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

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MANUFACTURERS' PREFACE

Preparation of this report was sponsored by UNI-GROUP U.S.A., one of the nation's leading concrete paver producer organizations, as a part of their research, education, and technology transfer efforts regarding permeable interlocking concrete paver block pavements.

The information included in this report represents just one of many design approaches that may be considered in the planning and design of projects utilizing the UNI Eco-Stone® Paving System. It is not intended to replace the judgement and discretion of professional pavement engineers. Additional design approaches are detailed in UNI-GROUP U.S.A.'s report, *"Design Considerations for the UNI Eco-Stone® Concrete Paver"* by Drs. Rollings and Rollings, and in LOCKPAVE® PRO, a structural design software program by Dr. Brian Shackel. The statements, analyses, and conclusions contained in this report are those of the authors and do not necessarily reflect the opinions of UNI-GROUP U.S.A. as a whole or of its individual members.

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IMPLEMENTATION STATEMENT

The information provided in this report serves as a guideline for the design of concrete paver block pavements using the UNI Eco-Stone® product. These 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 the Eco-Stone® system 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. These 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.

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CHAPTER I
INTRODUCTION

Traditional pavements are generally classified as either rigid or flexible pavement. Flexible pavement, also referred to as asphalt concrete pavement, is typically composed of an asphalt surface layer, a base course, a subbase course and a subgrade as shown in Figure 1. Rigid pavement, also referred to as concrete pavement, is typically composed of a concrete surface layer, a subbase course, and a subgrade, as shown in Figure 2. The base course is the layer of material immediately beneath the surface. Crushed stone, untreated or stabilized material, dense-graded material, and open-graded material are most often used for base courses. The subbase course is the layer of material beneath the base course and above the subgrade, (which is the bottom layer). The subgrade may be natural soil or fill material that is compacted near the optimum moisture content.

Asphalt concrete and Portland cement concrete are the most commonly used types of paving surface material in the United States. They have high durability and are appropriate for high-volume, high-traffic applications. Both of these pavement surfaces are, for all practical purposes, impermeable. As more real estate is developed and covered with these two traditional pavement types, particularly in developing areas, several problems are magnified regarding runoff management and the control of downstream flooding.

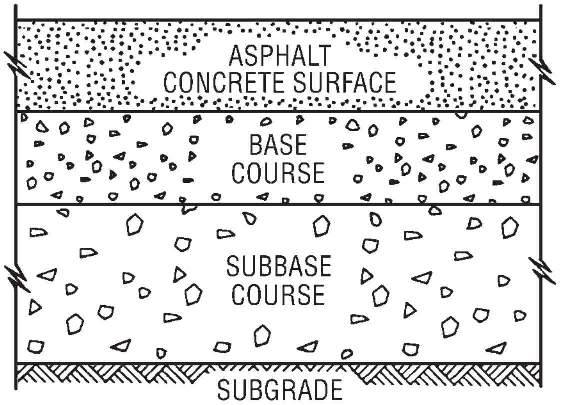

Figure 1 - Cross-Section of Asphalt Pavement (3)

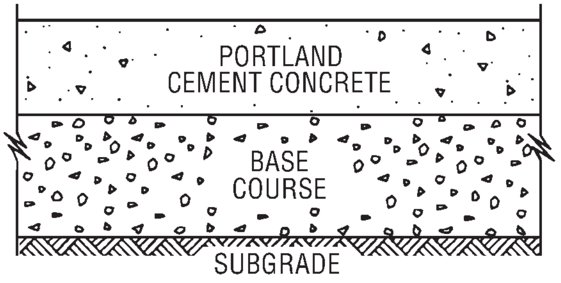

Figure 2 - Cross-Section of Rigid Pavement (3)

Use of impervious paving surfaces in urban areas eliminates natural water recharge of local ground water aquifers and causes an increase in the quantity and rate of storm runoff. Therefore, the result is an increase in the incidences of flooding and potential down stream erosion. When stormwater runoff moves from upstream to downstream, solid material and various contaminates from streets and parking areas will flow into the water system resulting in water pollution. Numerous local mandatory regulations have been implemented in order to combat the effects of urbanization and to manage the problems associated with stormwater runoff (1). Various methods have been used to meet these stormwater regulations, such as on-site ponds or detention basins, weirs, and the use of permeable pavement for recharge purposes. However, it is recognized that "porous pavement has the potential for reducing the overall quantity of runoff, without requiring the use of additional space on the (construction) site" (2). Therefore, a great advantage exists in using permeable pavement surfaces to decrease the quantity of stormwater runoff and potential water pollution.

Recently, several types of permeable pavement have been suggested as alternative pavement systems. The Eco-Stone® pavement system is one of these alternative permeable pavement surfaces. The UNI Eco-Stone® paver has been widely used in various paving projects in urban and municipal areas worldwide (1).

UNI Eco-Stone® is a concrete paving block that is produced to a specific size and shape and, when installed, forms openings in the surface of the pavement as shown in Figure 3. These openings in the surface are filled with unstabilized permeable material to allow water to pass through the surface pavement down to the layers below.

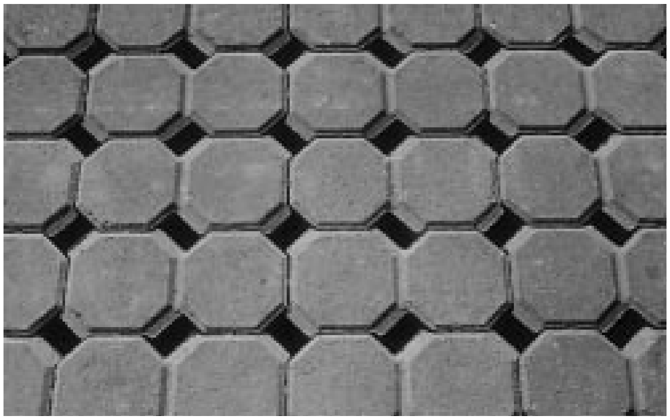

Figure 3 - Drainage Voids in UNI Eco-Stone®

A cross-section of a UNI Eco-Stone® pavement is shown in Figure 4. The pavement is comprised of the Eco-Stone® surface, a bedding layer, a base course, a subbase course (if needed), and the existing subgrade. The bedding layer, placed immediately below the surface layer, is usually one inch in thickness. The base layer must be carefully selected for accommodating infiltrated water and traffic loads.

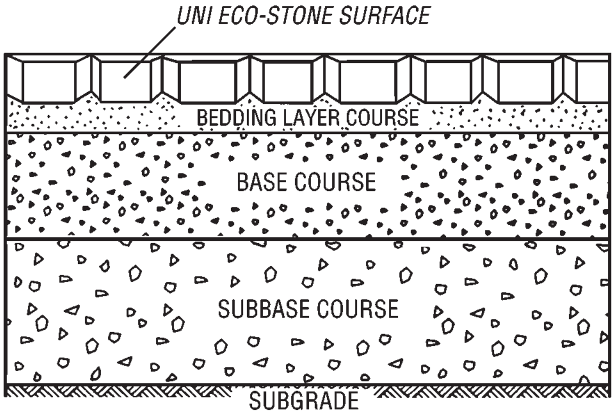

Figure 4 - Components of a UNI Eco-Stone® Pavement

ADVANTAGES OF USING UNI ECO-STONE® PAVEMENTS

The UNI Eco-Stone® concrete paver is a manufactured product that has high strength and durability. The Eco-Stone® concrete paver, when installed, creates openings in the pavement surface for water to pass through into the layers below. Compared with impervious pavement surfaces, UNI Eco-Stone® paving blocks offer not only strength, durability, and aesthetics, but also several other advantages (1, 2, 4):

1) Reduces both runoff volume and the intensity of overland flow by as much as 100 percent for a developed area to facilitate requirements associated with local municipalities, counties, regional authorities, regulatory standards, and the managerial challenges associated with stormwater runoff for a developed area. Infiltration of stormwater near to where it falls to the earth reduces the storm drainage detention basin requirements. Although initial cost for UNI Eco-Stone® pavement construction may be higher than that for traditional pavement construction, a reduction in stormwater storage area requirements will also reduce land-use requirements which should result in the reduction of overall project development costs.

2) Increases water quality standards by soil filtration of rainwater through the pavement structure and the soil below.

3) Increases natural groundwater recharge due to less use of impervious pavement surfaces, and reduces down-stream erosion and siltation.

The Considerations for Water

It has been recognized for many years that water can reduce pavement performance through many different forms of distress mechanisms. This has led many design engineers to put more emphasis on keeping the water content in supporting layers to a minimum (6). Although pavement deterioration and failure is a very complex process, recent investigations have demonstrated that water in pavements is a leading factor in causing damage. As a result, the design of saturated pavement layers will need to be sensitive to the material properties and pavement characteristics that are affected by moisture. It has been noted that various pavement distresses, such as the loss of support, are related to the effects of water in pavements. Water can deteriorate pavement performance in the following ways (6):

1) Strength of the base and subbase decreases with the increase in water content, resulting in the reduction of subbase or base support and the increase in the rate of permanent deformation and loss of serviceability of the pavement.

2) Under heavy wheel loads, free water contained within the layers of the pavement structure will build up water pressure. This water pressure will lead to erosion, ejection of the base material, disintegration of the base layer, and will cause pumping in concrete pavements and serious damage to asphalt pavements.

Because water in the pavement is of particular concern, it is of interest to control water in the pavement and reduce maintenance. Current practices to accomplish this are:

1) Keeping surface water out of the pavement system, or
2) Minimizing the presence of water in the pavement structure for extended periods of time.

During the past decade, a belief has developed with respect to the minimization of the impact of water on pavement performance by waterproofing the surface layer to reduce infiltration of water into the pavement structure. Maintenance efforts for asphalt and concrete pavement types have focused a great deal of effort on sealing the pavement surface layer. A seal coat has often been used on top of asphalt pavement surfaces to prevent rainfall from infiltrating into the pavement. Several joint sealing technologies and methods have been developed to minimize water infiltration into both asphalt and concrete pavement joints/cracks. But in practice, it is very difficult to keep water completely out of the pavement system because of development of random cracking or other failures only a few years after construction (6). Pavement engineers have come to realize that proper drainage design is important for good pavement performance with respect to infiltrated water.

Investigations by Cedergren (6) indicate that if a properly designed drainage system is provided, even though infiltration is allowed, the presence of water in the structure for a short period of time (i.e. 24 hours) should have little impact on pavement performance. Therefore, the ingress of water into the pavement structure by way of the openings in the UNI Eco-Stone® pavement surface should be acceptable in terms of pavement performance as long as special drainage design considerations are taken into account. It is important for a UNI Eco-Stone® pavement system to properly drain water from the pavement structure to minimize potential damage.

THE PURPOSE OF THIS REPORT

This report is written in conjunction with current information and technology regarding drainable pavement systems. However, its ultimate purpose is to provide guidance for an engineer to design both a pavement structure and a drainage system incorporating UNI Eco-Stone® and to define the limits and conditions associated with the retention of water within the pavement system and long-term pavement performance. The Eco-Stone® pavement system, which allows water to infiltrate into the pavement structure, provides the design engineer with possibilities for pavement surface water control. However, the engineer must properly design each component of the pavement system to reduce the impact of water retention on performance. It is well recognized that the base and subgrade strength will decrease as water content increases and that the infiltrated water will influence the pavement performance. In order to control runoff water so that it will have as little impact as possible on pavement performance, the UNI Eco-Stone® pavement system will need to be designed to accommodate the anticipated traffic for the expected infiltrated moisture conditions. The process to design the base layer thickness and drainage components and to select the base material gradation relative to the performance of the pavement is essential to the designer. Consideration should also be given to aggregate mineralogy, as some aggregate types have less abrasion resistance than others.

CHAPTER 2
GENERAL HYDROLOGY CONCEPT

Engineering Hydrology refers to broad subjects such as estimates of precipitation, characterization of runoff processes, and ground water and soil water infiltration movement. Many excellent references (9, 18, 19) cover the details for each subject, however, the objective of this chapter is to introduce the drainage engineer to the general concept of precipitation and the runoff process that are related to drainage design.

RAINFALL

Precipitation, especially in form of rainfall, is an important input into the drainage design. Rainfall can be described on the basis of rate (inches per hour), depth (inches of rainfall), duration (rainfall event lasted 2 hours), and frequency (a 2-hour rainfall event occurs about once every five years). All of these descriptions provide useful information regarding the design of the drainage system.

Intensity-Frequency-Duration Curve

An example of an Intensity-Frequency-Duration curve is shown in Figure 5, which displays the types of data mentioned above. These curves are prepared data for a particular geographic location based on long-term rainfall records. For example, the rainfall event with a duration of 30 minutes that occurs approximately once in five years has an intensity of 3.5 inches. As indicated in the Intensity-Frequency-Duration Curve, the shorter the duration of rainfall, the higher the intensity is likely to be. The data in Figure 5 also indicates that the more intense rainfall events are less likely to occur frequently.

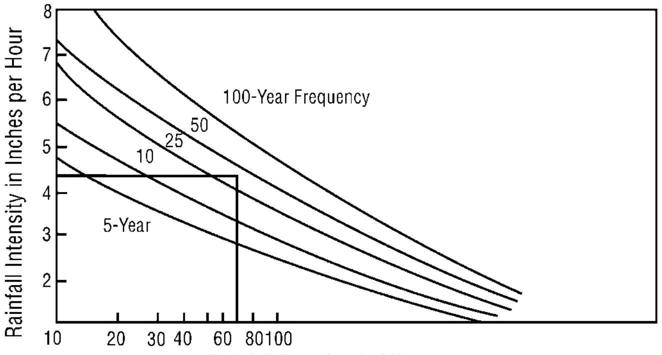

Figure 5 - Intensity-Frequency-Duration Curve (8).

The Depth of Rainfall

The depth of rainfall is actually a measure of the volume of rainfall since it expresses the number of inches of precipitation over a certain drainage area. The depth of rainfall is useful information in regard to the storage of water and can be calculated by knowing the intensity and duration of the rainfall. For example, a rainfall event with a duration of 30 minutes that occurs on the average of approximately once in 5 years has an intensity of 3.5 inches per hour. The depth of rainfall can be calculated as follows:

Depth of rainfall = 3.5 (inches per hour) * 30/60 (per hour) = 1.75 inches

Stormwater Runoff Volume

The volume of rainfall is equal to the rainfall intensity multiplied by the duration of rainfall and the drainage area. The volume of stormwater runoff is the volume of rainfall minus the volume of abstraction by interception, surface detention, and infiltration, etc. A runoff volume and peak flow rate can be obtained from a runoff hydrograph (a continuous record of streamflow over time). The area under the runoff hydrograph is equal to the stormwater runoff volume. The volume of runoff divided by the area of drainage results in the depth of runoff.

Unit Hydrograph

As previously mentioned, a runoff hydrograph is a continuous record of stream flow over time. Hydrographs of stormwater runoff are necessary in the design of stormwater detention structures. A unit hydrograph is the runoff hydrograph that would occur if there were one inch of runoff. A unit hydrograph can be obtained by several methods (SCS Unit Hydrograph method, Rectangular Unit Hydrograph method, etc.).

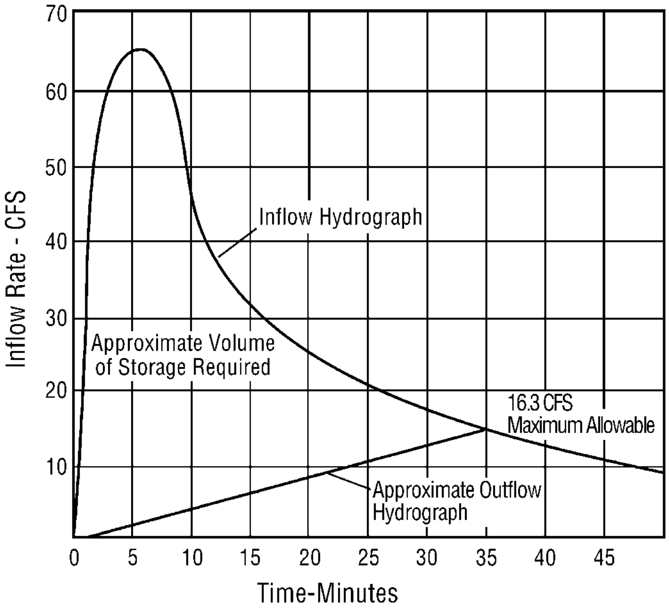

Figure 6 - Inflow Hydrography (8).

Details for developing a unit hydrograph can be found in various textbooks such as "Design Hydrology and Sedimentology for Small Catchments" (7). A runoff hydrograph can be developed from a unit hydrograph and is shown in Figure 6.

CHAPTER 3
SURFACE DRAINAGE SYSTEM DESIGN

Surface drainage should be designed to remove surface water from the pavement system. An important step in surface drainage design is the determination of the expected quantities and rate of runoff water. Commonly, in new developments, detention basins are used for stormwater management to reduce peak flows. Whether or not a detention basin is needed with a pavement surfacing of UNI Eco-Stone® pavers depends on the expected peak runoff rate, the degree of infiltration, and local stormwater regulations. Often, local mandates require that the peak runoff rates for a design storm after development do not exceed the peak runoff rates for the same design storm before development (7, 8). If the peak runoff rate using the Eco-Stone® pavement system exceeds the allowable release rate, a detention basin is needed and storage for the excess water must be provided. The amount of runoff and runoff rate can be obtained from a runoff hydrograph which is a continuous record of flow rate over time for a given area.

COMPUTATION OF RUNOFF

A surface drainage system should be designed to remove surface water within certain time limits and physical constraints. The capacity of the surface drainage system depends on the amount of runoff that will occur on a given area. The runoff rate depends on a number of factors (1, 9). The following factors have a pronounced influence on the rate of runoff:

1) Intensity and duration of the rainfall.
2) Type and moisture condition of the base and soil at the time of the rainfall.
3) Slope of the surface.
4) Permeability of fill material in drainage voids on the pavement surface.
5) Drainage voids in the pavement surface.

There are several methods available for calculating the runoff (peak runoff rate), such as the rational method or the SCS curve number method (7). The engineer can choose either method, but this report is referenced to the rational method (10). The rational method is based on the direct relationship between rainfall and runoff. It is expressed by the equation (9):

$$Q_p = C \times I \times A \qquad (1)$$

where

Q_p = The peak runoff rate (cfs)
C = The runoff coefficient
I = Mean rainfall intensity over a period equal to the time of concentration (in./hr)
A = The area (acres)

Runoff coefficients (C) for several materials are listed in Table 1. The value of C for UNI Eco-Stone® pavements must be designed with respect to required drainage characteristics of the base and subgrade material, the slope of the pavement, the fill material in the surface openings, and the jointing material. The selection of the fill material in the drainage voids, the jointing material, and the slope of the pavement can have significant influence on the value of the runoff coefficient. It may also be possible to derive a C value from actual flow data, as was suggested by Rollings (1) of flow data published by Muth (11), and shown in Table 2.

Table 1. Values C for Several Material Surfaces (10).

Type of Surface	Factor C
For all watertight roof surfaces	0.75 to 0.95
For asphalt runway pavements	0.80 to 0.95
For concrete runway pavements	0.70 to 0.90
For gravel or macadam pavements	0.35 to 0.70

Table 2. The Value of Runoff Coefficient for UNI Eco-Stone Surface (1).

Fill	Slope	I (in/hr)	% Infiltration	C
Muth Mix	2.5 %	4.2	75 %	0.25
Muth Mix	0 %	4.2	85 %	0.15

Muth Mix comprised of 2-5mm gravel chips and 2mm clean sand.

Design engineers should anticipate considerable increase in C values after a period of 5 to 6 years of service due to an accumulation of fine particles in the jointing sand and bedding layer material. Research results indicated that infiltration rates could be reduced by as much as 50 percent (35). Since infiltration is associated with the permeability (discussed in the following chapter), certain inferences can be made relative to the factors that influence infiltration. An increase in the amount of material finer than the #200 sieve size by $^1/_2$ percent may reduce the infiltration coefficient by a factor of 15. However, it may be possible to offset this effect by using material gradations that yield void ratios greater than 0.40. It is noted that void ratio depends upon dry rodded unit weight as it is affected by aggregate shape, angularity, and grading. Although more research data is needed, it is suggested void ratios be held to a minimum of 0.48 to 0.50 to minimize the effect of aging and the tendency for fine particle accumulation to develop in the drainage holes and bedding layers. Examples of gradations manifesting porosity in this range are shown in Table D2, samples 5 and 6. It should be noted that permeability has been successfully restored in some UNI Eco-Stone® projects using conventional street sweeper equipment with vacuums, water, and brushes (1).

CHAPTER 4
SUBSURFACE DRAINAGE SYSTEM DESIGN

INTRODUCTION

The process of subsurface drainage design focuses on the removal of water from within the pavement structure. Typical components of a subsurface drainage system are (a) a base drainage layer, (b) a filter layer, (c) a collector pipe, and (d) an outlet pipe. The base drainage layer has two purposes: first, the base drainage layer helps transmit the structural load from the pavement to the natural subgrade and second, it transmits the drainage water from the pavement structure to the collector pipe. The filter layer's primary function is to act as a filter and prevent the migration of the fine material into the permeable base or the collector pipe and, in some instances, it must allow the drainage water to flow freely through it with minor energy loss. The collector pipe intercepts infiltrated water from the base layer and transmits the water to the outlet pipe. The outlet pipe transmits the water to a natural drain or an open channel.

Subsurface water generally comes from two sources:

a) Groundwater, which is defined as the water existing in the natural ground in the zone of saturation below the water table.
b) Infiltration water, which is defined as surface water that seeps down through voids or cracks in the pavement surface to the pavement substructure.

Because an Eco-Stone® pavement contains openings on the surface, rainfall will infiltrate from the pavement surface to the pavement substructure. This chapter focuses on the removal of infiltrated water by a subsurface drainage system.

GENERAL CONSIDERATIONS

There are two basic approaches to the consideration of water in the design of a pavement system. One approach, which is the typical practice, is to attempt to keep the natural soil and the base material under the pavement dry by making the pavement surface waterproof. This results in high runoff rates from the pavement. A similar effect can be achieved if the construction materials in the pavement base are well graded with more than 20 percent passing the #50 sieve size.

The alternate approach, which is applicable to the UNI Eco-Stone® pavement system, is to allow water to infiltrate into the pavement surface and to disperse throughout the base layers, thereby reducing runoff. Since the water is allowed to infiltrate into the pavement, designers should consider the potential impact of water on pavement performance. Each component of the subsurface drainage system should be designed properly to maintain sufficient strength in the presence of water. Moisture retention must be balanced against pavement performance, in that base layers must be constructed of coarse materials with a sufficient permeability so that the strength of base material is held to certain levels while infiltrated water is transmitted to the drain pipe or to the natural soil. If runoff water is stored in the pavement or the base material, then the construction materials must be chosen to assure sufficient permeability and a high strength while these materials are in the presence of water to minimize the loss of stability in the supporting layers. The pavement design procedure outlined in Appendix A takes these considerations into account in the prediction of rutting performance.

Properties of Pavement Materials

Permeability and mineralogy of the base material are the important engineering characteristics that should be considered in the design of UNI Eco-Stone® pavement systems. Factors that affect permeability, such as grain size distribution and the percent of fines passing the #50 sieve size, are important considerations and should be carefully selected by the engineer relative to retention time and the desired amount of storage capacity. Aggregate mineralogy determines aggregate abrasion resistance and hardness and consequently, is often related to aggregate shape and texture. Crushed aggregates taken from a quarry typically have 100 percent fractured faces, but may vary widely in abrasion resistance from quarry to quarry.

As for fine-grained soils and subgrade materials, plasticity characteristics in terms of Atterberg limits, and soil classification (i.e. the

Unified Soil Classification System) are indicators of material performance and permeability. Therefore, whenever possible, representative samples of material and natural soil should be subjected to the testing and classification.

Silts and clays are classified as fine-grained soils because their particle size is smaller than the #200 mesh sieve (particles smaller than the #200 mesh sieve are at the boundary of visibility to the naked eye). Fine-grained soils are relatively impermeable, where their shear strength is relatively low and is reduced when saturated. Sands and gravels are classified according to their size and are, relatively speaking, course-grained materials in comparison to silts and clays since the majority of particle sizes are larger than the #200 mesh sieve. For purpose of drainage design, soil layers comprised largely of silts and clays can be regarded as impermeable, allowing infiltration in layers consisting of these types of soils to be ignored.

The base and materials that serve as a permeable layer and are typically used with UNI Eco-Stone® pavements consist of crushed aggregates, and combinations of rounded (or natural) and angular sands. Crushed aggregates and sands have less than 5 percent by weight of materials passing through the #200 mesh sieve. These clean materials should be non-plastic (Liquid Limit and Plastic Limit will be zero). Crushed aggregates and sands can have a relatively high permeability (depending upon the gradation) and a relatively high shear strength that is largely independent of water content.

It may also be advantageous to use a filter fabric between the base course and the natural subgrade (particularly one that is fine grained) to prevent the mixing of the fine-grained soil material and the coarse-grained base. If mixing occurs, the permeability of the coarse-grained base may be reduced, and the strength of these materials will then be more dependent upon water content.

Determination of the coefficient of permeability can be facilitated by several methods (12):

a) In-situ measurement,
b) Laboratory testing,
c) Theoretical analysis, and the
d) Empirical method.

Ideally, the coefficient of permeability should be determined by in-situ measurements because these can reflect overall permeability of the existing soil. Laboratory determination of permeability of selected soil samples is also a possibility, but physical measurements may not be feasible for most design situations. Although in-situ or laboratory evaluation of the coefficient of permeability may provide the most reliable data, project-related constraints may require that the permeability of a material be estimated based on soil classification and other empirical formulations. Table 3 lists ranges of coefficient of permeability as related to the Unified Soil Classification System:

Table 3. Correlation between Permeability and Unified Soil Classification (12).

Unified Soil Classification	**Relative Permeability**	**Coefficient of Permeability k (ft/day)**
GW	Pervious	2.7 to 274
GP	Pervious to Very Pervious	13.7 to 27400
GM	Semipervious	2.7×10^{-4} to 27
GC	Impervious	2.7×10^{-4} to 2.7×10^{-2}
SW	Pervious	1.4 to 137
SP	Semipervious to Pervious	0.14 to 1.4
SM	Impervious to Semipervious	2.7×10^{-4} to 1.4
SC	Impervious	2.7×10^{-5} to 0.14
ML	Impervious	2.7×10^{-5} to 0.14
CL	Impervious	2.7×10^{-5} to 2.7×10^{-3}
OL	Impervious	2.7×10^{-5} to 2.7×10^{-2}
MH	Very Impervious	2.7×10^{-6} to 2.7×10^{-5}
CH	Very Impervious	2.7×10^{-7} to 2.7×10^{-5}

The permeability of a clean sand can be calculated from an empirical equation developed by Hazen (13):

$$K = C_1 (D_{10})^2 \qquad (2)$$

where

K = Permeability (cm/sec)
C_1 = A constant which ranges from 90-120
D_{10} = Effective grain size at 10% passing (cm)

An empirical equation for determining the permeability of granular drainage materials was developed by Moulton (12):

$$K = \frac{6.214x10^5 \, (D_{10})^{1.178} \, n^{6.654}}{P_{200}^{\;0.597}} \text{ (ft/day)} \qquad (3)$$

where

n = Porosity = $1 - \frac{\gamma_d}{62.4G}$
G = Specific gravity
P_{200} = Percent passing the #200 sieve
γ_d = Dry rodded unit weight (lb/ft^3)
D_{10} = Effective grain size at 10 % passing (in.)

This expression shows that the coefficient of permeability of a granular drainage material is mainly influenced by the effective grain size (D_{10}), the percent passing the #200 sieve (P_{200}), and the porosity of the material, which is defined as the ratio of the volume of voids to the total volume of material. This can be very useful in design for materials containing minus 200 sized particles.

For materials void of minus 200 particle sizes, the following expression may be used to estimate the permeability:

$$K = 3 \times 10^{-3} \, e^{27.25 * n} \text{ (ft/day)} \qquad (4)$$

Note that this expression is only a function of the percent voids and can be easily applied in the design process. It should also be pointed out that porosity is determined as a function of the dry-rodded unit weight (ASTM C29) and the specific gravity (ASTM C33) of the base material. These test procedures are rather common and can be carried out by most testing laboratories. Otherwise, engineers knowledgeable of the materials to be used in the pavement structure may find it useful to estimate these values.

The material that is used to fill the drainage voids in UNI Eco-Stone® pavers plays an important role in the infiltration rate. However, permeability of the fill material varies significantly with grain size and is extremely sensitive to the quantity, character, and distribution of the fine fractions. As previously noted, it should also be pointed out that the percent voids of the base layer also have a large influence on the infiltration capacity of the pavement system and can be very useful in determining the desired gradation. When permeable base material is used as the underlying material, the infiltration capacity of the pavement system is higher than when a low-density base is used. In order to design the subsurface drainage system properly, the overall

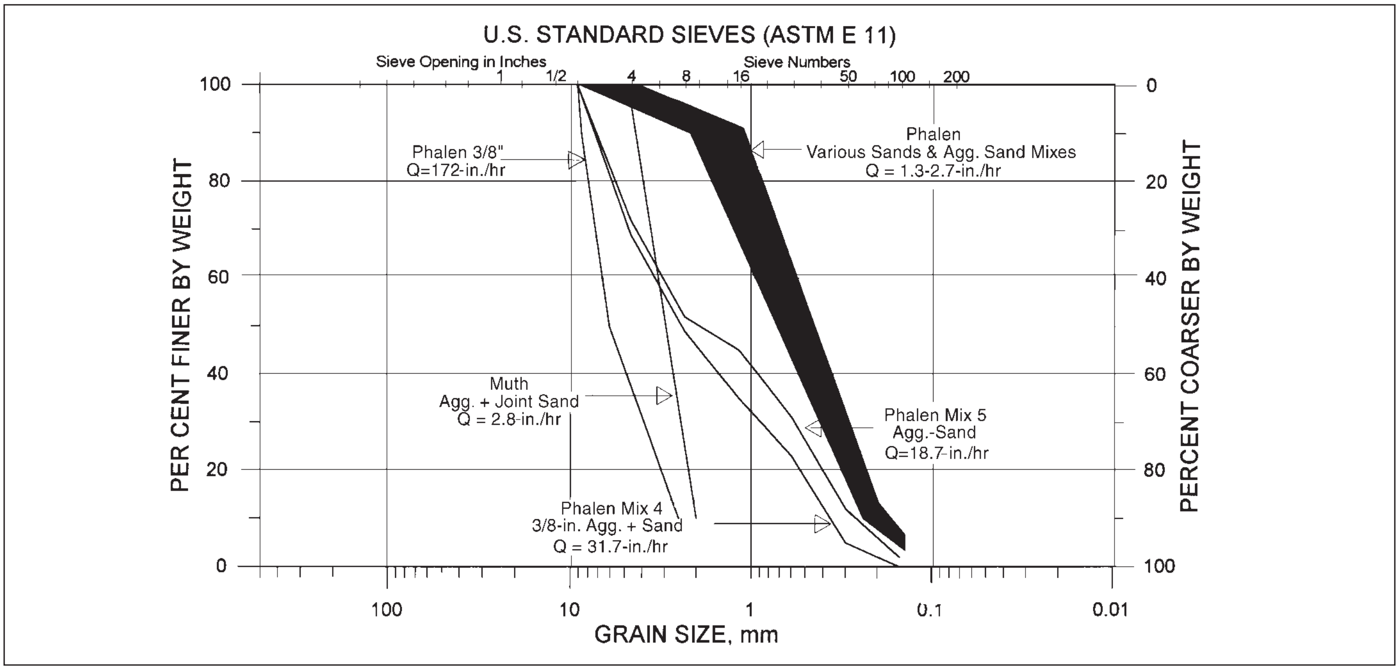

Figure 7 - Jointing Sands and Bedding Layer Gradations and Flow Rates (1).

permeability of the pavement system is a major parameter in design. Phalen's (1, 16) and Muth's (1, 11) experimental results are guides to determine the surface infiltration rate based on selection of fill material as shown in Figure 7. Table D.1 lists various drainage material gradations and permeability. The ASTM C 33 and ASTM 448 No. 9 gradations may yield infiltration rates that are too low and are not recommended for bedding layer applications in UNI Eco-Stone® pavement systems. However, ASTM C 448 sizes No. 7 and No. 8 are recommended.

Design Alternatives

Water that is allowed into a pavement structure must eventually be drained out of the pavement structure. There are several ways to remove infiltrated water from a UNI Eco-Stone® pavement system. Most of them can be categorized as:

a) Permeability of base, or
b) Permeability of the subgrade.

Examples of several design alternatives (1) are shown in the following figures. Figure 8 shows an example of an Eco-Stone® pavement over a natural low-permeability subgrade with a high water table. In this case, the surface water passes through the UNI Eco-Stone® drainage voids and the bedding layer, flowing downward into the permeable base. A drainage pipe is installed to facilitate moving infiltrated water out of the base layer. Water can be stored above the low-permeability subgrade in the permeable base, if required, because of the high water table. The low-permeability subgrade will always be wet because of the high water table, so storing water on top of it should not affect subgrade strength significantly. The time for stored water to be discharged is dependent upon permeability of base and the slope of the base layer.

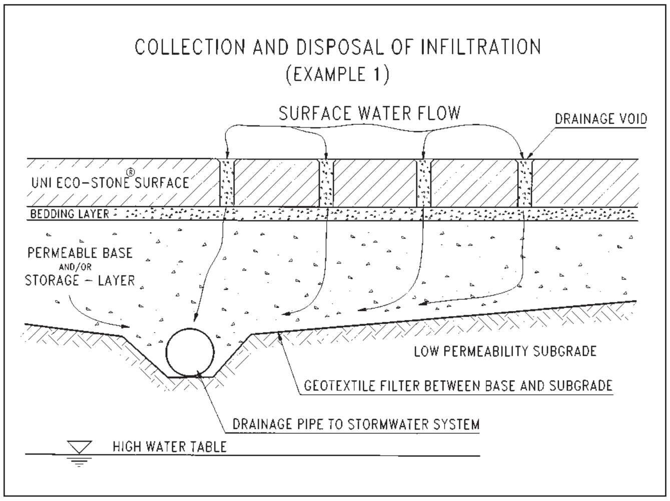

Figure 8 - Collection and Disposal of Infiltration (1).

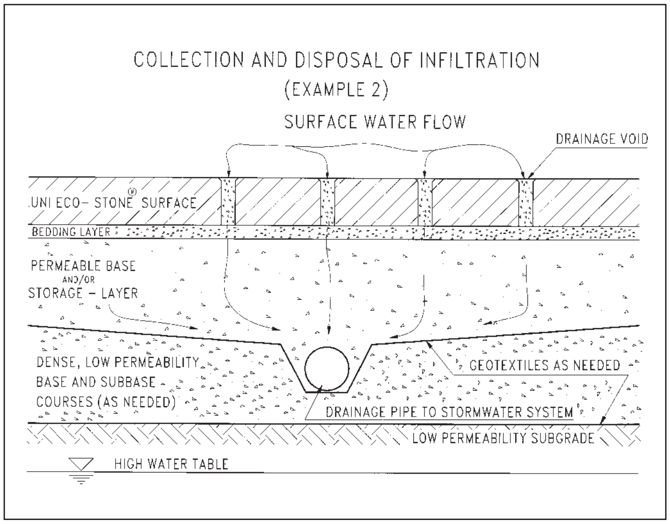

Figure 9 - Double Base Drainage System (1).

Figure 9 shows an example of an Eco-Stone® pavement over a natural low-permeability subgrade using a two-layer base system. In this case, it is of interest to store water in the upper permeable layer while protecting the strength of the natural subgrade with a low-permeability base layer. This dense, low-permeability layer has a slope so that the water will flow to the collection trench. The water percolates through the pavement voids and the bedding layer, into a permeable drainage layer for storage purposes. From there, the water flows to a collection trench and is ultimately discharged from the pavement system. This design is feasible when a low-strength subgrade exists.

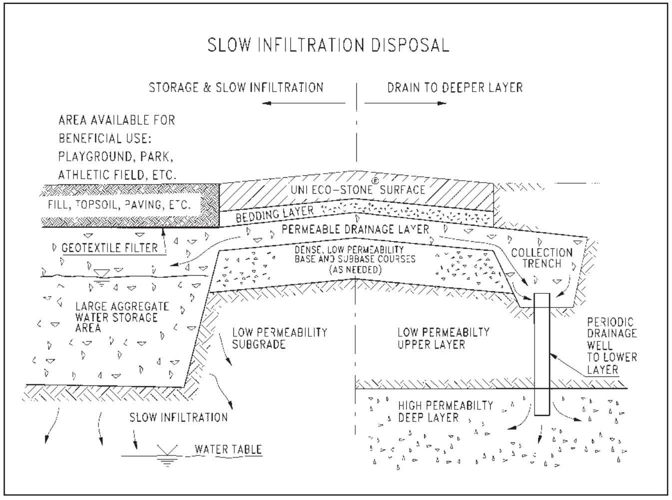

Figure 10 - Protected Subgrade System (1).

Figure 10 provides two other alternatives to placement of a pavement over a low-permeability subgrade. A dense, low-permeability base is constructed in order to protect the low-permeability or weak subgrade. A permeable base layer transmits infiltrated water to a larger aggregate water storage area. This aggregate storage area can be placed directly under the pavement, or be constructed adjacent to the pavement. Alternatively, if a deeper permeable layer exists beneath a low-permeability layer, water can be conducted to it through drainage wells.

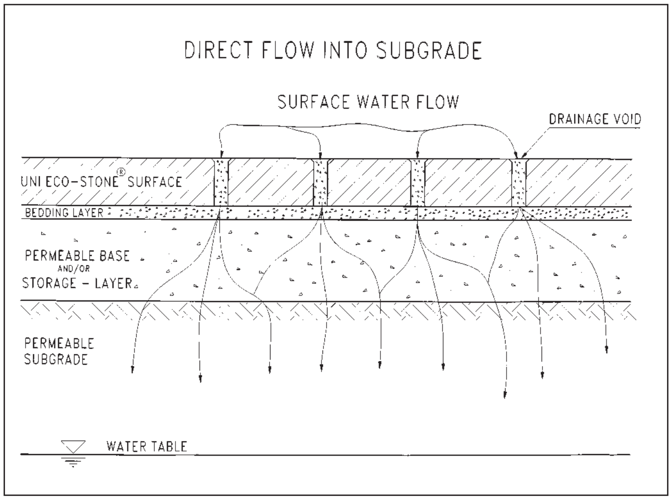

Figure 11 - Permeable Subgrade System (1).

Figure 11 indicates the construction of a pavement over a permeable subgrade. In this case, a permeable base is constructed over the naturally permeable subgrade and the water simply infiltrates into the subgrade.

DESIGN CRITERIA

The pavement subsurface drainage system is primarily used to remove free water that enters into the pavement. The base layer is usually considered to be the best location for the drainage layer. Whether infiltrated water will accumulate in a pavement depends on the outflow capacity of the drainage layer. When outflow capacity of the drainage layer is less than the infiltration rate, the infiltrated water will accumulate in the pavement. In some cases, the outflow rate may be designed to be less than the infiltration rate in order to control stormwater runoff. Sometimes, outflow capacity of the drainage layer may be designed to be equal to the inflow rate in order to remove water as quickly as possible to minimize the impact of water on pavement performance. Design criteria for the UNI Eco-Stone® pavement subsurface drainage layer are:

1) Outflow less than inflow criterion where outflow must be delayed. It has been suggested that a retention time of 6 -12 hours for 50 percent of drainage from the base layer is suitable for many applications.
2) An inflow = outflow criterion where the base or subbase should be capable of draining the water at a rate equal to the inflow rate without becoming completely saturated or flooded (21).

The selection of criteria will depend upon stormwater runoff regulations, traffic conditions, and the conditions under which the pavement must perform.

When heavy traffic is applied to an Eco-Stone® pavement system, water that enters into the pavement may need to be removed as fast as possible from the subsurface drainage system to prevent loss of subgrade stiffness and excessive rutting. The inflow = outflow criterion may be selected to design the subsurface drainage system in this instance. If it is necessary to store water in the pavement to reduce peak runoff discharge and meet stormwater regulations, Criterion 1 may be selected to design the subsurface drainage system, however, restrictions may need to be applied to the categories of traffic allowed to use the roadway.

Under Criterion 1, the inflow rate and the outflow rate influence the quantity of free water retained in the pavement structure. The time required to drain water from the base is controlled by the outflow rate. Rate of outflow depends on the subsurface drainage design. If free water is removed vertically through the subgrade, as shown in Figure 10, the permeability of the subgrade controls the outflow rate. If a lateral drain is incorporated to remove free water, as shown in Figures 7 and 8, the outflow rate is controlled by the geometry and permeability of the base layer.

The thickness, percent voids or porosity, and permeability of the drainage layer play an important role in controlling the amount of storage and the time of retention of the runoff water within the base layer. If this information, along with the pavement section drainage geometry and amount of infiltration is known, the required thickness and permeability of the base layer can be determined. Details of how to determine permeability and thickness of the drainage layer are discussed in the following sections.

Inflow Considerations

In a subsurface drainage system design, it is important to estimate the rate of water infiltration into the pavement system. The sources of pavement infiltration water are:

a) Rainfall,
b) Groundwater,
c) Melting ice, and
d) Snow.

The quantity of water that potentially can flow into a UNI Eco-Stone® pavement system is controlled by the infiltration of water. Other sources, such as groundwater and melting ice, would provide minor quantities of water and are not considerations in the design of the Eco-Stone® drainage. However, infiltration of rainfall runoff is an important consideration that depends on many factors (1, 12):

a) Slope of the pavement surface.
b) The rate at which water is applied to the pavement surface.
c) Permeability and overall drainage capability of the underlying layers.
d) Materials used to fill the drainage voids in the pavement surface, and the ambient moisture conditions.

The infiltration rate of rainfall into a pavement system will vary based on the age and condition of the pavement surface, the gradation of the bedding layer and fill material in the drainage voids, and the intensity of rainfall, as previously stated. In order to design the subsurface drainage and storage system, the surface water infiltration rate may be estimated based on the infiltration coefficient and the design precipitation rate (design storm). Cedergren (6, 12) recommends the one-hour/one-year frequency storm for designing the subsurface drainage. This is the maximum rainfall in one hour that can be expected to occur on the average of one time each year. The U.S. Army Corps of Engineers (17) recommends the one-hour/ two-year frequency storm for design purposes. The one-hour/one-year and one-hour/two-year frequency storm maps are shown in Appendix C. If the drainage design requirements call for more severe conditions in order to meet local stormwater control regulations, one-hour/10-year and one-hour/100-year frequency storm maps are also shown in Appendix C.

The infiltration rate of rainfall into the pavement is controlled by the infiltration capacity of the pavement system and may be equal to the intensity of the design storm. (For instance, if the design storm is 1.8 in/hour, and the infiltration capacity of the pavement is 2.4 in/hour, the infiltration rate of rainfall into pavement would be 1.8 in/hour.) It is also customary to express the infiltration rate of the rainfall into the pavement relative to the infiltration coefficient ($F = \frac{\text{infiltration rate}}{\text{design storm (R)}} \leq 1$).

If the design storm (R) is less than the infiltration capacity of the pavement, the infiltration coefficient is equal to 1, and the infiltration rate is equal to the design storm. Equation *4* is recommended to determine the infiltration capacity. Muth (1, 11) has shown that a one-hour/one-year frequency storm can fully infiltrate into a UNI Eco-Stone® pavement (assuming the drainage void fill material gradation consists of a porosity greater than 0.40). So for a one-hour/one-year frequency design storm, the infiltration rate for an Eco-Stone® pavement can be justified as being equal to a one-hour/one-year frequency design storm. If the design storm is larger than the infiltration capacity of the pavement, the infiltration rate may be determined by multiplying an infiltration coefficient by the design storm. The infiltration coefficient will typically range between 0.3 and 0.6 and will vary according to the fill material, slope of the pavement, and the design storm.

Once the infiltration rate has been estimated, the inflow or quantity of water entering the pavement is determined by applying Darcy's law as follows:

$$Q = k*i*A \qquad (5)$$

where

Q_{ent} = Quantity of water entering pavement surface (ft^3/day)
k = Permeability or infiltration rate (ft/day)
i = Hydraulic gradient; a hydraulic gradient of unity for rain falling on a surface is suggested (20)
A = Drainage Area (ft^2)

Modifying equation *5* relative to an infiltration coefficient (F), k is replaced by L × R and i replaced by F, then the rate of water inflow per foot of width of drainage is computed by following equation (18):

$$q_{ent} = 2*L*R*F \qquad (6)$$

where

q_{ent} = Infiltration flow rate (ft^3/day per foot of width)
F = Infiltration coefficient = $\frac{\text{infiltration rate (in./hr)}}{\text{R}}$
R = Design storm (in./hour)
L = Length of the drainage path (feet)

The length of the drainage path can be computed by following equation:

$$L = \frac{X \sqrt{S_t^2 + S_e^2}}{S_t} \qquad (7)$$

where

X = The length (feet) of the transverse slope of the drainage layer
S_e = The longitudinal slope of the drainage layer
S_t = The transverse slope of the drainage layer

The slope of the drainage path may be computed by the equation:

$$S = \sqrt{S_t^2 + S_e^2} \qquad (8)$$

Outflow Considerations

Water can be removed from a pavement section in the following ways (6):

1) Surface evaporation.
2) Removal by subgrade percolation.
3) Removal by a subsurface drainage system.

Since surface evaporation is insignificant in most cases (6), further discussion will focus only on the removal of water by subgrade percolation or by a subsurface drainage system.

Removal by Subgrade Percolation

With soils high in clay content, removal by subgrade percolation will, for the most part, be negligible. However, if the subgrade of a pavement consists of highly permeable sands or gravel where permeability is greater than 500 ft/day (17), it may be assumed that water will drain directly through the subgrade to recharge the water table, as shown in Figure 11. The relationship between the coefficient of permeability and various soil types and density is shown in Figure 12. Infiltration into the subgrade can be estimated using equation *5*.

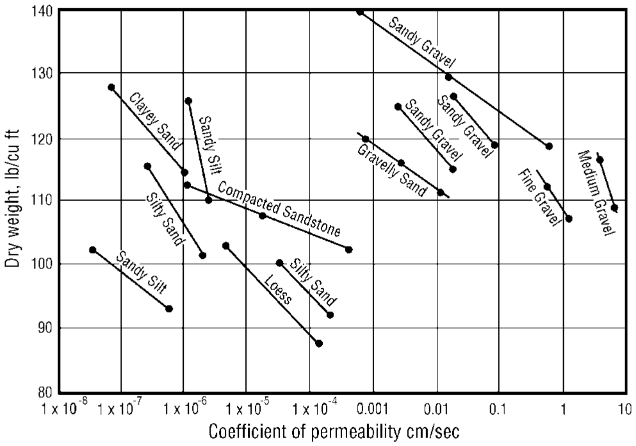

Figure 12 - Relation between Coefficient of Permeability and Soil Type and Density (log Scale) (22) (1cm/sec = 2835 ft/day).

Removal by Subsurface Drainage

As previously noted, the drainage of low-permeability silt or clay subgrades will be very slow. Free water may accumulate in the pavement over a long period of time, which may be detrimental to the performance of the pavement. Therefore, a lateral drain may need to be considered to remove the water in a shorter time period. The slope of the drainage layer is generally designed to be 1-3 percent to facilitate water draining to a collector pipe. The geometry and porosity of the base controls the storage capacity of drainage layer. Based on the degree of drainage (i.e. the percentage of water removed from a saturated layer), the thickness or permeability of the base can be determined to meet specific storage requirements. The relationship between the amount of time for 50 percent of the water to drain and the thickness and permeability of the base is given by following equation (21):

$$K = \frac{n_e L^2}{2t_{50}\,(H + SL)} \qquad (9)$$

where

t_{50} = The time for 50% drainage (days)
n_e = The effective porosity
H = Thickness of the drainage layer (ft)
S = Slope of the drainage layer
L = Length of the drainage path (ft)
K = Permeability (ft/day)

Permeability for any degree of drainage can be determined graphically, as shown in Figure 13. In this figure, the degree of drainage (U) depends on two factors - the time factor (T_f) and the slope factor (S_f,) which are defined as:

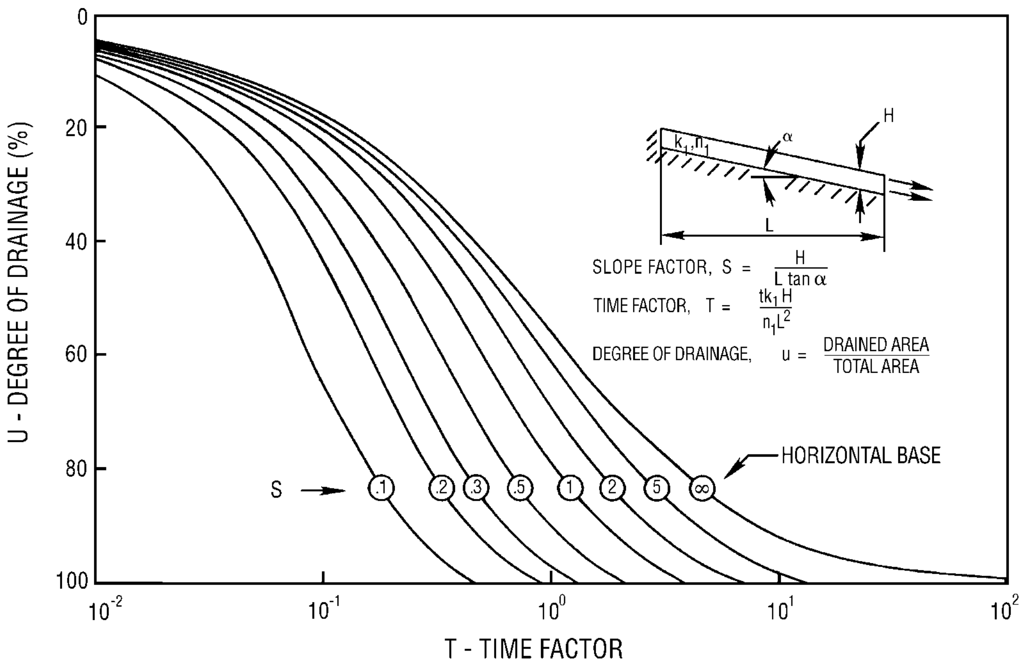

Figure 13 - Time-Dependent Drainage of a Saturated Base Layer (5).

$$T_f = \frac{KHt}{n_e L^2} \tag{10}$$

$$S_f = \frac{LS}{H} \tag{11}$$

where

t = The time since the rain stopped and drainage began, and
K, H, L, S, and n_e are as previously defined

After the permeability of the base layer has been calculated, the amount of storage in the pavement that occurs over a certain period of time can be estimated as follows:

Amount of storage = quantity of water entered into the pavement - quantity of water drained out of the pavement
= (2 L F R) – (K i H) (*12*)

The maximum volume of water per unit of surface area that can be stored in the underlying layers can be calculated as:

$$V = \sum_i \left[1 - \frac{\gamma_d}{G_s \times \gamma_w} \right] \times h_i \tag{13}$$

where

V = Volume of water in one cubic foot of soil or aggregate
$1-\frac{\gamma_d}{G_s \times \gamma_w}$ = Dry-density of in-place soil or aggregate
G_s = Specific gravity of soil or aggregate
γ_w = Unit weight of water
i = Number of layer
h_i = Thickness of each layer

As mentioned earlier, surface infiltration (largely from rainfall) is often the major source of all possible inflow (6), and it can be calculated using equation *6*. If the inflow rate is equal to the outflow rate (i.e. storage = 0), the permeability of the drainage layer is obtained by:

$$K = \frac{2 \times L \times R \times F}{H \times i} \tag{14}$$

where L, F, R, H, i, and K are as previously defined.

It is noted that for a given drainage layer slope, an outflow rate can be obtained for various combinations of the base thickness and permeability. Therefore, designers may either 1) try several thicknesses and calculate the required permeability of the material for each, or 2) select one or more permeabilities of the drainable layer which are representative of local materials with acceptable grading and calculate the required thickness from equation *14*. Whatever combination, a variety of choices are available in terms of available materials, economy, and construction feasibility. Table D2 gives the general relationship between gradation and permeability, which can be useful in the selection of a base material. Also, if the quantity of water to be removed by the drainage layer is known, then the quantity of KH in Darcy's equation ($KH = Q/i$) allows for the permeability of the drainage layer to be obtained from Figure 13.

The Selection of Base Material

The design of the base layer is essential to the designer because the base course is not only the major structural load carrying element, but also the medium of water transmission. It plays an important role in facilitating drainage capacity and in carrying traffic load. Several factors should be considered in base material selection:

1) Performance of the pavement,
2) Stability, and
3) Storage capacity.

In order to enhance the stability of the base in the presence of water, the base material should consist of non-plastic material and contain less than 3-5 percent passing the #200 sieve (1). Reducing the percentage of fine materials increases permeability but may decrease the stability of the base. An investigation of the influence of base permeability on pavement performance (23) found higher pavement deflections in pavements consisting of high permeability subbase sections than those consisting of lower permeability base sections. However, there was lower distress development using permeable bases (24, 25). Because optimum permeability and good stability cannot always be compatible, high-permeability material would appear to be the best from a drainage aspect. But stability may be of concern in such a material. Conversely, a very dense and stable material would most likely produce poor drainage conditions. It is necessary to strike a balance between drainability and stability in the design of the subbase/base systems. One way to achieve this would be by stabilization of the drainage layer with a small amount of asphalt (2-2.5 percent by weight) or Portland cement (200 to 300 lb per cu yd) (26). Studies have shown that a certain percentage of asphalt or cement added to a base material improves the stability of the drainage layer without significantly affecting the layer's permeability (27). Examples of base material gradations are provided in Table D.2.

Filter Criteria

When water flows from one soil or aggregate material into another of different gradation, fine particles from the first material may wash into the second, especially when a lower permeability bedding layer material is placed directly on a higher permeability base layer. Fine particles may tend to migrate into the high-permeability material, resulting in the clogging of pore spaces and an overall reduction of permeability of the base layer. In order to eliminate the fine soil movement, certain filter criteria must be satisfied between two different gradation layers, otherwise a protective filter layer should be used. Filter material should meet the following criteria to prevent the adjacent finer material from piping or migrating into the filter material, yet still be coarse enough to carry water without any significant resistance. Criteria recommended by Moulton (12) are:

Clogging Criteria:

$$\frac{D_{15}\,\text{filter}}{D_{85}\,\text{soil}} \leq 5 \tag{15}$$

Permeability Criteria:

$$\frac{D_{15}\,\text{filter}}{D_{15}\,\text{soil}} \geq 5 \tag{16}$$

Additional Criteria:

$$\frac{D_{50}\,\text{filter}}{D_{50}\,\text{soil}} \leq 25 \tag{17}$$

$$C_u = \frac{D_{60}\,\text{filter}}{D_{10}\,\text{filter}} \leq 20 \tag{18}$$

where

D_{15} = Grain diameter at 15% passing
D_{85} = Grain diameter at 85% passing
D_{50} = Grain diameter at 50% passing
D_{10} = Grain diameter at 10% passing
D_{60} = Grain diameter at 60% passing
C_u is the coefficient of uniformity

Geotextiles have been widely used in drainage systems for several years. Investigations have shown that geotextiles used as a part of the filter of a drainage system were easily installed and cost effective (28, 29). Geotextiles are categorized as woven and nonwoven according to the method of manufacture. A geotextile has not only vertical plane drain capacity, which lets the water pass perpendicular to the geotextile plane, but also in-plane drain capacity,

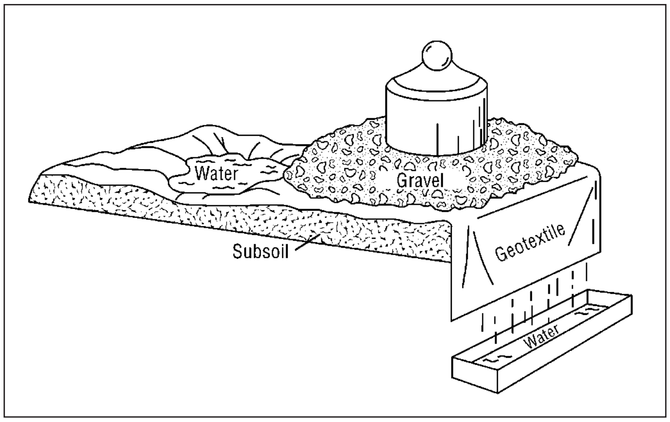

Figure 14 - Sketch of Drainage of Water through Geotextile (28).

which lets water flow from the geotextile plane. The fabric's vertical plane drain can allow water to pass while minimizing fine particle migration. However, in-plane drain capacity can help drain water out of the pavement if proper design is provided. (A nonwoven geotextile has higher in-plane drainage capacity than woven.) Figure 14 shows how the geotextile in-plane drain capacity functions.

When geotextile replaces granular soil filters, the opening of the geotextile is an important characteristic for design. Apparent opening size (AOS) or equivalent opening size (EOS) was developed by the U.S. Army Corps of Engineers to evaluate the geotextile opening (28). AOS or EOS is defined as the number of standard beads at 5 percent passing though the geotextile. The design of a geotextile filter has three parameters to be considered:

a. Adequate permeability,
b. Proper soil retention, and
c. Long-term performance.

There are various design criteria to meet these three requirements. However, the Christopher and Holtz criteria (30) is currently used by the Federal Highway Administration. Criteria for geotextile filter for soil retention:

1) For fine-grained soils with more than 50 percent passing though a #200 sieve:

Woven: AOS $\leq D_{85}$
Nonwoven: AOS $\leq 1.8D_{85}$
AOS $\leq$ 0.3 mm or $\geq$ No. 50 sieve

2) For granular material with 50 percent or less passing though a #200 sieve:

AOS $\leq B \times D_{85}$

where

$B = 1$ for $2 \geq C_u \geq 8$
$B = 0.5$ for $2 < C_u < 4$
$B = 8/C_u$ for $4 < C_u < 8$
C_u is the coefficient of uniformity = D_{60} / D_{10}

Permeability Criteria:

k (fabric) $\geq$ k (soil)

Clogging Criteria:

Woven: percent of open area $\geq$ 4%
Nonwoven: porosity $\geq$ 30%

The use of a geotextile between the base and the subgrade was investigated by Anderson and Killeavy (31). Results showed that the use of a geotextile between the base and the subgrade improves the modulus of base and subgrade, decreases the deflection of the pavement, and improves pavement performance. Actually, placing a geotextile between the base and the subgrade provides not only filtration, but also serves as a reinforcement and separation function as shown in Figure 15. As a separator, a geotextile prevents mixing of the base and the weak underlying soil, thereby allowing the original thickness of the granular base to be maintained. A geotextile used as a reinforcement increases the whole system modulus. The loss of stiffness due to the presence of water in a pavement system may be compensated to some extent by the use of a geotextile.

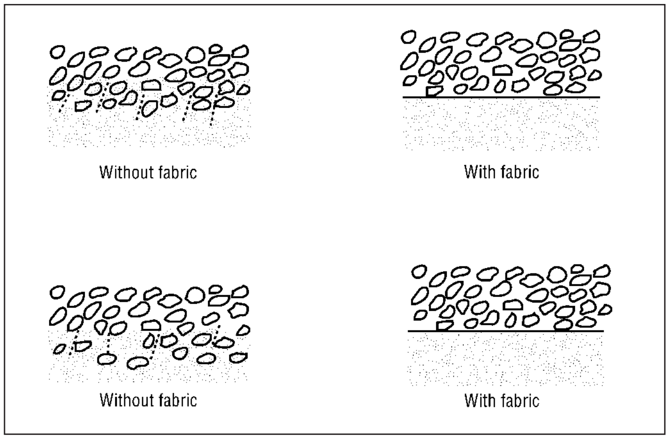

Figure 15 - Separation Mechanisms of Geotextile (28).

Collection System

A collection system is used to collect water from the drainage layer and then convey it to suitable outlets outside of the pavement. The design of a collection system includes (12):

a) Collection system drainage capacity.
b) The location and depth of the collectors and their outlets.
c) Type of collection system to be utilized.
d) Filter protection to provide sufficient drainage capacity and to prevent flushing of the drainage aggregate into the collection system.

Various types of edge drains are available. There are traditional perforated or slotted pipe underdrains, prefabricated geocomposite fin drains, geotextile wrapped underdrains, and geotextile socked perforated pipes, as shown in Figure 16. In contrast to the edge drain made of perforated pipe and natural soil, the prefabricated edge drain has a lower cost, requires less excavated soil to be removed, and is easy to install (32). A prefabricated geocomposite fin drain is made of two components - the drainage core and the geotextile filters that are wrapped around the drainage core. Investigation of the prefabricated edge drain showed that the placement of the prefabricated edge drain is important. When placed on the opposite side of the drainage layer, it alleviated the problem of soil loss through the geotextile filters better than when placed on the side next to the drainage layer (27).

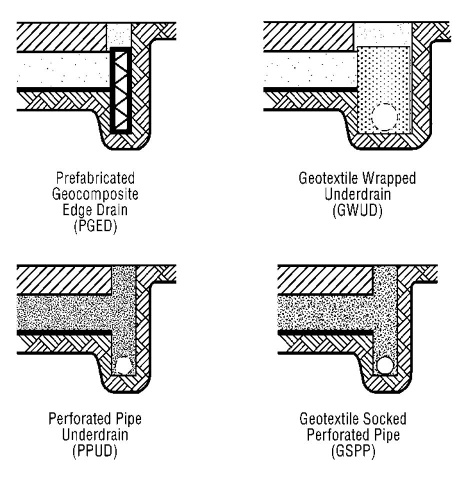

Figure 16 - Various Types of Subdrainage Systems Using Geotextiles (29).

The selection of the type of collection system depends on specific soil conditions at the site, the function of the collection system (i.e. to be temporary storage or to be a medium for water to pass through), construction feasibility, and economy considerations. Further details regarding subdrainage designs similar to those shown in Figure 16 can be obtained from local geotextile suppliers.

Maintenance

The prime function of the surface drainage voids inherent in the Eco-Stone® pavement system (filled with appropriate aggregate material) is to allow rainwater to penetrate into the pavement. However, various contaminants like oil, dust, and other fine road debris will be carried into the voids. Therefore, the infiltration capacity of UNI Eco-Stone® pavement decreases with time. In order to maintain the permeability of the surface drainage, routine inspection of the permeability of the pavement is necessary. If the permeability of the pavement has been significantly reduced, conventional street sweepers equipped with vacuums, water, and brushes could be used for restoring the permeability of the pavement (1).

CHAPTER 5
PERFORMANCE OF PERMEABLE BLOCK PAVEMENT SYSTEMS

Although the concept of storing water in a pavement system for short periods of time may appear contrary to conventional pavement design wisdom, European experience has clearly demonstrated, with increasing frequency, that permeable concrete block paving systems can reliably perform within limits relative to applied traffic levels (35, 37). Certain factors key to the performance of permeable pavement systems are discussed below and should be a focus in the design process and evident in related construction specifications.

Prior to elucidating these factors, it is important to understand the performance behavior of concrete block pavements. Under load, a concrete paver will tend to rock, rotate, and slide horizontally unless it is held in place by the interlock of adjacent pavers, edge restraints, and the bedding layer. As a result, the stresses in the bedding layer can become very high unless the pavers work together as a "stiffened" layer to distribute the load stresses beyond those pavers that are immediately below or within the boundaries of the tire print. In this sense, the jointing sand plays an important role in providing aggregate interlock and the transfer of load between adjacent blocks. Under this type of loading action, the support base materials (and particularly the bedding materials) will have a tendency to displace laterally away from the vicinity of the loading pattern due to the lack of shear resistance within the bedding layer and joints of the pavers. This displacement is referred to as "rutting" and, if the loads are frequent and severe enough will accumulate to several hundred micro-inches. Experience and research have clearly shown that the most critical layer in the permeable pavement structure is the bedding layer and that improper placement carries a high probability of premature failure.

Along with the development of rutting, is a distortion of the longitudinal profile of the pavement surface. This distortion is largely due to variability in the development of rutting from point to point along the longitudinal alignment of the pavement surface. The variation in rutting can be due to differences in layer thickness, level of compaction, particle shape characteristics, gradation, or undulations in the initial constructed surface (37). Any initial variation tends to exacerbate the negative impact of dynamic wheel effects on the development of longitudinal distortion. For this purpose the longitudinal profile needs to be as smooth as possible. In light of this, recent research (35, 36, 37) identifies the key performance factors as being related to:

1) Width of joints (0.08 - 0.12 in.) between blocks and the proper placement of the jointing sand.
2) Use of edge restraints to facilitate development of shear between concrete blocks.
3) Minimal roughness in the initial construction of the longitudinal profile.
4) Uniformity of the bedding layer (maintaining a thickness of 1-1.5 in.) and proper compaction of pavers. Improperly designed and placed bedding layers may result in premature rutting.
5) Quality of materials (gradation, shape, etc.) should be as uniform as possible.
6) Relative to (4) above, proper balance between void ratio and gradation limits and material stability and strength to simultaneously meet both the drainage and structural requirements of the design.

The subgrade strength and stiffness affect soil deformation properties, which significantly influences pavement performance. Studies of fine-grained soils have demonstrated that the major factors affecting its strength and stiffness are water content and soil type (14, 15). Research has also shown that permanent deformation increases with an increase in water content (under the same load strain), and that the moduli of soils consisting of high-clay contents and high-plasticity indexes are less sensitive to changes in moisture content than soils containing higher silt contents and demonstrating lower plasticity indexes. However, the moisture content of soil is influenced by soil drainage capacity. Therefore, it is important to have adequate soil characteristic and permeability data for consideration of limited subgrade stiffness and drainage design. To ensure sufficient subgrade support, a minimum CBR (California Bearing Ratio) of 8 to 10 is recommended (14). CBR is the ratio of load required to force a piston (consisting of a 3-in.^{2} area) into a soil to the load required to obtain similar penetration into a standard high-quality crushed stone. When soil has a CBR of less than 6, stabilization is typically used to improve subgrade strength.

PERMANENT DEFORMATION CHARACTERIZATION

The method used to characterize rutting in permeable pavements is very innovative, yet easy to apply and implementable within a design process. Rutting predictions are made by the use of a model that consists of three characteristic material parameters (ε_0, β, and ρ) that were calibrated for specific pavement types and conditions such as those associated with a concrete block pavement system. These parameters were developed by fitting test data consisting of permanent strains versus the number of load cycles that was obtained from a paver block test track located at the TTI annex on the Riverside Campus of Texas A&M University (34) in support of the development of this procedure. A typical behavioral pattern of rut development with load cycles is shown in Figure 17. The curve illustrated in this figure is represented by:

$$\varepsilon_a = \varepsilon_0 e^{-(\rho/N)^{\beta}}$$

where

ε_a = permanent strain
N = number of load cycles, and
ε_0, β, and ρ = material parameters

The values of β and ρ are different for each soil type and moisture content. The ε_0 term is also used to adjust the model to represent the behavior of permeable, concrete block pavements. As noted above, the parameter can be determined from loading data by rearranging the derivation of the above expression as (38):

$$\text{Log}\,[\Delta(\ln \varepsilon_a)/\Delta(\ln N)] = \log(\beta\rho^{\beta}) - \beta \log N$$

in which β is the slope of line relating rutting accumulation and number of load cycles. Once β is determined, ρ can be found from the first term on the right hand side of the above equation and ε_0 serves as a scaling factor which shifts the curve up and down the vertical scale. Figure 18 illustrates some of the loading and permanent deformation data collected from the permeable pavement test track at the TTI research annex site that was used to calibrate the FLEXPASS model and the design charts provided in Appendix B.

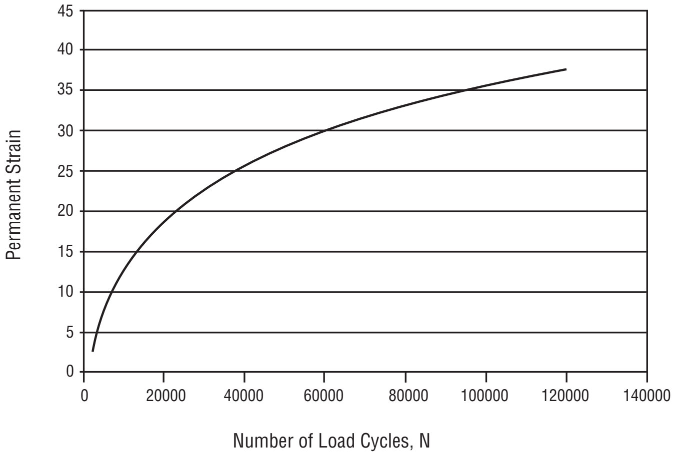

Figure 17 - Relationship Between Permanent Strain and Loading Cycles.

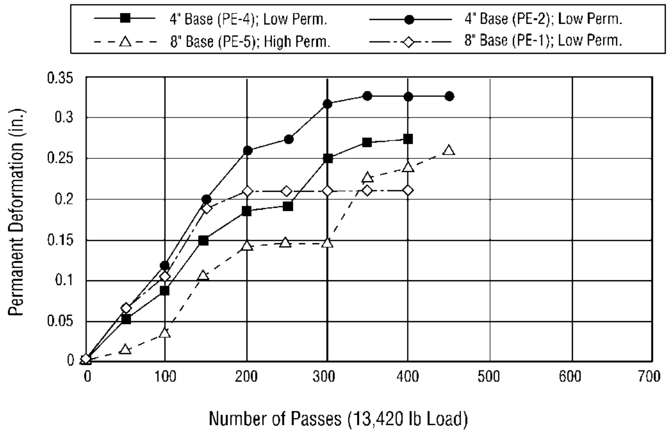

Figure 18 - Permanent Deformation of the Surface Layer - TTI Annex Test Track.

PERMANENT DEFORMATION PREDICTION

The development of permanent deformation in a permeable concrete block pavement system may occur in the wheel paths due to the accumulation of permanent strains caused by repetitive traffic loads. The model of permanent deformation was originally developed from using the finite element method of analysis to evaluate the resilient strain in the vertical direction in each layer of a pavement system and the accumulated strains relative to the parameters ε_0, β, and ρ. The finite-element analysis allowed for both linear and non-linear stress-strain behaviors to be taken into account within the FLEXPASS program (38) which was used to generate the performance curves included in Appendix B. Rutting is predicted in this program by:

$$\delta_a(N) = \sum_{t=1}^{n}\left\{ \frac{\varepsilon_{0i}}{\varepsilon_{ri}}\; e^{-\left[\frac{\rho_i}{N}\right]^{\beta_i}} \int_{d_{i-1}}^{d_i} \varepsilon_i(z)dz \right\}$$

where

n = number of pavement layers

ε_{ri} = resilient strain of the material in the ith layer
N = expected number of load cycles
d_i = depth of ith layer, and
ε_i = vertical resilient strain in the layer i from the finite-element solution

The term $\frac{\varepsilon_{0i}}{\varepsilon_{ri}} e^{-\left(\frac{\rho_i}{N}\right)^{\beta_i}}$ is defined as the fractional increase in the permanent strains in each layer. The integral in the above expression (right side) is solved numerically using the trapezoidal rule of integration relative to the vertical strain in each element below the center of the tire load (38).

Summary

The procedures outlined in this guide represent a significant advancement in the methodology used for the design of permeable paver block pavement systems. Methodologies adopted for pavement design must be based upon the mechanisms that affect performance. Although many design procedures in the past may have been proposed to design these types of pavements, few have manifested the necessary relevance to the behavior and performance characteristics of interlocking paving block pavement systems. A behavior characteristic that significantly affects performance in concrete paving block systems is rutting in the supporting layers below the concrete pavers, and the development of rutting is the focus of the procedure detailed within this design guide. Following the process described herein, the engineer is presented with a variety of choices, relative to layer thickness and drainage characteristics, that will ensure an appropriate pavement structure is selected to achieve the desired service level over the performance period.

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APPENDIX A

DESIGN PROCEDURE FOR DRAINAGE AND BASE THICKNESS FOR ECO-STONE PAVER BLOCK PAVEMENT SYSTEMS

Description of the Design Process

The design procedure provided in this appendix addresses both drainage and performance issues in a simple step by step process to determine suitable base thickness and permeability to meet design criteria, as established by the engineer, for the given subgrade soil conditions for lightly trafficked roadways, driveways, and access roads. The design procedure allows for the selection of base thickness and permeability to limit rutting to selected levels (low, medium, and high) for pavement base layers used to store storm runoff for a 24-hour period or less. The rutting prediction charts included in the procedure were derived from the computer program FLEXPASS (33), which is a finite element model for the analysis and performance of flexible pavements. The rutting model in this program is mechanistic in nature and was calibrated and adopted for paver-block systems based on measured rutting performance and material properties obtained at the test track sponsored by Uni-Group U.S.A. at the Riverside Campus of Texas A&M University (34).

The program was calibrated by adjusting the number of load applications in the model until the rutting predicted by FLEXPASS matched the rutting that was recorded during the load testing at the test track for the given pavement configuration. It found that in general, the ratio of load test applications to FLEXPASS load applications was approximately 0.3. A pass-to-coverage ratio of 3.5 was assumed in transforming the test track applications to actual traffic conditions due to wheel wander in the wheel path for pavement configurations other than those at the test track.

The outline of the design procedure is illustrated in Figure A.1. Essentially, the design engineer determines the drainage requirements of the pavement first and then evaluates if the pavement structure satisfies the rutting requirements established by the engineer. The engineer has several design options if the structure fails to meet the rutting criteria. One option includes lowering the permeability of the base material by increasing the number of

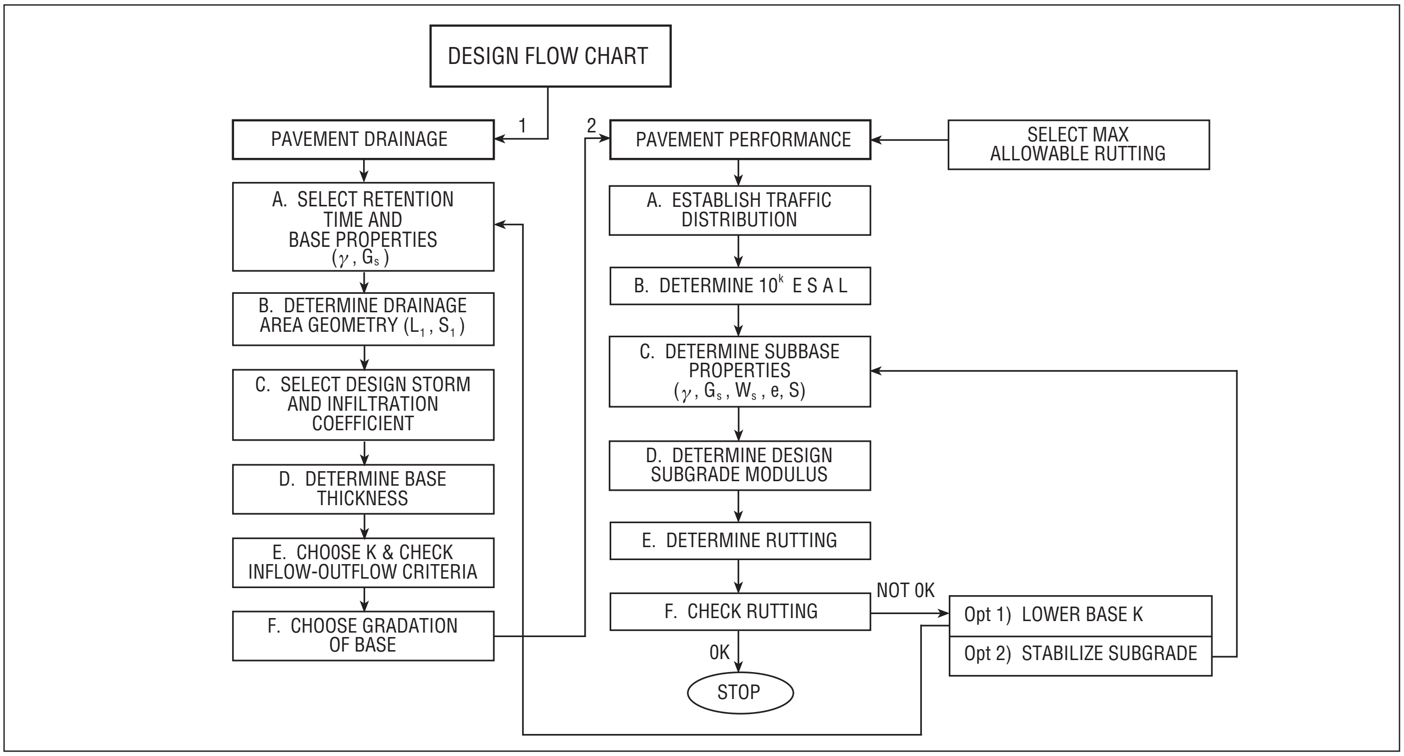


Figure A.1 - Pavement Drainage and Design Flowchart.

fines in the gradation to provide a greater degree of protection to the subgrade soil. This can also be achieved with a two-layer base structure that has a less permeable layer at the bottom and a higher permeability layer at the top. Another option is to strengthen the subgrade layer by stabilization. The engineer can reasonably assume the subgrade stiffness can be increased by a factor of 1.5 for design purposes when it is stabilized. In highly trafficked areas, such as entryways to parking lots or in areas where rutting needs to be kept to a minimum, stabilized, open-graded, drainable bases may be considered. Local lime and Portland cement associations can be contacted for information on stabilization procedures.

The design process entails the use of the charts and worksheets provided in Appendix B. The worksheets are to assist the engineer in organizing the data from the charts. Chart 1 is used to determine base thickness given the storage requirements - which is a function of the design storm. Charts 2-5 are used to obtain base permeability to drain the base layer to 50 percent saturation over either 6, 12, 18, or 24 hours. Charts 6-10 predict rutting as a function of vehicle (i.e. axle) weight, quantity, and subgrade stiffness. The design charts represent a 50 percent reliability design and a pass-to-coverage ratio of approximately 3.5. Other pass-to-coverage ratios may be considered for other types of facilities (different than those noted above), such as cargo storage areas, by applying a multiplying factor to the design chart traffic level. (For a cargo storage area, a pass-to-coverage ratio of 7 may be more appropriate, which translates to a factor of 0.5 times the number of axles/year listed in the axles/year column).

It should also be pointed out that this design procedure is predicated upon quality construction and compaction being achieved in the subgrade and base materials used in the UNI Eco-Stone® pavement system and that rutting in the bedding and jointing sand materials does not exceed 0.10 inches.

Description of the Design Steps

As previously noted, the design flow chart shown in Figure A.1 outlines the variety of steps that are needed in the design process. The example worksheets provided on pages A.6 and A.7 illustrate the design steps and the exaction of information from the design charts to work through the design process. Prior to discussion of an example using the worksheets and design charts, the design steps are described as follows:

Pavement Drainage

Step A. Select the retention time to achieve 50 percent drainage of the base and determine the properties of the base.

It is common to require pavement layers to drain from 100 percent saturation to 50 percent saturation within 24 hours. Therefore, the design charts have been based on a retention time of 6, 12, 18, or 24 hours to achieve 50 percent drainage. List the dry unit weight and the specific gravity of the base materials and calculate its porosity using the formula provided in the worksheet.

Step B. Input the drainage area geometry parameters: drainage path length (L_i) and slope (S_i) and calculate the effective drainage length (L_e) and slope (S_e).

Longitudinal and transverse lengths (L_1 and L_2, respectively) of the drainage area and the associate slopes are used to calculate the length and slope according to the formulas provided in the worksheet. The effective drainage path length should be adjusted, if needed, to fit within the limits of the drainage area. It may be necessary to sub-divide a paving area into multiple drainage areas.

Step C. Select the design storm and the infiltration coefficient, and determine the amount of storage needed in the base layer.

It will be necessary to base the amount of storage needed on the design storm that is used to determine the amount of water that will fall on the paved area. The user determines the infiltration coefficient of the pavement in the process of determining the maximum amount of water that could infiltrate into the pavement. Discussion of the infiltration coefficient is provided in Chapter 4 and can vary from 40-100 percent. Equation *4* is recommended for determination of the infiltration capacity.

Step D. Determine base thickness.

This step will require the use of Chart 1: Storage vs. Base Thickness. The available storage is the maximum amount of storage corresponding to the thickness of the base. The porosity of granular material generally falls within the range of 0.2-0.4, and the available storage will vary with respect to the porosity of the base material.

Step E. Determine the permeability of the base material and check inflow/outflow criteria.

This step will require the use of one of Charts 2-5, depending on the desired retention time. These charts are based upon Figure 13 (for a $T_f = 1$) and equations *10* and *11*, which can be used in cases where L^2/H ratios exceed the chart limits. The drainage path length (L) is the distance that the water has to travel out of the base, and H is the base thickness. The charts are based on work originally done by Casagrande and revised by Liu and Lytton (5), as discussed in Chapter 4, and correspond to a time factor of 1 at 50 percent drainage for a base layer porosity between 0.2 and 0.4.

The engineer calculates the ratio L^2/H and then uses the chart to determine the range of permeability that is capable of achieving 50 percent drainage. Assuming the base thickness when n = 0.2 and n = 0.4 from Chart 1 will result in the widest range of permeability and will also provide the engineer with multiple combinations of thickness and permeability. The final decision of base thickness and permeability may be dependent upon the cost and availability of materials. The permeability determined from the chart is compared to the k calculated in the worksheet (equation *13* - Chapter 4) to insure that storage will occur in the base layer.

Step F. Gradation of the base.

The gradation of the base layer can be selected or determined to meet the desired permeability from information provided in Table D2 of Appendix D or other references.

Pavement Performance

Step A. Establish Traffic Distribution.

The designer should provide accurate information regarding the traffic expected to use the pavement facility. This information needs to be in the form of single axle load groups and number of loads in each group. Pavements subjected to axle loads greater than 18 kips should be designed with a stabilized base layer. The designer should also determine the maximum allowable rutting and enter it in the worksheet. Low rutting is considered to be 0.25 inches or less, medium up to 0.5 inches and severe 0.75 inches.

Step B. Determine 10 kip ESAL.

If the traffic distribution contains more than one load group, then the axle groups should be converted, as a matter of convenience, to an equivalent load group such as the 10 kip axle load group. Equivalency factors (which is the ratio between the load group in question and the 10 kip axle load group) are determined for each load group by selecting the life (number of load repetitions for that group) at the same subgrade modulus and level of rutting (i.e. maximum allowable) from Charts 6-10. The factors are calculated by dividing the life for each load group by the 10 kip load group life. The equivalency factor for the 10 kip load group is 1.0. Other load groups can be chosen as the base equivalent load group if desired. The 10 kip ESAL is determined by multiplying the number of axles in each load group by the 10 kip ESAL factor and summing across each load group. Rutting is then simply determined for a 10 kip axle load.

Step C. Determine subgrade properties.

Provide the type, unit weight, specific gravity, and water content of the subgrade and calculate the void ratio (e) and the degree of saturation (S). The void ratio of the subgrade can be calculated using the following formula.

$$e = G_s \gamma_w (1+w)/\gamma - 1$$

where

G_s = specific gravity, 2.6-2.8
γ_w = unit weight of water, 62.4 lb/ft^3
w = water content of the subgrade
γ = unit weight of subgrade, lb/ft^3

The degree of saturation is calculated using the following equation.

$$S = w\,G_s/e$$

Step D. Determine design subgrade modulus, E.

Depending upon the classification of the subgrade, the following equations should be used to calculate E_o.

CL, ML-CL: $E_o = 32.0 - 0.312\,S$ (ksi)
CH: $E_o = 22.5 - 0.155\,S$
ML, MH: $E_o = 30.2 - 0.308\,S$

Since the base of the pavement will allow water to reach the subgrade, the subgrade will inevitably increase in saturation, thereby decreasing the modulus of the subgrade. The equation to calculate the actual modulus of the subgrade is as follows:

$$E = E_o e^{(-0.07\ SDIF)}$$

E_o = initial modulus value calculated above
SDIF = change in pF from initial to present state

It is reasonable to assume that the subgrade moisture at its optimum water content may be very close to its plastic limit, which corresponds to a pF of 3.5. It can also be assumed that as the soil increases in water content, it reaches a limit that corresponds to a pF of 2.5. Based on these conditions, the maximum value of SDIF will be 1.0, which results in a minimum value of subgrade modulus.

Step E. Determining the amount of rutting.

Step E will again require the use of one of the Charts 6-10, depending upon the critical load category of the vehicles. The level of rutting is determined at the design subgrade modulus and vehicle axle load. If the level of rutting is unacceptable, then one of several options may be considered - a few of which are suggested here. One option is to decrease the permeability of the base layer, which will in effect, maintain the subgrade at a lower moisture content. For this condition, set SDIF to 0.5 and redetermine the amount of rutting. If the level of rutting is still unacceptable, stabilization of the subgrade should be considered. This will increase the subgrade modulus by a factor of 1.5. Another option would be the use of a stabilized base layer or a two-layer base system, as previously described.

The rutting design charts are based on the results of the load testing performed at the Riverside test track at Texas A&M University; the predicted rutting using the computer program FLEXPASS; and the assumption of the use of a 4-inch base layer. Adjustments to the design number of loads per year for bases greater than 4 inches can be made using the multiplying factor obtained from Chart 11 in Appendix B to increase the expected number of loads for greater base thicknesses.

Example Design

The following example is also provided in the form of a completed worksheet that is shown on page A-6. This example illustrates a design for a 40 by 100-foot parking lot that will be subjected to 20,000, 10 kip vehicles per year.

Pavement Drainage

Step A

Retention time is to be 12 hours and the base properties are as noted in the worksheet.

Step B

Dimensions of the drainage area are as previously given with the grading noted in the worksheet. First, calculate the length of the drainage path as:

$$L = \frac{x\sqrt{S_1^2 + S_2^2}}{S_1}$$

$$= \frac{40ft\sqrt{0.02^2 + 0.03^2}}{0.02} = 72 \text{ ft}$$

Use 72 ft since this drainage path fits within the boundary of the paving area. Calculate the slope of drainage layer (S) as:

$$S = \sqrt{S_1^2 + S_2^2} = \sqrt{0.02^2 + 0.03^2} = 0.0361; 3.61\%$$

Step C

Using a design storm of 2 in./hr for 1 hour, calculate the volume of rainfall on the parking lot as:

(2 in/hr)(1ft/12inches)(1 hr)(40')(100') = 667 ft^3

Calculate the maximum amount of rain infiltrating into the base and the potential storage.

Assume infiltration coefficient = 0.4
(0.4)(667 ft^3) = 267 ft^3 or 2905 ft^3 per acre
(400 ft^3 of runoff per 4000 sq ft of pavement)

Step D

Using Chart 1, it is determined that the required base thickness is approximately 3 inches thick to store 2905 ft^3/acre. (Note: use a minimum 4-inch base.)

Step E

L = 72 ft and H = 4 inches with a porosity of 0.30

Using Chart 3 (or k = $\frac{nL^2}{tH}$ ft/hr), and (L^2/H = (72 ft)^2/(4in /12) = 15,552 ft) the permeability can be found to be 389 ft/hr or approximately 9331 ft/day. Checking the permeability to allow the inflow = outflow (inflow/outflow criteria):

$$k = \frac{2*72*0.4*2}{\frac{4}{12}*3.61\%} = 9573\,\text{ft/day which is} > 9331\,\text{ft/day.}$$

The design storm is sufficient to cause retention within the base layer. Otherwise lower porosity materials could be considered to lower the base permeability.

$$\begin{aligned}\text{Storage} &= 2\ L\ F\ R - K\ i\ H \\ &= 115.2 - 111.2 = 4.0\ \text{ft}^3\text{/hr per foot of width}\end{aligned}$$

Step F

A gradation of material ranging in size from a 1-inch to #8 sieve will have a k greater than 9331 ft/day.

<u>Pavement Performance</u>

Step A

Traffic for this example is as previously noted: 20,000-10 kip axle loads. A medium level of rutting will be acceptable.

Step B

Since only one load group is involved in this example, no determination of an ESAL factor is necessary. However, an example where the traffic distribution consists of a mix of axle groups is shown on page A.7.

Step C

The subgrade is a high-plastic clay, CH, with unit weight of 115 lb/ft^3 and water content of 22 percent. Assume the specific gravity (G_s) is 2.7.

$$\begin{aligned} e &= (2.7)(62.4\ \text{lb/ft}^3)(1+.22)/115\text{lb/ft}^3 - 1 \\ &= 78.7\% \\ S &= (.22)(2.7)/(.787) \\ &= 75.5\% \end{aligned}$$

The subgrade was classified as a CH, so use the following equation:

$$\begin{aligned} E_o &= 22.5 - 0.155\ S \\ &= 22.5 - 0.155(75.5) \\ &= 10.8\ \text{ksi} \end{aligned}$$

Step D

Assume that the subgrade goes from its plastic limit (PL) to a condition that approaches a moisture condition that is midway between the PL and the liquid limit. Therefore,

$$\begin{aligned} \text{SDIF} &= 1.0 \\ E &= (10{,}800)e^{(-0.07(1.0))} = 10{,}800\ (0.93) \\ &= 10{,}070\ \text{psi} \end{aligned}$$

Step E

Use Chart 8 to determine the amount of rutting with a subgrade modulus value of 10,070 psi and 20,000, 10 kip vehicles.

The amount of rutting is approximately 0.4 inches, which is in the medium range.

A rutting calculation is also provided for a case where the traffic mix consists of multiple axle load groups.

Eco-Stone Pavement Design and Drainage Worksheet

Drainage

Retention Time: 12 hrs

Base Properties

Dry Unit Wt (γ_d): 110 1b/cf $\qquad n = 1 - \frac{\gamma_d}{G_s \gamma_w} =$ 0.30

Specific

Gravity (G_s): 2.65

Drainage Area Data

Drainage Length	Slope	Design Storm	F	Drain Area	Base Infiltration	Base Thickness*
$L_1 = 40'$	$S_1 = 2\%$	2"/hr	0.40	4000 ft^2	267 ft^3	3 (4 is min.)
$L_2 = 100'$	$S_2 = 3\%$					

* Note: Use Chart 1

$S_e = \sqrt{S_1^2 + S_2^2} =$ 3.61% $\qquad L_e = \frac{L_i S_e}{S_i} =$ 72 ft $\qquad k =$ 389 ft/hr (Charts 2-5)

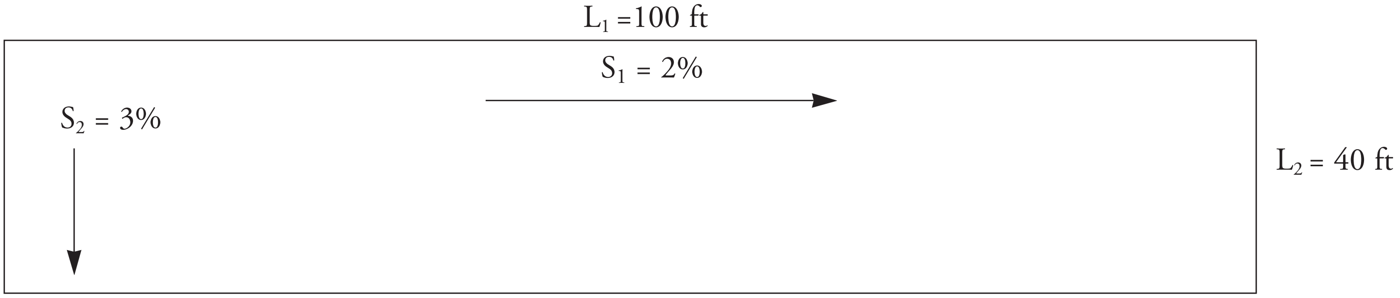
Outflow = Inflow Criteria

$k = \frac{2 * L * F * R}{H * i} =$ 9573 ft/day or 399 ft/hr > 389 ft/hr O.K., retention will occur.

Base Gradation

Particle Size	%P	Particle Size	%P
2"		#10	
$1^1/_2$"		#16	
1"	100	#30	
$^3/_4$"	90-100	#40	
$^1/_2$"		#50	
$^3/_8$"	20-55	#100	
#4	0-10	#200	
#8	0-5		

Drainage Area Layout



Eco-Stone Pavement Design and Drainage Worksheet

Rutting

Max Allowable: 0.50

Subgrade Properties

Unit Wt (γ): 115 lbs/cf
Specific Gravity (G_s): 2.70

Moisture Content (w_c): 22%
Type: CH

$$e = \frac{G_s \gamma_w}{(1 + w_e)\gamma_s} - 1 = 78.7\% \qquad S = \frac{w_c G_s}{e} = 75.5\%$$

Subgrade E = $E_o(0.93)$ = 10070 psi

If subgrade type = CL;ML-CL then $E_o = 32.0 - 0.312*S$ = ________
If subgrade type = CH then $E_o = 22.5 - 0.155*S$ = 10,800 psi
If subgrade type = ML;MH then $E_o = 30.2 - 0.308*S$ = ________

Traffic Data and Rutting Prediction

Traffic Axle Load (Kips)	*Number of Axles/yr*	*Chart Life E: 10070psi*	*10^k ESAL Factor*	*10^k ESAL*	*Rutting (Charts 6-10)*
0-4					
4-8					
8-12	*20,000*		*1.0*	*20,000*	*0.40"*
12-16					
16-20					

For multiple axle load groups:

Traffic Axle Load (Kips)	*Number of Axles/yr*	*Chart Life* E: 10070psi*	*10^k ESAL Factor*	*10^k ESAL*	*Rutting (Charts 6-10)*
0-4	*10,000*	*32,000*	*0.78*	*7,800*	
4-8	*12,000*	*27,000*	*0.93*	*11,100*	
8-12	*5,000*	*25,000*	*1.0*	*5,000*	
12-16	*2,000*	*19,000*	*1.3*	*2,600*	
16-20	*1,000*	*16,500*	*1.5*	*1,500*	

*Note: Equivalency determined at 0.5 inches of rutting.

Total 10^k ESAL = 28,000

Rutting = 0.55"

APPENDIX B

Eco-Stone Pavement Design and Drainage Worksheet

Drainage

Retention Time: __________

Base Properties

Dry Unit Wt (γ_d):________
Specific
Gravity (G_s):______

$$n = 1 - \frac{\gamma_d}{G_s \gamma_w} = \_\_\_\_\_\_\_\_\_\_$$

Drainage Area Data

Drainage Length	Slope	Design Storm	F	Drain Area	Base Infiltration	Base Thickness*
L_1 =	S_1 =					
L_2 =	S_2 =					

* Note: Use Chart 1

$S_e = \sqrt{S_1^2 + S_2^2}$ = __________ $L_e = \dfrac{L_i S_e}{S_i}$ = ___________ k = __________ (Charts 2-5)

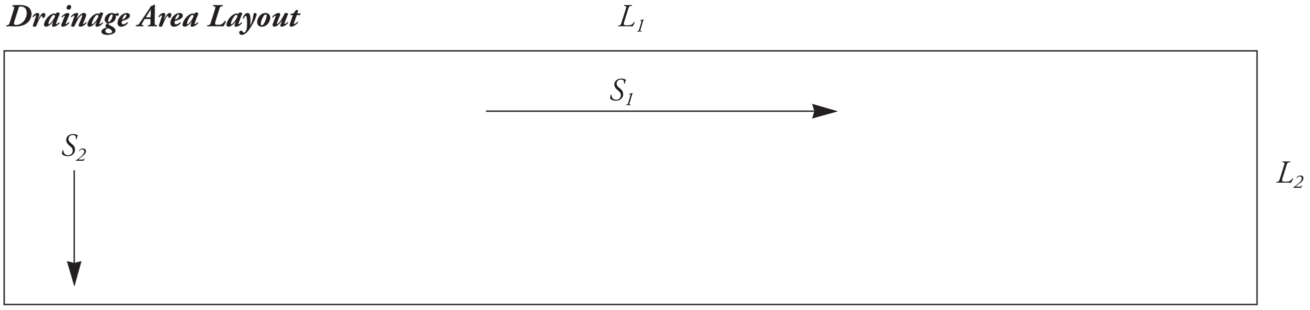
Outflow = Inflow Criteria

$$k = \frac{2 * L * F * R}{H * i} = \_\_\_\_\_\_\_\_\_\_$$

Base Gradation

Particle Size	%P	Particle Size	%P
2"			
$1\frac{1}{2}$"		#16	
1"		#30	
$\frac{3}{4}$"		#40	
$\frac{1}{2}$"		#50	
$\frac{3}{8}$"		#100	
#4		#200	
#8			

Drainage Area Layout



Eco-Stone Pavement Design and Drainage Worksheet

Rutting

Max Allowable: __________

Subgrade Properties

Unit Wt (γ): __________

Specific Gravity (G_s): __________

Moisture Content (w_c): __________

Type: __________

$$e = \frac{G_s \gamma_w}{(1 + w_e)\gamma_s} - 1 = \_\_\_\_\_\_\_\_\_\_ \qquad S = \frac{w_c G_s}{e} = \_\_\_\_\_\_\_\_\_\_$$

Subgrade E = $E_o(0.93)$ = __________

If subgrade type = CL;ML-CL then $E_o = 32.0 - 0.312*S$ = __________
If subgrade type = CH then $E_o = 22.5 - 0.155*S$ = __________
If subgrade type = ML;MH then $E_o = 30.2 - 0.308*S$ = __________

Traffic Data and Rutting Prediction

Traffic Axle Load (Kips)	*Number of Axles/yr*	*Chart Life E: 10070psi*	*10^k ESAL Factor*	*10^k ESAL*	*Rutting (Charts 6-10)*
0-4					
4-8					
8-12			*1.0*		
12-16					
16-20					

Chart 1: Storage vs. Base Thickness

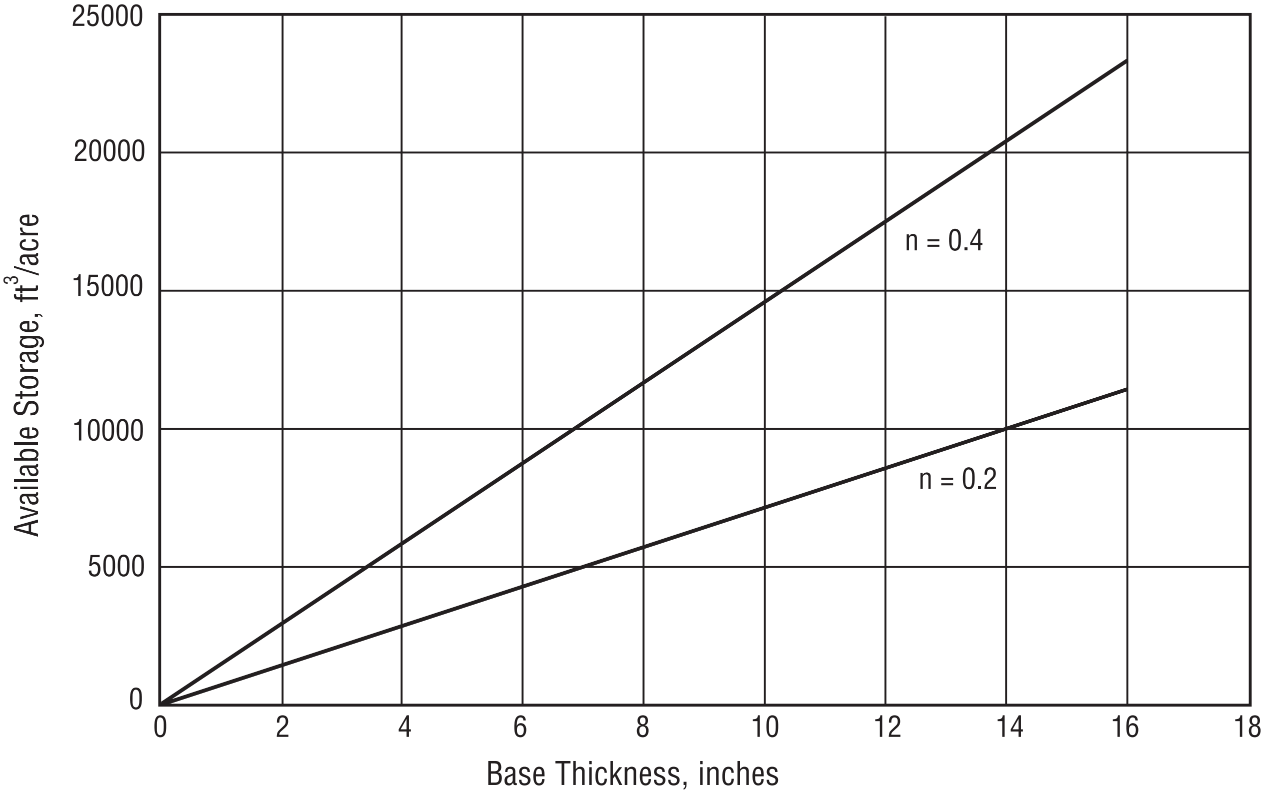


Chart 2: Permeability for 6-Hour, 50% Drainage Retention Time

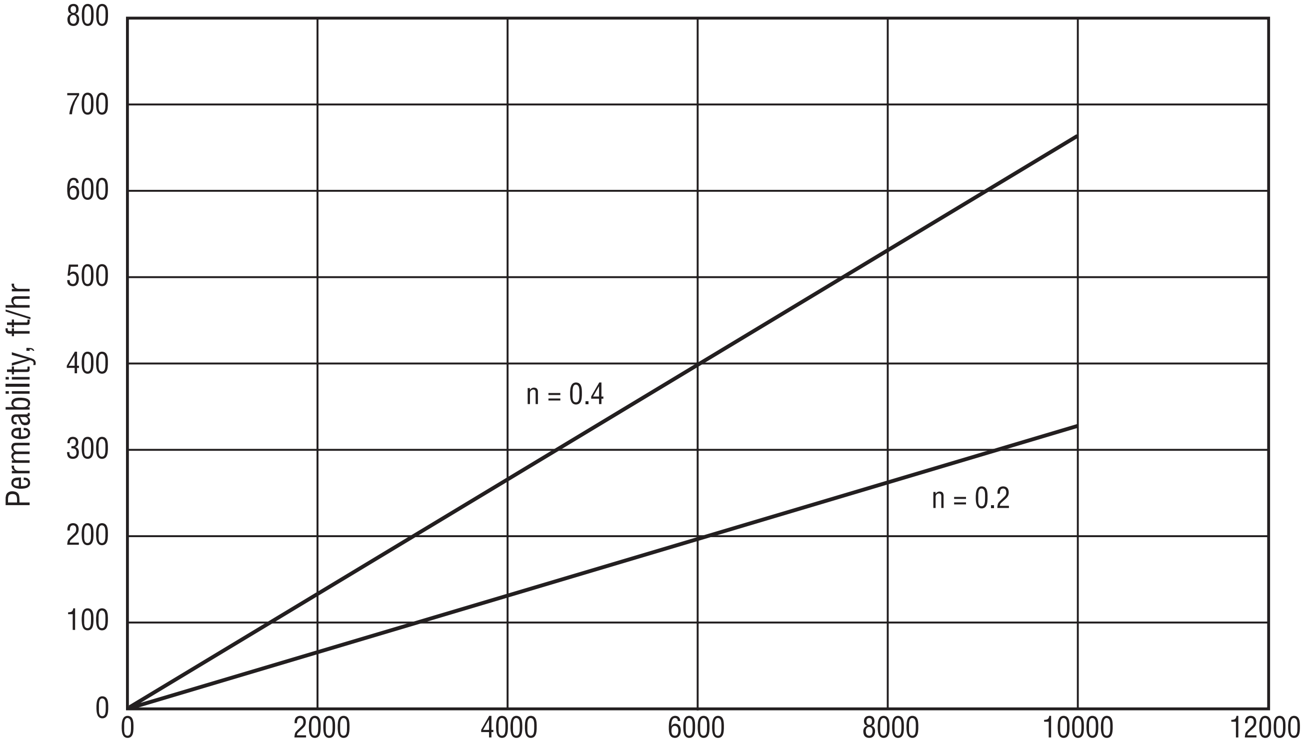


Chart 3: Permeability for 12-Hour, 50% Drainage Retention Time

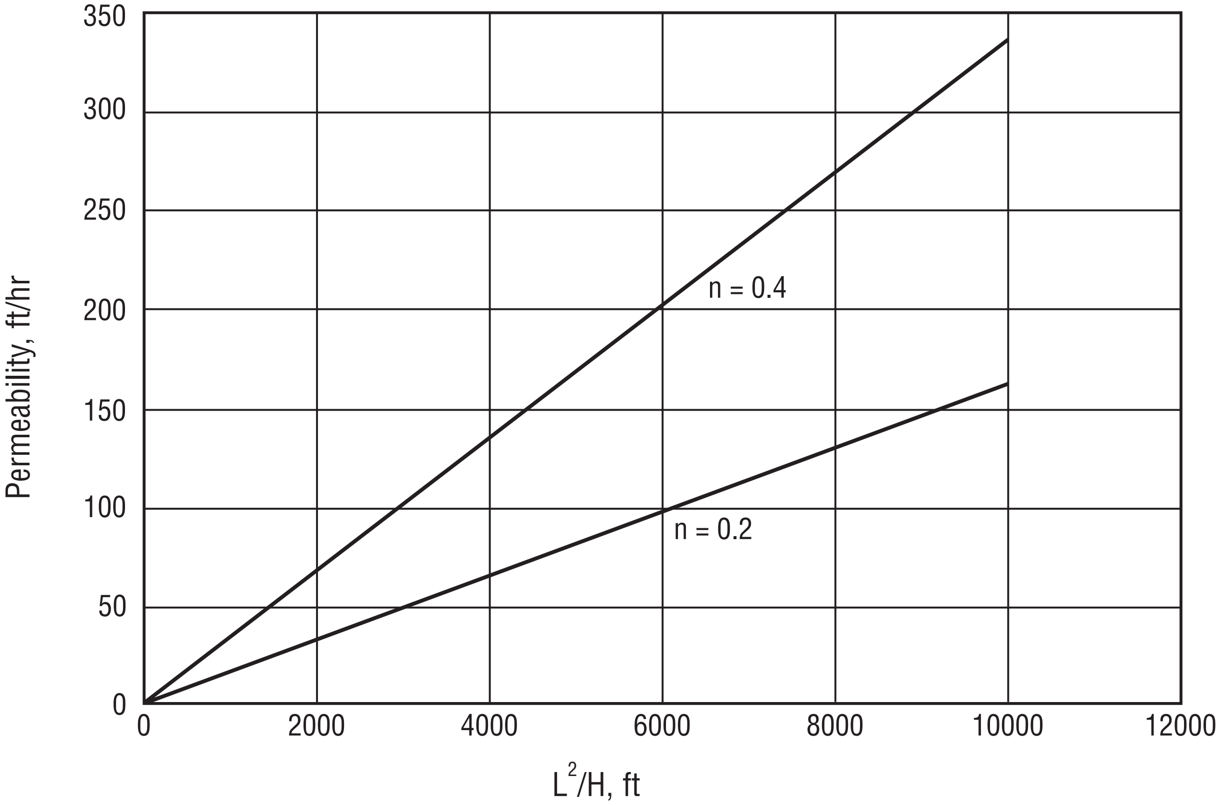


Chart 4: Permeability for 18-Hour, 50% Drainage Retention Time

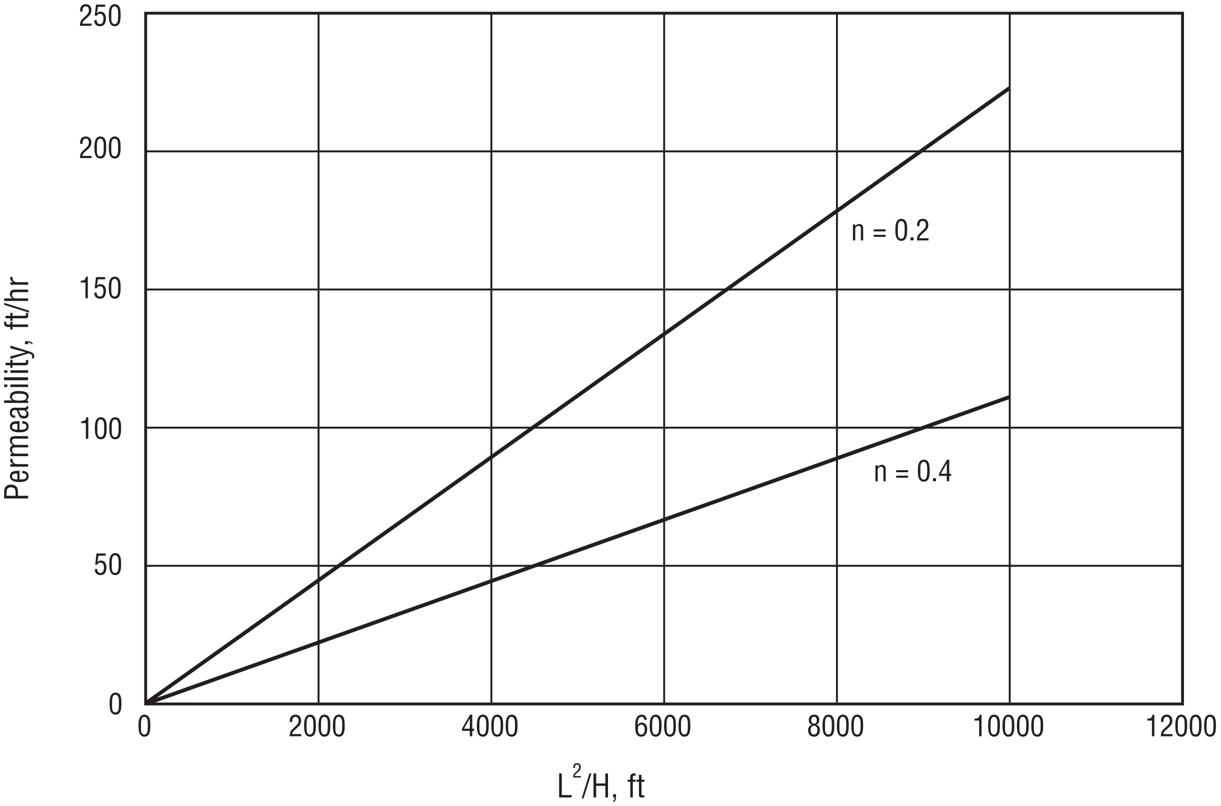


Chart 5: Permeability for 24-Hour, 50% Drainage Retention Time

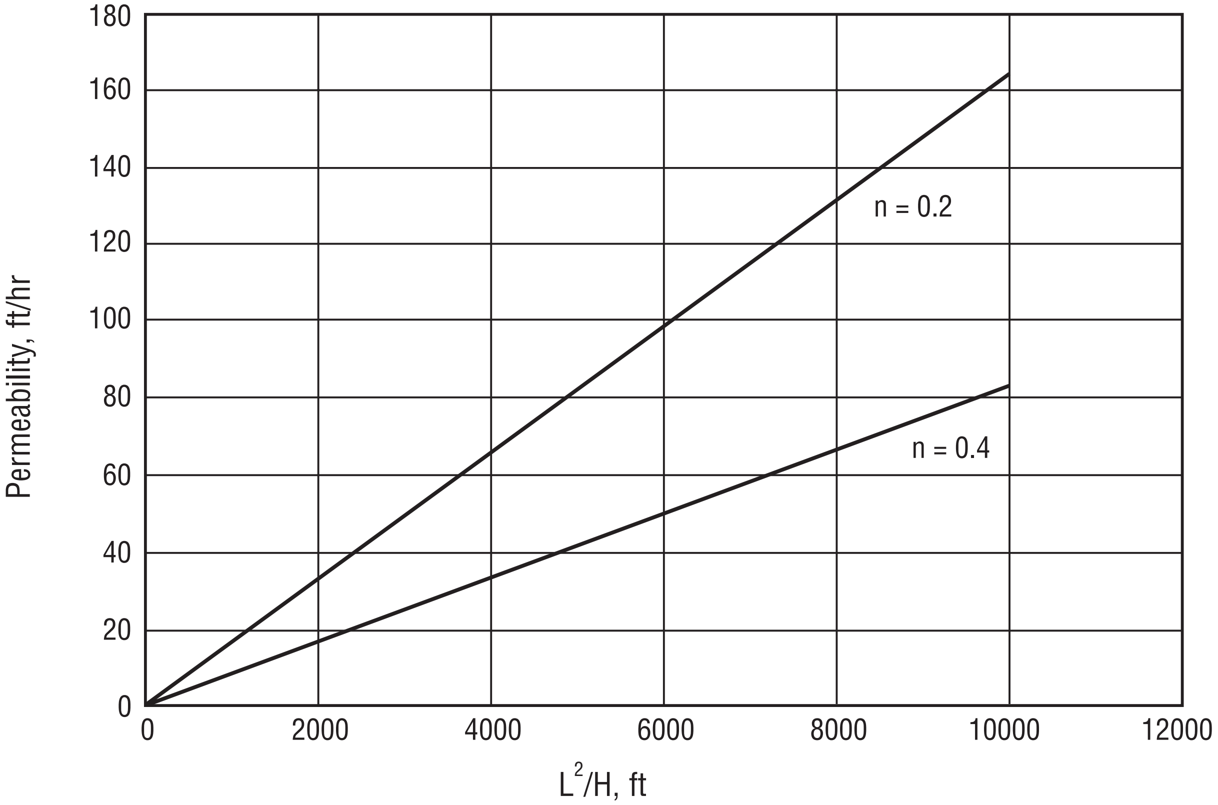


Chart 6: Rutting for 2 Kip Vehicles

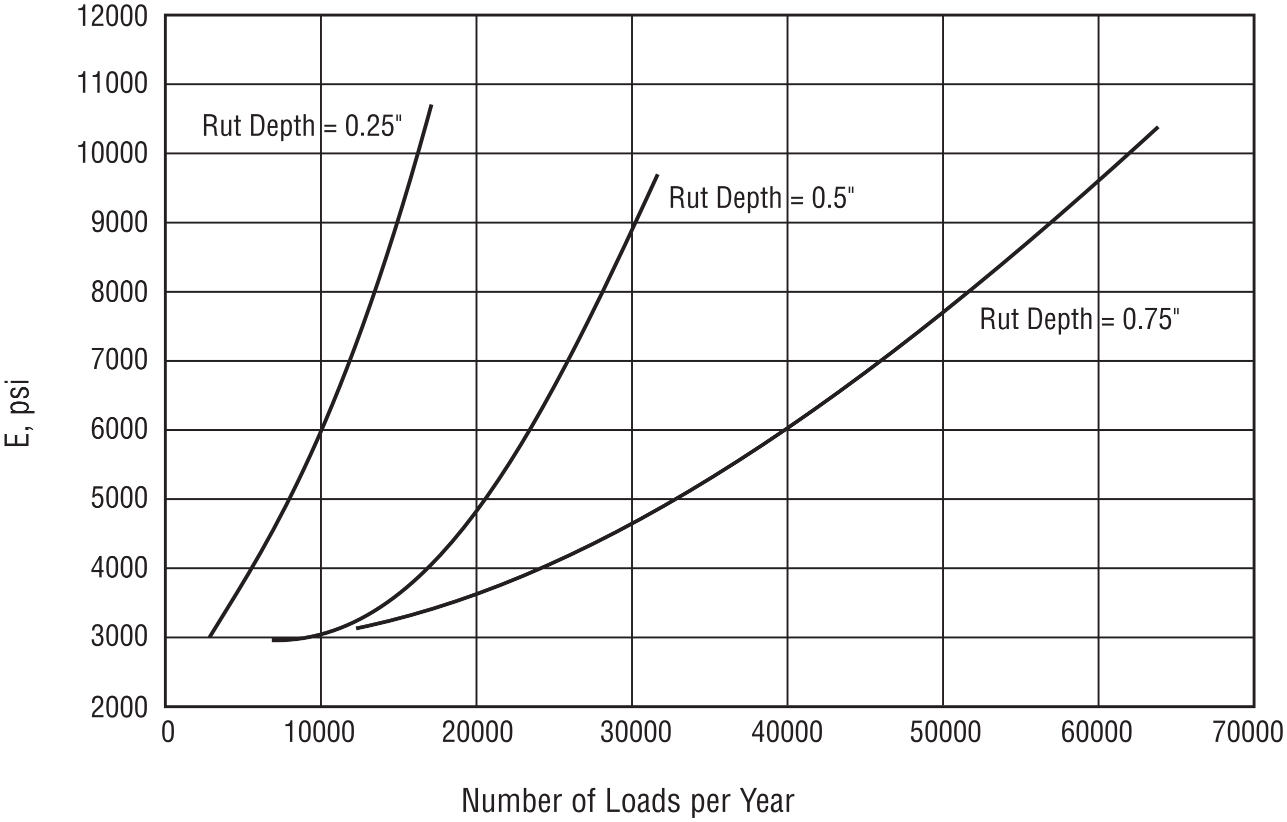


Chart 7: Rutting for 6 Kip Vehicles

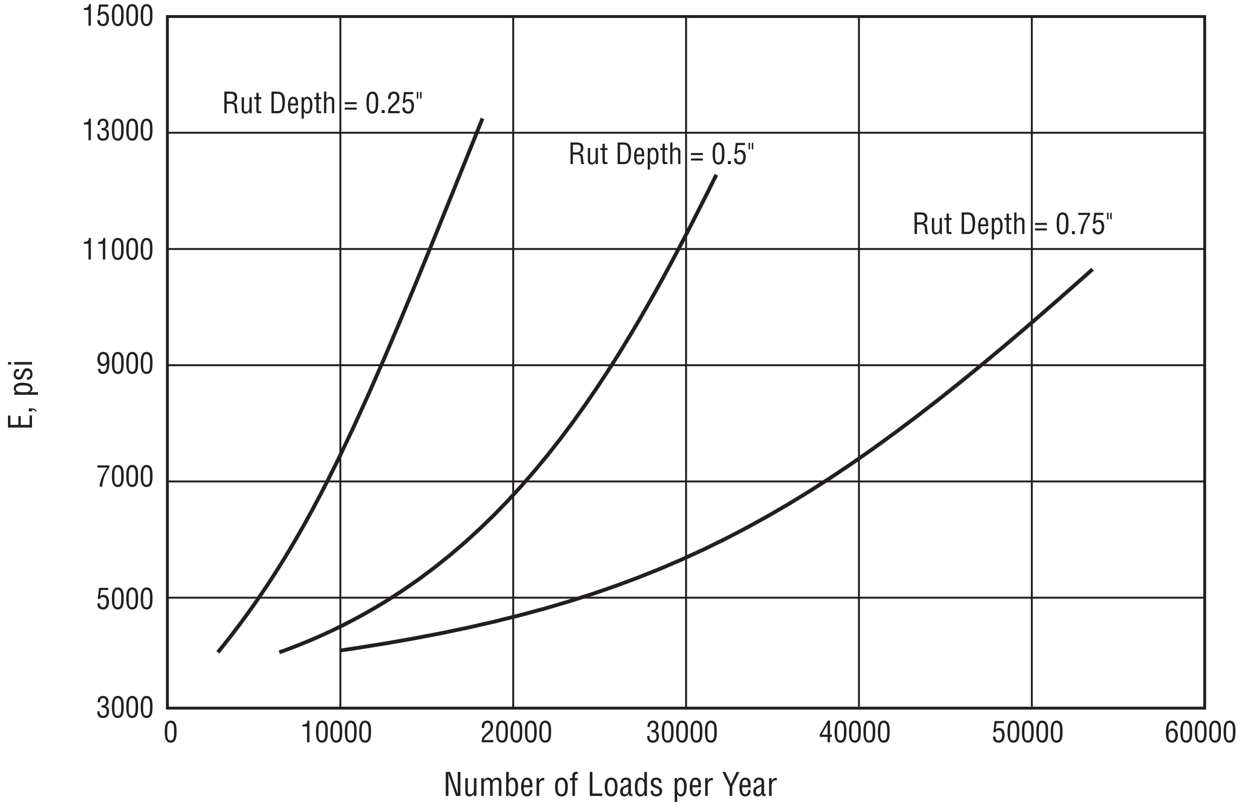


Chart 8: Rutting for 10 Kip Vehicles

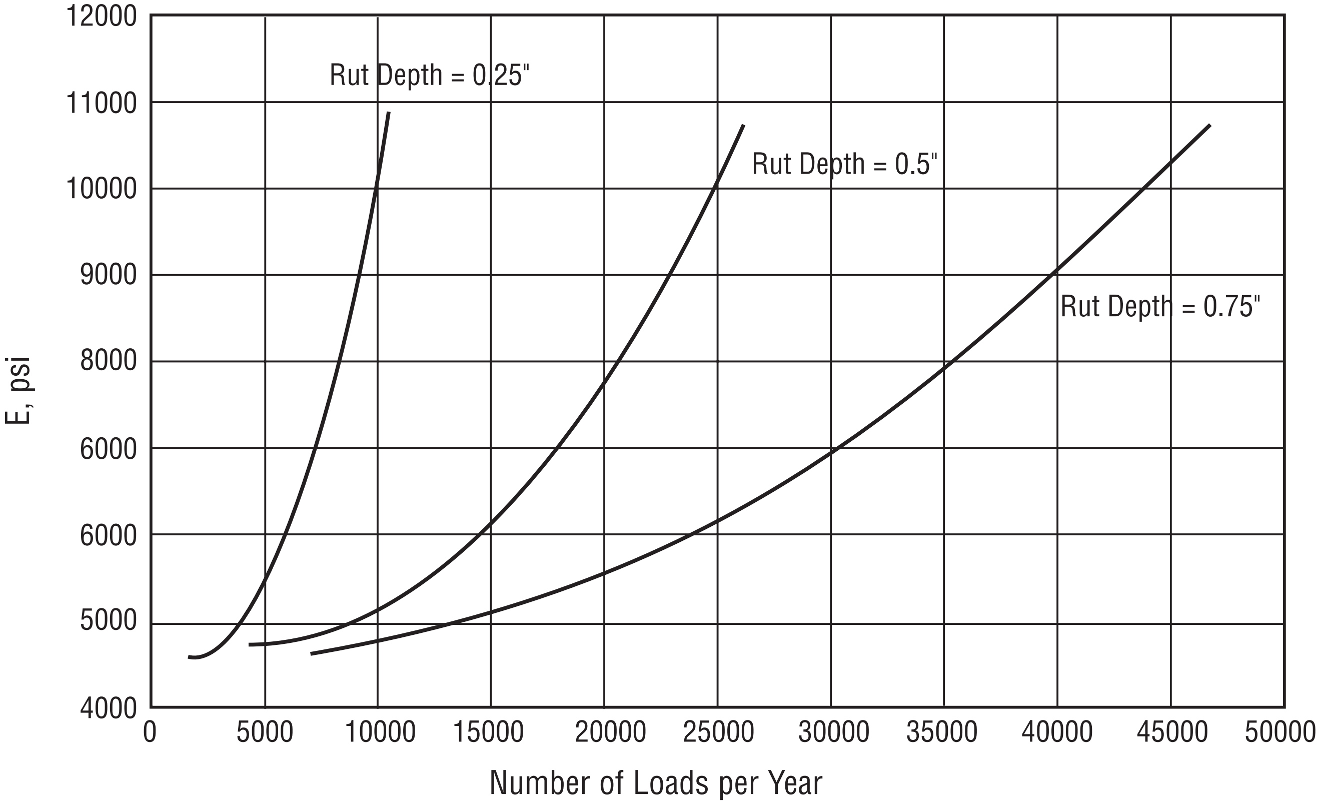


Chart 9: Rutting for 14 Kip Vehicles

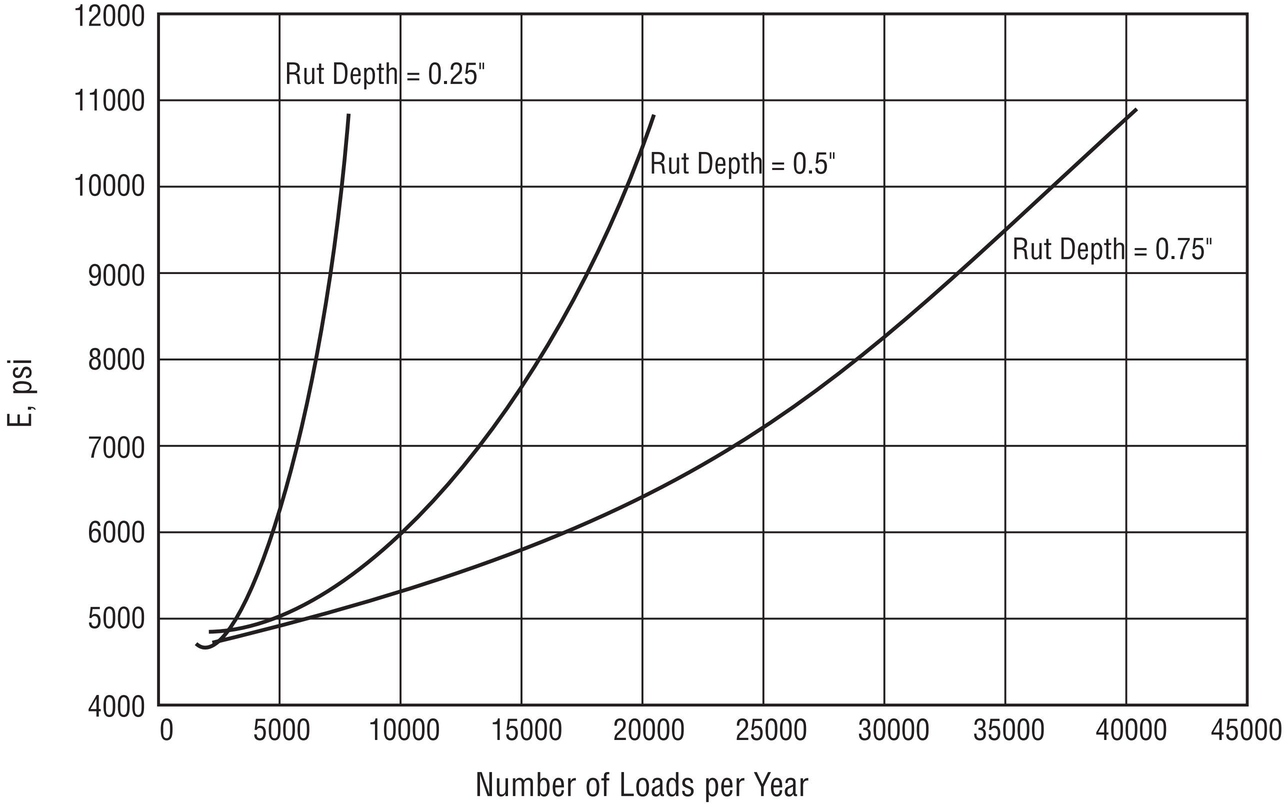


Chart 10: Rutting for 18 Kip Vehicles

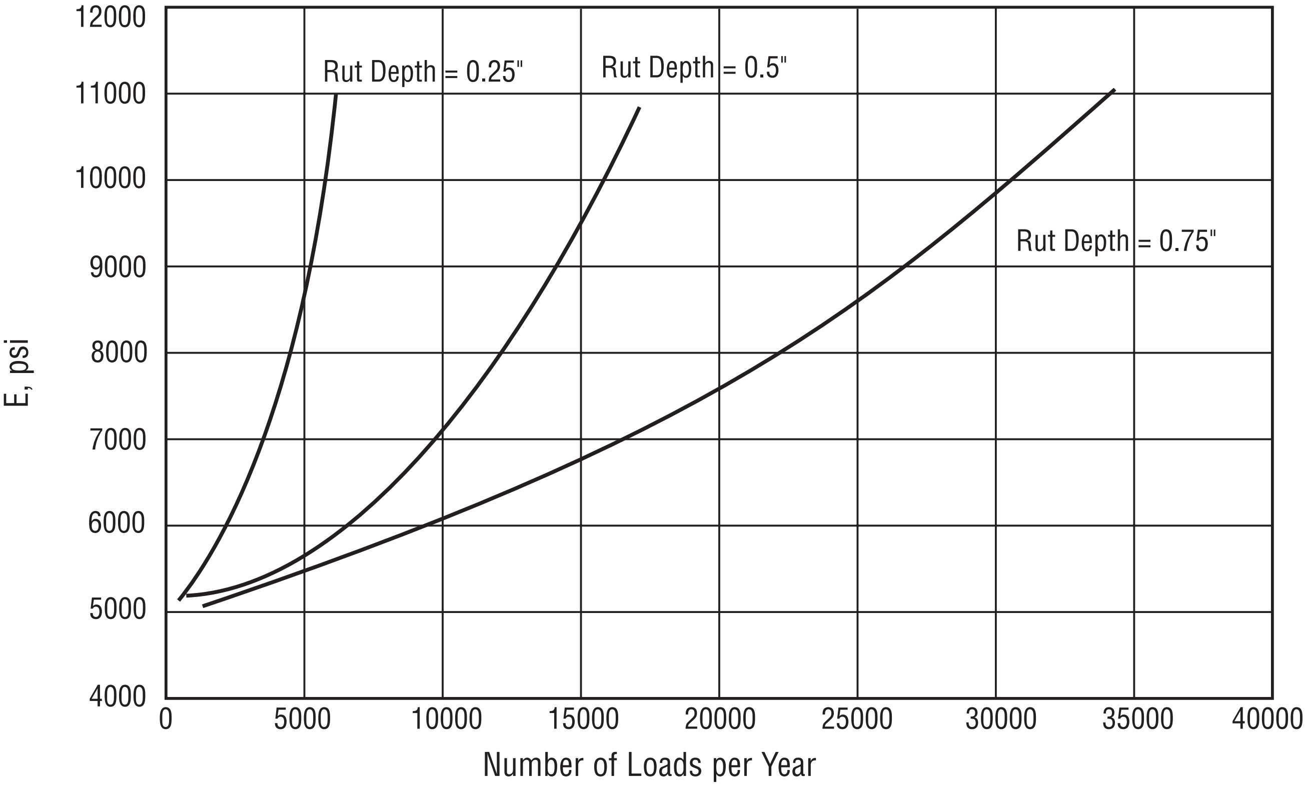
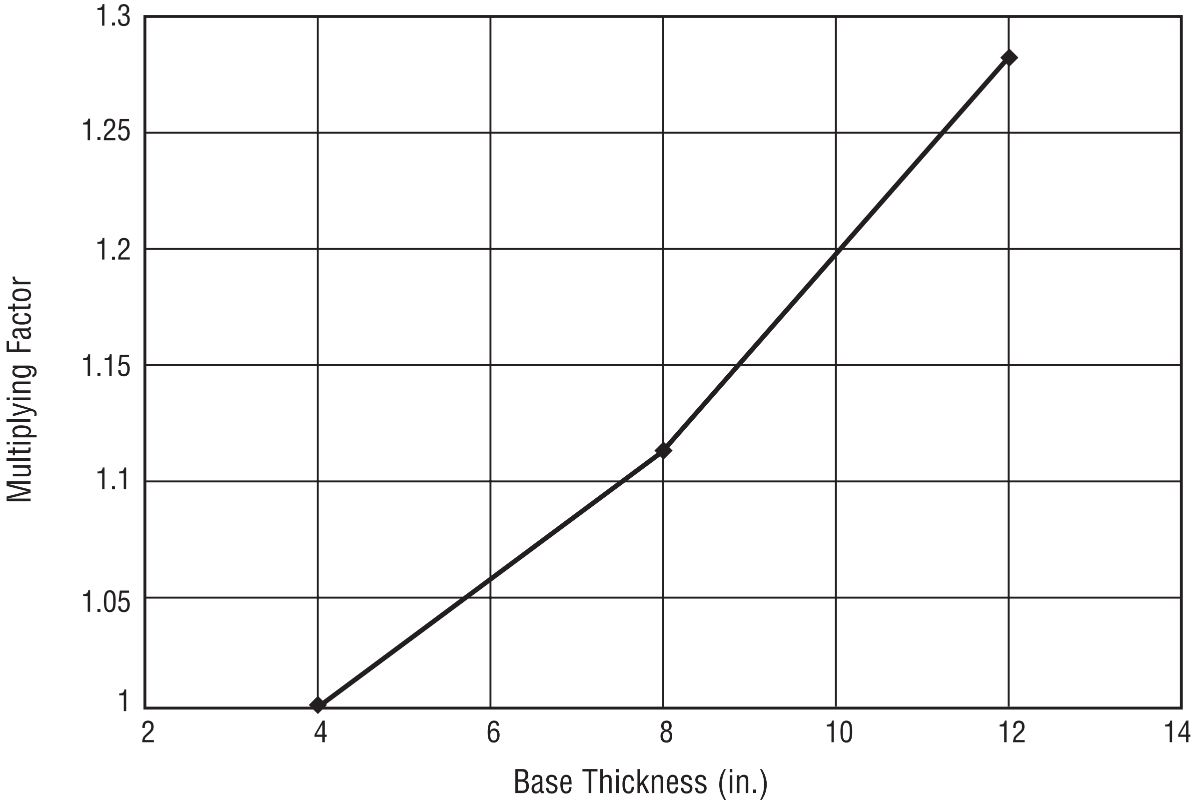


Chart 11: Adjustment for Base Thickness Greater Than 4 Inches



APPENDIX C

Storm Frequency Data

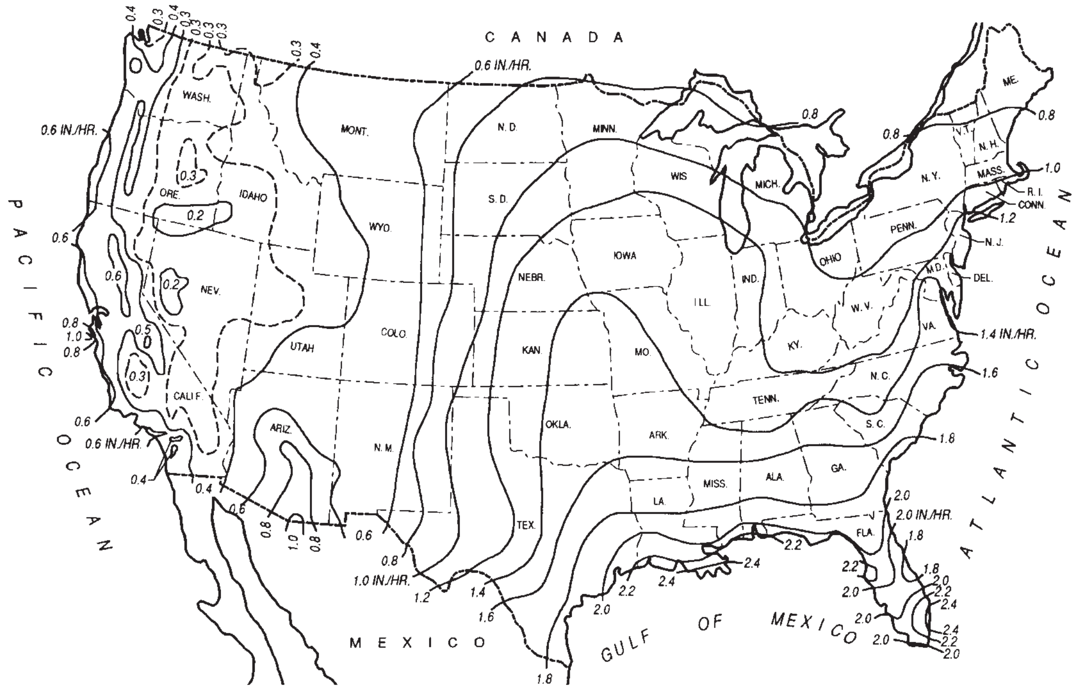


Figure C1 - One-Hour/One-Year Frequency Storm

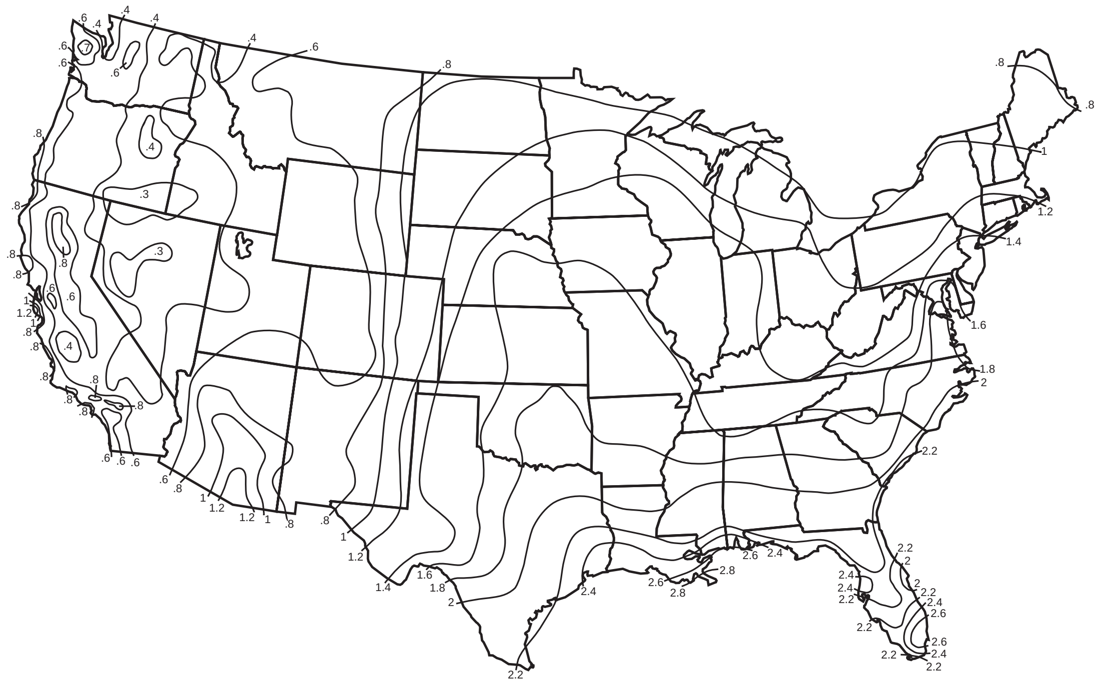


Figure C2 - One-Hour/Two-Year Frequency Storm

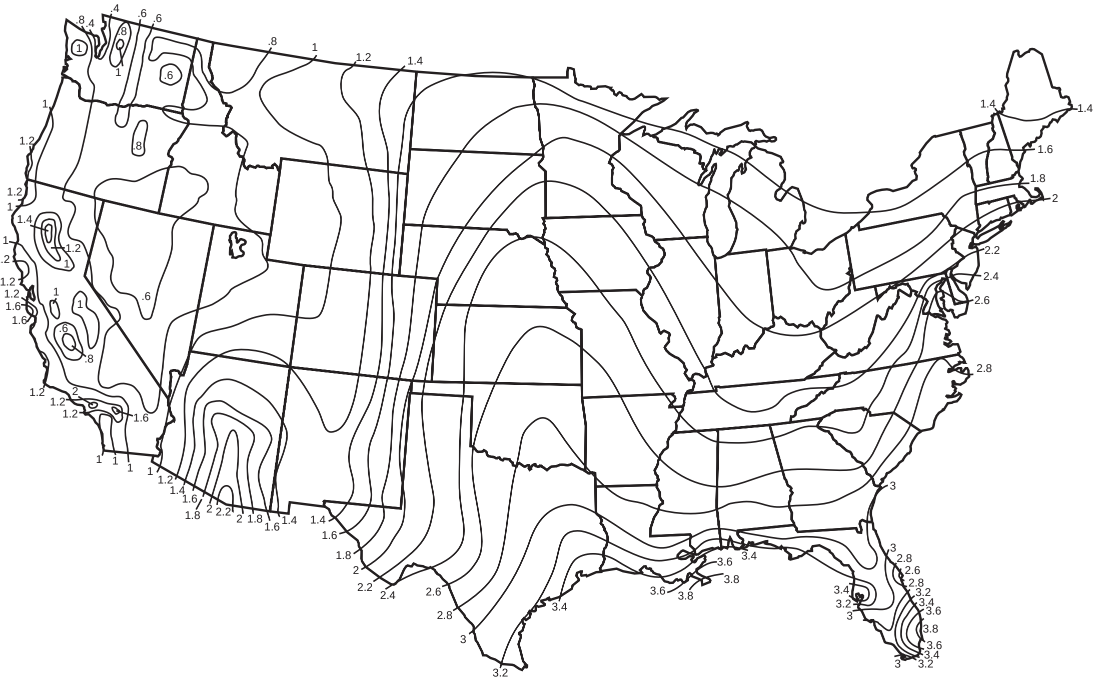


Figure C3 - One-Hour/Ten-Year Frequency Storm

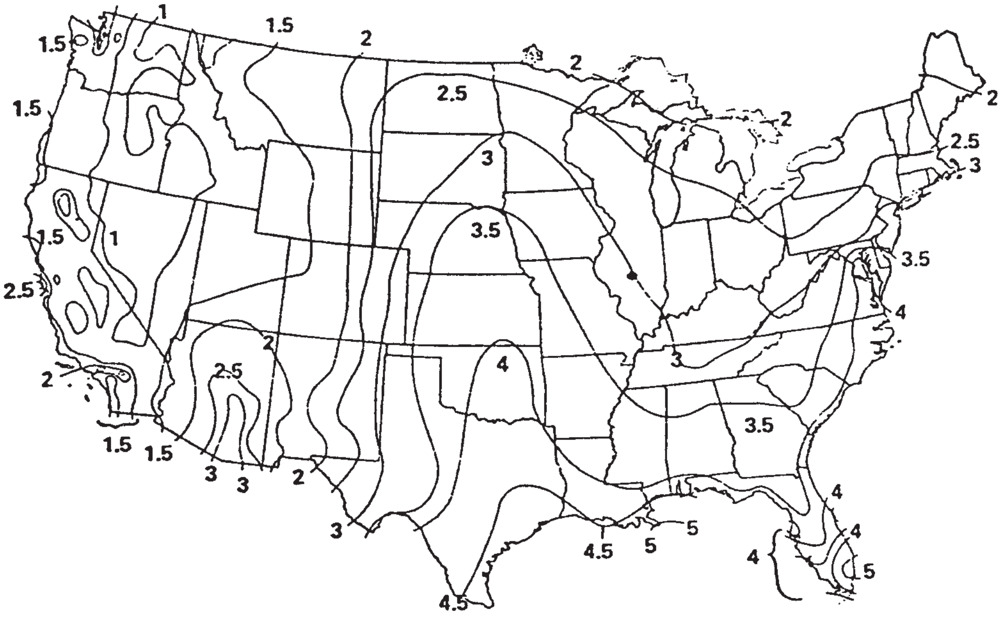


Figure C4 - One-Hour/One Hundred-Year Frequency Storm

APPENDIX D

Permeability and Gradation Data

Table D1 - Gradation and Permeability (1).

Sieve No.	ASTM 448 Sizes				ASTM	Phalen's
	No. 7	No. 8	No. 89	No. 9	C 33	3/8-in
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 at the approximate midpoint of the gradation band

Table D2 - Grain Size, Density, and Permeability of Graded Aggregates (12)

% Passing	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6
3/4 in.	100	100	100	100	100	100
1/2 in.	85	84	83	81.5	79.5	75
3/8 in.	77.5	76	74	72.5	69.5	63
No. 4	58.5	56	52.5	49	43.5	32
No. 8	42.5	39	34	9.5	22	5.8
No. 10	39	35	30	25	17	0
No. 20	26.5	22	15.5	9.8	0	0
No. 40	18.5	13.3	6.3	0	0	0
No. 60	13	7.5	0	0	0	0
No. 140	6	0	0	0	0	0
No. 200	0	0	0	0	0	0
Dry Density (pcf)	121	117	115	111	104	101
k (ft/day)	10	110	320	1000	2600	3000

DISCLAIMER

The design procedure and criteria contained in these design guidelines are intended to guide pavement engineers or consultants in the design of paver block systems relative to drainage and rutting performance. It should be used to augment standards and specifications published by various municipal and government agencies. While every precaution has been taken to insure that all data and information furnished are as accurate as possible, Texas A&M University will not assume responsibility for errors or oversights in the use of this information or in the preparation of engineering plans. The information presented herein is based on the facts, tests, and authorities as stated and is intended for the use of professional personnel competent to evaluate the significance and limitations of the reported findings and who will accept responsibility of the application of the material it contains. The information in this guideline is not intended to replace the judgement of an experienced pavement engineer, or pavement designs that have demonstrated satisfactory performance. Texas A&M University also disclaims any and all responsibility for any other application of the stated principles or for the accuracy of any of the sources on which this report is based.

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