorporate a number of best management practices (BMPs) that would filter and infiltrate stormwater prior to entering the lake, and eventually, the east branch of the DuPage River. To facilitate construction of the parking lot, the Arboretum applied for and received an IEPA 319 Grant to construct BMPs within the parking area. The matching 60/40 grant would give the Arboretum up to \$1.2 million for the design and construction of the parking lot. The designers selected Ecoloc® permeable interlocking pavers for the project's parking areas. Project goals included a reduction in overall stormwater runoff and improvement in downstream water quality. The Arboretum decided to initiate a 2-year research study on the effectiveness of the BMPs utilized in the project. Plans call for monitoring the reduction in stormwater runoff entering the downstream receiving system and tracking of water quality improvements.

OUTLINE

- **ABSTRACT**
- **INTRODUCTION**
- **SELECTION OF BEST MANAGEMENT PRACTICES**
- **DESIGN DETAILS**
 - Bio-swales
 - Permeable Pavement
 - Perforated Sewers/Water Level Control Structure
 - Created Wetland/Level Spreading Pool
 - Level Spreader
- **CONSTRUCTION**
- **RESEARCH**
- **SUMMARY**
 1. The main parking lot project was exemplary from the onset of the project.
 2. A cooperative design process between the owner, engineers, landscape architects, regulators, and contractors facilitated and end product that is not only good for the environment, but also very functional for the Arboretum.
 3. The public outreach and educational requirements of the project will help ensure the project is in the public eye and the hope is for it to be used as a pilot project in future.
 4. The project should help to facilitate additional research, and increase confidence of local regulators and public officials to increase use of such applications on a widespread basis.



Morton Arboretum, DuPage County, IL

INTERLOCKING CONCRETE BLOCK PAVEMENTS AT HOWLAND HOOK MARINE TERMINAL

Walter E. Sieglen Jr., PE, and Harald von Langsdorff - 2004

GENERAL SUMMARY

The Port Authority of New York and New Jersey constructed the first port pavement in North America featuring both traditional impermeable and permeable interlocking concrete block pavements capable of supporting container handling equipment loads. The pavement is located at the Howland Hook Marine Terminal, where their existing container yard was enlarged by approximately 5 ha (12 acres). The area features a subgrade that is subject to failure due to the presence of gypsum. Interlocking concrete block pavement (ICBP) is known worldwide for its ability to withstand the heavy loads generated by containers, which can cause damage at corner castings on traditional pavements, as well as function well in areas with potential subgrade problems. The pavement was designed for a 20-year service life for a container yard that uses highway and off-road chassis to move containers between the yard and the ship, and top picks and lift trucks at the 4-high container stacks. Container handling equipment dual wheel axles generate loads of 97,500 kg (215,000 lb) excluding dynamic forces. The stacked containers generate point loads of up to 23,000 kg (50,000 lb) at each corner casting at the bottom container. Unlike any other port in North America, this project included installation of 0.1 ha (0.25 acres) of permeable interlocking concrete block pavement (PICBP - Ecoloc®). The intent of the test project is to demonstrate the structural, hydraulic and water quality enhancement properties of PICBP. Permeable pavement is being considered for meeting water quality requirements that are anticipated for future expansions of existing facilities or for new port facilities. This paper presents information on the selection, design, and construction of the ICBP and PICBP and the experience during the initial container yard operations.

OUTLINE

- **ABSTRACT**
- **SITE HISTORY**
- **DEVELOPMENT OF THE “MOONSCAPE” AREA**
- **INTERLOCKING CONCRETE BLOCK PAVEMENT**
 - Preliminary Design Selection
 - Final Design of the Interlocking Concrete Block Pavement
 - Pavement Section
- **PERMEABLE CONCRETE BLOCK PAVEMENT SECTION**
 - Identification of the Need for a Demonstration of PICBP
 - Permeable Concrete Block Pavement Section
 - Drainage Design
- **PAVEMENT CONSTRUCTION AND PERFORMANCE**
 - Construction of the Moonscape Area
 - Initial Pavement Performance
 - Impact on Future Projects
- **CONCLUSIONS**

1. ICBP is a low maintenance, high quality, flexible surface that can accommodate a wide range of operations, equipment, etc.
2. A permeable pavement also fulfills requirements for Best Management Practice (BMP) to meet water quality requirements at approximately the same cost as traditional (impermeable) pavements.
3. PICBP eliminates or reduces the costs to provide traditional BMPs that detain and/or treat runoff, and provides more flexibility to change the operational layout, equipment, etc. without concern for the load carrying capacity and access to the BMPs.
4. Port operation can be improved by a reduction in pavement slopes and an increase in the spacing of drainage inlets without compromising surface drainage.
5. Permeable pavements eliminate “birdbaths” at the inevitable depressions that develop due to differential settlements.
6. Permeable pavements provide the advantages in structural performance of a “drainable” pavement section.
7. PICBP provides a cost effective, high quality pavement section that also meets environmental requirements for water quality, and should continue to attract the attention of the port community.



*Howland Hook Marine Terminal
Port of New York and New Jersey*

USING PERMEABLE ECO-PAVING TO ACHIEVE IMPROVED WATER QUALITY FOR URBAN PAVEMENTS

B. Shackel, J. Ball and M. Mearing - 2003

GENERAL SUMMARY

This paper addresses the use of Ecoloc® permeable pavements as part of a Water Sensitive Urban Design that infiltrates stormwater, reduces pollutants and slows reticulation of the stormwater to an ecologically sensitive water system. Management of urban stormwater runoff is a major concern for government agencies. The increase in impervious surfaces associated with development results in an increase in the volumes of stormwater runoff that must be handled by stormwater drainage systems, as well as an increase in pollutants conveyed in the stormwater runoff. Pollutants include those from vehicle exhausts, brakes, tires, community activities, and atmospheric deposition. Where the stormwater system drains to ecologically sensitive areas, such as beaches, lakes or creeks, communities demand that the stormwater not degrade water quality. This paper describes how a seaside suburb of Sydney, Australia, assisted by the Urban Stormwater Initiative of the Commonwealth Department of Environment and Heritage, Environment Australia, has replaced an old impervious asphalt roadway with a UNI-Ecoloc® concrete segmental permeable pavement system as part of a stormwater project using the concepts of Water Sensitive Urban Design. The project is being monitored on a long-term basis.

OUTLINE

- **ABSTRACT**
- **INTRODUCTION**
- **PROJECT BACKGROUND**
- **PAVEMENT DESIGN**
 - Structural Design
 - Hydraulic Design
 - Pavement Details
- **STORMWATER MONITORING**
- **CATCHMENT MONITORING**
- **ATTAINMENT OF PERFORMANCE INDICATORS**
 - Catchment Imperviousness
 - Depression Storage
 - Water Quality
- **CONCLUDING COMMENTS**
 1. Though initial public reaction to the project was hostile due to the disruption and inconvenience of construction, it was enthusiastically accepted upon completion.
 2. Improved aesthetics of the street led to significant increases in property values.
 3. Early results indicate that the Ecoloc® permeable pavement has significantly reduced runoff and the capacity for pollutants to be carried to the storm sewer system.
 4. Overall, there appears to be a 60% reduction in the stormwater runoff attributed to the permeable paving.
 5. Depression storage appears to have increased four-fold, which will significantly reduce the runoff from frequent storm events.

DRAINAGE DESIGN AND PERFORMANCE GUIDELINES FOR UNI ECO-STONE® PERMEABLE PAVEMENT

Dan G. Zollinger, Su Ling Cao, and Daryl Poduska – 1998

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
 - Unit Hydrograph
- **SURFACE DRAINAGE SYSTEM**
 - Computation of Runoff
- **SUBSURFACE DRAINAGE DESIGN**
 - Introduction
 - General Considerations
 - Properties of Material
 - Design Alternatives
 - Design Criteria
 - Inflow Considerations
 - Outflow Considerations
 - Removal by Subgrade Percolation
 - Removal by Subsurface Drainage
 - The Selection of Base Material
 - Filter Criteria
 - Collection System
 - Maintenance
- **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 - 1996

GENERAL SUMMARY

In laboratory tests conducted on UNI Eco-Stone® and UNI Ecoloc® 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 2-5mm 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 2-5mm 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 Ecoloc® 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 4-5mm. 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 Ecoloc® 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.

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**

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.

CLOGGING OF ECO-STONE® PERMEABLE PAVERS - VOLUME 2, EXPERIMENTS 2, 3, AND 4 AT THE UNIVERSITY OF GUELPH

Rizwan ul Haq and William James - 2002

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 200 mm thick was installed in an apparatus rig with a surface area of 0.93 m² 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 10 mm 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. This report covers results of infiltration experiments for low, medium and high traffic usage areas.

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™ PP for UNI Eco-Stone® permeable pavers.

OUTLINE

1.0 INTRODUCTION

- 1.1 Porous Pavement
- 1.2 Types of Porous Pavement
- 1.3 Purpose of Research
- 1.4 Study Objectives
- 1.5 Research Needed

2.0 LITERATURE REVIEW

- 2.1 Benefits of Porous Pavement
- 2.2 Impacts of Suspended Sediments

- 2.3 Government Agencies and Water Quality Regulations in Ontario
- 2.4 Existing Information on the Life-span of Porous Pavement Systems
- 2.5 Maintenance Considerations
- 2.6 Cost Considerations
- 3.0 EXPERIMENTAL DESIGN AND CONSTRUCTION**
 - 3.1 Experimental Apparatus
 - 3.2 Slope of the Experimental Apparatus
 - 3.3 The Rainfall Simulator
- 4.0 SIMULATION OF RAINFALL**
 - 4.1 Selection of the Applied Duration and Rate of Simulated Rain
 - 4.2 Calibration of the Rainfall Simulator
 - 4.3 Rainfall Intensity
 - 4.4 Rainfall Uniformity
- 5.0 APPLICABLE THEORY**
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 - 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 1m² 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 230 mm/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 1m² 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
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RESTORATION OF INFILTRATION CAPACITY OF PERMEABLE PAVERS

Christopher Gerrits - 2001

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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- 1.2 Study Scope

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- 4.2 The Rainfall Simulator
 - 4.2.1 Rainfall Intensity Calibrations and Spatial Uniformity
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 - 4.6.1 Example Calculations

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6.0 DISCUSSION

- 6.1 Infiltration Rates
- 6.2 Particle Size Analysis
 - 6.2.1 Bedding Material
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- 6.4 Volatile Organic Matter (VOC Content)
- 6.5 Effect of Pounded Water
 - 6.5.1 Frequently Flooded vs. Well-Drained Plots

6.6 Vegetated Plots

6.6.1 Vegetated vs. Unvegetated Plots

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 an 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

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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1.0 INTRODUCTION

- 1.1 Project Objective
- 1.2 Project Scope

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- 2.1 Urban Stormwater
- 2.2 Permeable Pavement
 - 2.2.1 Porous Pavements
 - 2.2.2 Permeable Pavement Structure
- 2.3 Permeable Pavement Applications
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3.0 STORMWATER MANAGEMENT MODEL (SWMM)

- 3.1 Stormwater Modelling
- 3.2 U.S. EPA's Stormwater Management Model
- 3.3 SWMM: Overview of Program Structure
- 3.4 SWMM RUNOFF Block
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- 3.6 Infiltration in the SWMM RUNOFF Block
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4.0 COMPILING WITH LF90 VER. 4.0

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- 5.1 Changes made to the SWMM 4.4 Program
- 5.2 Changes to RHYDRO.FOR
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6.0 RESULTS AND DISCUSSION

- 6.1 Test File
 - 6.1.1 Data File
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- 6.2 Test 1 - Comparison of Non-Degradable versus Degradable Permeable Pavement
- 6.3 Test 2 - Comparison of Impervious and Degradable Permeable Pavement
- 6.4 Test 3 - Comparison of Different Saturated Hydraulic Conductivities

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.

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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- 1.1 Study Objective
- 1.2 Study Scope
- 1.3 Need

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 - 2.1.1 Traditional Stormwater Management Practices
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 - 2.1.3 Environmentally Responsible (Better) Management Techniques
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 - 2.2.1 Types of Porous Pavements
 - 2.2.2 Permeable Pavement Structure
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- 4.2 The Rainfall Simulator
 - 4.2.1 Rainfall Intensity Calibration and Spatial Uniformity
- 4.3 Experimental Procedure
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- 4.6 Computational Methods
 - 4.6.1 Computational Process - Example Calculations

5.0 RESULTS

- 5.1 Darcy Infiltration Capacities
- 5.2 EDC (External Drainage Cell) and Crust Materials

6.0 DISCUSSION

- 6.1 Regeneration of Infiltration Capacity
- 6.2 Reliability of Results
 - 6.2.1 Data Collection Phase
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- 6.3 Permeable Pavement Design and Installation
 - 6.3.1 UNI Eco-Stone® Installation and Specifications
- 6.4 Cost Comparison - MICBEC (Modular Interlocking Concrete Block with External Drainage Cells) and PAP (Porous Asphalt Pavement)
 - 6.4.1 Capital
 - 6.4.2 Maintenance and Repair
 - 6.4.3 Environmental
- 6.5 SWMM and Permeable Pavement
 - 6.5.1 LF90 Performance Enhancement
 - 6.5.2 Accommodation of More Complex Models
 - 6.5.3 Code Modifications

7.0 CONCLUSIONS AND RECOMMENDATIONS

- 7.1 Conclusions Based on Experimental Results
 - 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.

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 stormwater. 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 nitrites, chromium, chloride, phosphates, ammonium and E.coli. References included.

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 - 2.1.2 Temperature
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- 2.2 Porous Pavements
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 - 3.1.1 Pollutant Build-up, PBU
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6.0 RESULTS AND DISCUSSION

- 6.1 Introduction
- 6.2 Temperatures
- 6.3 Contaminant Load Results
 - 6.3.1 Flow Results
 - 6.3.2 Contaminant Results
 - 6.3.3 Contaminant Load Analysis

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. Subbase temperatures, measured up to 600 mm below the surface, showed little diurnal temperature fluctuation. In early summer, subbase 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.

EXPERIMENTAL INVESTIGATION OF THERMAL ENRICHMENT OF STORMWATER RUNOFF FROM TWO PAVING SURFACES

Brian Verspagen - 1995

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 cited.

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 $\Delta T_{sr} = A \ln(t) + B$ 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⁻¹]; 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.

THE LEACHING OF POLLUTANTS FROM FOUR PAVEMENTS USING LABORATORY APPARATUS

Reem Shabin - 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

3.0 PROCESSES AT THE PAVEMENT

- 3.1 Impact energy of raindrops
- 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
- 3.9 Clogging of pores

4.0 THE LABORATORY EXPERIMENTS

- 4.1 Water collection
 - 4.1.1 Laboratory rainwater
 - 4.1.2 Fresh rainwater

- 4.2 The rainfall simulator
 - 4.2.1 Rainfall intensity calibration
 - 4.2.2 Areal uniformity calibration
- 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
 - 6.2.4 Runoff collection
 - 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. 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.

Professional seminar and conference papers by William James, Professor of Water Resources Engineering University of Guelph, Ontario:

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.

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 1994-2003. They are based on the research conducted at Guelph University described on the previous pages.

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.

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.

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.

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.

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.

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® permeable 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 should be used more extensively. The asphalt pavement was found to increase the temperature of the runoff more than the Eco-Stone® 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.

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.

ADDITIONAL UNI® PERMEABLE PAVER RESEARCH AND TESTING

LOADING TESTS OF CONVENTIONAL AND ECOLOGICAL PAVING BLOCK

Brian Shackel, School of Civil and Environmental Engineering, University of New South Wales, Australia - 2000

This paper describes the experimental testing of a variety of both well-established and newly developed pavers – UNI-Anchorlock®, UNI-Optiloc®, UNI Priora® and Eco-Priora®. The pavers were evaluated under laboratory conditions using a special test designed to ensure that the paver surface could be characterized independently of any bedding or pavement substructure. The test allowed the pavers load distribution capabilities to be quantified in terms of their resilient modulus i.e., in a manner suitable for characterizing them for the purposes of pavement analysis and design. Factors studied included the paver shape and the laying pattern. Both conventional and ecological pavers were studied. The tests showed that the main factor influencing the load distributing characteristics of the pavers was their shape. The effects of the laying pattern were minor and there was little practical difference between the performance of conventional and ecological pavers. Typical ranges of resilient moduli for the pavers studied are given and compared.

TEST RESULTS ON THE STIFFNESS OF PAVED SURFACES

Brian Shackel, Sydney, Australia and Johann Litzka, M. Zieger, Vienna, Austria - 2000

The stiffness of block-paved surfaces depends on the shape, the thickness of the paving stone and the laying pattern. It is an essential value for the analysis and design of pavements surfaced with concrete block pavers, but despite its significance, it is often not sufficiently examined due to the complexity involved. The paving stones tested included UNI Priora®, Eco-Priora® and UNI-Optiloc®.

REPORT ON THE INFILTRATION PERFORMANCE OF THE UNI PRIORA® INTERLOCKING PAVING STONE SYSTEM

Dr. Soenke Borgwardt, Landscape Architect BDLA and Environmental Consultant - 1999

Field tests were conducted on the UNI Priora® paving stone system using an infiltrometer. Newly installed pavements that used a range of joint fill aggregates resulted in infiltration values far above the German standard of 270 l/s ha – namely 3250, 1670 and 750 l/s ha were infiltrated. In consideration of the reduction of the infiltration value over time by a power of ten, only the use of a fill material of 2 to 5 mm will maintain a 0 % runoff. By doing so, the infiltration values for new permeable pavements required by ATV Guideline A-138 are met. Using joint aggregate (sand) 1 to 3 mm or 0 to 5 mm, an infiltration value of 70% and 30% respectively can still be achieved. Because of the high initial infiltration rates, it is expected that the German standard value can be maintained over time. Additional research on aged pavements could confirm this.

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.



Wedge Park, Phase II, Fife, WA

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, infiltrability, and water-quality benefits of four types of permeable pavements - UNI Eco-Stone®, Grasspave2®, Gravel-pave2® 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 2-5mm 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.

ADDITIONAL PERMEABLE PAVEMENT RESEARCH AND TESTING

LONG-TERM IN-SITU INFILTRATION PERFORMANCE OF PERMEABLE CONCRETE BLOCK PAVEMENT

Dr. Soenke Borgwardt - 2006

Due to the entrainment of mineral and organic fines into the pores of porous concrete blocks or into the aggregates used in joints or openings, the reduction of water permeability can be assumed. Research results show that the infiltration performance decreases in the order of the power to ten after a few years. The study states moreover that the long-term in-situ infiltration performance and its observed decrease depend on the grain size of the aggregates used for joint filling. It is furthermore partly induced by the ratio of openings of permeable pavements respectively the pore size of porous concrete blocks. Despite the reduction in permeability rates after 10 years, it was demonstrated that the pavements were still capable of infiltrating virtually any design storm.

STUDY ON THE SURFACE INFILTRATION RATE OF PERMEABLE PAVEMENTS

E. Z. Bean, W. F. Hunt, and D. A. Bidelspach - 2003

This study tested the surface infiltration rate of 27 permeable pavement sites in North Carolina, Maryland and Delaware. Concrete grid pavers (CGP) and permeable interlocking concrete pavers (PICP) were tested with pavement ages ranging from six months to 20 years. Two infiltration tests were run on 14 CGP pavements. Maintenance improved the infiltration rate on 13 of 14 sites. Analysis of the data showed that maintenance improves surface permeability at a confidence level of 99.8%. The median average infiltration rate increased from 5.0 cm/hr., for existing conditions, to 8.0 cm/hr after maintenance. Eleven PICP sites were also tested. Sites built in close proximity to loose fine particles had infiltration rates significantly less than sites free of loose fines. Averages of each condition are 60 cm/hr and 2000 cm/hr respectively. Even the minimum existing infiltration rates were comparable to those of a grassed sandy loam soil. Water quality data included in this study shows the results of six storms from June to October, 2003.



Triangle Parking Lot, Stone Mountain, GA

WORKING WITH REGULATORS TO CHANGE PERMEABLE PAVEMENT ACCEPTANCE

*William F. Hunt III - Oct. 18-21, 2009, 9th International
Conference on Concrete Block Paving, Buenos Aires, Argentina*

In 1999, North Carolina State University began research on segmental permeable pavers used to infiltrate stormwater runoff. NC State conducted several studies from 1999 to 2005, all of which repeatedly showed positive performance of permeable pavement. Faculty at NC State worked with regulators at the North Carolina Department of Environment and Natural Resources (NC DENR) and eventually helped persuade the regulators to accept permeable pavement as a stormwater best management practice in 2006. Permeable pavement's initial "approval" was confined to the eastern, sandier soil region in North Carolina. Subsequently, faculty at NC State further cooperated with staff of State Senator Marc Basnight who passed a law requiring the use of permeable pavement, or an acceptable alternative, in parking lots across the state of North Carolina. This loosened the restriction for use of permeable pavement for only sandy in-situ soils. Due to the

change in state policy, certain communities have embraced the use of permeable pavement, and the implementation of permeable pavements has increased substantially. One of the main reasons for this was the NC DENR's treating of permeable pavement as a mostly permeable (and partially impermeable) surface. The relationship of a university working hand-in-hand with regulators has proven very beneficial for the use of permeable pavement.

STRUCTURAL & HYDROLOGIC 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 in an easy to use program. 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 hydrologic modeling based on the USEPA's SWMM model.

FEATURES OF PC-SWMM™ PP

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.

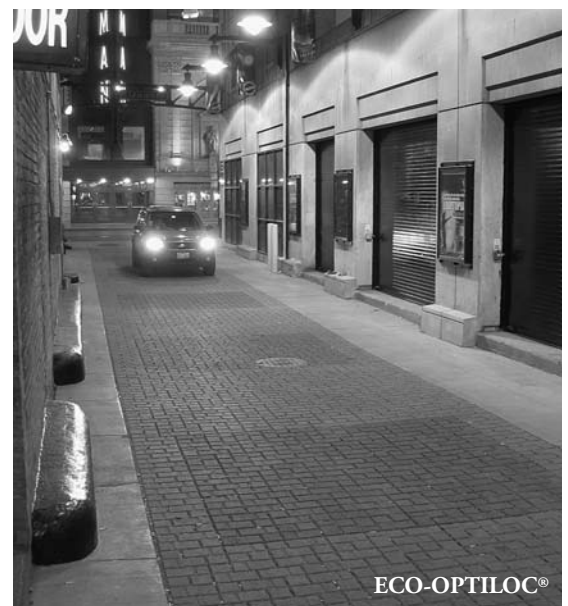
- An Input Wizard interface guides the user through the required parameters
- Model results include graphs of the input function (design storm), surface runoff (if any), depth of water in the base material, and drainage of the base material for the duration of the model run
- A summary report includes 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™ PP 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 hydrologic parameters are met.

POWERPOINT PRESENTATION

UNI® PERMEABLE PAVERS POWERPOINT® PRESENTATION

This comprehensive PowerPoint® presentation is oriented to the design professional and municipalities. It includes basic design guidance, hydrologic and structural information, research information, case study highlights, and project references.



Couch Place Green Alley, Theatre District, Chicago, IL

UNI® PERMEABLE PAVEMENT CASE STUDIES



St. Clares Parish, Westerly, RI

UNI-ECO-STONE FAMILY OF PERMEABLE INTERLOCKING CONCRETE PAVEMENT MULTI-PROJECT CASE STUDIES

Case Study – 24-page

Several case studies from across the United States and Canada are featured in this comprehensive 24-page brochure. It includes examples of all the UNI® permeable pavers and many types of applications - residential, commercial, and municipal.

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 – 6-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.

MORTON ARBORETUM CASE STUDY

Case Study – 2-page

Case study on the Morton Arboretum project in Dupage County, IL - Features 173,000 sq ft of permeable Ecoloc® pavers used in conjunction with 32,000 sq ft of traditional UNI-Anchorlock® pavers in the facilities parking area. This project is also a USEPA's National Monitoring Program Section 319 project.

WESTMORELAND STREET CASE STUDY

Case Study – 2-page

This case study details a pilot project to install Ecoloc® permeable interlocking concrete pavement (PICP) in the 80-year old Westmoreland neighborhood of Portland, OR. Over 19,000 sq ft of pavers were installed along four residential blocks.



Westmoreland Street, Portland, OR

ADDITIONAL REFERENCES

- American Association of State Highway and Transportation Officials (AASHTO), 1993. *AASHTO Guide for Design of Pavement Structures*, Washington, DC.
- American Society for Testing and Materials (ASTM), Volume 04.05. *Annual Book of ASTM Standards*, West Conshohocken, PA
- American Society of Civil Engineers, 1992. *Design and Construction of Urban Stormwater Management Systems*, ASCE, New York, NY.
- Bean, E.Z., Hunt, W.F., Bidelspach, D.A. and Smith, J.T., *Study on the Infiltration of Permeable Pavements*, 2004, Interlocking Concrete Pavement Institute, Washington, DC.
- 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.
- Cedegren, H., 1987. *Drainage of Highway and Airfield Pavements*, Krieger Publishing Company, Malabar, FL.
- Corps of Engineers, 1991. *Subsurface Drainage of Pavement Structures, Research and Development Service: Current Corps of Engineers and Industry Practice*, Hanover, NH.
- Corps of Engineers, 1992. Engineering and Design Drainage Layers for Pavements, Engineer Technical Letter 1110-3-435, Department of the Army, U.S. Army Corps of Engineers, Washington, DC.
- Cote Jr., M., J. Clausen, B. Morton, P. Stacey, and S. Zaremba, 1997. *Jordan Cove Urban Watershed National Monitoring Project*, USEPA, University of Connecticut, Aqua Solutions, Connecticut Department of Environmental Protection, Waterford, CT.
- Federal Highway Administration (FHWA), 1990. *FHWA Technical Guide Paper 90-01: Subsurface Pavement Drainage*, FHWA, Office of Engineering, Pavement Division, Washington, DC.
- Federal Highway Administration (FHWA), 1992. *Demonstration Project 87: Drainable Pavement Systems Participant Notebook*, FHWA, Publication No. FHWA-SA-92-008, Washington, DC.
- Ferguson, B., 2005. *Porous Pavements*, Taylor and Francis Group, CRC Press, Boca Raton, FL.
- Ferguson, B., 1991. "The Failure of Stormwater Detention and the Future of Stormwater Design", *Landscape Design*, Vol. 4, No. 12, Gold Trade Publications, Van Nuys, CA.
- Ferguson, B., 1994. *Stormwater Infiltration*, Lewis Publishers, CRC Press, Boca Raton, FL.
- Ferguson, B. and T. Debo, 1990. *On-site Stormwater Management*, Second Edition, Van Nostrand Reinhold, New York, NY.
- Goforth, G., E. Diniz, and J. Rauhut, 1983. *Stormwater Hydrological Characteristics of Porous and Conventional Paving Systems*, United States Environmental Protection Agency, Grant No. R806338-01-2, Austin, TX.
- Interlocking Concrete Pavement Institute and Low Impact Development Center, 2008. *Permeable Interlocking Concrete Pavements Fact Sheets*, Herndon, VA.
- National Association of Home Builders, 2006. *Building Greener, Building Better*, National Association of Home Builders Research Center, Washington, DC.
- National Cooperative Highway Research Program (NCHRP), 1982, 1997. *Synthesis of Highway Practice 96: Pavement Subsurface Drainage Systems*, Sequim, WA.
- National Resources Defense Council, 1999. *Stormwater Strategies, Community Responses to Runoff Pollution*, New York, NY.
- National Resources Conservation Service, 2007. *National Soil Survey Handbook*, National Soil Survey Center, Lincoln NE.
- Portland Cement Association, 1992. *Properties and Uses of Cement-Modified Soil*, Skokie, IL.
- Rollings, R. and M. Rollings, 1992. *Applications for Concrete Paving Block in the United States Market*, Uni-Group U.S.A., Palm Beach Gardens, FL.
- Shackel, B., 1990. *Design and Construction of Interlocking Concrete Block Pavements*, Elsevier Science Publishing Co., New York, NY.
- Smith, D., 2001. *Permeable Interlocking Concrete Pavements*, Interlocking Concrete Pavement Institute, Washington, DC.
- State of Maryland, Department of the Environment 1985. *Standard Specification for Infiltration Practices*, Baltimore, MD.
- State of Maryland, Department of the Environment 1985. *Maryland Stormwater Manual*, Baltimore, MD.
- The Asphalt Institute, 1989. *The Asphalt Handbook*, MS-4, Lexington, KY.
- United States Environmental Protection Agency (USEPA), Office of Water and Low Impact Development Center, 2000. *Low Impact Development (LID). A Literature Review*, EPA-841-B-00-005, Washington, DC.

United States Environmental Protection Agency (USEPA), Office of Water, 2000. *National Menu of Best Management Practices for Storm Water Phase II*, Washington, DC.

United States Environmental Protection Agency (USEPA), Office of Water, 2005. *National Management Measures to Control Nonpoint Source Pollution from Urban Areas*, Washington, DC.

United States Environmental Protection Agency (USEPA), Office of Policy, Economics and Innovation, 2004. *Protecting Water Resources with Smart Growth*, Washington, DC.

United States Environmental Protection Agency (USEPA), Office of Policy, Economics and Innovation, 2005. *Using Smart Growth Techniques as Stormwater Best Management Practices*, Washington, DC.

United States Environmental Protection Agency (USEPA), Development, Community and Environment Division, 2006. *Parking Spaces/Community Places - Finding the Balance through Smart Growth Solutions*, Washington, DC.

United States Environmental Protection Agency (USEPA), Office of Water, 2007. *Post Construction Stormwater Management in New Development and Redevelopment*, Washington, DC.

United States Environmental Protection Agency (USEPA), Office of Water, 2007. *Low Impact Development (LID) and Other Green Design Strategies*, Washington, DC.

United States Environmental Protection Agency (USEPA), Office of Wastewater Management, 2008. *Urban Stormwater Management in the United States*, Washington, DC.

United States Environmental Protection Agency (USEPA), Office of Wastewater Management, 2008. *Green Infrastructure Action Strategy*, Washington, DC.

United States Environmental Protection Agency (USEPA), Office of Wastewater Management, 2008. *Urban BMP Performance Tool*, Washington, DC.

United States Soil Conservation Service, *Urban Hydrology for Small Watersheds*, Technical Release 55, Second Edition, 1986. Washington, DC.

United States Department of Agriculture, Natural Resources Conservation Service, 2007. *Part 630 Hydrology National Engineering Handbook - Hydrologic Soil Groups*, Washington, DC.

STORMWATER MANAGEMENT INSPECTION FORM WATERSHED MANAGEMENT INSTITUTE AND USEPA

INFILTRATION PAVING CONSTRUCTION INSPECTION REPORT

DATE: _____ INDIVIDUAL CONTACTED: _____

PROJECT: _____

LOCATION: _____

SITE STATUS: _____ ACTIVE _____ INACTIVE _____ COMPLETED

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

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

	Satisfactory	Unsatisfactory
1. Debris on infiltration paving area (Monthly)	_____	_____
2. Vegetation areas (Monthly)		
Mowing done when needed	_____	_____
Fertilized per specifications	_____	_____
No evidence of erosion	_____	_____
3. Dewatering (Monthly)		
Infiltration paving dewaterers between storms	_____	_____
4. Sediments (Monthly)		
Area clean of sediments	_____	_____
Area vacuum swept on a periodic basis as needed	_____	_____
5. Structural condition (Annual)		
No evidence of surface deterioration	_____	_____
No evidence of rutting or spalling	_____	_____

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 _____

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