

Gas transmission in geocomposite systems

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Over the past decade, we have had the pleasure of teaching over 300 courses and seminars on the use of geosynthetics for landfill and general civil engineering projects. Just when you begin to think that all problems are solved, a new failure or well thought out question demonstrates that we are not all science at this time. One area of continued concern regards the design of gas collection systems within the caps placed over landfills. We thought it might be timely to review just what we do know and what we do based on faith (or empirical experience).

Darcy's Law

We have traditionally modeled the movement of both gas and fluids through porous media using Darcy's Law as follows:

$$Q = kiA \quad \text{Eq. 1}$$

Where Q is the flow rate (L^3/T), k is permeability (L/T), i is the dimensionless flow gradient defined as the head loss (L) divided by the flow length (L), and A is the area of flow (L^2). This law assumes that the permeability is independent of the gradient, which requires that the flow be laminar. The requirement for laminar flow means that we should be conscious of the concept of laminar, transitional, and turbulent flows of fluids and their respective properties. Classical definitions of these flow regimes are:

Laminar flow occurs when the fluid particles move parallel to each other such that their respective flow lines do not cross. Under these flow conditions, the relative velocity between the flow lines is controlled by the viscosity of the fluid.

Turbulent flow occurs when the particle flow lines cross such that a mixing occurs and energy is lost due to both viscosity and the mixing. Since additional mechanisms exist to remove energy from the fluid, turbulent flow is inherently less efficient than laminar flow.

So how do we know when we move from laminar to turbulent flow? Lets start with a review of flow in natural soils and then move to geosynthetic drainage media. Studies performed by men such as Terzaghi (1915-1925) and Fancher (1933) determined that the applicability of Darcy's Law to soils was limited by the Reynold's number, Re , of the flow (Reynolds, 1883). Re is defined as:

$$Re = \frac{dvp}{\mu} = \frac{dv}{v} \quad \text{Eq. 2}$$

where d is the diameter of flow path (L), v is the average velocity of flow, ρ is the fluid density (M/L^3), μ is

the dynamic viscosity ($M-T/L^2$) and ν is the kinematic viscosity (L^2/T). Values of ρ and μ for common liquids and gases of concern are presented in **Table 1**. Note that these values are temperature dependent. What complicates our use of Reynold's number is the discovery that value of R_e at the transition from laminar to turbulent flow is dependent on the flow diameter d . For flow of fluids in pipes, the transition from laminar flow, to transitional flow, to turbulent flow occurs at R_e values of 2000 and 4000, respectively. However, for porous media, essentially having thousands of interconnecting flow tubes, the transition for laminar flow occurs at values of R_e from approximately 1 to 10! **Figure 1** shows test data from Fancher's work that clearly shows these transitions for many sands. This work included oil, water and air as fluids. This also means that fluid flows in gravel and riprap will be turbulent and not obey Darcy's Law, *since the apparent permeability, k , is not independent of the gradient, i* . Most engineers are aware, however, that Darcy's Law is commonly applied to such coarse materials.

	Density, ρ		Unit Weight, γ		Dynamic Viscosity, μ			Kinematic Viscosity, ν	
	slug/ft ³	kg/m ³	pcf	N/m ³	Centi-poise	lb-s/ft ²	N-s/m ²	ft ² /s	m ² /s
Water	1.94	1000	62.4	9800	1.01	2.12E-5	1.01E-3	1.09E-5	1.01E-6
Air	.00234	1.2	.0753	11.8	.018	3.78E-7	1.79E-5	1.63E-4	1.48E-5
CO2	3.55E-3	1.83	.114	17.9	.015	3.15E-7	1.50E-5	8.88E-5	8.21E-6
Methane	1.29E-3	.666	.0416	6.54	.011	2.31E-7	1.1E-5	1.79E-4	1.65E-5
LFG ⁽¹⁾	2.53E-3	1.31	.0815	12.8	.0132	2.77E-7	1.32E-5	1.09E-4	1.01E-5
(1) 55% CO ₂ , 45% CH ₄									

TABLE 1. INTRINSIC PERMEABILITY VARIABLES FOR COMMON FLUIDS AND GASES (70°F)

For laminar flow, Darcy's Law can be expressed in terms of intrinsic permeability as:

$$Q = \frac{K \cdot \gamma_f}{\mu_f} \cdot i_f \cdot A \quad \text{Eq. 3}$$

where γ_f is the density of the fluid, μ_f is the dynamic viscosity of the fluid, and i_f is the fluid gradient. The permeability, k , commonly used by engineers is related to the intrinsic permeability, K , as follows:

$$k_f = \frac{K \cdot \gamma_f}{\mu_f} \quad \text{Eq. 4}$$

Thus if the permeability is known for a given fluid (or gas), it can

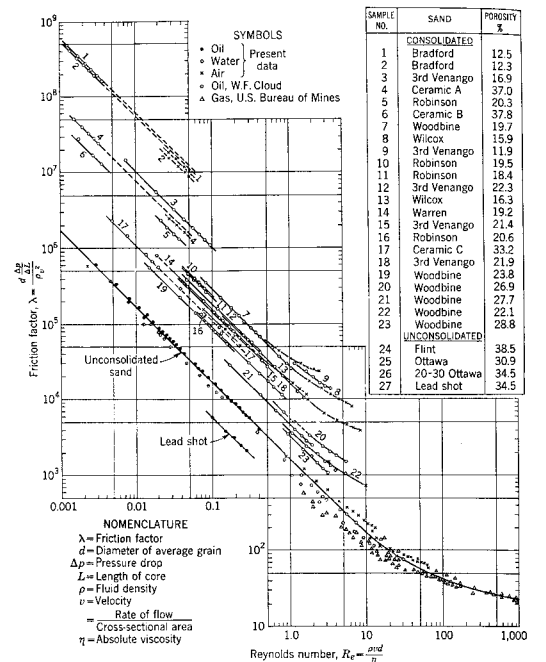


Figure 1: Fluid flow in sands.

be determined for any second fluid using the following expression:

$$\frac{k_1}{k_2} = \frac{\mu_2}{\mu_1} \cdot \frac{\gamma_1}{\gamma_2} \quad \text{Eq. 5}$$

This is true only for laminar flow, e.g. permeability, k , is independent of gradient, i . Thus, knowing the permeability of the porous media to water, k_{h20} , the permeability for air, methane, and landfill gas can be obtained by dividing k_{h20} by 14.8, 16.3, and 10.0 respectively.

Application to gas flow in geotextiles

The flow of air (and water) in the plane of a geotextile is commonly measured using a radial flow device. The geotextile sample is cut in a donut shape and the fluid flows from the pressurized interior, p_i , to exterior atmospheric conditions. The flow gradient is:

$$i = \frac{\frac{\rho t}{\gamma f}}{\tau_r} \quad \text{Eq. 6}$$

where τ_r is the difference between the inner and outer diameter of the sample. Unfortunately this device cannot be used in other geosynthetic drainage media such as geonets due to their large opening size and non-radial structure. Radial transmissivity tests are commonly performed only by manufacturers and a limited number of people at commercial laboratories, including Rich Lacey at Geotechnics Inc., and Sam Allen at Texas Research Institute. A draft standard for this test is now under consideration by Committee D35 using a larger sample diameter (12-in. outer) than used in generating the data presented in this paper.

Sample radial transmissivity data for a 17 osy nonwoven geotextile (Bove, 1983), is shown on **Figure 2**. The pressure gradient is the difference between the interior and atmospheric pressures. The actual flow gradient, i , can be calculated by converting interior pressure to head, pi/γ , and dividing by flow length, $((5.-2.25)/ 2=1.375'' =0.11')$. Thus the flow gradient for a test using air, $\gamma = 0.0753$ pcf, and an internal pressure of 0.4 psi (57.6 psf) would be $6675 ((57.6/0.0753) /0.11)$.

The average flow velocity, V_{avg} , is calculated from the flow volume as follows:

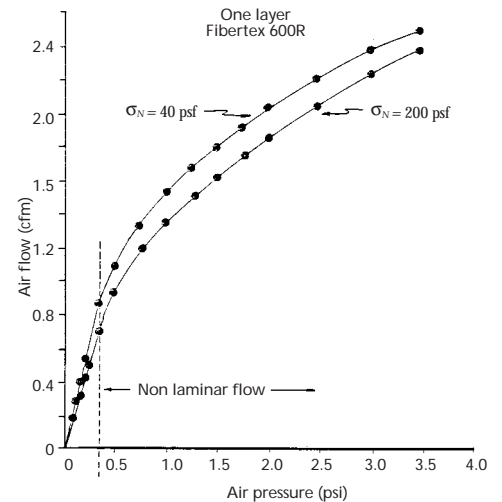


Figure 2: Geotextile radial air flow test.

$$V_{avg} = Q \div [t \cdot \frac{\pi(D_o - D_i)}{2}]$$

Eq. 7

where D_o and D_i are the outer and inner diameters of the sample, respectively. For the 0.4 psi test on **Figure 2**, the flow rate is 0.7 cfm at 2000 psf normal load, $t = 0.2$ in., $D_o = 5.0$ in., and $D_i = 2.25$ in. The calculated average velocity is equal to 0.73 ft/sec. The Reynold's number for this test can be calculated from Eq. 2 with $d \approx 212$ mm or 6.96×10^{-4} ft (AOS = #70 sieve) as follows:

$$R_e = \frac{dv}{\nu} = \frac{6.96 \cdot 10^{-4} \cdot 0.73}{1.63 \times 10^{-4}} = 3.1 \quad \text{Eq. 8}$$

This would indicate laminar flow. The air transmissivity, θ_{air} , value at the 0.4 psi air pressure can be calculated as follows:

$$\theta = \frac{Q}{i} = \frac{Q \ln(D_o / D_i)}{2\pi(\Delta p / \gamma)} \quad \text{Eq. 9}$$

Solving Equation 8 for θ_{air} yields 1.1×10^{-4} ft³/min-ft (1.7×10^{-7} m³/s-m). Based on Equation 5, this would predict a water transmissivity for the geotextile of $14.8 \times 1.1 \times 10^{-4}$ ft³/min-ft or 1.63×10^{-3} ft³/min-ft.

For the above test, the flow rate when water was used at the same pressure difference was reported as approximately two orders of magnitude less than the air flow. This provides a check on our intrinsic permeability conversion as follows:

$Q_{air} = 0.7$ cfm at 0.4 psi (57.6 psf) air
pressure difference

$$i_{h2o} = 2\pi(57.6/62.4)/(1\ln(5/2.25)) = 7.26$$

$$Q_{h2o} = 1.63 \cdot 10^{-3} \cdot 7.26 = 1.18 \cdot 10^{-2} \text{ cfm}$$

$$\text{Ratio } Q_{air}/Q_{h2o} = 0.7/1.18 \times 10^{-2} = 59$$

Clearly, gas flow in geotextiles must be under low flow velocities such that laminar flow is assured before the intrinsic permeability conversion is an accurate predictor of flow rate. Prior work by Emcon, 1980, indicates that landfill gas collection systems are typically under laminar flow conditions. Sample applications of this theory to actual field geotextile gas-collection systems including the influence of partial satu-

ration have been presented by Thiel, 1999, and will be of interest to all landfill designers.

Application to gas flow in geonets

Geonets are the “gravel” of geosynthetic drainage media, and therefore would reasonably be expected to have turbulent flow. This means the permeability, and therefore the transmissivity, are influenced by the gradient. This is clearly shown on **Figure 3** by the typical water transmissivity data obtained from a geonet. The approximate diameter of the flow path as increased from the 0.212 mm of the previous geotextile to approximately 6.1 mm (0.02 ft). Interpretation of this data is aided by solving for the flow velocity such that the Reynold’s number for the flow is known. At a gradient of 0.02 and normal load of 512 psf (25 kPa), the flow rate is θ_{h20}^i or $17.8 \times 10^{-5} \text{ m}^3/\text{sec-m}$ ($8.9 \times 10^{-3} \times 0.02 \text{ m}^3/\text{sec-m}$). For a typical geonet thickness of 6 mm, this indicates an average flow velocity of $3.0 \times 10^{-2} \text{ m/s}$ ($9.2 \times 10^{-3} \text{ ft/sec}$). The Reynold’s number for this flow is then equal to:

$$R_e = \frac{dv}{v} = \frac{0.02 \cdot 9.2 \cdot 10^{-2}}{1.09 \cdot 10^{-5}} = 168 \quad \text{Eq. 10}$$

Similarly, the Reynold’s numbers at gradients of 0.1 and 1.0 are equal to 394 and 1345, respectively. The actual flow rates for this test are plotted as a function of gradient on Figure 4. Since laminar flow in sands is defined at $Re < \approx 10$ and pipes at $Re < 2000$, it is reasonable to assume that the transition from laminar flow for geonets occurs at approximately $100 < Re < 500$ for geonets. This will occur in most geonets at a flow gradient less than 0.1.

Recommendation

Note: the intrinsic permeability conversion between fluids is conservative if the flow experienced in the field is laminar. This will be true whether the measured flow, in the laboratory transmissivity test, is turbulent or laminar. **Figure 3** clearly shows that under turbulent flow, the measures of transmissivity decrease dramatically. Projections based on turbulent measurements in the laboratory will be conservative in field applications as long as laminar flow conditions exist in the field. This is irrespective of the field gradient. Thus, it is very important that the actual flow conditions in the field application be verified.

Conversely, if the flow conditions in the field are turbulent, then the use of intrinsic permeability to convert a laboratory transmissivity obtained under laminar flow conditions will be non-conservative. When field conditions indicate turbulent flow, the laboratory test must be performed under similar turbulent flow conditions. For most drainage materials, the measured transmissivity under turbulent conditions will approach

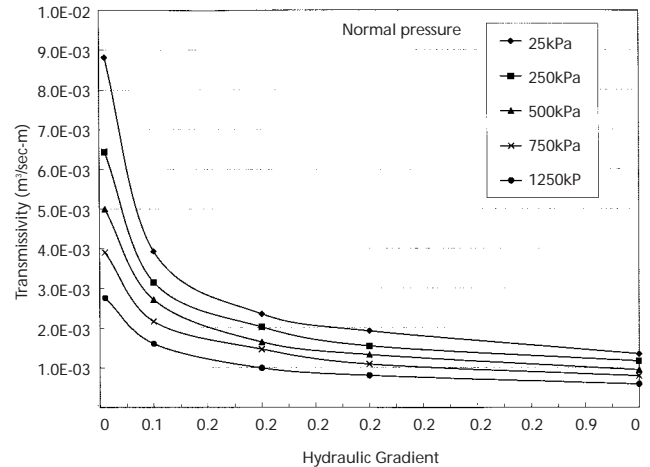


Figure 3: Transmissivity vs. hydraulic gradient for geonet.

a constant as the flow gradient increases. Thus, a lower value for the transmissivity under turbulent flow conditions can be obtained by using a suitably high flow gradient. At this time, the authors do not have data to support the use of the intrinsic permeability fluid “ratios” to convert transmissivity measured under turbulent flow conditions.

For coarse drainage media such as geonets, it is recommended that the laboratory water transmissivity be obtained at as low a gradient as practical and repeatable. For most geonets, this is a gradient of 0.1. The field transmissivity for fluids other than water is then determined using the relationship presented in Equation 5. The Reynold’s number for the field flow conditions must be evaluated to ensure that laminar flow conditions exist ($R_e < \approx 10$). Sample applications of this theory related to geotextiles in actual field gas-collection systems including the influence of partial saturation have been presented by Thiel, 1999, and will be of interest to all landfill designers.

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