Hydraulic Requirements of Permeable Bases

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To address the need for increased drainage within the pavement system, open-graded permeable materials (OGPM) are finding their way into standard design sections throughout the country. The design requirements of the OGPM to handle surface water infiltration are reported. Infiltration rates and required permeabilities of the OGPM are calculated for a range of conditions typical for pavement design. The effects of pavement geometry on required permeabilities, including cross slope, longitudinal gradient, and drainage layer thickness and width, are discussed. Analysis of selected materials, typical for use in Illinois, is completed to determine appropriate permeabilities.

The subject of drainage has been an integral part of pavement design since the early days of road building. Pursuant to this need, open-graded permeable materials (OGPM) have been used within portland cement concrete (PCC) pavement structures as long as these pavements have been built. The trend toward dense-graded aggregate base layers, both stabilized and unstabilized, that predominated the middle of this century lessened the use of these materials. However, in the past two decades there has been a resurgence in the use of OGPM within pavement structures. Highway agencies throughout the country have renewed efforts to evaluate OGPM, with the aim of developing pertinent design methodologies compatible with design specifications, climatic conditions, materials availability, and construction procedures. A research project initiated to address these topics was recently completed at the University of Illinois and the findings were published in a report entitled *Pavement Subbases* (*1*).

From a hydraulic perspective, a complete pavement drainage system is typically composed of many parts, including the base layers under the driving surface, longitudinal collector/transport systems located in the vicinity of the pavement edge, and sequential transverse outlet systems daylighted to surface drainage channels or attached to storm drains. Figure 1 gives a schematic illustration of the subdrainage components in a PCC pavement system. Basically stated, a positive drainage system should move water from the point of inception to the final exit through materials with sequentially lesser resistance (i.e., greater permeability) and greater capacity and should eliminate any conditions that would constrict flow.

This paper focuses on the first of these drainage components, the base layer under the driving surface. This layer is now constructed with OGPM to effectively transport surface water, which infiltrates the pavement surface through open cracks and joints to the remaining components of the drainage system. To intercept infiltrated surface water as quickly as possible, the OGPM layer is often placed immediately below the surface layer, as shown in Figure 1. Although it is possible for other sources of water, such as groundwater flow, artesian flow, and meltwater flow, to contribute to the total water to be drained by the OGPM, surface infiltration typically remains the dominant water source in structural pavement subdrainage design (*2*). To function properly as a drainage material, OGPM must be selected to meet the permeability and hydraulic gradient requirements of the pavement system.

OBJECTIVES

The general objectives of this paper are to detail the properties of open-graded permeable materials (OGPM) that satisfy the permeability and hydraulic gradient requirements in pavements. The specific objectives are

- To relate pavement longitudinal grade and cross slope to permeability requirements of OGPM,
- To evaluate the hydraulic properties of various aggregates in Illinois pavement construction, and
- To discuss methods for evaluating the permeability of OGPM.

PERMEABILITY AND HYDRAULIC GRADIENT REQUIREMENTS IN PAVEMENTS

Surface Infiltration

Infiltration of water into a pavement system is a very complicated phenomenon. Theoretical transient flow studies in uniformly porous pavements have provided some insight into this complex problem (*3*). Generally stated, the amount of water that may infiltrate a given area of pavement surface depends on the permeability of the intact surface, the number of ingress channels (joints and cracks), and the quantity of water supplied. Research conducted by Ridgeway (*4*) indicates that the condition of the ingress channel (i.e., sealed or unsealed and debris filled, wide or narrow cracks/joints) and the type of base layer that underlies the pavement surface (i.e., open graded or dense graded) both play a role in defining the infiltration capacity of the joint/crack. For high capacity joints/cracks, high intensity, short duration storms are important. For low capacity joints/cracks, storm duration is more important than intensity.

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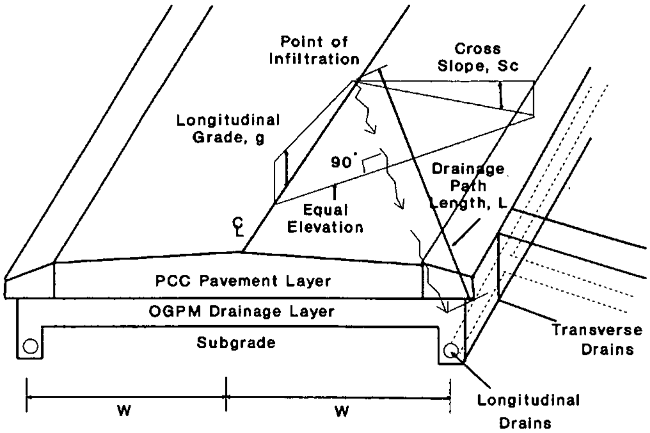


FIGURE 1 Typical pavement cross section.

Two separate methods for estimating surface infiltration rates in highway pavements are presented in the FHWA *Highway Subdrainage Design* manual (*5*). One approach recommended by Cedegren suggests calculating the infiltration by multiplying the 1 hr/1 year frequency precipitation rate by a standard coefficient based on pavement type. Throughout the United States, the 1 hr/1 year frequency precipitation rate varies from less than 0.5 cm/hr (0.2 in./hr) up to approximately 6.1 cm/hr (2.4 in./hr), which results in calculated infiltration rates approaching 0.5 cubic meters per day per square meter of pavement (m^3d/m^2) using this approach ($0.5\ m^3d/m^2 = 1.6\ ft^3d/ft^2$).

The second approach recommended in the FHWA manual (*5*) calculates the potential surface infiltration rate on the basis of the total length of cracks/joints per unit area of pavement and the infiltration capacity of the joints/cracks. For "normal" conditions, it is assumed that (a) the pavement surface layer is impermeable in uncracked locations, (b) continuous longitudinal joints separate at least two individual driving lanes and separate outer driving lanes and shoulders, and (c) transverse joints or cracks are regularly spaced. On the basis of those conditions, potential surface infiltration rates may be calculated using an equation of the form

$$q_i = I_c\left(\frac{N+1}{W} + \frac{W_c}{W\,C_s}\right) \tag{1}$$

where

q_i = surface infiltration rate (m^3d/m^2),
I_c = crack infiltration rate (m^3d/m),
N = number of traffic lanes,
W_c = average length of transverse cracks and/or joints,
W = width of the OGPM layer, and
C_s = spacing of transverse cracks or joints.

Equation 1 may be rewritten in a more generic form as

$$q_i = I_c\left(\frac{Y}{W}\right) \tag{2}$$

where Y is the average length of cracks/joints per meter of pavement, which is numerically equal to $(N + 1) + (W_c/C_s)$.

A value of $I_c = 0.223\ m^3d/m$ ($2.4\ ft^3d/ft$) is suggested for computations based on studies of saturated joints/cracks conducted by Ridgeway (*4*). It is important to note that this suggested value approximates the average infiltration rate measured through cracks in bituminous concrete pavements underlain by open-graded materials. Data presented by Ridgeway indicate wide variations in measured infiltration rates for these pavements with values ranging from 0.005 to 1.521 m^3d/m (0.05 to 16.37 ft^3d/ft). In addition, for tests conucted over saturated, unsealed joints and cracks in PCC pavements (PCC pavements were constructed over dense-graded base materials) measured infiltration rates varied from 0 to 0.181 m^3d/m (0 to 1.95 ft^3d/ft), with an average of 0.07 m^3d/m (0.74 ft^3d/ft). Also for one PCC test site with sealed joints, an infiltration rate of 0.116 m^3d/m (1.24 ft^3d/ft) was measured (*4*).

From evaluation of the Ridgeway data, it is observed that no one value of I_c can serve to quantify the spectrum of field conditions that may exist and that appropriate selection of I_c values should include an awareness of component pavement layers. Although further research is indicated, it may be generally concluded from collected data that (a) for PCC pavements the condition of crack/joint sealants does not play a significant role in altering surface infiltration rates over dense-graded materials and (b) the suggested value of $I_c = 0.223$ m^3d/m (2.4 ft^3d/ft) represents a reasonably conservative value for most cases where OGPM are to be considered.

When using Equation 1, it is important to recognize the relative sensitivity and interdependence of individual terms. For any given crack infiltration rate the total surface infiltration will increase as the number or length, or both, of included joints and cracks increase. Thus, as additional lanes are to be drained, the total infiltration will increase. However, when this total infiltration is averaged over the total width of the pavement to be drained, the net result is a reduction in the average infiltration rate, expressed in units of m^3d/m^2 (ft^3d/ft^2). This is because for one lane drainage two longitudinal joints are typically included, and each additional lane to be drained includes only one additional longitudinal joint. This reduced average infiltration rate, upon which required permeability will ultimately be based, does not result in a lower required permeability because there is a concurrent net increase in the length of the drainage path.

It must be recognized that the amount of water that passes through the OGPM base layer under each lane is not a constant value, as would be assumed during the averaging procedure detailed. The outside section of the OGPM base, which is below the lane closest to the longitudinal drain, must carry all of the infiltrated water from this lane in addition to water that infiltrates adjacent lanes that are drained toward this section. Therefore, the design infiltration rate for this outside OGPM base section should increase as the number of lanes to be drained increases to account for both infiltration and accumulated flow from the other lanes. In addition, the flow path length within this outside OGPM base section should remain constant, as determined from the pavements geometrics.

Flow Hydraulics

As water infiltrates the pavement surface it will flow both vertically and horizontally within the sublayers by following the path of least resistance. The geometry of constructed pavement sublayers (e.g., thin, gently sloping layers with relatively large horizontal extent) typically results in a dominant horizontal flow component. The key factors controlling the time required to adequately drain a pavement system with predominantly horizontal flow include hydraulic gradient, flow path length, and permeability. The general orientation of the controlling geometric parameters is given in Figure 1.

The flow-path gradient is an important parameter during horizontal flow analysis. This slope is a function of pavement geometry and may be obtained using the equation

$$S = \sqrt{S_c^2 + g^2} \qquad (3)$$

where

S = flow-path gradient (m/m),
S_c = cross slope (m/m), and
g = longitudinal gradient (m/m).

Figure 2 shows the potential range of flow-path gradients for a variety of longitudinal gradients and cross slopes (the flow-path gradient is independent of drainage layer width).

The length of the drainage path defines the distance the water flows from the furthest point of infiltration to the point of exit. This length is a function of the cross slope, the longitudinal gradient or slope, and the width of the drainage layer. The drainage path length is calculated using the equation

$$L = W\sqrt{1 + \left(\frac{g}{S_c}\right)^2} \qquad (4)$$

where L is the length of the drainage path in meters and W is the width of the drainage layer in meters. Figure 3 shows drainage path lengths for drainage layer widths varying from 3.7 to 14.6 m (12 to 48 ft), or 1 to 4 lanes, for longitudinal gradients varying from 0 m/m to 0.05 m/m (0 to 5 percent), and for cross slopes varying from 1 to 2 percent. As shown in Figures 2 and 3, increasing the pavement cross slope from 1 to 2 percent will increase flow-path gradients and significantly reduce flow lengths for any given longitudinal gradient. The end result will be a reduction in drainage times. Equations 3 and 4 may be rewritten in the form

$$\frac{S}{S_c} = \sqrt{1 + \left(\frac{g}{S_c}\right)^2} \qquad (5)$$

$$\frac{L}{W} = \sqrt{1 + \left(\frac{g}{S_c}\right)^2} \qquad (6)$$

By comparing Equations 5 and 6, it can be seen that for any longitudinal gradient and cross-slope combination, $L/W = S/S_c$, indicating the proportional increase in drainage path length over the baseline value W is exactly equal to the proportional increase in the slope of the flow path over the baseline cross slope of the pavement.

Permeability Requirements

The surface infiltration described represents a source of water for which drainage must always be provided. In addition,

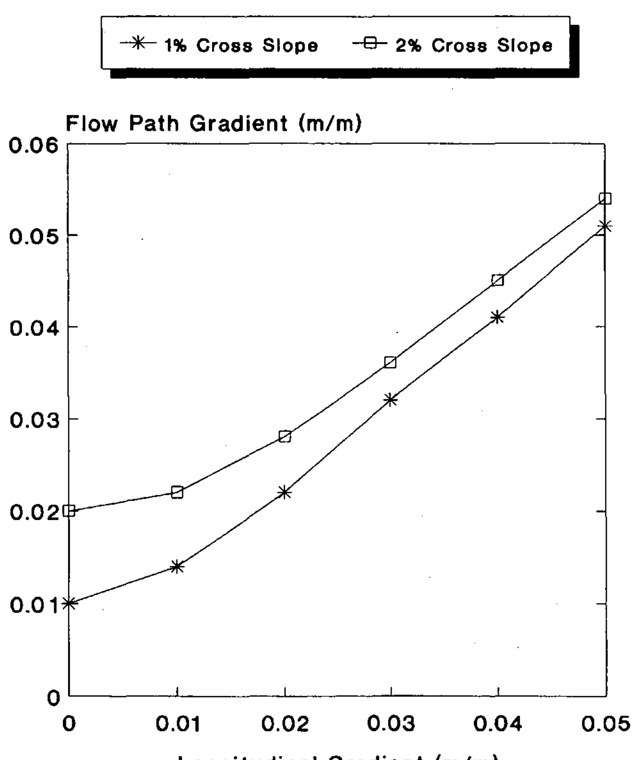


FIGURE 2 Flow path gradients.

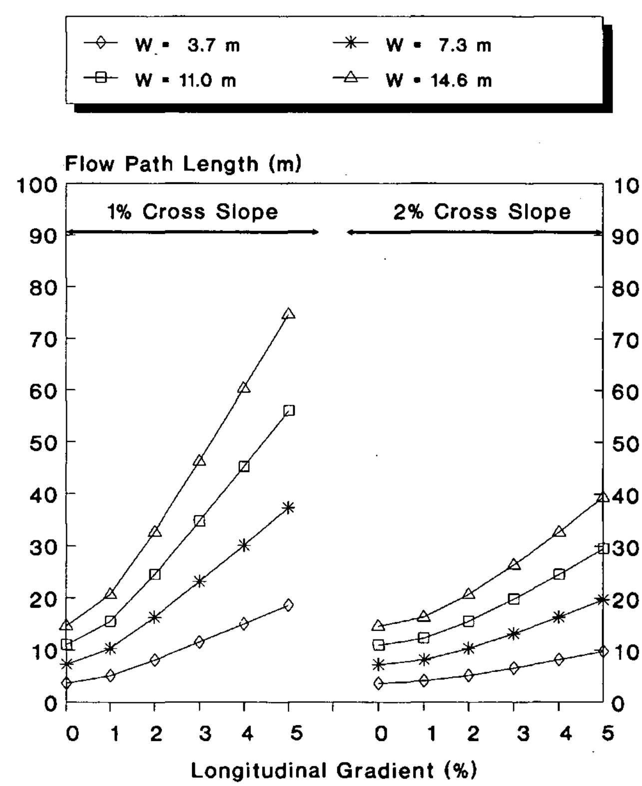


FIGURE 3 Drainage path lengths.

groundwater flow (either by gravity or artesian conditions) and meltwater (from surface ice, snow melt, ice lens development during frost action, or all) may provide significant increases to this design inflow that must pass through the drainage layer. The permeability requirements, which will be presented, account only for the surface infiltration rates caused by rainfall. In locations where other sources of water may be significant, adjustments to the permeability requirements will be warranted.

To effectively drain surface infiltration, the drainage layer must be designed with an optimal combination of thickness and horizontal permeability. The coefficient of transmissibility, defined as the product of thickness and permeability, controls the ability of the drainage layer to transmit water when flowing full or at a constant depth. It is often infeasible to design a drainage layer that will never become saturated; therefore, the design of the drainage layer is typically conducted to satisfy two conditions.

1. To provide adequate permeability to transmit all infiltrated water during rain under partially or fully saturated flow conditions and
2. To limit the time that the drainage layer is fully saturated to a relatively short duration of a few hours or less after the rain stops (*3*).

For any given design inflow, the required permeability will ultimately depend on the slope and length of the flow path. The FHWA design manual (*5*) includes a design nomograph for determining required permeability (partially saturated flow conditions) based on OGPM thickness, flow path length, flow path slope, and design rate of infiltration. By using this nomograph, required permeabilities were determined for a 10-cm (4-in.) drainage layer thicknesses with varying longitudinal gradient, cross slope, and drainage layer width combinations. Figure 4 gives the results of this analysis using a constant infiltration rate of 0.305 m^3d/m^2 (1.0 ft^3d/ft^2). The required permeabilities illustrated are directly proportional to design inflow rates and thus can be used to extrapolate any given design inflow rate. For example, the required permeability for a design inflow rate of 0.152 m^3d/m^2 (0.5 ft^3d/ft^2) would be exactly half of that required for a design inflow of 0.305 m^3d/m^2 (1.0 ft^3d/ft^2).

Figure 4 shows how the permeability requirements of the drainage layer can be significantly reduced by increasing cross slopes from 1 to 2 percent. One proposed solution for obtaining this increased cross slope within the drainage layer while still maintaining a finished pavement surface cross slope of something less than 2 percent is simply to grade the prepared subgrade layer with a 2 percent cross slope. Assuming the surface cross slope of the compacted OGPM layer will be less than 2 percent (equal to the finished pavement surface), the net result will be to provide for a variable thickness OGPM layer that becomes thicker toward the edge. This solution also provides for increased flow capacity in the critical pavement edge locations.

Permeability Measurements

Throughout the years, a wide variety of theoretical and empirical equations has been presented for estimating the coefficient of permeability of porous media (*6–8*), or more correctly the saturated hydraulic conductivity, k_s. It is desirable to evaluate the hydraulic conductivity through field or laboratory testing, but it is often necessary to estimate this quantity on the basis of correlations with material properties such as grain size characteristics, dry density, and porosity or void ratio.

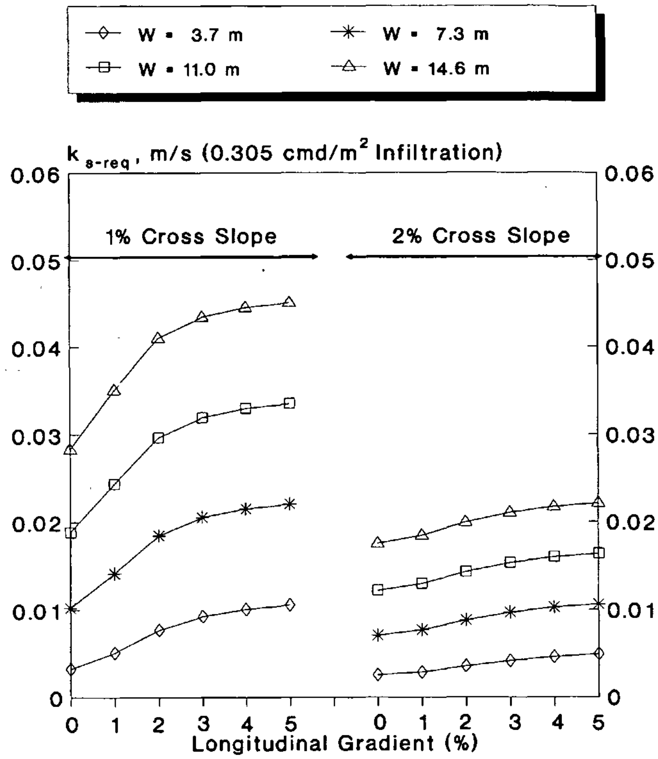


FIGURE 4 Required permeability for 10-cm OGPM.

Permeability Estimation Based on Gradation Analysis

One simple method for obtaining estimates of the hydraulic conductivity of materials uses an analysis of the gradation band of the material. A figure developed by Cedegren (*9*) and Cedegren et al. (*10*) is provided in the FHWA manual (*5*) as an aid to estimating the hydraulic conductivity of selected materials. Another simple gradation-based analysis method, which is also included in the FHWA manual (*5*), was developed from statistical correlations between measured hydraulic conductivities and properties known to influence hydraulic conductivity (*11–15*). The most significant properties found were effective grain size, D_{10}, porosity, n, and percent passing the No. 200 Sieve, P_{200}. The percentage passing, P_{200}, accounted for over 91 percent of the variation in the hydraulic conductivities measured. A nomograph is provided that graphically solves the equation

$$k_s = \frac{6.214 \times 10^5 D_{10}^{1.478} n^{6.654}}{P_{200}^{0.597}} \tag{7}$$

The character of the fines (e.g., plastic, nonplastic), compacted density, and hydraulic gradient may significantly alter in-place permeability. Therefore, it is suggested that the estimation methods described be used only to establish trial gradations targeted to achieve desired permeabilities rather than for final design. (Graphical procedures currently employed in the FHWA manual yield permeability estimates in units of feet per day (fpd). To convert to SI units of meters per second (m/sec), use the relation 1 fpd = 3.528 μm/sec.)

Equation 7 was used to analyze standard Illinois DOT gradation specifications suitable for use as OGPM or filter materials and for the AASHTO #57 gradation (the AASHTO #57 gradation is used for OGPM in some states). Figure 5 shows the mid-range gradation bands for these materials. The fine, mid-range, and coarse specification limits of the materials were analyzed in each case. Table 1 gives the results of this analysis and indicates how the hydraulic conductivity may vary significantly between the fine and coarse limits of most of the gradation specifications. Actual laboratory measurements of permeability for these materials are discussed later.

The FHWA *Highway Subdrainage Design by Microcomputer* manual, developed at the University of Illinois (*16*), includes a software program DAMP (Drainage Analysis & Modeling Programs). The DAMP program provides computerized solutions for the design charts and equations included in the FHWA manual. The program incorporates Barber and Casagrande's equations for calculating drainage times to various saturation levels, along with analysis methodology for determining AASHTO drainage coefficients. This program was used to determine the estimated drainage time from complete saturation to 85 percent saturation for each of the materials. These values, which are also included in Table 1,

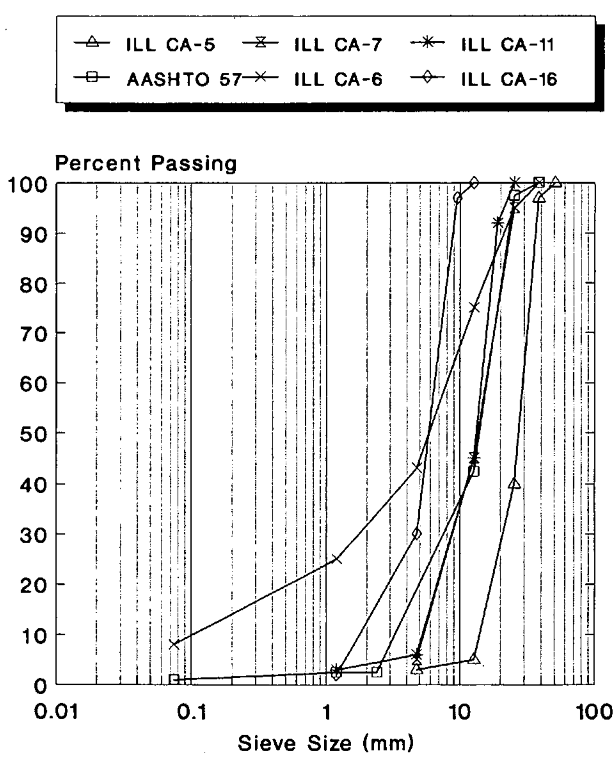


FIGURE 5 Midrange gradation bands for selected materials.

are important because many granular materials experience significant strength loss and high deformations as saturation levels exceed 85 percent (*17,18*). It should be noted that the Barber equations tend to produce slightly longer drainage times and some researchers believe these are more appropriate than the Casagrande equations when analyzing base course drainage. It should also be noted that calculated drainage times assume an initially saturated medium, which is a condition contrary to the partially saturated flow regime assumed during the determination of hydraulic requirements of existing methods (*5*).

Permeability Measurement from Laboratory Testing—Constant Head

Darcy's law for saturated steady-state flow may be used to estimate the hydraulic conductivity of materials using the equation

$$Q = k_s\, i\, A \qquad (8)$$

where

Q = volumetric flow rate (m^3/sec),
k_s = hydraulic conductivity (m/sec),
i = hydraulic gradient (m/m), and
A = cross-sectional area of flow (m^2).

Equation 8 can be rewritten in the form

$$k_s = \frac{Q}{i\, A} \qquad (9)$$

and used to compute hydraulic conductivity based on flow parameters obtained during constant head permeability testing. ASTM Test Method D2434-68 Standard Test Method for Permeability of Granular Soils (Constant Head) also uses this relationship. Assuming that saturated flow, constant head conditions exist in the field, the potential exists to use Equation 9 to directly calculate required permeability of a porous medium based on design infiltration and geometric parameters previously discussed.

Research conducted as part of IHR Project 525 Pavement Subbases (*1*) indicated the usefulness of a constant head permeability device that would more closely represent field conditions by producing water flow perpendicular to the direction of compaction of a large OGPM sample. To satisfy this requirement, the flow chamber given in Figure 6 was fabricated on the basis of a previously built apparatus used for measuring in-plane flow through geocomposites and geotextiles. The flow chamber is equipped with a removable mold that allows for the placement of material samples with cross-sectional areas up to 0.09 m^2 (1 ft^2) and lengths up to 0.91 m (3.0 ft). The hydraulic gradient across the sample can be varied from 0 m/m up to 4 m/m by adjusting water flow or downstream weir heights, or both.

During testing, saturated samples were subjected to flows with hydraulic gradients ranging from near 0 to more than 1.0 m/m. The upstream head, downstream head, and flow height above the V-notch weir were measured with a Lowry point gauge capable of reading to the nearest 0.3 mm (0.001 ft). The volumetric flow rate through the sample was directly

TABLE 1 Calculated Permeabilities and Drainage Times for Selected Materials

Material Designation	D10 (mm)	P200 (%)	Saturated Permeability (m/s)	Drainage Time to 85% Saturation: Barber Equations (hrs)	Drainage Time to 85% Saturation: Casagrande Equations (hrs)
OGPM Materials					
IDOT - CA5					
Fine	12.9	6	2.68E–02	0.170	0.150
Midrange	14.1	3	4.63E–02	0.090	0.080
Coarse	20.4	0	6.00E–01	0.005	0.004
IDOT - CA7					
Fine	4.7	10	4.42E–03	1.210	1.160
Midrange	5.3	5	8.06E–03	0.630	0.590
Coarse	6.4	0	1.06E–01	0.030	0.030
IDOT - CA11					
Fine	2.8	6	2.87E–03	1.940	1.890
Midrange	5.2	3	1.07E–02	0.460	0.420
Coarse	6.5	0	1.23E–01	0.030	0.030
AASHTO #57					
Fine	2.7	2	5.08E–03	1.040	0.990
Midrange	3.2	1	1.00E–02	0.490	0.460
Coarse	4.6	0	7.06E–02	0.060	0.050
Filter Materials					
IDOT - CA6					
Fine	0.074	12	7.06E–06	788.000	950.000
Midrange	0.1	8	1.76E–05	462.000	557.000
Coarse	1.2	4	9.70E–04	6.360	6.480
IDOT - CA16					
Fine	1.45	4	1.35E–03	4.400	4.420
Midrange	1.75	2	2.69E–03	2.080	2.030
Coarse	2.91	0	3.53E–02	0.130	0.110

Saturated permeabilities calculated assuming dry density = 1.76 metric tons per cubic meter
1 m/s = 2.77 E+05 ft/day

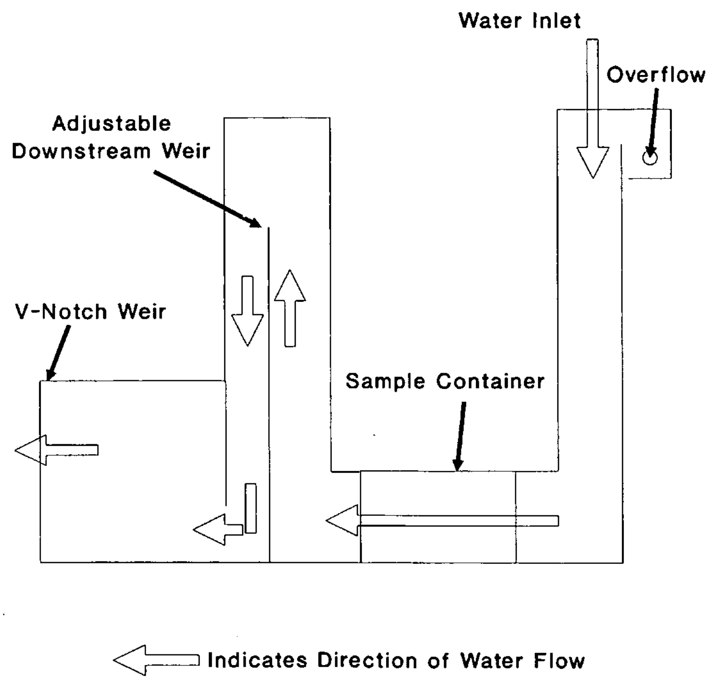


FIGURE 6 Schematic of IHR-525 flow chamber.

calculated based on V-notch weir flow heights. Hydraulic conductivities of the various materials were calculated using Equation 9. Figure 7 gives the results of tests conducted on typical Illinois DOT gradation specifications. It is interesting to note that a significant drop in hydraulic conductivity (approximately 50 percent) occurs as the hydraulic gradient is increased. This is most likely caused by turbulence within the sample, which both restricts flow volume and causes a divergence from the assumed laminar flow conditions on which Darcy's equation is based. This trend, which occurs under hydraulic gradients well in excess of typical in situ conditions, was typical for all of the materials tested.

Permeability Measurement from Laboratory Testing—Falling Head

The saturated hydraulic conductivity of a material may also be determined under falling head conditions using the equation

$$k_s = \left(\frac{a\,l}{A\,t}\right) \ln\left(\frac{h_1}{h_2}\right) \tag{10}$$

where

a = cross-sectional area of reservoir (m^2),
l = length of specimen (m),
A = cross-sectional area of specimen (m^2),
h_1 = head loss across specimen at time t_1,
h_2 = head loss across specimen at time t_2, and
t = elapsed time ($t_2 - t_1$).

Various types of falling head apparatus have been fabricated and used by states to quantify the hydraulic conductivity of aggregate samples. On the basis of the particular dimensions of the apparatus used, hydraulic conductivity is typically determined directly using the equation

$$k_s = \frac{B}{t} \tag{11}$$

where B is the permeameter constant, which is numerically equal to $(al/A)*\ln(h_1/h_2)$.

The New Jersey DOT fabricated a falling head permeameter assembly (*19*) similar to that shown in Figure 8, which reportedly was used successfully for materials having hydraulic conductivities ranging from 3.528×10^{-4} to 7.1×10^{-2} m/sec (100 to 20,000 fpd).

Longitudinal Drainage Requirements

The longitudinal drain system is typically composed of three components: a geotextile filter fabric wrapping, an aggregate trench backfill, and a perforated pipe. As a system, the fabric wrapping acts as a protection against subgrade intrusion, the aggregate trench backfill as an envelope/permeable medium, and the pipe as a drainage conduit. For this system to perform adequately, the following conditions should be met:

1. The filter fabric must satisfy filtration requirements dictated by the particle size distribution of the subgrade materials.

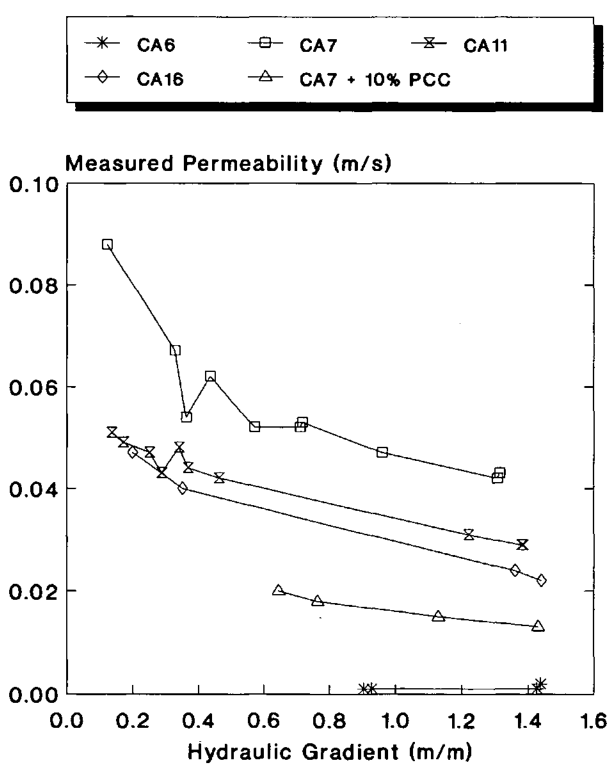


FIGURE 7 Measured permeabilities using IHR-525 flow chamber.

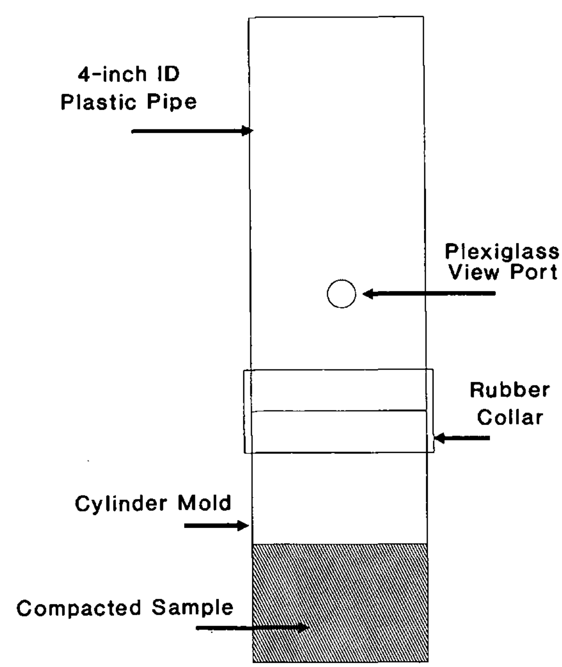


FIGURE 8 Schematic of New Jersey DOT falling head permeameter.

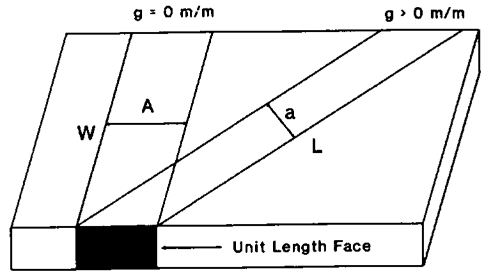
2. The aggregate trench backfill should have a hydraulic conductivity at least as great as the OGPM base layer.
3. The pipe must have sufficient dimensions and perforations to handle expected inflow.

Condition 1 may be satisfied using a number of design criteria (*20–22*). As an example, Carroll (*21*) suggests selecting a filter fabric with an apparent opening size (AOS), which is less than 2 or 3 times subgrade particle size for which 85 percent of the subgrade is finer (D_{85}).

Condition 2 may be satisfied by selecting aggregate backfill materials identical to those used for the OGPM base layer. Care must be exercised to ensure that the trench backfill material is composed of high permeable materials, otherwise a damming effect may result that would restrict flow within the OGPM base layer.

Condition 3 is typically satisfied using a design nomograph presented in the FWHA design manual (*5*). The use of this nomograph to determine the required pipe size uses three basic input values: the flow rate into the drain, q_d (ft³d/ft), the distance between transverse outlets (ft), and the pipe gradient (ft/ft). The first of these inputs is calculated based on q_n, the net design inflow (ft³d/ft²) multiplied by L, the length of the flow path (ft), providing the proper units of ft³d/ft of pipe. The remaining inputs are determined directly from design conditions. (English units were used to match input values used within the nomograph.)

The equation $q_d = q_n * L$ for calculation of flow rate into the drain can increase the conservative value of inflow for drainage design. As presented, the length of the flow path is used. In reality, the width of the drainage layer, W (meters or feet) should be used. The reason for this statement can be explained in two ways. First, in the initial calculations for inflow, the units of cubic meters per day per square meter (cubic feet per day per square foot) are obtained by dividing the inflow rate, with units of cubic meter per day per meter of pavement, by the width of the drainage layer, with units of meters (feet), to produce units of cubic meters per day per square meter (cubic feet per day per square foot). It would therefore be logical to multiply by the width of the drainage layer (meters or feet) to revert back to inflow rate in units of cubic meter per day per meter (cubic foot per day per foot of pavement). Second, the required pipe size is determined from the inflow quantity per unit length of pipe. The inflow quantity can be envisioned as the quantity of inflow, in units of cubic meters per day per square meter (cubic feet per day per square foot), multiplied by the surface area accepting this inflow rate, square meter per meter (square foot per foot), which results in inflow quantities with units of cubic meter per day per meter (cubic foot per day per foot). For the baseline case, where $g = 0$ m/m (0 ft/ft), the surface area accepting the inflow is a rectangle with a length equal to the width of the drainage layer, W, and a width equal to the unit pavement length (AREA $= W * 1$). If a longitudinal gradient is involved, the drainage area accepting inflow becomes a parallelogram, with an average length equal to the flow path length, L, and a width equal to W/L (AREA $= L * W/L = W$). Figure 9 shows this concept. Therefore, because the surface area accepting inflow remains constant regardless of longitudinal gradient, the design inflow rate into a unit length of pipe should also remain constant.



$$a = A * W/L$$
$$L * a = L * A * W/L = W * A$$

FIGURE 9 Surface infiltration areas.

The implication of the present method is that for those cases where $g > 0$ m/m, using the design nomograph with flow rate equal to $q_n * L$ will result in required pipe sizes larger than necessary. This error can be eliminated by replacing the flow path length, L, by the width of the drainage layer, W, in the equation. This will result in constant pipe inflow quantities throughout the length of any given project, regardless of longitudinal gradient, as long as the width of the drainage layer remains constant.

SUMMARY AND CONCLUSIONS

This paper focused on the permeability aspects of OGPM necessary for various surface infiltration rates. Different methodologies have been presented for the calculation of surface infiltration and for the determination of required permeabilities. It has been shown that pavement geometry, including cross slope, longitudinal gradient, and drainage layer thickness and width, play an important role in these calculations. It is apparent that there is no magic number that can be given for a required permeability that will satisfy all conditions while still maintaining a measure of economy. For conditions that prevail in Illinois, typical permeability requirements for Interstate highway design would range from approximately 3.5×10^{-3} m/sec to 10.6×10^{-3} m/sec (1,000 to 3,000 fpd) when designing a 10-cm (4-in.) base layer thickness and a drainage width of 3.6 m (12 ft). This required permeability may be drastically increased under adverse conditions of steep slopes, super elevations, or multiple lanes, or all three.

Permeability requirements of OGPM represent one important function that must be considered in design; however, the provision for permeability must be balanced by the quality of support provided by the OGPM to the surface layer. Although this topic is beyond the scope of this paper, items for further study include

1. Density requirements necessary during placement of the OGPM,
2. Construction stability of the OGPM needed to ensure proper placement of surfacing materials without loss of permeability,
3. Evaluation of the degradation of OGPM during service to determine whether support conditions deteriorate over time, and

4. Investigation of OGPM hydraulic conductivity to determine whether it changes significantly over time because of degradation, intrusion, and other factors.

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