

# 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, coarse-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               | $2.7 \times 10^{-4}$ to 27                   |
| GC                          | Impervious                 | $2.7 \times 10^{-4}$ to $2.7 \times 10^{-2}$ |
| SW                          | Pervious                   | 1.4 to 137                                   |
| SP                          | Semipervious to Pervious   | 0.14 to 1.4                                  |
| SM                          | Impervious to Semipervious | $2.7 \times 10^{-4}$ to 1.4                  |
| SC                          | Impervious                 | $2.7 \times 10^{-5}$ to 0.14                 |
| ML                          | Impervious                 | $2.7 \times 10^{-5}$ to 0.14                 |
| CL                          | Impervious                 | $2.7 \times 10^{-5}$ to $2.7 \times 10^{-3}$ |
| OL                          | Impervious                 | $2.7 \times 10^{-5}$ to $2.7 \times 10^{-2}$ |
| MH                          | Very Impervious            | $2.7 \times 10^{-6}$ to $2.7 \times 10^{-5}$ |
| CH                          | Very Impervious            | $2.7 \times 10^{-7}$ to $2.7 \times 10^{-5}$ |

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

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

where

- K = Permeability (cm/sec)
- C<sub>1</sub> = A constant which ranges from 90-120
- D<sub>10</sub> = Effective grain size at 10% passing (cm)

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

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

where

- n = Porosity =  $1 - \frac{\gamma_d}{62.4G}$
- G = Specific gravity
- P<sub>200</sub> = Percent passing the #200 sieve
- γ<sub>d</sub> = Dry rodded unit weight (lb/ft<sup>3</sup>)
- D<sub>10</sub> = 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<sub>10</sub>), the percent passing the #200 sieve (P<sub>200</sub>), 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:

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

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

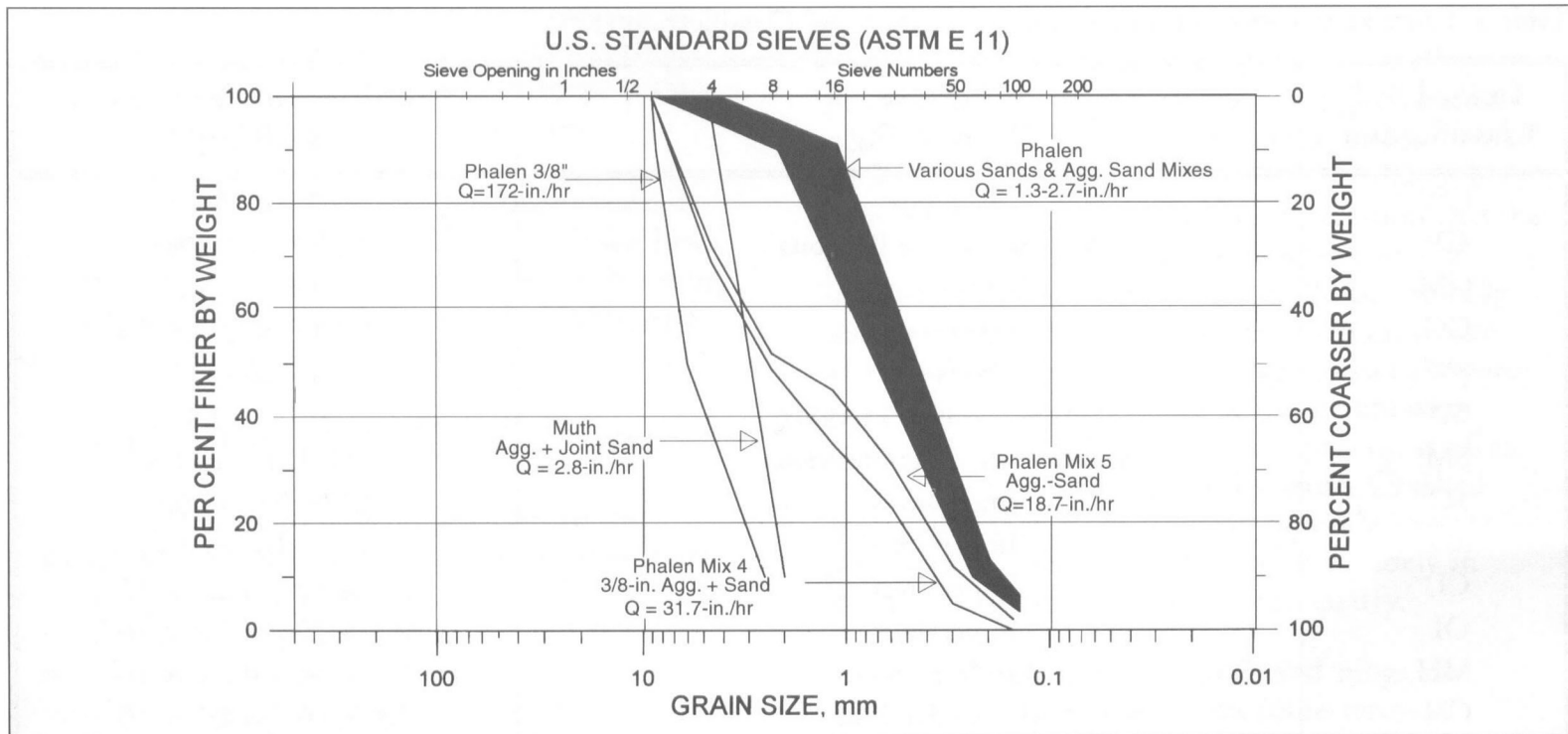


Figure 7 - Jointing Sands and Bedding Layer Gradations and Flow Rates (1).

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.

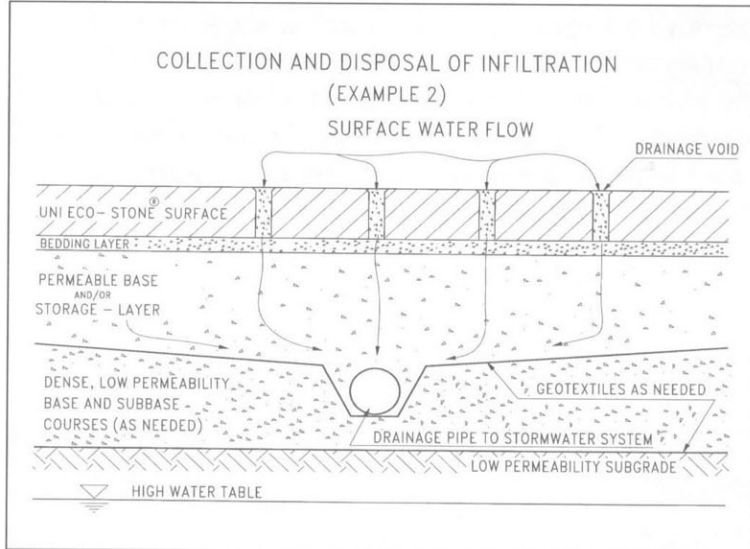


Figure 9 - Double Base Drainage System (1).

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.

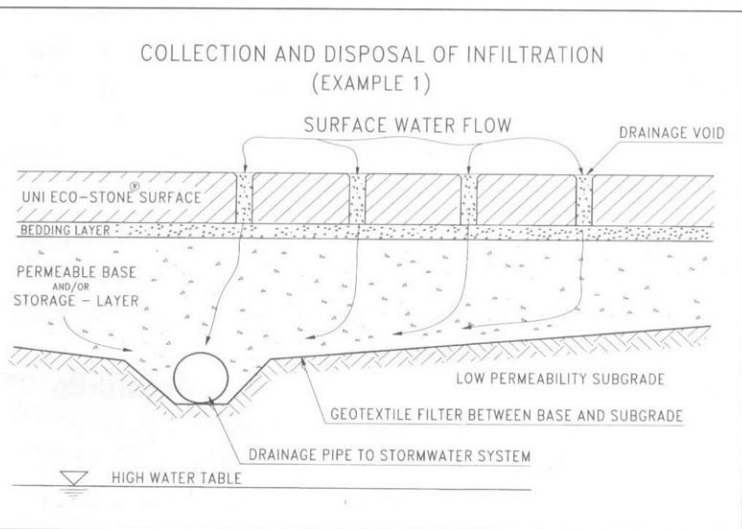


Figure 8 - Collection and Disposal of Infiltration (1).

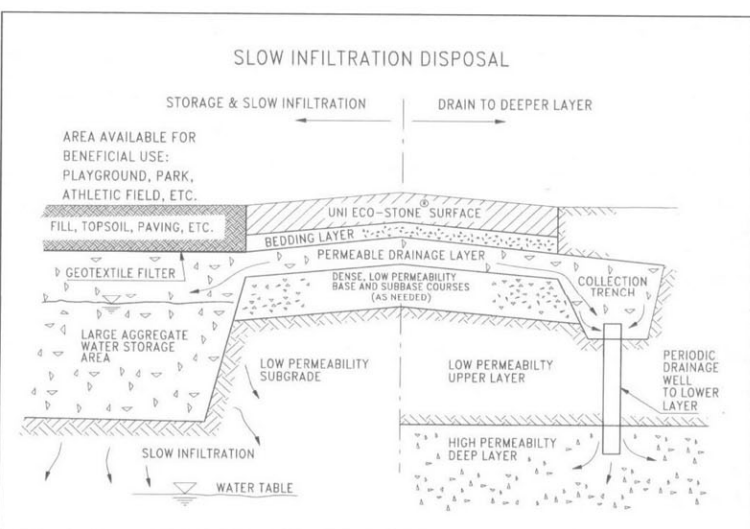


Figure 10 - Protected Subgrade System (1).

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.

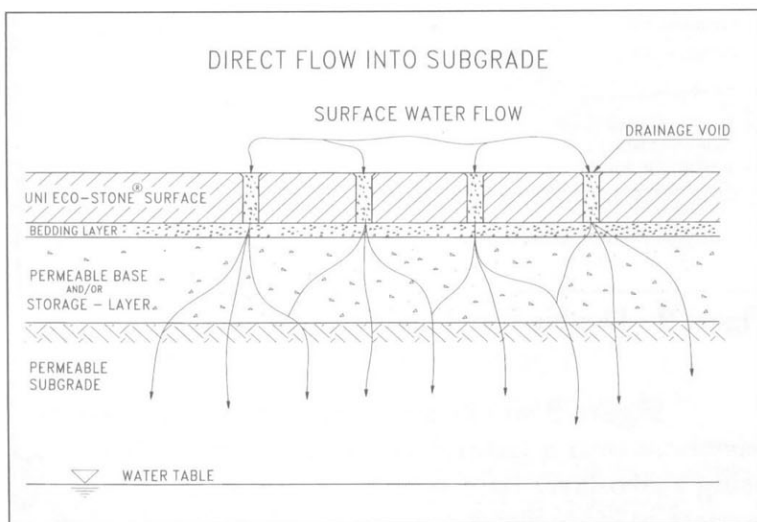


Figure 11 - Permeable Subgrade System (1).

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.

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

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

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

where

- $X$  = The length (feet) of the transverse slope of the drainage layer
- $S_c$  = 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:

$$S = \sqrt{S_t^2 + S_c^2} \quad (8)$$

## Outflow Considerations

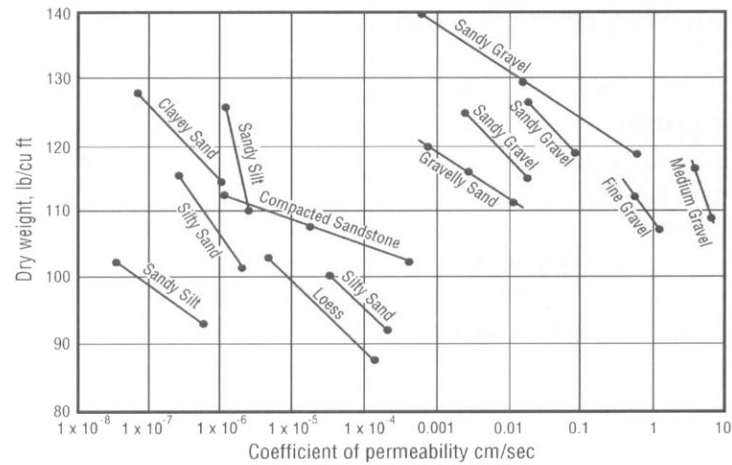
Water can be removed from a pavement section in the following ways (6):

- 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):

$$K = \frac{n_c L^2}{2t_{50} (H + SL)} \quad (9)$$

where

- $t_{50}$  = The time for 50% drainage (days)
- $n_c$  = 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:

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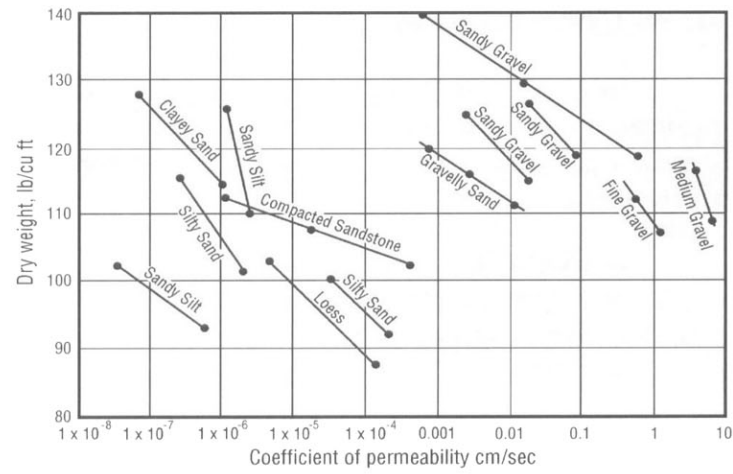
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Permeability for any degree of drainage can be determined graphically, as shown in Figure 13. In this figure, the degree of drainage ( $U$ ) depends on two factors - the time factor ( $T_f$ ) and the slope factor ( $S_f$ ), which are defined as:

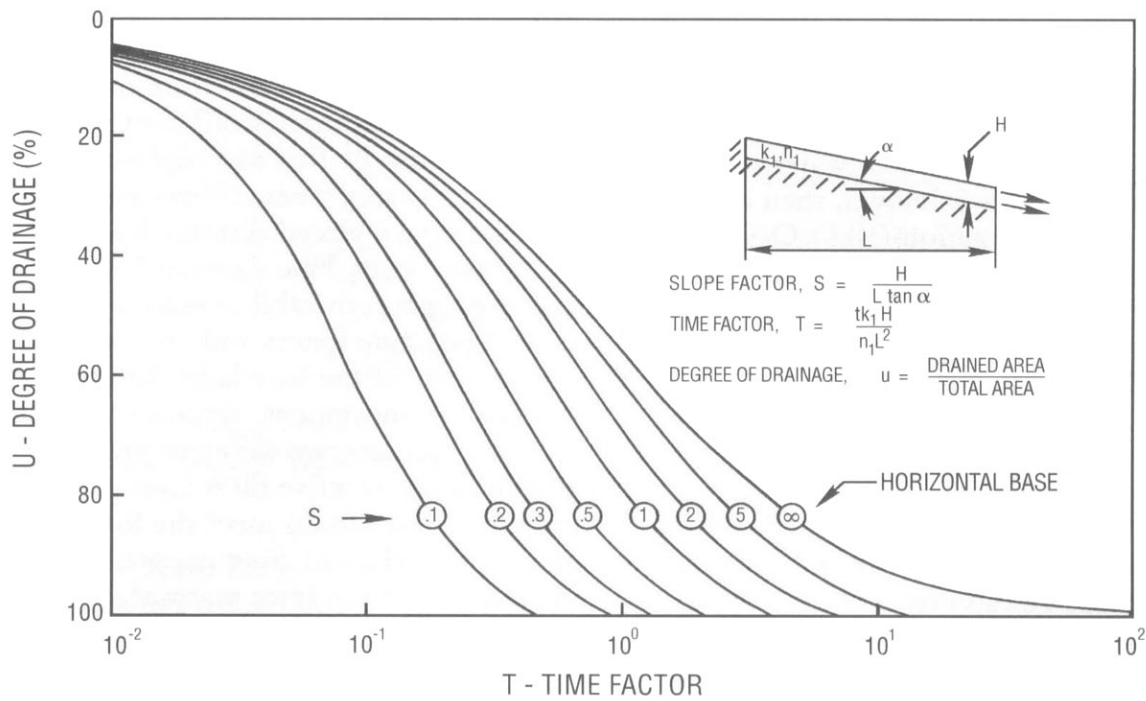


Figure 13 - Time-Dependent Drainage of a Saturated Base Layer (5).

$$T_f = \frac{KHt}{n_c L^2} \quad (10)$$

$$S_f = \frac{LS}{H} \quad (11)$$

where

$t$  = The time since the rain stopped and drainage began, and  
 $K$ ,  $H$ ,  $L$ ,  $S$ , and  $n_c$  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:

$$\begin{aligned} \text{Amount of storage} &= \text{quantity of water entered} \\ &\quad \text{into the pavement} - \\ &\quad \text{quantity of water drained} \\ &\quad \text{out of the pavement} \\ &= (2 L F R) - (K i H) \quad (12) \end{aligned}$$

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

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

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

$\gamma_w$  = 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:

$$K = \frac{2 \times L \times R \times F}{H \times i} \quad (14)$$

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.