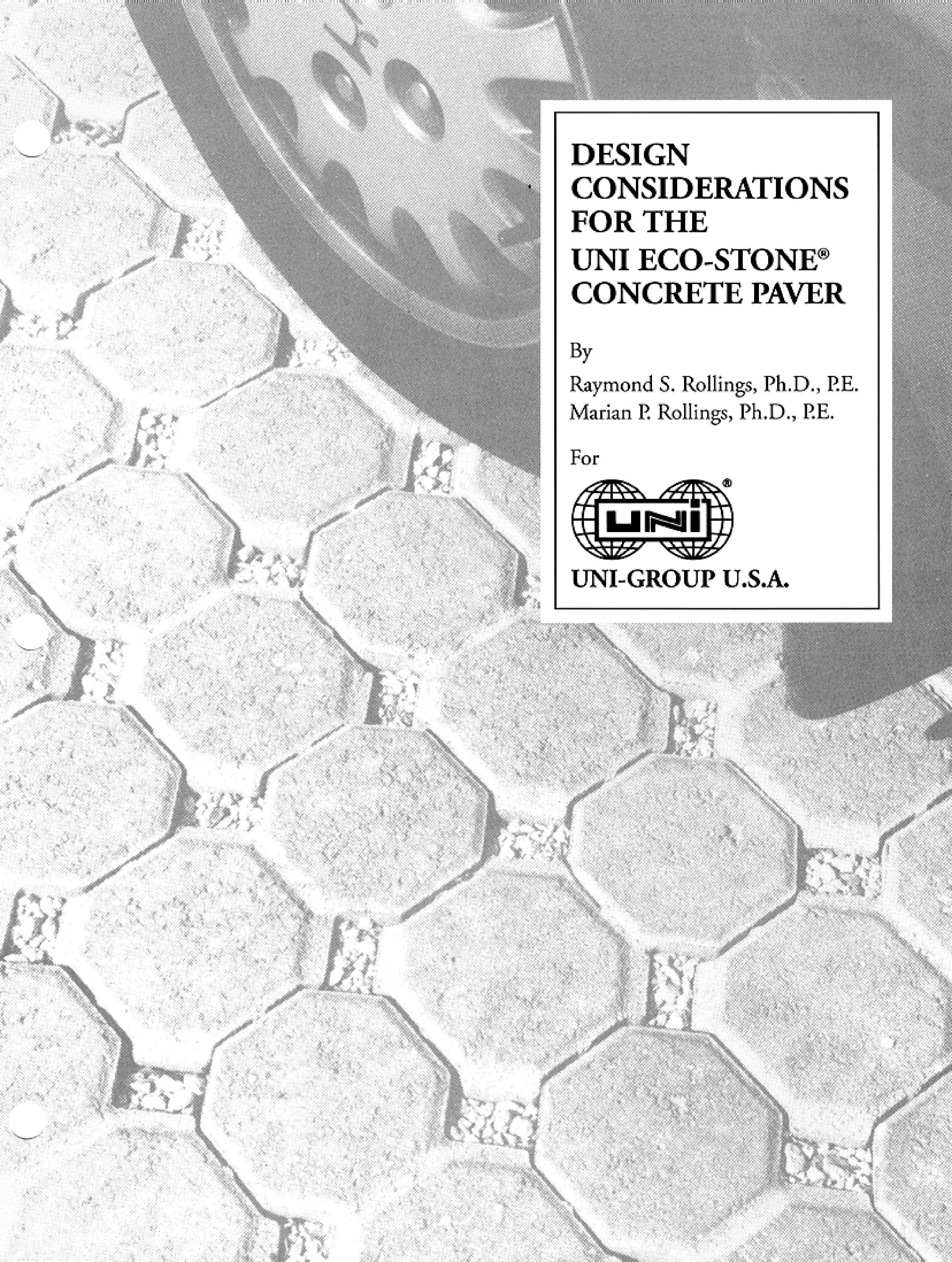


DESIGN CONSIDERATIONS FOR THE UNI ECO-STONE® CONCRETE PAVER

By

Raymond S. Rollings, Ph.D., P.E.

Marian P. Rollings, Ph.D., P.E.

For

UNI-GROUP U.S.A.

ADDENDUM

As a leader in the interlocking concrete paver industry in North America, UNI-GROUP U.S.A. is committed to providing design professionals with the latest research and development technology for the UNI Eco-Stone® Permeable Paving System. Since the preparation of this report in 1993, substantial additional testing and research has been conducted in the United States, Canada, and overseas on infiltration, structural design, environmental engineering, stormwater management, and pavement maintenance. Case studies on the UNI Eco-Stone® Pavement System are also available. For a copy of any of these reports, contact UNI-GROUP U.S.A. or call your local UNI Manufacturer.

INFILTRATION AND STRUCTURAL TESTS OF PERMEABLE ECO-PAVING

B. Shackel, J.O. Kaligis, Y. Muktiarto, and Pamudji

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

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. The structural design aspects of UNI Eco-Stone® pavements are included in the program, as well as an hydraulic design program based on SWMM, the Environmental Protection Agency's Stormwater Management Model.

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

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

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 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.

ONGOING RESEARCH AT GUELPH UNIVERSITY

Professor William James

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

THE LEACHING OF POLLUTANTS FROM FOUR PAVEMENTS USING LABORATORY APPARATUS

Reem Shahin - 1994

This thesis describes a laboratory investigation of pavement leachate. Four types of pavements were installed in the engineering laboratory: asphalt, conventional interlocking pavers, and two 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.

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

Brian Verspagen - 1995

This study examines the thermal enrichment of surface runoff from an impervious asphalt surface and a UNI Eco-Stone® permeable concrete paver surface. The pavement samples were heated and a rainfall simulator was used to generate rainfall and cool the pavement samples. Thermocouples were used to monitor 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 Eco-Stone® pavement produced very little surface runoff and exhibited less thermal impact than the asphalt surface. The environmental advantage with the UNI Eco-Stone® permeable pavement is its ability to allow rainfall to infiltrate the surface and thereby reduce total thermal loading on surrounding surface waters.

DESIGN AND INSTALLATION OF TEST SECTIONS OF POROUS PAVEMENTS FOR IMPROVED QUALITY OF PARKING LOT RUNOFF

Michael Kaestner Thompson, P.Eng. - 1995

This 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. It was found that 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.

LONG-TERM STORMWATER INFILTRATION THROUGH CONCRETE PAVERS

Christopher Kresin - 1996

This study investigates the infiltration capacity of porous concrete paver installations of various ages. Using a rainfall simulating infiltrometer, several test plots at four Eco-Stone® installations were subjected to a total of 60 tests comprising two simulated rainfalls of known intensity and duration. The first rainfall provided initial moisture losses to wetting the drainage cell material, while data collected during the second rainfall was 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.

FEASIBILITY OF A PERMEABLE PAVEMENT OPTION IN THE STORM WATER MANAGEMENT MODEL (SWMM) FOR LONG-TERM CONTINUOS MODELING

Craig Kipkie - 1998

The purpose of this 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 pavement can greatly reduce flows when compared to impervious surfaces.

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

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

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

RIO VISTA WATER TREATMENT PLANT - *Case Study*

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® pavers.

MICKEL FIELD AND HIGHLANDS PARK - *Case Study*

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

JORDAN COVE URBAN WATERSHED PROJECT - *Case Study*

Case Study on EPA Section 319 National Monitoring Program project - Use of Best Management Practices in a paired watershed study in Waterford, CT. Features over 15,000 sq ft of UNI Eco-Stone® permeable pavers.

UNI-GROUP U.S.A.

MANUFACTURERS OF UNI PAVING STONES

For more information, contact UNI-GROUP U.S.A. at 1-800-872-1864
or visit our website at www.uni-groupusa.org.

ACKER STONE
13296 Temescal Canyon Rd.,
Corona, CA 92883
(951) 674-0047 / FAX (909) 674-0477

BORGERT PRODUCTS, INC.
8646 Ridgewood Rd., St. Joseph, MN 56374
(320) 363-4671 / FAX (320) 363-8516

IDEAL CONCRETE BLOCK CO.
45 Power Rd., Westford, MA 01886
(781) 894-3200 / FAX (978) 692-0817
(800) 444-7287

232 Lexington St., Waltham, MA 02454
(781) 894-3200 / FAX (781) 894-8526
(800) 444-7287

MUTUAL MATERIALS, INC.
Toll Free US: 1-888-688-8250
Canada: 1-888-816-2111

605 119th Ave. NE, Bellevue, WA 98005
2201 112th St. S, Tacoma, WA 98444
4140 Bakerview Spur, Bellingham, WA 98266
1357 W Valley Hwy. N, Auburn, WA 98002
1912 S Burlington Blvd.,
Burlington, WA 98233
3150 29th Avenue SW, Tumwater, WA 98512
12406 Mukilteo Speedway,
Mukilteo, WA 98275
1515 Vivian Court, Port Orchard, WA 98366
7760 185th Ave. NE, Redmond, WA 98052
6721 E Trent Ave., Spokane, WA 99212
30 W. Orchard Ave., Hayden, ID 83835
18230 SW Boones Ferry Rd.,
Durham, OR 97224
10019 NE 72nd Ave., Vancouver, WA 98686
1705 NE Lytle St., Bend, OR 97701
15791 SE Piazza Ave., Clackamas, OR 97015
1561 SE Enterprise Circle,
Hillsboro, OR 97123
2245 Judson St. SE, Salem, OR 97302
2910 American Way, Missoula, MT 59808
3020 Hwy 2 East , Kallispell, MT 59901
19675 98th Avenue, Langley, BC V1M 2X5

OLDCASTLE COASTAL
7167 Interpace Rd., West Palm Beach, FL 33407
(561) 844-5202 / FAX (561) 844-5454
(800) 226-0004

39 West Landstreet Rd., Orlando, FL 32824
(407) 859-9117 / FAX (407) 851-9316
(800) 226-9117

8910 N. 12th St., Tampa, FL 33604
(813) 932-2212 / FAX (813) 933-4914
(800) 356-PAVE

2200 12th Street, Sarasota, FL 34237
(941) 957-3933 / FAX (941) 366-1343

5959 Soutel Dr. Jacksonville, FL 32219
(904) 713-9996 / FAX (905) 713-9985

For our other Florida locations call
1-888-321-BELGARD (2354)

PAVESTONE COMPANY
CORPORATE HEADQUARTERS
4835 LBJ Freeway, Ste. 700, Dallas, TX 75244
(972) 404-0400 / FAX (972) 404-9200
(800) 580-PAVE

3215 State Highway 360, Grapevine, TX 76051
(817) 481-5802 / FAX (817) 481-3216

30001 Katy-Brookshire Rd., Katy, TX 77494
(281) 391-7283 / FAX (281) 391-7337

1900 Clovis Barker Rd., San Marcos, TX 78666
(512) 558-7283 / FAX (512) 558-7289

169 Peggy Lane, Tyrone, GA 30290
(770) 306-9691 / FAX (770) 306-8741

1101 Westinghouse Blvd., Charlotte, NC 28273
(704) 588-4747 / FAX (704) 588-4055

29095 Krentel Rd., LaCombe, LA 70445
(985) 882-9111 / FAX (985) 882-5225

8479 Broadwell Rd., Cincinnati, OH 45244
(513) 474-3783 / FAX (513) 474-6683

601 N. E. Pavestone Dr.,
Lee's Summit, MO 64064
(816) 524-9900 / FAX (816) 524-9901

9401 E. 96th Ave., Henderson, CO 80640
(303) 287-3700 / FAX (303) 287-9759

11110 Charter Oak Ranch Rd.,
Fountain, CO 80817
(719) 322-0101 / FAX (719) 322-0123

1015 S. 43rd Ave., Phoenix, AZ 85009
(602) 257-4588 / FAX (602) 257-1224

4720 Alto Ave., Las Vegas, NV 89115
(702) 221-2700 / FAX (702) 221-2727

27600 County Rd. 90, Winters, CA 95674
(530) 795-4400 / FAX (530) 795-4441

UNILOCK, LTD.
287 Armstrong Ave., Georgetown,
Ontario, Canada L7G-4X6
(416) 646-9000 / FAX (905) 874-3034
Toll Free US: 1-800-UNILOCK

UNILOCK, INC.
510 Smith St., Buffalo, NY 14210
(716) 822-6074 / FAX (716) 822-6076

UNILOCK NEW YORK, INC.
51 International Blvd., Brewster, NY 10509
(845) 278-6700 / FAX (845) 278-6788

UNILOCK - PHILADELPHIA
A Division of Unilock New York, Inc.
229 Mount Holly Bypass
Lumberton, NJ 08048
(609) 914-0000 / FAX (609) 914-0290

UNILOCK - NEW ENGLAND
A Division of Unilock New York, Inc.
35 Commerce Drive, Uxbridge, MA 01569
(508) 278-4536 / FAX (508) 278-4572

UNILOCK CHICAGO, INC.
301 E. Sullivan Rd., Aurora, IL 60504
(630) 892-9191 / FAX (630) 892-9215

UNILOCK - WISCONSIN
A Division of Unilock Chicago, Inc.
W 4814 Highway A, Elkhorn, WI 53121
(262) 742-3890 / FAX (262) 742-2168

UNILOCK MICHIGAN, INC.
12591 Emerson Dr., Brighton, MI 48116
(248) 437-7037 / FAX (248) 437-4619

UNILOCK OHIO, INC.
12560 Sheets Rd., Rittman, OH 44270
(330) 927-4000 / FAX (330) 927-4100

LICENSING OFFICE:
F. VON LANGSDORFF LICENSING LTD.
14145 Kennedy Road, Caledon,
Ontario, Canada L7C 2H4
(905) 838-1980 / FAX (905) 838-1981

PREFACE

Preparation of this report was sponsored by the UNI-GROUP U.S.A. as part of their research, education, and technology transfer efforts regarding interlocking concrete block pavements and their use in the United States. The UNI-GROUP U.S.A. is an association of concrete block manufacturers in the United States and Canada and is an affiliate of the worldwide UNI® organization.

Design Considerations For The UNI Eco-Stone® Concrete Paver was prepared by Raymond S. Rollings, Ph.D., P.E. and Marian P. Rollings, Ph.D., P.E. of Rollings Engineering, 11 Lake Circle Drive, Vicksburg, Mississippi, 39180.

UNI-GROUP U.S.A. HEADQUARTERS OFFICE:
4362 Northlake Blvd., Suite 204, Palm Beach Gardens, Florida 33410 • (561) 626-4666 • Fax (561) 627-6403

TABLE OF CONTENTS

FIGURES

TABLES

SECTION I: INTRODUCTION

As increasingly large areas of the United States have been developed, stormwater control and management has become a major public problem. As more land is developed and covered with impermeable surfacings, storm runoff has increased, and potential for downstream flooding due to this elevated runoff has risen. Approximately seven percent of the land in the United States is within recognized flood plains (Wanielista and Yousef 1993). Also, the increased runoff from developed areas has degraded water quality significantly. Nonpoint pollution sources (e.g., stormwater runoff and atmospheric fallout, as opposed to point pollution sources such as sewage discharges) have caused over 50 percent of the organic chemicals and 98 percent of the suspended solids in the Great Lakes (International Joint Commission on the Great Lakes 1978). This is not an isolated incidence. Studies of combined stormwater/sewage systems have found that 40 to 80 percent of the annual oxygen-consuming load is due to stormwater runoff (Pisano 1976); in Florida, nonpoint sources such as stormwater runoff account for 85 to 90 percent of the metals, 90 percent of the oxygen-consuming material, and 99 percent of the suspended solids in the water system (Livingston and Cox 1989).

Local municipalities, counties, regional authorities, and state agencies are increasingly using a variety of mandatory regulatory standards in an attempt to control the problems associated with stormwater runoff in developed areas. These regulatory restrictions vary from agency to agency but might include requirements such as:

a. A specified design storm must be retained on-site and discharged to the surrounding drainage system slowly over a specified time (e.g., a 4-in. rain must be retained on-site and discharged over 7 days).

b. For a developed area, specific stormwater discharge rates and water quality standards may be established quantitatively or may be set to some proportion of predevelopment levels (e.g., flow rates and suspended solids in the water from a developed site cannot exceed predevelopment rates for the site).

c. The amount of impermeable surfacing may be limited to some percentage of the whole site (e.g., 20 percent of a site may not be covered with an impervious surface).

e. Sediment and other pollutants must be reduced to the same degree as required for point sources.

There is considerable variation in specific regulatory requirements, but increasingly, the design of stormwater control basins, ponds, weirs, and similar structures is becoming a major aspect of site development. *The cost of these structures is significant, but the lost value of property used for these basins and similar structures or left undeveloped to meet regulatory requirements may be even more significant.*

Much of the problem with stormwater runoff is due to use of large expanses of relatively impermeable asphalt and concrete for parking areas, roads, sidewalks, plazas, etc., in developed sites. To overcome this problem, permeable pavements of various types have been tried, but because of various problems with them, their use has been fairly limited (Nichols 1993). Open-graded asphalts and permeable "no fines" concrete are expensive and difficult to build and maintain. Open-graded polymer concretes can be used but are very expensive relative to conventional paving. Open-celled blocks or grid pavers have a number of environmental advantages but are generally used for occasional traffic. Another alternative is to use permeable gravel-surfaced pavements, but their high maintenance costs and poor quality surface often makes this approach unacceptable. Consequently, even though permeable pavements offer some promising alternatives to solving stormwater runoff problems, technology had not provided an effective permeable surface even as recently as the early 1990's.

In 1991, the UNI Eco-Stone® concrete paver was introduced in North America following its development in Germany. UNI Eco-Stone® provides, for the first time, a structurally sound, low maintenance, high quality, permeable pavement surface. This interlocking paver continues to offer the strength, aesthetics, and durability of the traditional solid concrete paver, but also introduces new characteristics that provide the design engineer and architect new possibilities in pavement surface water control. When the UNI Eco-Stone® pavers are installed, they form a tight surface with narrow joints separating the pavers, just as with conventional solid pavers. However, the design of the UNI Eco-Stone® pavers also creates openings comprising approximately 12 percent of the surface area as shown in Figure 1. When properly filled with permeable material, these voids drain rainwater through the pavement surface into the layers below. This offers some unique opportunities for the designer to develop new ways of handling surface water to meet regulatory requirements and potentially reduce the size or need for special storm-water retention facilities, reduce runoff and resultant downstream flooding, mitigate pollution impact on surrounding surface waters, and contribute to groundwater recharge or storage.

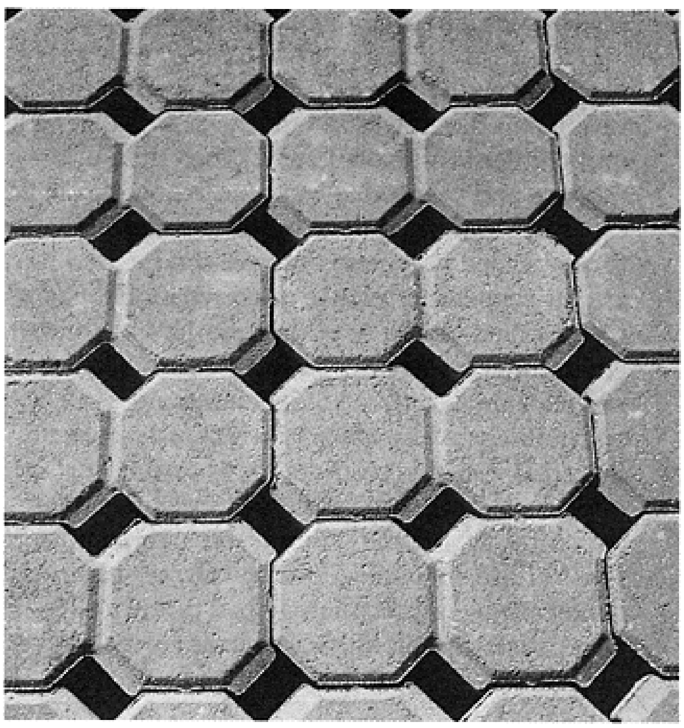


Figure 1 Drainage Voids in UNI Eco-Stone® Surface

UNI Eco-Stone® provides the engineer and architect with the opportunity to develop new nontraditional pavement designs which can offer major environmental benefits. In today's ecologically aware environment, this product gives the designer a tool with the flexibility to be used in a variety of ways to overcome stormwater management problems and decrease the adverse impact of developing land for public use. It should also significantly decrease the cost of compliance with many regulatory requirements for stormwater management.

"In today's ecologically aware environment, this product gives the designer a tool with the flexibility to be used in a variety of ways to overcome stormwater management problems and decrease the adverse impact of developing land for public use."

Purpose

Experience with the UNI Eco-Stone® in the United States is limited, and guidance for the design professional on how to incorporate this product in projects is also scarce. This report will review available testing information from the U.S. and Germany and will extrapolate from existing practice to provide basic design information on how designs can be developed for UNI Eco-Stone® pavements. Test data on this product is not extensive, but much of the information developed for solid concrete pavers and for conventional pavements can be applied to UNI Eco-Stone® installations. Preparation of this report was sponsored by UNI-GROUP U.S.A. as part of their research, education, and technology transfer program to provide the designer with up-to-date and reliable technical information on UNI® concrete paving products.

Description

Figure 2 shows the typical components found in any interlocking concrete paver pavement whether it is a solid concrete paver or a UNI Eco-Stone® pavement. The surface is composed of high quality concrete pavers which are separated from one another by narrow sand-filled joints. The high quality of the concrete pavers provides strength, durability, and aesthetics, and their tight manufacturing tolerances, combined with interlocking shapes, laying patterns, and sand-filled joints, allow the pavers to interact so that they function together as a unified structure rather than as individual units.

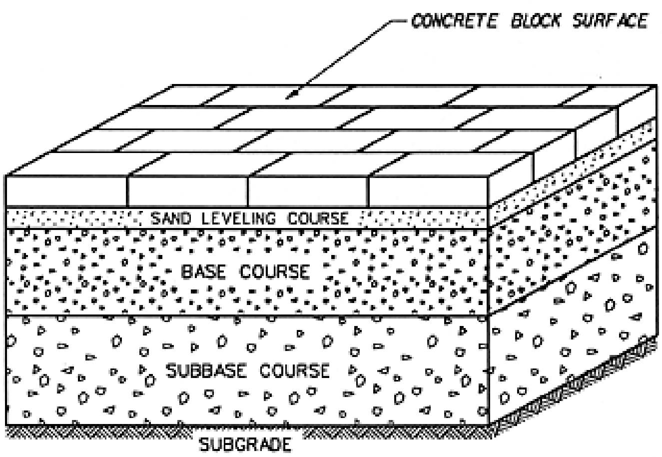


Figure 2 Components of a Concrete Paver Pavement

Subgrade and Base Course

Extensive research summarized in detail in Rollings and Rollings (1992) has shown that concrete paver-surfaced pavements behave as flexible pavements, and they should be designed as such. The base and subbase courses are the major structural load-carrying elements of any flexible pavement since they distribute the load to levels that can be tolerated by the subgrade. The most common example of a flexible pavement is the traditional asphalt-surfaced road that uses a relatively thin asphalt surface over thicker underlying granular base and subbase courses. The base and subbase provide the structural strength of the flexible pavement (whether paver or asphalt surfaced), and consequently, must be a major element in the structural design. The underlying natural soil or fill upon which the pavement will be built is the subgrade. The strength of this soil when wet has a major impact on the required thickness of the flexible pavement, and improper estimation of the final subgrade strength can cause major failures in flexible pavements.

Construction of the UNI Eco-Stone® pavement is similar to that of traditional solid pavers. The subgrade, subbase, and base course are designed and constructed in the same manner as conventional solid paver-surfaced pavements, and more detailed guidance is available in Rollings and Rollings (1992). The ingress of water into the pavement through the openings in the Eco-Stone® pavement surface requires some special design considerations that are discussed in Section II and III of this report.

Surfacing Materials

UNI Eco-Stone® is used for the pavement surface and differs from the traditional solid concrete paver only in having the drainage openings shown in Figure 1. The individual UNI Eco-Stone® paver is shown in Figure 3, and the typical paver dimensions are shown in Figure 4. The UNI Eco-Stone® paver itself is manufactured to the same standards as specified in ASTM C 936 "Standard Specification for Solid Concrete Interlocking Paving Units" that is used for traditional solid pavers. The unique characteristic of UNI Eco-Stone® is the void which allows drainage of surface water into the pavement structure.

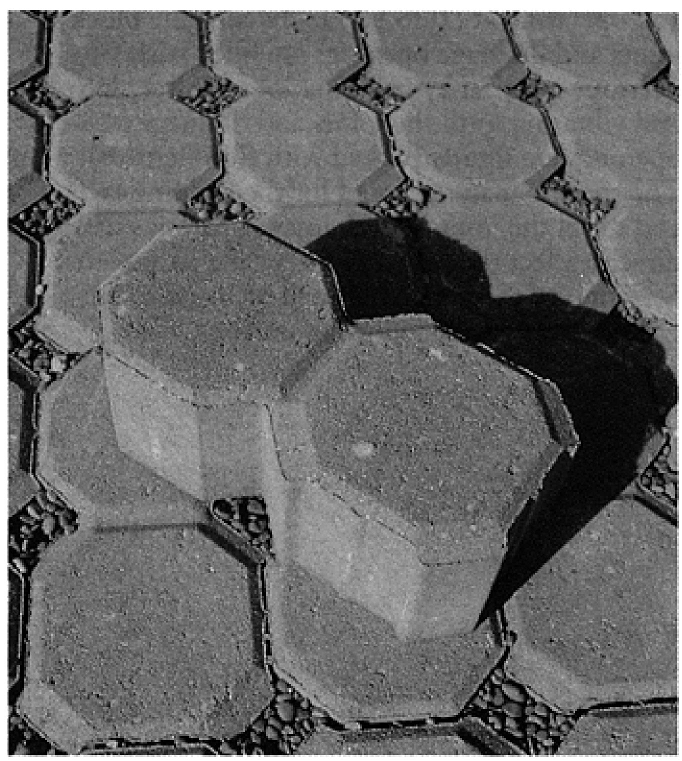
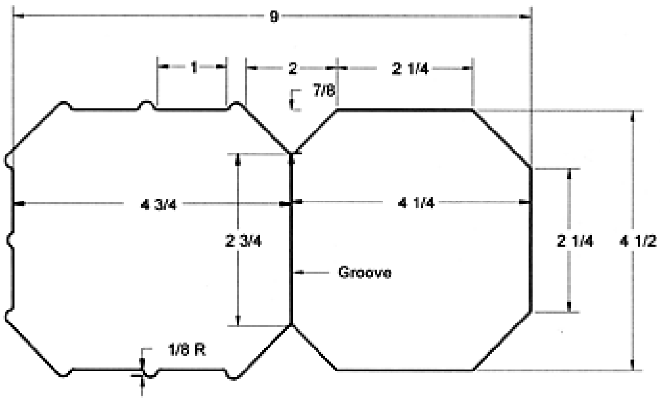


Figure 3 UNI Eco-Stone®



Physical Characteristics

Height/Thickness	3 1/8"	=	80mm
Width	Approx. 4 1/2"	=	115mm
Length	Approx. 9"	=	230mm
Number of stones per sq ft		=	3.55
Percentage of void area per sq ft		=	12.18%

Figure 4 Dimensions of UNI Eco-Stone®

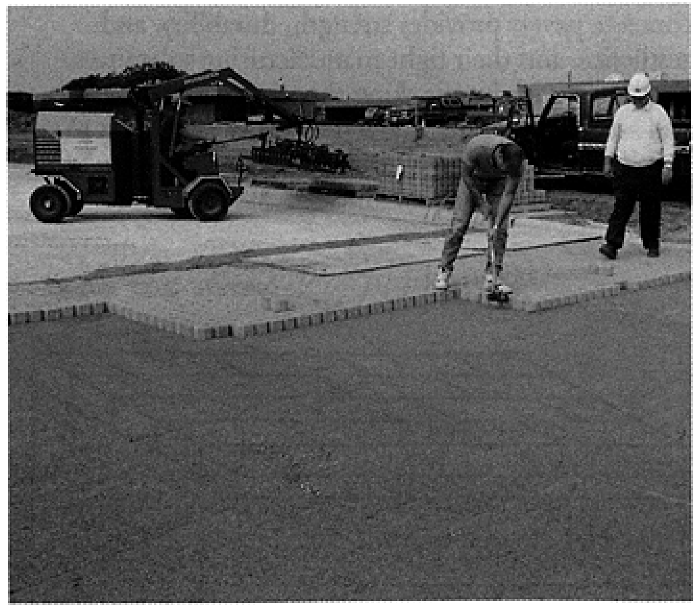


Figure 5 Machine Placement of UNI Eco-Stone®

The bedding layer is loosely spread by hand-screeding or with equipment to a depth of 1 inch. The pavers are placed on the bedding layer by hand or by machine (Figure 5). The pavers are then seated and leveled by compacting them with a vibratory plate compactor typically capable of providing more than 5,000 lb. centrifugal force and operating at 80 to 90 Hz. Finally, the block joints and drainage openings are filled with pervious material by combinations of sweeping and vibrating until the joints and drainage openings are tightly packed with fill (Figure 6). The specific materials used for the bedding layer and to fill the joints and drainage openings will directly affect the permeability of the pavement. Selection of these materials will be discussed in greater detail in the following sections.

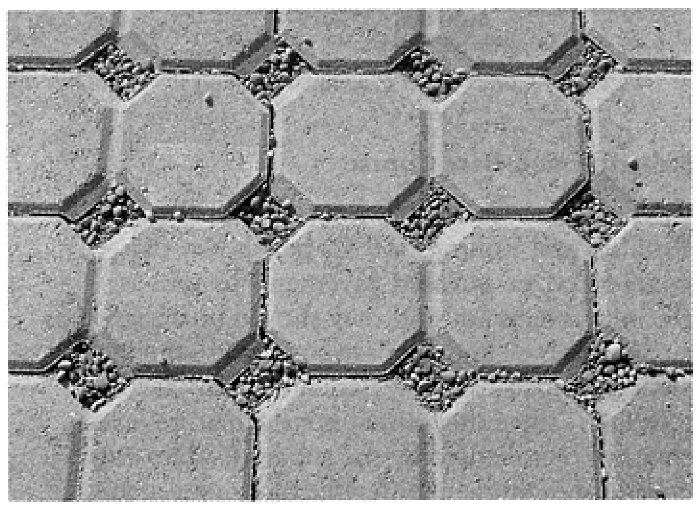


Figure 6 UNI Eco-Stone® Surface with Joints and Drainage Voids Filled

SECTION II: DESIGN CONSIDERATIONS

This section will examine some of the factors that must be addressed in designing a UNI Eco-Stone® pavement. UNI Eco-Stone's® allowance of water into the pavement structure is a departure from conventional pavement practice, and this requires that some structural and hydraulic considerations be addressed in order to insure that the water flow is properly controlled. It is also important to remember that no pavement design is any better than the quality of the construction. Poor pavement performance, whether in conventional pavements such as asphalt or concrete, or in pavers, is most often due to use of poor quality materials in the pavement or poor construction rather than design (Michau and Wilson 1988; Rollings and Rollings 1991). Consequently, proper design must be coupled with proper material use and construction in order to achieve a satisfactory pavement.

Structural Considerations

As noted earlier, extensive research in the U.S. and overseas has established that concrete paver-surfaced pavements should be designed according to flexible pavement design theory. Discussion of flexible pavement design approaches can be found in standard texts such as Yoder and Witczak (1975), and an in-depth review of its application to pavers can be found in Rollings and Rollings (1992). Briefly, the basic concepts of flexible pavement design can be summarized as:

- Provide sufficient pavement thickness to protect the subgrade from being overstressed by traffic loads.
- Provide quality base and subbase materials that can support the applied loads.
- Provide a stable surface that serves as the wearing course for traffic.
- Compact all materials to provide strength and resist densification under traffic.

This report will only consider the impact of UNI Eco-Stone's® unique characteristics on the design process, and the reader is referred to the aforementioned references for more extensive detail and discussion of design.

Most researchers have found that traditional solid pavers interact with one another, so their load spreading ability or stiffness, is greater than that of conventional asphaltic concrete surfacings (Rollings and Rollings 1992). UNI Eco-Stone® is manufactured to the same tolerances as the traditional solid paver; it is placed in an interlocking pattern, as is the traditional solid paver; and it uses a bedding layer and filled joints between pavers, as do traditional solid pavers. The only difference from the traditional solid paver is UNI Eco-Stone's® drainage openings which are typically filled with permeable gravel. Any attempt for a paver to displace vertically will be resisted by shear in the gravel-filled voids and friction in the joints, as with traditional pavers. Table 1 shows some representative soil shear strength data in terms of friction angles. Typical jointing sand used in traditional paver installation would correspond to uniform fine to medium sands with corresponding ϕ values in the low thirties. *As gravel-sized particles are added, grading improves, or as the particles become more angular, ϕ increases. In the case of an angular, crushed gravel which might be used to fill the drainage opening in UNI Eco-Stone®, the ϕ value would be expected to be in the upper thirties or low forties. As a result, if proper materials are used in the drainage voids, UNI Eco-Stone® should have structural strength characteristics and load distributing capabilities similar to traditional solid pavers.*

Therefore, the thickness design methods for traditional pavers that are discussed in depth in Rollings and Rollings (1992), should also be valid for UNI Eco-Stone®.

Water Impact on Design

Traditionally, pavement design attempts to prevent the penetration of water into the pavement structure. Asphalt surfaces are applied to keep underlying materials dry and to serve as a wearing course, and joints in concrete pavements are meticulously sealed to prevent water from getting through. However, pavement engineers know that

Table 1 Typical Friction Angles for Nonplastic Materials			
Soil Type	**Gradation**	**Particle Shape**	**ϕ (degrees)**
Silt	-	-	28
Fine Sand	Uniform	Rounded	30
Fine Sand	Uniform	Angular	34
Sand	Well Graded	Rounded	34
Sand	Well Graded	Angular	40
Sand & Gravel	Well Graded	Rounded	36
Sand & Gravel	Well Graded	Angular	40
Note: Friction Angle, ϕ, values are approximate and vary with specific soil characteristics and test conditions.			

pavements are not really impermeable and that water must eventually get into the pavement. This may occur in a wide variety of ways such as:

- Leakage through cracks in the pavement
- Poor densification of asphaltic concrete
- Concrete joint sealant failure (typical life 3-4 years)
- Leakage through construction joints between asphaltic concrete placement lanes
- Infiltration from the sides of the pavement
- Ground water and/or frost effects
- Vapor movement and capillary rise in the soil

As a result, the pavement engineer commonly designs on the assumption that his subgrade and other pavement layers will become saturated, and the soaked CBR test remains the most common criterion for estimating subgrade strength for pavement design (Yoder and Witczak 1975; Rollings and Rollings 1992). The problem of internal drainage of pavements is currently a hot topic of debate and study in the technical pavement community (e.g., Cedergren 1974; Federal Highway Administration 1980).

Thus, even though UNI Eco-Stone® allows water to drain directly into the pavement structure, it is not as radical a departure from conventional paving technology as it may at first appear, because current pavement design approaches already assume water penetration into the pavement. In fact, one notable pavement authority recommends that design assume that 50 to 67 percent of the rain on a portland cement concrete pavement and 33 to 50 percent of the rain on an asphaltic concrete pavement will penetrate the pavement (through the methods listed earlier) and must be drained off (Cedergren 1974; Cedergren et al 1973; Federal Highway Administration 1980).[1] The key factor with UNI Eco-Stone® will be to insure that the water is controlled and managed so that the pavement performance is not adversely affected.

Wearing Course and Bedding Layer

The granular materials used in the joints, drainage openings, and bedding layer under the UNI Eco-Stone® must be highly permeable, must retain their strength when wet, and must drain freely enough that no pore pressures develop under traffic loadings. Considerations for permeability will be discussed in more detail in following sections. Strength in the presence of water can be achieved by using only nonplastic, granular materials that are preferably composed of crushed particles. *To assure that no pore pressure develops under loading, the materials should be free of material passing the No. 200 sieve (which will also improve permeability).* These are very similar to the requirements used for bedding and jointing sands for traditional paver installations (see Rollings and Rollings 1992 for detailed discussion), except that

[1]This is a conservative assumption insuring adequate drainage capacity at the worst point rather than an actual estimate of the water penetration expected everywhere.

the allowable percentage passing the No. 200 sieve is reduced and the desirability of using crushed particles is emphasized. As will be discussed later, the gradation will also tend to be coarser to increase permeability.

Base and Subbase Courses

The base and subbase courses are major structural load carrying elements in the pavement and they must retain strength in the presence of water if the pavement is to be stable. Rollings and Rollings (1992) compare different requirements for these layers and provide guidance for their specification for traditional solid pavers. For pavements using UNI Eco-Stone®, the stability of the base and subbase material in the presence of water must be assured, and their stability will be enhanced if nonplastic materials are used. *Common pavement specifications allow a plasticity index of 4 to 6 percent for base courses and 4 to 12 percent for subbases, but with UNI Eco-Stone®, it would be prudent to use only nonplastic materials (i.e., plasticity index of 0). Similarly, some common pavement specifications allow up to 10 percent passing the No. 200 sieve for base courses and up to 25 percent for subbases. It would be prudent for this application to restrict these limits more tightly, perhaps to 3 and 5 percent, respectively.*

Subgrade

As with conventional pavements, the subgrade strength should be estimated based on soaked CBR values. Frost introduces some special design considerations, and these are probably best addressed using the Corps of Engineers procedures (Department of the Army 1985, Yoder and Witczak 1975). Use of UNI Eco-Stone® does not directly impact these considerations of subgrade design strength or frost effects. However, certain highly expansive or swelling soils that are found in some locations change volume drastically whenever their moisture content changes. These soils would probably not be appropriate under a permeable surface such as UNI Eco-Stone® unless very careful design was done to insure the volume stability of these soils.

UNI Eco-Stone® allows penetration of water into the pavement structure, but if the system is designed to accommodate the water in-flow, pavement performance can be maintained. The major consideration from a structural point of view will be to use materials that do not lose strength in the presence of water and to maintain adequate permeability so that pore pressure does not develop in the pavement due to dynamic traffic loading. The following section will further examine hydraulic design.

Hydraulic Design

The hydraulic design will consist of determining how much water flows into the pavement system, and once it is in the system, what will be done with it (i.e., will it be allowed to soak into the subgrade or will it be diverted through a drainage layer to another location). The coefficient of permeability, k, of the materials comprising the pavement will be a critical parameter in determining how water flows into and through the system. Unfortunately, soil permeability is one of the most complex phenomena encountered in soil mechanics. Values can vary from 10^2 to 10^{-10} cm/sec (twelve orders of magnitude). Few properties of any material vary so widely and are so difficult to determine. Empirical correlations between permeability and simple soil properties often give erroneous results. Laboratory tests are difficult to conduct, and often the laboratory test conditions and test sample are very different from the real field conditions. Finally, field tests are expensive and often difficult to interpret because of complex field stratification and other conditions. Milligan (1975) offers some guidance on selection of appropriate methods of determining permeability for soil materials.

Many small concrete paver projects have limited funding for testing, so permeability determinations may often have to be based on empirical correlations between soil properties and permeability or estimates based on soil classification. In general, the parameters which seem to correlate with permeabilities of materials used in bases and subbases in pavements are the effective grain size (D_{10}), the percent passing the No. 200 sieve, and the porosity (a function of density and specific gravity). One of the oldest equations is Hazen's equation (Hazen 1911)

$$k = C_1 D_{10}^2$$

where

k is permeability in m/sec

C_1 is a constant equal to 0.010 to 0.015 for clean sands

D_{10} is the effective grain size or the particle size in mm at which 10 percent of the soil particles are smaller.

Another theoretical equation derived by Taylor (1948) takes the form

$$k = D_S^2 \frac{\gamma}{\mu} \frac{e^3}{(1+e)} C$$

where

k is the coefficient of permeability

D_S is the effective particle diameter, usually taken as D_{10}

γ is the unit weight of the permeant

μ is the viscosity of the permeant

e is the void ratio

C is a shape factor

Obviously, there are many factors that affect permeability, and simple, widely used relations such as Hazen's equation do not address all of these. Such empirical relations are not very reliable, and tests have found the constant C_1 in Hazen's equation can vary from 0.004 to 0.120 rather than the typical values 0.01 to 0.015 given earlier (Carter and Bentley 1991). Consequently, calculations based on such imprecise estimates of permeability will not be very accurate and considerable conservatism in selection of parameters is warranted. Table 2 shows typical permeability values for common materials encountered in pavements and may be useful in assessing the appropriateness of permeability values whether derived from laboratory tests, field tests, estimates, or correlations. More detailed discussion of permeability determination for pavement applications can be found in Federal Highway Administration (1980) and Cedergren (1974).

Generally, pavement subsurface drainage is designed to accommodate the one-hour/one-year frequency storm (Federal Highway Administration 1980, Cedergren 1974) or the one-hour/two-year frequency storm (Corps of Engineers 1992). The one-hour/one-year frequency storm map for the U.S. is shown in Figure 7 (Department of Commerce 1961). From this Figure, design storms would range from 0.2 to 2.4 inches/hour depending on location within the U.S. The guidance in Figure 7 would appear to be a reasonable method of estimating a typical design storm for a UNI Eco-Stone® pavement to handle common pavement surface drainage conditions. However, if the Eco-Stone® pavement is being designed to meet local stormwater control

Table 2 Typical Permeability Values for Highway Material

Material	Permeability (cm/s)
Portland Cement Concrete	$<10^{-8}$
Asphaltic Concrete	4×10^{-3} to 4×10^{-8}
Compacted Clays	$<10^{-7}$
Compacted Silts	7×10^{-6} to 7×10^{-8}
Silty and Clayey Sands	10^{-5} to 10^{-7}
Concrete Sand with Fines	7×10^{-4} to 7×10^{-6}
Clean Concrete Sands	7×10^{-2} to 7×10^{-4}
Well Graded Aggregate Without Fines	10^{-1} to 10^{-3}
Uniformly Graded Coarse Aggregate	10^{2} to 10^{-1}

Note: This table adapted from Carter and Bentley (1991).

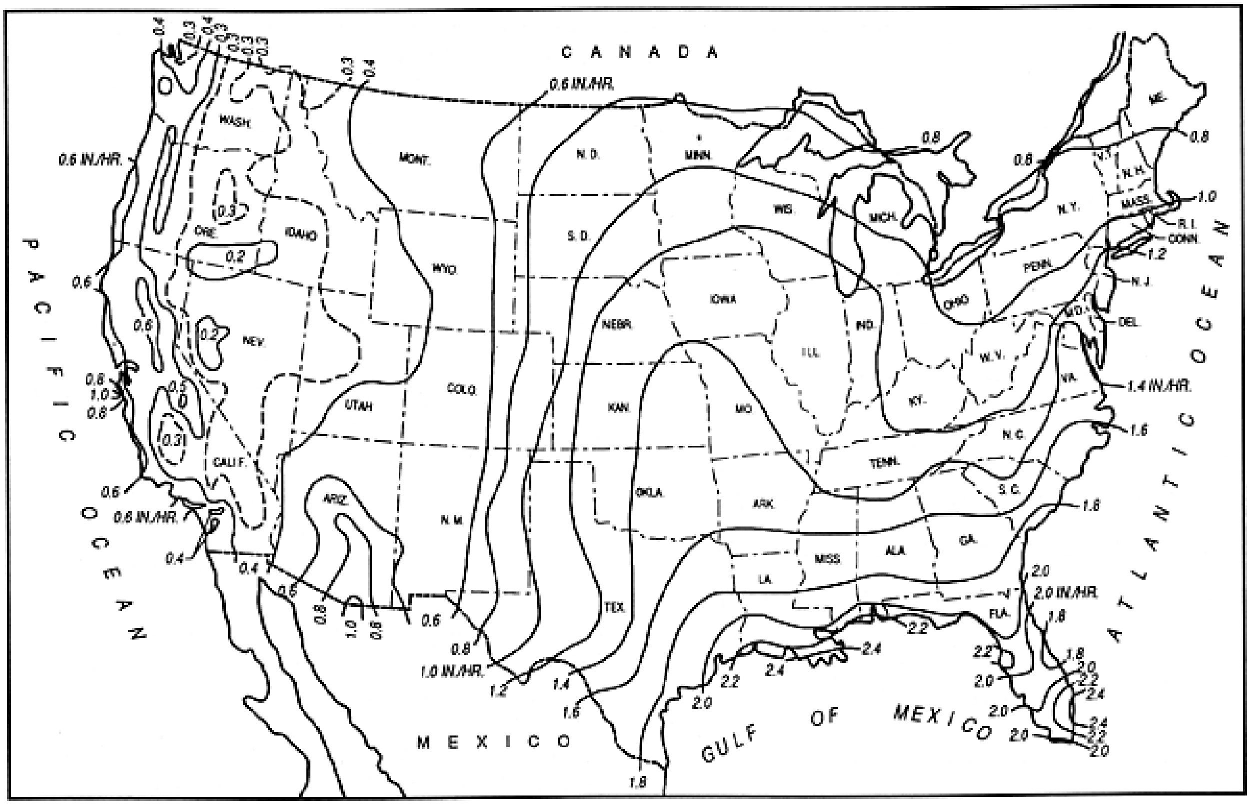


Figure 7 One-Hour/One-Year Frequency Storm (Department of Commerce 1961)

regulations, the design storm will be specified by the regulatory agency and will normally be more severe than the one-hour/one-year storm (e.g., 100-year storm requirements are common).

The rate at which water will flow through the UNI Eco-Stone® surface will depend on the specific materials used to fill the drainage voids and on the slope of the pavement. Tests at the Karlsruhe University of Engineering in Germany used gravel chips sized between 5/64-inch and 1/4-inch (2 to 5 mm) to fill the drainage openings and for the bedding layer, and used a clean sand free of fines and with a maximum particle size of 5/64-inch to fill the joints between the UNI Eco-Stone® pavers. The gravel in the drainage opening was tamped down so that it was covered with a 3/4-inch thick layer of the joint sand. This represents the most common current design of UNI Eco-Stone® pavements in Germany (Langsdorff 1993).

Table 3 shows the results of this infiltration testing by Muth (1988). *Essentially any storm in Figure 7 can be drained by the UNI Eco-Stone® with zero slope on the pavement.* With increasing slope or increasing storm intensity, some runoff may occur, but UNI Eco-Stone® has significantly reduced the runoff.

Phalen (1992) conducted tests of several materials with different gradations in the Eco-Stone® drainage openings. Unlike Muth, Phalen tested only a single fill material in the drainage openings and did not cover the material in the openings with a layer of jointing sand. The gradations of the materials tested by Muth and Phalen, along with their drainage rates at very shallow grades are shown in Figure 8. When the jointing sand covers the coarse aggregate in the drainage openings, the permeability of the sand controls the inflow of water. This can be clearly seen by comparing the 2.8-in./hour rate reported by Muth (1988) for jointing sand over highly permeable gravel to the rates of 1.3 to 2.7-in./hour reported by Phalen (1992) for sand alone in the drainage openings. Phalen's other reported results for increasingly coarse fill material in the drainage voids show that flow rates of 18.7 to 172-in./hour are possible. By judicious selection of drainage opening fill and jointing material, the designer can achieve a wide range of permeabilities for the UNI Eco-Stone® surface to achieve a specific project's drainage objectives.

Table 3 Infiltration Tests on UNI Eco-Stone® by Muth (1988)		
Rainfall (in./hr)	**Slope (%)**	**Runoff (%)**
2.8	0.0	0
1.4	2.5	0
4.2	0.0	15
4.2	2.5	25

"By judicious selection of drainage opening fill and jointing material, the designer can achieve a wide range of permeabilities for the UNI Eco-Stone® surface to achieve a specific project's drainage objectives."

The tests by Muth (1988) also found that UNI Eco-Stone®, with a 1.2 inch (3 cm) thick gravel bedding layer, gravel-filled drainage voids with a thin sand surfacing, and sand-filled joints, would hold the equivalent of a 0.6 in. (16 l/m2) rain within the voids of the system. Once this retention volume is reached, the base course and other underlying materials must be able to drain water from the UNI Eco-Stone® voids and joints to allow further absorption of water.

Once the water penetrates into the base course, it must be handled in some manner. If the sub-grade is sufficiently permeable, water can simply drain vertically into the ground; however, as seen

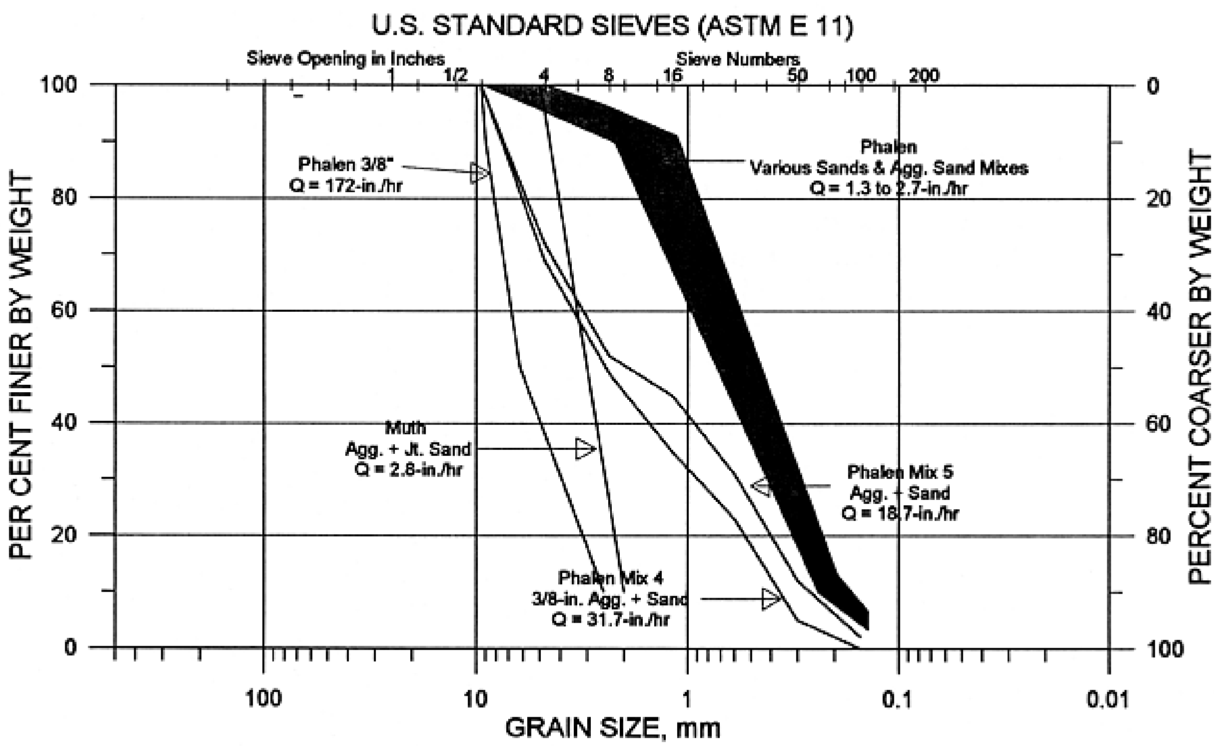


Figure 8 Drainage Fill Gradations and Flow Rates

Table 4 Typical Soil Infiltration Rates (Department of the Army 1965)		
Soil	**USCS Symbol**	**Infiltration (in./hour)**
Sand and Gravel Mixtures	GW, GP, SW, SP	0.8 - 1.0
Silty Gravels and Sands to Silts	GM, SM, ML, MH, OL	0.3 - 0.6
Silty Clay to Sandy Clay	SC, CL	0.2 - 0.3
Clays	CH, OH	0.1 - 0.2
Rock, not badly fractured	—	0.0 - 0.1

in Table 4, most soils are appreciably less permeable than the UNI Eco-Stone® pavement surface. Under these conditions, and particularly if the subgrade is clay or there is any significant traffic loading of the pavement, it will not be desirable to have the water sit in the pavement structure while it infiltrates slowly into the subgrade. In such cases, water will need to be drained away from the pavement, where it can be stored to allow infiltration into the soil or discharged into other drainage systems. In any case, design of subsurface drainage systems within pavements is treated extensively in existing literature, and the reader is referred to references such as Cedergren (1974), Federal Highway Administration (1980), or Corps of Engineers (1992) for details on layout, materials for drainage layers, drainage calculations, etc., that are common to all pavements. The data in Table 3 and Figure 8 should provide some reasonable preliminary guidance on infiltration rates through the UNI Eco-Stone® surface to use with these established design methods.

The water collected from the drainage layers of the pavement does not have to be discharged to a holding basin or storage pond. If the impermeable surface soil layer is relatively thin, it may be possible to place a well or trench through this layer to more pervious underlying layers that can accommodate water from the drainage layer. *It is also feasible to store the water in a gravel-filled trench or well and allow it to percolate slowly into even relatively impermeable soils.* This allows the surface area above these storage areas to be used for other purposes. The volume of water that can be stored in a completely saturated soil or aggregate (whether in a pavement layer or in a storage area) can be calculated as

$$V = 1 \quad \frac{\gamma_d}{G_s \times \gamma_w}$$

where

V = volume of water in one cubic foot of soil or aggregate

γ_d = dry density of in-place soil or aggregate

G_s = specific gravity of soil or aggregate

γ_w = unit weight of water = 62.4 lb/cf

Filter Requirements

When water flows from one soil or aggregate material into another of different gradation, there is danger that fine particles from the first material may wash into the second. This will result in gradual erosion of fines from the first material and an accumulation of these fines in the second material. Internal movement of fine materials is highly undesirable and can cause problems with structural stability and plugging of the drainage system. Each material used in the UNI Eco-Stone® pavement system should be checked against established filter criteria to insure that problems with clogging and internal erosion are avoided. Table 5 shows several different criteria published by two federal agencies that can be used with the UNI Eco-Stone® system. These and other similar criteria were originally developed from steady state seepage tests for earth dams, so they may not be totally accurate for pavement applications with dynamic traffic loads. As a result, some conservatism in applying these criteria is warranted; however, they constitute the best guidance currently available. Gap graded materials are notoriously susceptible to internal erosion problems, so they should probably be avoided in UNI Eco-Stone® pavements.

Special Considerations

Drainage structures and filters tend to clog with time, and the designer should consider the potential for reduced water flow through the UNI Eco-Stone® pavement surface over time. Fine debris and detritus may accumulate between the surface particles in the drainage openings, thereby reducing the material's flow capacity. Qualitative success in restoring permeability to UNI Eco-Stone® surfaces has been reported from Germany using conventional street sweepers equipped with vacuums, water, and brushes (UNI-Group U.S.A. 1992). Therefore, as the normal accumulation of debris and fines reduces the UNI Eco-Stone® pavement's permeability, periodic cleaning using commercial street sweeping equipment should be all that is needed to restore the pavement's permeability. Additional aggregate fill material can be added at the same time, if necessary. Conventional pavement maintenance requirements for traditional solid concrete pavers are low (Rollings and Rollings 1992) and should be similar for UNI Eco-Stone® pavements.

There is generally some loss of permeability of filters and granular drainage systems over time. For example, relief wells along the Mississippi River have observed a 35 percent reduction in efficiency over 25 years due to clogging. In light of this experience, it is probably prudent for the designer of UNI Eco-Stone® pavements to allow for some loss in flow capacity within the pavement system over the life of the pavement.

Tests have shown that UNI Eco-Stone® can accommodate women's high heels and wheelchairs. Tests with a 165 lb weight on a lady's shoe heel left imprints of 0.03 and 0.07-in. in UNI Eco-Stone® fill material (Bretsschneider 1992a). Good quality and compaction of the fill material will obviously avoid problems in this area. Trials with a wheel chair found that UNI Eco-Stone® could be traversed without problem, and if drainage openings were not properly filled, the ride was noticeably rougher , although still feasible (Bretsschneider 1992b). Available information indicates that properly constructed UNI Eco-Stone® pavements should not pose problems for ladies in high heels or for the handicapped.

Table 5 Recommended Filter Criteria

Source	Recommended Particle Size Ratios			Limitations
	D_{15}/D_{15}	D_{15}/D_{85}	D_{50}/D_{50}	
COE	≥5	≤5	≤25	C_u ≤20, no gap graded material
USBR	—	—	≥5, ≤10	Uniform filters
	≥12, ≤40	—	≥12, ≤58	Graded filters with rounded particles
	≥6, ≤18	—	≥9, ≤30	Graded filters with angular particles

Notes:

1. COE from Department of the Army (1979) and Federal Highway Administration (1980), USBR from U.S. Bureau of Reclamation (1974).
2. All ratios, D_x/D_y, give particle diameter of filter to particle size of protected soil. D_x is particle diameter at which x percent of the particles in soil are smaller.
3. $C_u = D_{60}/D_{10}$, suggested limit not mandatory.
4. Federal Highway Administration (1980) also suggests that D_5 of the filter ≥0.074 mm.

SECTION III: SPECIFICATIONS

UNI Eco-Stone® should generally be specified to meet ASTM C 936 "Standard Specification for Solid Concrete Interlocking Paving Units." Rollings and Rollings (1992) has a detailed description of specification requirements for traditional solid pavers, and this material will be equally valid for UNI Eco-Stone®.

One of the critical elements of the UNI Eco-Stone® pavement system is the fill material for the drainage openings, and quantitative data on this topic has been reported by Muth (1988) and Phalen (1992), as discussed in the previous section. Conceptually, it is clear that the material needs to be highly permeable. Depending on the amount of drainage needed for a specific project, this fill would normally be a clean gravel. It would be desirable for this to be a crushed material to provide maximum stability, and it would simplify construction if the same material was used in both the bedding layer and drainage openings. The filter criteria in Table 5 should be checked to insure the material used in the joints does not wash into the bedding and drainage opening material and to insure that the drainage opening fill does not wash into the bedding layer if different materials are used.

Table 6 compares Phalen's 3/8-in. aggregate (Phalen 1992) that achieved very high flow rates with several standard ASTM gradations that might be used for filling the drainage openings and for the bedding layer. Figure 9 compares several of these ASTM gradations with Muth and Phalen's test gradations. Muth used a gravel gradation corresponding to an ASTM No. 9, and even with a 3/4-in. thick layer of sand over this, he achieved a flow rate of 2.8-in./hr. Phalen's various sand and aggregate-sand mixes in Figure 8 achieved roughly comparable results to Muth's and are approximately covered by the ASTM C 33 gradations in Figure 9. This data shows that sand-filled drainage voids or gravel-filled drainage voids covered with sand can achieve flow rates on the order of 1 to 3-in./hr. This should suffice for handling the rain from common storms (such as shown in Figure 7) and maintaining a dry pavement under these conditions. However, if the designer needs to

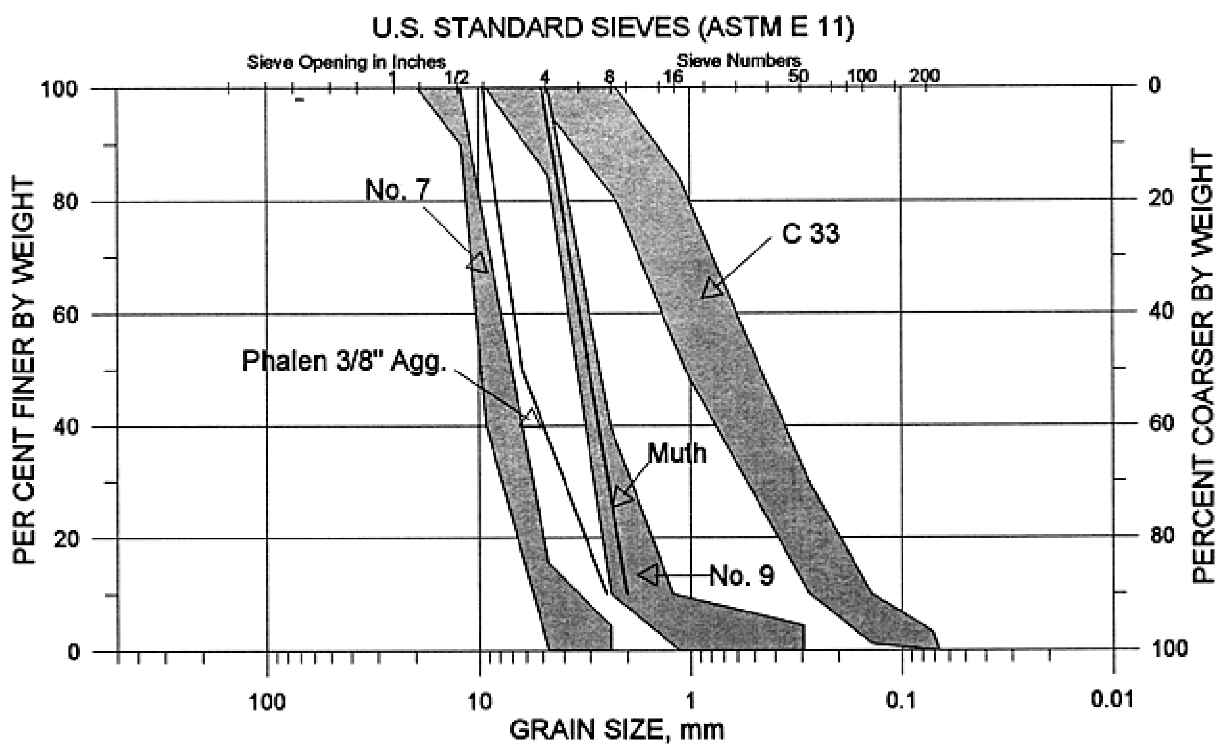


Figure 9 Comparison of Test and ASTM Gradations

Table 6 Potential Drainage Void Gradations						
Sieve No.	ASTM D 448 Sizes				ASTM C 33	Phalen's 3/8-in.
	No. 7	No. 8	No. 89	No.9		
1/2-in.	90-100	100	100			
3/8-in.	40-75	85-100	90-100	100	100	100
No. 4	0-15	10-30	20-55	85-100	95-100	35
No. 8	0-5	0-10	5-30	10-40	80-100	8
No. 16		0-5	0-10	0-10	50-85	1
No. 50			0-5	0-5	10-30	
No. 100					2-10	
No. 200					0-3	
Nominal k in cm/sec	25	12	2	1	0.03	6

Notes:

1. Gradations are given as percent passing.
2. Nominal k was calculated using Hazen's equation and the approximate midpoint of the gradation band

accommodate more severe storms such as the 100-year storm to meet regulatory requirements, then a more pervious fill is needed. Phalen's work with Mixes 4 and 5 and the 3/8-in. aggregate in Figure 8 clearly shows that proper selection of the drainage fill material will allow any design storm to be accommodated. Standard ASTM gradations No. 7 through 9 in Table 6 are all candidates for high capacity drainage opening fill materials. Their nominal permeabilities provide the designer with an indication of their relative drainage potential. *The designer should select the drainage opening and joint materials to achieve the specific design objectives of the individual project.*

"Phalen's work with Mixes 4 and 5 and the 3/8-in. aggregate in Figure 8 clearly shows that proper selection of the drainage fill material will allow any design storm to be accommodated."

There are two basic approaches to selecting and placing the fill materials for the joints and drainage openings. A gravel gradation may be selected that contains sand particle sizes that can penetrate into the approximately 1/8-inch wide joints between the pavers but is predominately gravel sized to fill the drainage voids and provide high permeability. This material is swept and vibrated into the joints and void spaces. The sweeping will tend to concentrate gravel particles in the drainage openings, and the smaller sand particles will fill the joints between pavers. Alternatively, a gravel gradation can first be swept and vibrated into the drainage voids, and then a sand can be swept and vibrated into the joints and drainage openings. The first approach is probably the most efficient, but a gravel with precisely the right proportion and sizes of particles may not always be available or economical. The second approach requires handling two materials, but the requirements on the materials is less stringent. The filter requirements discussed earlier limit the relative gradations of the materials used in the joints and drainage openings (e.g., a fine sand could not meet the filter requirements if a coarse 3/8-in. gravel was used to fill the drainage openings).

The bedding layer must drain water quickly, must prevent the fill materials in the joints and drainage openings from washing into the underlying drainage layer, and must allow the pavers to be seated and leveled. Therefore, the bedding layer gradation should be selected to achieve the needed permeability using appropriate correlations or tests. Also, the filter criteria in Table 5 must be checked to insure that the joint and drainage opening fill materials are compatible with the bedding layer gradation. If the particles in the bedding layer are too large, some problems may be encountered in proper seating and leveling of the pavers. For example, the coarser size of the number 7 gradation could have up to 60 percent of the particles 3/8-in. or larger. This may be approaching the particle sizes where problems with leveling and seating of the pavers could develop. *No definitive guidance is available in this area, so it is probably prudent to avoid gradations that contain any aggregate larger than one-third the thickness of the bedding layer.*

"The whole pavement system, including the UNI Eco-Stone® surface, the underlying base, and subbase, must be designed as a complete system to ensure that the objectives of the project are met."

The whole pavement system, including the UNI Eco-Stone® surface, the underlying base, and subbase, must be designed as a complete system to ensure that the objectives of the project are met. For example, it does no good to have a highly permeable surface on top of an impermeable base course that will not let water drain. There are ample references such as Cedergren (1974), Federal Highway Administration (1980), Corps of Engineers (1992), or Department of the Army (1979) that provide detailed guidance on design of drainage systems for pavements including the characteristics needed in drainage layers.

SECTION IV: APPLICATIONS

Stormwater management is a difficult public policy problem, and attempts at regulation have placed increasingly restrictive requirements on site development. This was discussed briefly in Section I and is covered in more depth in a variety of current references (e.g., Wanielista and Yousef 1993, Reeve 1993, Nichols 1993). While specific approaches vary in different localities, the net effect of the regulatory requirements is either a)to limit the area that can be covered with impermeable pavements or structures on a site or b) (and more commonly) to require on-site stormwater retention, resulting in covering significant areas of each individual site with stormwater retention ponds or basins to hold the regulation specified storm. This latter approach of uniform on-site detention has been sharply criticized as largely ineffective in accomplishing its goal of preventing flooding and it accomplishes little for improving water quality (Ferguson 1991). Critics of uniform on-site detention advocate regional approaches to more rationally manage water flows, and they emphasize the importance of infiltration into the ground as the logical way of handling stormwater since it would then contribute to groundwater recharge, provide normal basal flow to surrounding streams, and improve the water quality.

Much of the past concern with stormwater management has been centered on preventing flooding, but today, pollution levels of stormwater runoff are causing new concerns. Table 7 illustrates this problem by comparing urban stormwater to current drinking water standards. Contamination problems with stormwater runoff include the content of suspended solids, toxic metals and chemicals, compounds with high oxygen demand, bacteriological contamination, various oils and fuels, deicing salts, and nutrients, and increased temperature. All of these factors have potentially harmful effects on the surrounding environment when stormwater is released to surrounding natural waters.

UNI Eco-Stone® offers the designer and developer a new option for handling stormwater that is both effective in water control and provides superior enhancement of stormwater quality. As discussed in preceding sections, UNI Eco-Stone® pavements can be designed to drain any desired design storm through the pavement surface to an underlying drainage layer where the water can either be held and allowed to drain slowly into the subgrade, or it can be collected for storage, treatment, or discharge depending on the specific

Table 7 Urban Stormwater Compared to Drinking Water Standards (After Wanielista and Yousef 1993)

Parameter	**Stormwater Concentration Greater Than (mg/L)[a]**			**Drinking Water Standards**
	50% of Samples	10% of Samples	5% of Samples	
Total Dissolved Solids	700	2000	9000	500
Total Phosphorus	0.27	0.65	0.82	—
Total Nitrogen	2.20	4.50	5.60	—
NO_3-N	0.50	1.10	1.40	10
Copper	0.02	0.10	0.21	1.3
Lead	0.04	0.10	0.50	0.010
Zinc	0.10	0.21	0.42	0.030
Cadmium	< 0.01	0.01	0.06	0.010

[a] Based on analysis of samples from three studies to determine percentage of samples equaling or exceeding given parameter, e.g., 50% of analyzed samples had 700 mg/L or more of total dissolved solids, 10% had 2000 or more, etc.

requirements of the project. The process of draining through the UNI Eco-Stone® surface and underlying drainage media will slow the water flow, allow time for oxidation of some contaminants, filter suspended solids and some contaminants, and cool the water temperature. Obviously, not all contaminants (e.g., salts) can be removed by this process, but if needed, the water accumulated under the UNI Eco-Stone® system could be collected and treated (e.g., run through an oil-water separator) to further enhance the water quality. Pavements have been a major contributor to the stormwater runoff and pollution problem, but with UNI Eco-Stone®, the paved surface is no longer necessarily a contributor to this problem.

UNI Eco-Stone® provides a functional pavement surface as well as being a powerful new concept for stormwater management. From the consumers' point of view, the rapid vertical drainage of UNI Eco-Stone® also ends the perennial problem of wading across channels of water and through puddles in parking lots.

Since its introduction in 1987, UNI Eco-Stone® placement in Europe is approaching five million square feet, and its use is growing (Langsdorff 1993).

Figure 11 Loading Area In Ft. Lauderdale, Florida

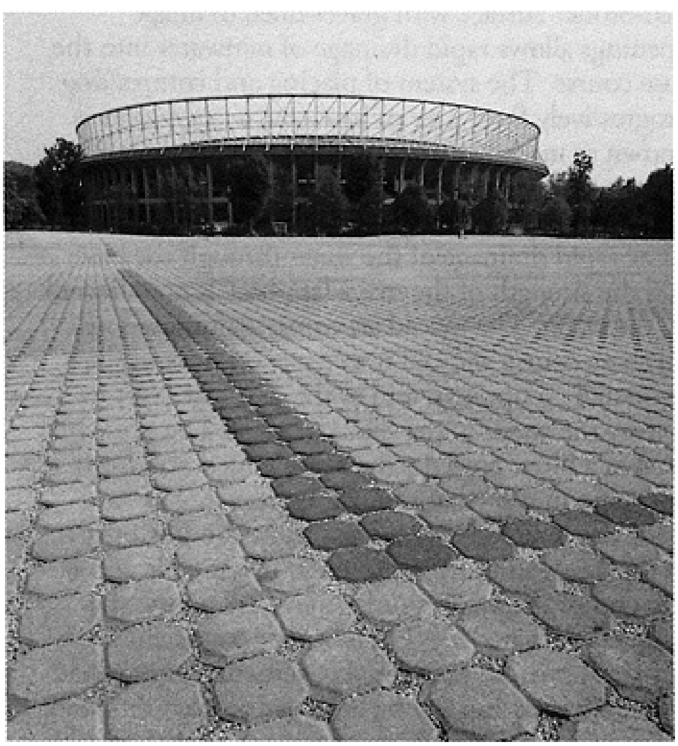


Figure 10 Vienna Soccer Stadium

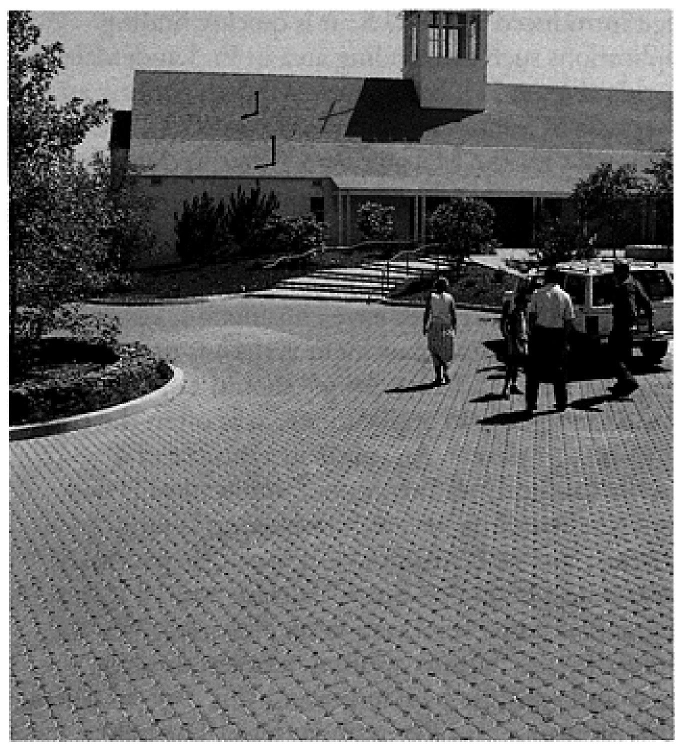


Figure 12 St. Andrews Church Parking Area, Sonoma, California

Figure 13 Metropolitan Water Reclamation District of Greater Chicago Parking Area

One of the most dramatic examples in Europe is the Vienna Soccer Stadium parking area shown in Figure 10. Although the UNI Eco-Stone® has just recently been introduced in the U.S., it is quickly finding applications such as a loading area in Ft. Lauderdale, Florida (Figure 11), St. Andrews Church parking and entry area in Sonoma, California (Figure 12), and a parking lot for the Metropolitan Water Reclamation District of Greater Chicago (Figure 13).

Initial use of UNI Eco-Stone® in the United States has been for relatively lightly loaded parking areas. The product does have considerable structural strength if the whole pavement system is properly designed, and UNI Eco-Stone® should not be limited to light load applications, as is often the case with the turf pavers. An excellent example of a heavily loaded UNI Eco-Stone® application is the aggregate handling area at Interlocking Paving Systems, Inc. in Hampton, Virginia. The pavement consists of a UNI Eco-Stone® surface and 18 inches of granular base over a wet, weak clay subgrade. A geotextile filter fabric was used between the subgrade and granular base to prevent fine clay particles from pumping into the granular base. The base consisted of three layers of aggregate. First a 12 inch layer of crushed 2-inch aggregate (railroad ballast rock) was placed . A 4-inch thick layer of 3/4 to 1-inch sized aggregate was placed and compacted next, followed by a 2-inch thick layer of 3/8 to 1/3-inch sized aggregate. The subgrade is sloped to one end where a 4-inch diameter perforated pipe collects the water and drains it away. This pavement is performing very well under heavy daily traffic of aggregate hauling trucks.

Properly designed UNI Eco-Stone® pavement systems will provide functional pavements for any loading conditions and can be designed to accommodate any needed stormwater management requirement.

This application of UNI Eco-Stone® is a good example of sound application of the engineering principles discussed earlier in this report. The UNI Eco-Stone® surface with gravel-filled drainage openings allows rapid drainage of rainwater into the base course. The system of placing and compacting progressively finer sizes of base course aggregates is known as macadam construction and provides a very porous and structurally strong pavement system. It has the strength to carry load; it is very pervious to allow rapid drainage of the water through the base; and the strength of the macadam base is not affected by the water. The macadam construction used in this base course allowed it to function both as the structural component and as the drainage layer to convey the water to the drainage pipe. The geotextile used as a filter, prevents the fine-grained clay from pumping into the base course aggregate. The saturated clay subgrade would not allow the stormwater in the base course to infiltrate, so it was collected at one end of the project and removed from the site. Properly designed UNI Eco-Stone® pavement systems will provide functional pavements for any loading conditions and can be designed to accommodate any needed stormwater management requirement.

SECTION V: CONCLUSIONS

The UNI Eco-Stone® paver is a highly versatile product that provides design professionals, developers, land planners, regulatory agencies, and environmental commissions with new options for stormwater management. It provides a highly functional pavement surface which can offer major environmental benefits, and when the entire pavement system is properly designed, virtually any traffic load or design storm, including 100-year design storms, can be accommodated.

A review of the information described in this report found that:

1. UNI Eco-Stone® offers new possibilities in pavement surface water control to meet regulatory requirements and potentially reduce the size or need for special stormwater retention facilities. It reduces runoff and downstream flooding, mitigates pollution impact on surrounding surface waters, and contributes to groundwater recharge and/or storage.

2. UNI Eco-Stone® will permit better land-use planning, allowing more efficient use of property for greater economic value. This makes UNI Eco-Stone® cost effective, as it will provide more usable property that otherwise would not be developed due to requirements for stormwater retention or by limitations on how much impermeable area is allowed on a site. Often, the footprint of a building is controlled by the amount of parking area available. This product gives the designer a tool that can be used in a variety of ways to address stormwater management problems and decrease the adverse impact of land development.

3. Cost of compliance with many regulatory requirements for stormwater management could significantly decrease with the use of UNI Eco-Stone®.

4. UNI Eco-Stone® is an innovative, environmentally-beneficial paving system that emphasizes infiltration as a natural way to handle storm runoff — conserving rainwater, recharging groundwater storage, improving water quality, and reducing storm runoff pollutants. In today's ecologically aware environment, UNI Eco-Stone® offers new options for lessening the impact of development on the eco-system.

5. UNI Eco-Stone® has the strength, aesthetics, and durability of traditional interlocking concrete pavers with the added benefit of permeability.

6. Construction of the UNI Eco-Stone® pavement is similar to that of traditional solid concrete pavers (a flexible pavement), with design considerations for water in-flow. The entire pavement system, including the UNI Eco-Stone® surface, the underlying base, and subbase, must be designed as a complete system to insure that all project objectives are met.

7. Properly designed UNI Eco-Stone® pavement systems will provide functional pavements for virtually any loading conditions and can be designed to accommodate any needed stormwater management requirements.

REFERENCES

Bretschneider, B. 1992a. "Expert Opinion on UNI Eco-Stone®," Hildesheim, Germany.

Bretschneider, B. 1992b. "Supplement to Expert Opinion on UNI Eco-Stone®," Hildesheim, Germany.

Carter, M. and S. Bentley, 1991. *Correlations of Soil Properties,* Pentech Press, London, United Kingdom.

Cedergren, H., J. Arman, and K. Obrien, 1973. "Development of Guidelines for the Design of Subsurface Drainage Systems for Highway Pavement Structural Sections," Final Report, Federal Highway Administration, Washington, D.C.

Cedergren, H., 1974. *Drainage of Highway and Airfield Pavements,* John Wiley and Sons, New York, New York.

Corps of Engineers, 1992. "Drainage Layers for Pavements," Engineering Technical Letter 110-3-435, Washington, D.C.

Department of the Army, 1965. "Drainage and Erosion Control, Drainage for Areas Other than Airfields," TM 5-820-4, Washington, D.C.

Department of the Army, 1979. "Drainage and Erosion Control, Subsurface Drainage Facilities for Airfield Pavements," TM 5-820-2, Washington, D.C.

Department of the Army, 1985. "Pavement Design for Seasonal Frost Conditions," TM 5-818-2, Washington, D.C.

Department of Commerce, 1961. "Rainfall Frequency Atlas of the United States," Technical Paper No. 40, U.S. Weather Bureau, Washington, D.C.

Federal Highway Administration, 1980. "Highway Subdrainage Design," Report No. FHWA-TS-80-224, Washington, D.C.

Ferguson, B., 1991. "The Failure of Detention and the Future of Stormwater Design," *Landscape Design,* Vol. 4, No. 12, Gold Trade Publications, Van Nuys, California.

International Joint Commission on the Great Lakes, 1978. "Environmental Management Strategies for the Great Lakes," Windsor, Ontario.

Hazen, A., 1911. Discussion of Dams on Sand Foundations, Transactions, No. 73, American Society of Civil Engineers, New York, New York.

Langsdorff, H. von, 1993. Private Communication, F. von Langsdorff Licensing Limited, Bauverfahren, Germany.

Livingston, E. and J. Cox, 1989. "Florida Development Manual," Vol. I, Florida Department of Environmental Regulation, Tallahassee, Florida.

Michau, P. and D. Wilson, 1988. "An Evaluation of Typical Concrete Paver Failures in South Africa," *Proceedings,* Third International Conference on Concrete Paver Paving, Rome, Italy.

Milligan, V., 1975. "Field Measurement of Permeability in Soil and Rock," Proceedings of the Conference on In Situ Measurement of Soil Properties, Volume II, American Society of Civil Engineers, New York, New York.

Muth W., 1988. "Drainage with Interlocked Paving Bricks," Research Institute for Water Resources, Karlsruhe University of Engineering, Karlsruhe, Germany.

Nichols, D., 1993. "Porous Paving: Stormwater Management Alternative," *Landscape Design,* Vol. 6, No. 1, Gold Trade Publications, Van Nuys, California.

Phalen, T., 1992. "Development of Design Criteria for Flood Control and Ground Water Recharge Utilizing UNI Eco-Stone® and Ecoloc® Paving Units," Northeastern University, Boston, Massachusetts.

Pisano, M., 1976. "Nonpoint Sources of Pollution: A Federal Perspective," *Journal of Environmental Engineering Division,* Vol. 102, American Society of Civil Engineers, New York, New York.

Reeve, A., 1993. "Understanding Stormwater Problems," *APWA Reporter,* Vol. 60, No. 1, American Public Works Association, Washington, D.C.

Rollings, R. S. and M. P. Rollings, 1991. "Pavement Failures: Oversights, Omissions, and Wishful Thinking," *Performance of Constructed Facilities Journal,* Vol. 5, No. 4, American Society of Civil Engineers, New York, New York.

Rollings, R. S. and M. P. Rollings, 1992. "Applications for Concrete Paving Blocks in the United States Market," Uni-Group U.S.A., Palm Beach Gardens, Florida.

Taylor, D., 1948. *Fundamentals of Soil Mechanics,* John Wiley and Sons, New York, New York.

Uni-Group U.S.A., 1992. "UNI ECO-STONE," video report, Palm Beach Gardens, Florida.

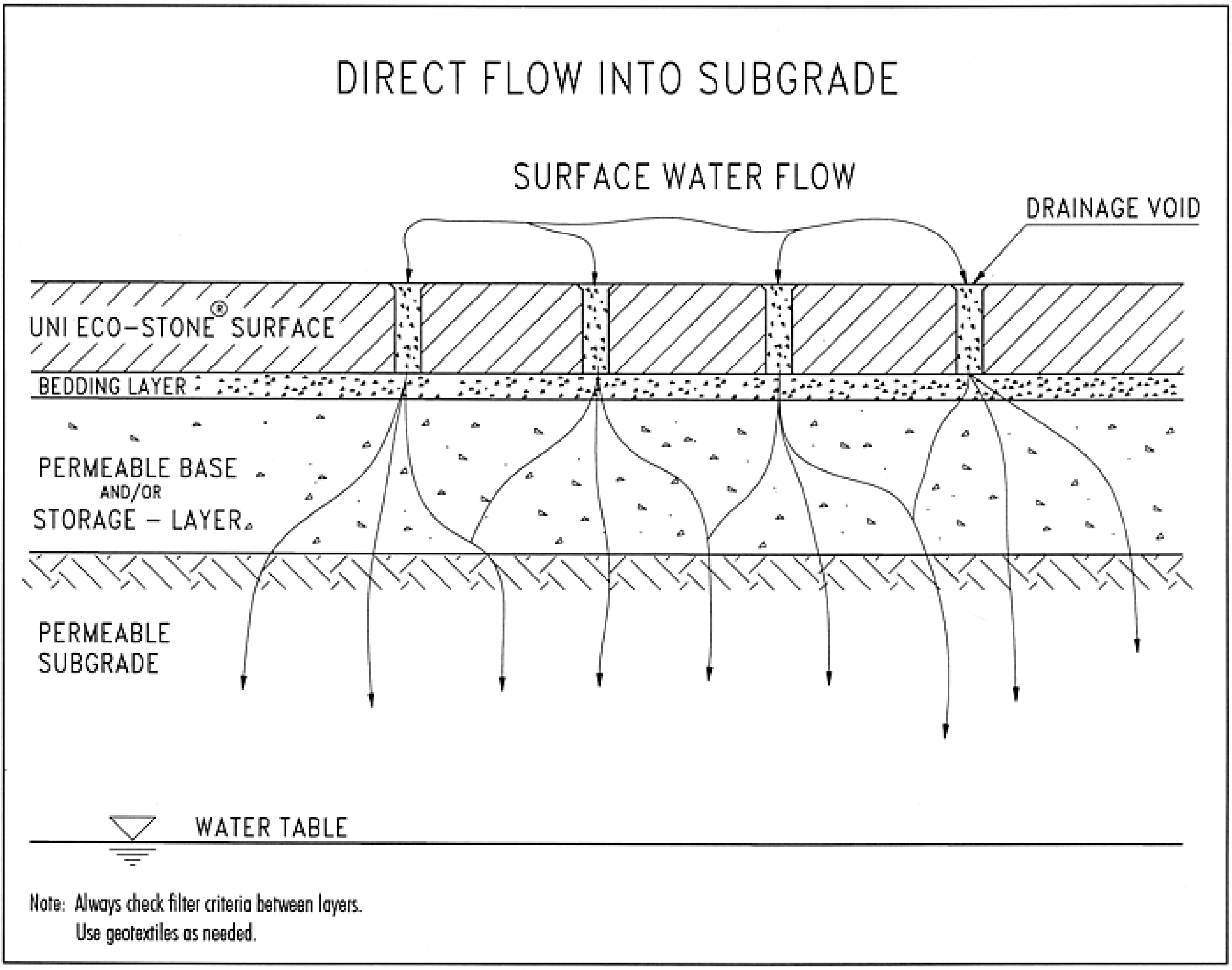
U.S. Bureau of Reclamation, 1974. "Earth Manual," Washington, D.C.

Wanielista, M. and Y. Yousef, 1993. *Stormwater Management,* John Wiley & Sons, Inc., New York, New York.

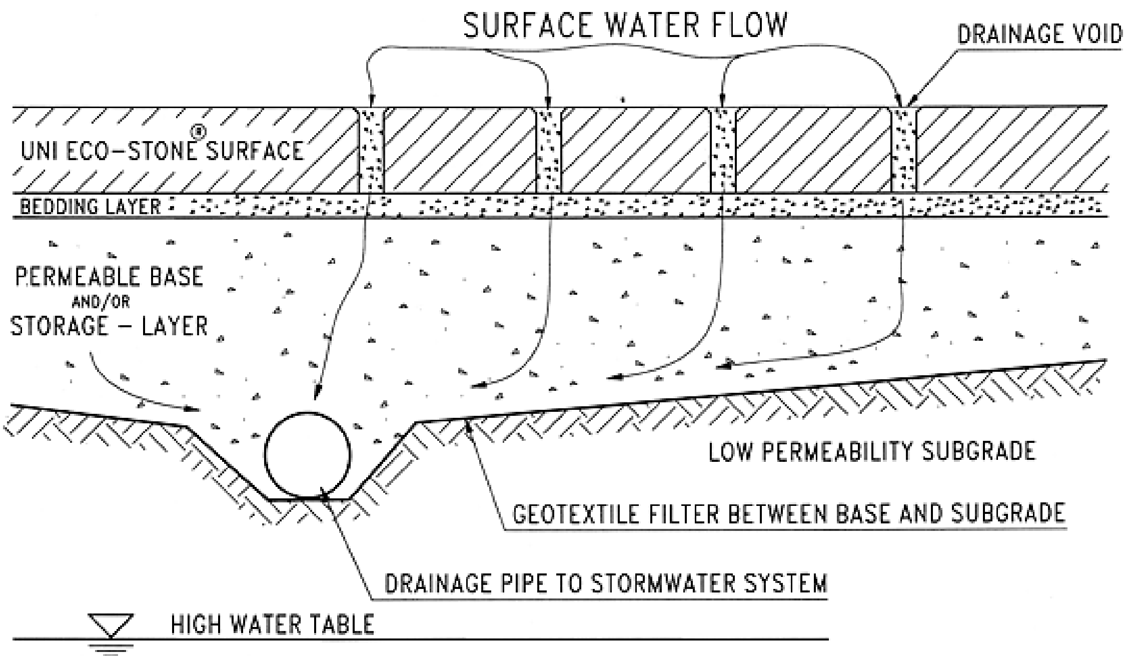
Yoder, E. J. and M. W. Witczak, 1975. *Principles of Pavement Design,* Second Edition, John Wiley and Sons, New York, New York.

SAMPLE DESIGN DRAWINGS

Please note: Sample design drawings are to demonstrate the potential of UNI Eco-Stone® for various design applications. Actual design of the pavement system will vary according to local environmental conditions, regulations, design storms, engineering practices and methods, available construction materials, soil conditions, traffic load, and so forth. A qualified engineer, architect, and/or landscape architect should be consulted in concrete paver applications to ensure desired results.

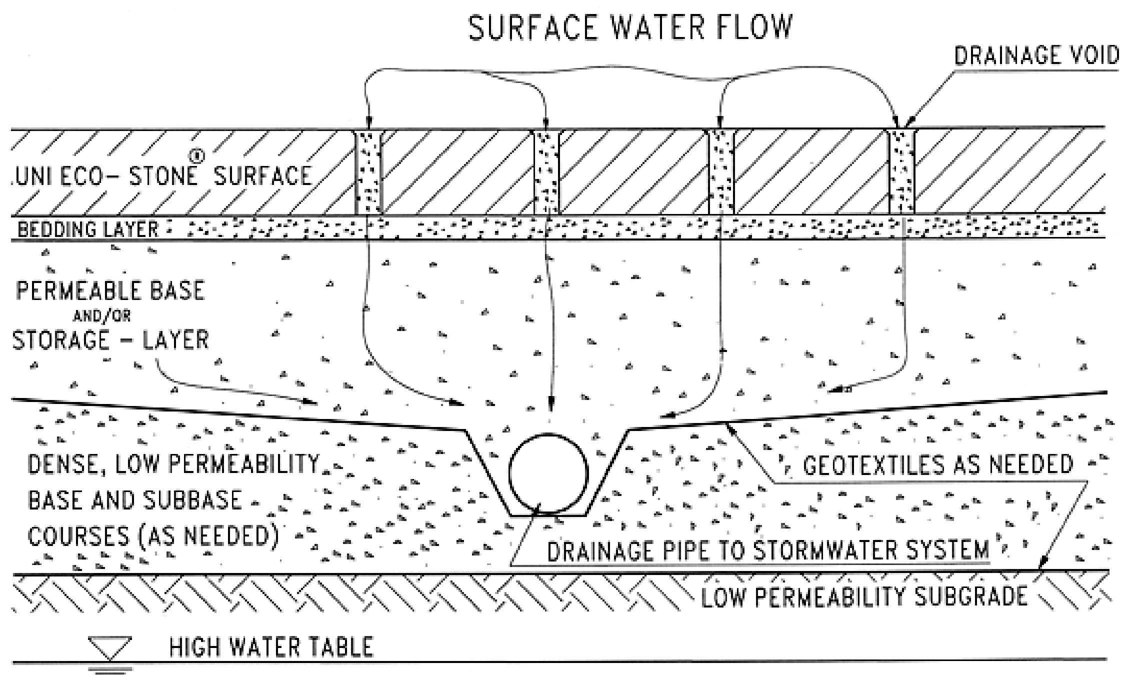


COLLECTION AND DISPOSAL OF INFILTRATION
(EXAMPLE 1)

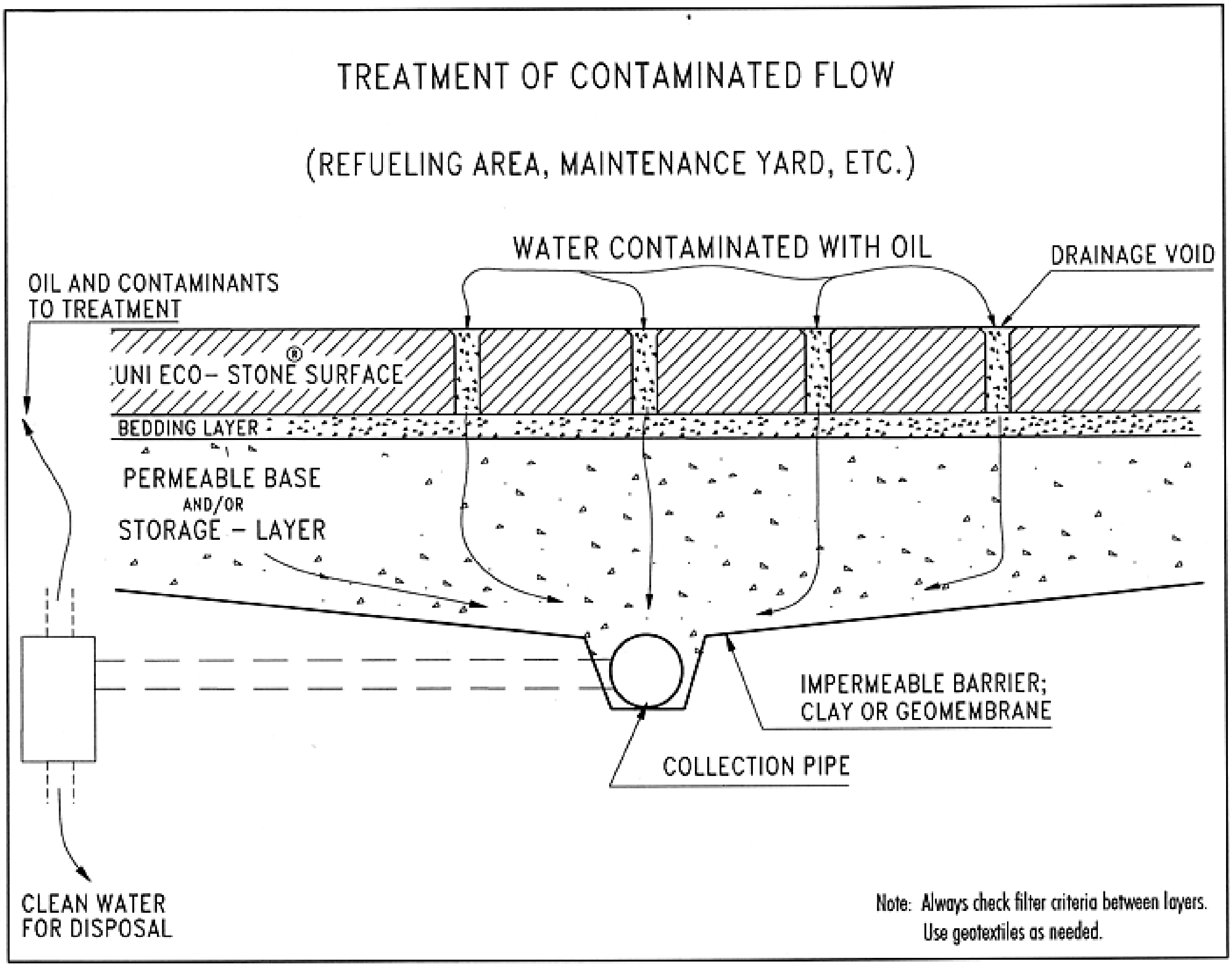


Note: Always check filter criteria between layers.
Use geotextiles as needed.

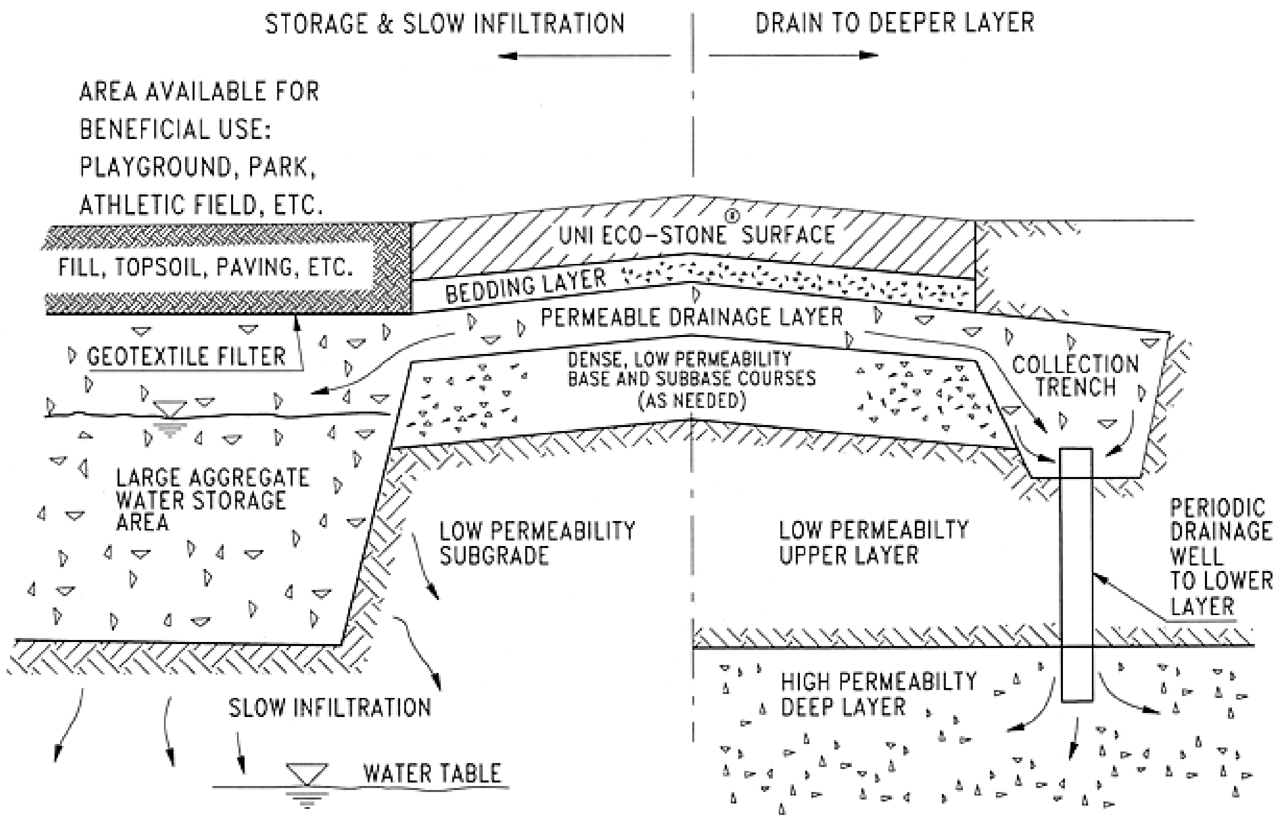
COLLECTION AND DISPOSAL OF INFILTRATION
(EXAMPLE 2)



Note: Always check filter criteria between layers.
Use geotextiles as needed.


TREATMENT OF CONTAMINATED FLOW
(REFUELING AREA, MAINTENANCE YARD, ETC.)
WATER CONTAMINATED WITH OIL
DRAINAGE VOID
OIL AND CONTAMINANTS TO TREATMENT
UNI ECO-STONE® SURFACE
BEDDING LAYER
PERMEABLE BASE AND/OR STORAGE - LAYER
IMPERMEABLE BARRIER; CLAY OR GEOMEMBRANE
COLLECTION PIPE
CLEAN WATER FOR DISPOSAL
Note: Always check filter criteria between layers.
Use geotextiles as needed.

SLOW INFILTRATION DISPOSAL



Note: Always check filter criteria between layers.
Use geotextiles as needed.