Geosynthetics - 7th ICG - Delmas, Gourc & Girard (eds) © 2002 Swets & Zeitlinger, Lisse ISBN 90 5809 523 1

Determination of gas transmissivity for a high flow capacity drainage geocomposite

G. ELLITHY, Design Engineer, Tenax Corporation, USA
A. ZHAO, VP Engineering, Tenax Corporation, USA

ABSTRACT: In this paper an attempt is made to determine both the air and water transmissivity of a high flow drainage geocomposite. The Air transmissivity is measured using the water transmissivity apparatus with special setup. The correlation between the flow of both fluids at different gradients is determined, taking into account the non-laminar flow at higher gradients. The critical Reynolds number for the geocomposite considered in this study is determined. A design example for gas transmissivity calculation based on the study's findings is provided.

1 INTRODUCTION

1.1 *Background*

Most landfill waste generates gas known as landfill gas (LFG). It is essential to relieve this gas pressure from underneath the cap liner to prevent slope instability caused by the reduction in effective stresses. Bioreactor landfills generate more gas fluxes than regular landfills. As the trend for constructing bioreactors is increasing, the need for higher transmissivity gas relief layers is increasing as well. The current design for gas relief layers or gas strip drains utilizes the intrinsic permeability concept that mandates that the flow is laminar. It also requires the validity of Darcy's law for both gas and water flow through the drainage medium as described in Thiel (1998). However, testing repeatedly shows that for drainage geocomposites with high flow capacities, the water flow may not be laminar at the low hydraulic gradients that are typically measured.

1.2 Available data

Very few attempts have been made to measure gas transmissivity in the lab for drainage geocomposites that are routinely tested for water transmissivity. Most of the available data are done on a radial transmissivity device, on geotextiles, at very high pressure gradients, at which the correlation to water transmissivity can be questionable. Faure et. al (1994) studied the flow behavior of water and air through a uniquely structured geocomposite that consisted of an arrangement of small pipes over nonwoven geotextile.

2 TESTING PROGRAM

The testing program presented in this study is focused on measuring both the air and water transmissivity of a drainage geocomposite typically used in landfill capping applications for surface drainage and gas relief underneath liners.

2.1 Materials and measuring apparatus

The material used in the testing program is a high flow capacity drainage geocomposite that will be referred to herein as DGC. The DGC is composed of a high density polyethylene geonet core with a triaxial structure and 0.008 thickness. Two needle-punched nonwoven geotextiles are laminated on both sides of the core. The water flow was tested in a regular transmissivity machine per ASTM standard D4716. Figures 1 and 2 show the special setup that was prepared for measuring the gas transmissivity.

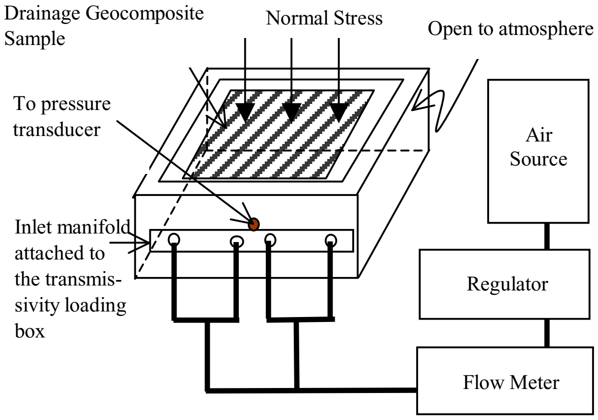

Figure 1. Special setup for measuring gas transmissivity.

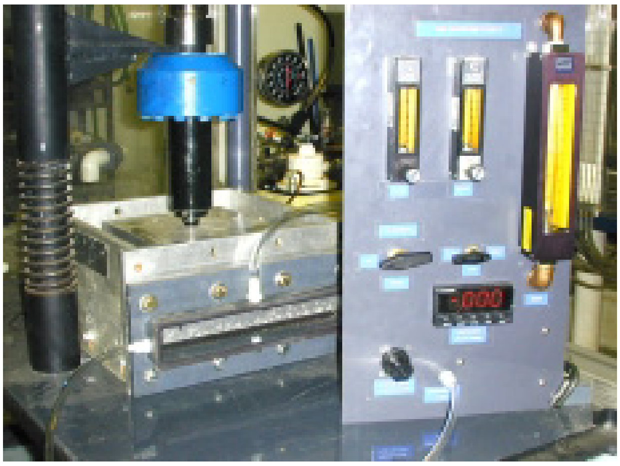

Figure 2. Photo shows the set up used for measuring gas transmissivity

The air transmissivity box is similar to the type used in water transmissivity with a 305 mm x 305 mm (12 inches x 12 inches) loading area. The upstream of the box was sealed and connected to the air source. The air source passes through a regulator, flow meter and a pressure transducer that measures the pressure drop between the upstream and the downstream of the sample at a given flow rate. The pressure transducer has a 0.0254 m (1 inch) of water maximum reading, and accuracy of 0.25%. Three different flow meters with 4, 45 and 280 lpm capacity, were used to ensure the accuracy of the readings along the measured range of airflow.

2.1 *Testing conditions*

Three normal stresses, 12, 24, and 48 kPa (250, 500, and 1,000 psf), typical values in landfill capping, were used for the testing. However, the differences in the results at the different stresses were insignificant, therefore, the results presented are considered to be valid up to 48 kPa (1,000 psf).

The gradients for the flow of both fluids through the drainage geocomposite were selected to be within the practical range observed in the field. Higher gradients were also selected to study the affect of turbulence on the flow behavior of both fluids. Air flow was evaluated from a gradient of 0.06 to 60, and the water from a gradient of 0.01 to 2.2.

The calculation of the pressure gradient of air flow assumes the unit weight of air to be 1.18x10^{-2} kN/m^3. The gradient for the water testing is a head gradient and it was controlled by the limitation of the transmissivity machine (size of the reservoir).

3 RESULTS AND ANALYSIS

3.1 *Flow against gradient*

The flow in m^3/min is plotted against the corresponding gradients for both fluids. Figure 3 shows the flow of water and air up to a gradient of 3.0. Figure 4 shows the same relationship but up to the full range of gradients at which the air flow was measured. The water testing showed a non-laminar flow for a gradients as low as 0.01. For the air testing, the flow started to become non-laminar at gradients higher than 3.0.

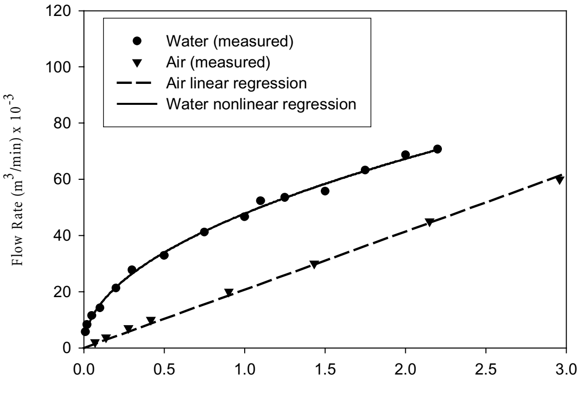

Figure 3. Flow against gradient (up to 3.0) for water and air.

The flow of fluids can be expressed using the following equation:

$$Q_f = K.g.A.\frac{(i_f)^m}{\nu_f} \tag{1}$$

where Q$_f$ is the fluid flow rate in m^3/sec, K is the intrinsic permeability of the flow medium in m^2, g is the gravity in m/sec^2, A is the cross sectional area of the flow medium in m^2, i is the flow gradient of the fluid, m is a power constant, when m =1 the flow is laminar and follows Darcy's law, and ν_f is the kinematic viscosity of the fluid in m^2/sec

The flow readings for both air and water were curve fitted using an algorithm that seeks the values of the parameters that minimize the sum of the squared differences between the values of the observed and predicted values of the dependent variable.

The values obtained from the curve fitting were then normalized for the kinematic viscosity of the corresponding fluid.

Using a nonlinear function, the water flow rate as a function of the hydraulic gradient is defined by Equation 2:

$$Q_w = \frac{8.16E{-}10}{\nu_w}.i_w^{0.5} \tag{2}$$

where Q$_w$ is the water flow rate in m^3/sec/m, i$_w$ is the water hydraulic gradient, and ν_w is the kinematic viscosity of water = 1.01x10^{-6} m^2/sec. It should be noted that the constant number in the equation is not dimensionless, and it has the dimensions of m^4/sec^2, which is a medium dependent constant. The solid line in Figures 3 and 4 shows that in Equation 2, the regression accuracy was 99.6%. Defining the transmissivity as the flow rate divided by the hydraulic gradient, water transmissivity θ_w in m^2/sec can therefore be defined by Equation 3:

$$\theta_w = \frac{8.16E{-}10}{\nu_w}\ i_w^{-0.5} \tag{3}$$

Similar steps were used for the air flow and Equation 4 describes the laminar (linear) air flow for gradients less than or equal to 3:

$$Q_{air} = \frac{5.1E{-}09}{\nu_{air}}.i_{air} \qquad for \quad i \le 3 \tag{4}$$

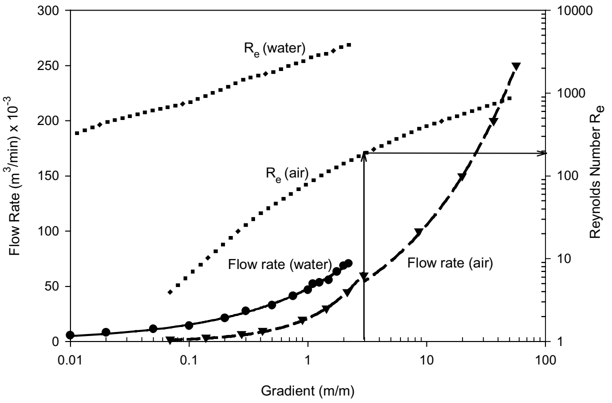

Figure 4. Flow and calculated Re against gradient (full range) for water and air.

where Q$_{air}$ is the air flow rate in m^3/sec/m, i$_{air}$ is the air pressure gradient ≤ 3, and ν_{air} is the kinematic viscosity of air = 1.48x10^{-5} m^2/sec. Air transmissivity θ_{air} in m^2/sec can be then described by Equation 4:

$$\theta_{air} = \frac{5.1E{-}09}{\nu_{air}} \qquad for \quad i \le 3 \tag{5}$$

For air gradients higher than 3, the flow starts to become non-laminar, Equations 5 and 6 describe the air flow rate in m^3/sec/m and transmissivity in m^2/sec respectively:

$$Q_{air} = \frac{(1.05E{-}08\ i_{air}^{0.5} - 3.81E{-}09)}{\nu_{air}} \qquad for \quad i > 3 \tag{6}$$

$$\theta_{air} = \frac{(1.05E{-}08\ i_{air}^{-0.5} - 3.81E{-}09 i_{air}^{-1.0})}{\nu_{air}} \qquad for \quad i > 3 \tag{7}$$

It can be seen in Figure 4 that Equations 4 and 6 are discontinuous at the value of i = 3, however the difference in the flow rate value is within 7%, this difference is mainly due to curve fitting. The regression accuracy for Equations 3 and 5 is 99.7% and 99.8% respectively.

If we assume the similarity of the air flow to that of other gases such as landfill gas and methane, the transmissivity of gases as a function of the pressure gradient are described in Equations 8 and 9:

$$\theta_{gas} = \frac{5.1E{-}09}{\nu_{gas}} \qquad for \quad i \le 3 \tag{8}$$

$$\theta_{gas} = \frac{(1.05E{-}08\ i_{gas}^{-0.5} - 3.81E{-}09 i_{gas}^{-1.0})}{\nu_{gas}} \qquad for \quad i > 3 \tag{9}$$

Figure 4 shows the transmissivity of water and air against the measured gradients (up to gradient of 3.0) together with curve fitted equations.

3.2 Reynolds Number

Reynolds number R_e is a dimensionless number that expresses the ratio of inertial to viscous forces during flow through porous media or any fluid conduit. It is widely used to distinguish between laminar flow at low velocities and turbulent flow at high velocities. Reynolds number is defined as:

$$R_e = \frac{Vd}{\nu} \tag{10}$$

where V is specific discharge or the flow rate per unit area in m/sec, d is a representative length dimension for the porous medium in m, and ν is the kinematic viscosity of the permeate fluid in m^2/sec.

Each medium that transmits flow has a unique Reynolds number curve versus the flow gradient that identifies where the flow changes from laminar to turbulent. This curve is independent of the type of the permeate fluid. For typical soils, the representative dimension, d, is usually taken as a mean pore dimension or mean grain dimension. It was found that for soils, the flow is considered laminar as long as Reynolds number does not exceed a value between 1 and 10. For pipes, where the representative dimension d is the pipe diameter, this range of Reynolds number was found to be between 2000 and 4000 , Thiel (1998).

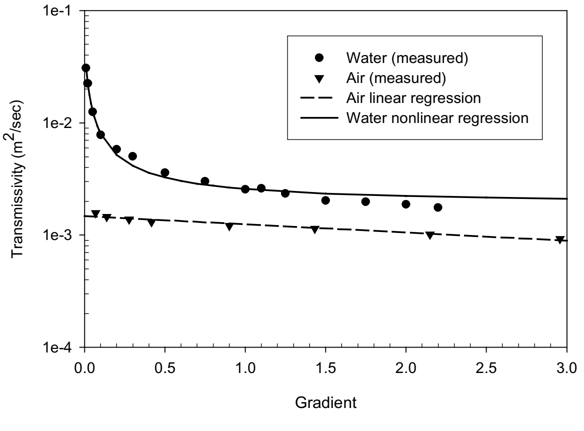

Figure 5. Transmissivity against gradient (up to 3.0) for water and air

In this paper, an attempt is made to determine the Reynolds number beyond which the flow is considered turbulent or non-laminar. It was assumed that the thickness of the DGC could be considered as the representative dimension of the medium. In this case V*d = θ*i, and Reynolds number is expressed as:

$$R_e = \frac{\theta i}{\nu} \tag{11}$$

Equation 10 was used to calculate Reynolds number for the flow in the DGC for both air and water. The results were plotted against the corresponding gradients in Figure 5. As expected from the previous discussion, the resulted R_e for water was much higher than that of air at the same gradient. The corresponding calculated R_e to a gradient of 3 for the airflow is around the value of 200 as indicated in Figure 5. This value is referred to as the critical Reynolds number where the flow becomes non-laminar, which agrees with the findings of Richardson & Zhao (2000).

3.2 *Significance of use*

The significance of the above presented equations is to enable the design engineer to correlate between required gas flow rate or transmissivity and the corresponding water flow rate or transmissivity, and vice versa. Knowing the gradient at which the flow of one of the fluids is obtained, the flow of the other fluid could be determined at a gradient of choice. It should be noted that these equations were developed using a high flow capacity drainage geocomposite and thus the correlation factors may not hold for other drainage products. Also, the results are limited to the range of gradients and normal pressures used in the testing program utilized for this study. The following section will give a quantitative example of these equations.

4 DESIGN EXAMPLE

Below is a design example to illustrate how to use the presented equations while designing for a gas pressure relief layer or a strip drain in a landfill gas venting system. This example also demonstrates how to determine the required water transmissivity for the proposed material based on the calculated gas transmissivity.

The design example is a bioreactor with landfill gas (LFG=55%CO_2, 45%CH_4) flux Φ_{LFG}= 2.5 x 10^{-5} $m^3/s/m^2$, half distance between strip drains L= 30 m, unit weight of LFG γ_{LFG}= 1.28 x 10^{-2} kN/m^3, and the allowed maximum pressure under the geomembrane u_{max} = 0.1 m (4 inches) water (1 kPa). Required is the equivalent water ultimate transmissivity that will satisfy the design requirement of the gas relief layer.

Using Equation 12 (Thiel, 1998), and substituting the given values:

$$\theta_{\mathrm{Re}qLFG} = \frac{\phi_{LFG}\gamma_{LFG}}{u_{\max}}\left[\frac{L^2}{8}\right] \tag{12}$$

The required LFG transmissivity is $\theta_{\text{Req LFG}}$ = 3.6 x $10^{-5}$$m^2$/sec. Applying the design by function approach by Koerner (1998) utilizing a serviceability index of 8 (typical for landfill closure systems), the ultimate LFG transmissivity = 8*3.6x10^{-5} = 2.9 x 10^{-4} m^2/sec. Equation 13 is used to calculate the corresponding gas pressure gradient i_{gas}:

$$i_{gas} = \frac{u_{\max}}{\gamma_{gas}.L} \tag{13}$$

This results in i_{gas} = 2.6 <3. It should be noted that if a backpressure in the strip drain is to be considered, then it should be subtracted from the u_{max} value to calculate the gas pressure gradient in the gas relief layer.

In order to calculate the correlated ultimate water transmissivity, the conversion factor must be first obtained by dividing Equation 3 by Equation 8 and then multiplying the result by the ultimate gas transmissivity. Choosing a water gradient of 0.1, Equation 3 yields a value of 2.6 x 10^{-3} m^2/sec. Equation 8 results in a value of 2.35 x 10^{-4} m^2/sec, given that ν_{LFG}= 1.01 x 10^{-5}. Therefore the conversion factor equals 11, and thus the ultimate water transmissivity = 3.2 x 10^{-3} m^2/sec determined at a gradient of 0.1.

If a gradient of 1.0 is selected for the water flow, Equation 3 will result in a value of 8.08 x 10^{-4} m^2/sec and thus the conversion factor is calculated to be 3.48. The reduction in the conversion factor value at a higher hydraulic gradient is expected do to the turbulence of the water flow at this gradient.

In another design example where the gas pressure gradient is calculated to be higher than 3 indicating a non-laminar flow in the field, either by allowing a higher pressure underneath the membrane or by shortening the distance between the strip drains, Equation 9 shall be used instead of Equation 8. Assume a scenario where i_{gas} equals to 10, Equation 9 will result in a value of 1.36 x 10^{-4} m2/sec. If a gradient of 0.1 for water flow is chosen the conversion factor will equal to 19.1, and a selected gradient of 1.0 will result in a conversion factor of 6.0.

Ideally the water transmissivity is measured at the same gradient of that of the gas in the field. However, due to machine limitations, it's not feasible to measure water transmissivity at hydraulic gradients more than 1.5. Thus, the authors recommend a gradient of 0.1 to measure water transmissivity when the field gradient is not achievable. A gradient of 0.1, although is not quite laminar, but is less turbulent than higher gradients yet maintains an acceptable reproducibility.

5 SUMMARY AND CONCLUSION

- Water and air transmissivity tests were performed using a high flow capacity drainage geocomposite (DGC) at gradients ranging from 0.01 to 2.2 in case of water and from 0.06 to 60 in case of air, the presented results are applicable up to a normal stress of 48 kPa (1,000 psf).
- Water showed a nonlaminar flow at gradients as low as 0.01. Air starts to show a non laminar flow above a gradient of 3.0.
- Linear and non-linear curve fitting were performed to describe water and air flow as a function of the corresponding gradient. The hydraulic constitutive functions were then normalized for the kinematic viscosity of each fluid.
- A gradient dependent correlation was established to convert from air transmissivity to water transmissivity and vice versa.
- It is observed that when the flow for both fluids is laminar or close to laminar, the value of the correlation factor from gas to water agrees with what has been previously used, assuming the validity of the intrinsic permeability, which is 10. This can be shown in the case of a LFG gradient of 2.6 (<3), the correlation factor is calculated to be 11.0 at a water gradient of 0.1.
- However, the value of the correlation factor increases as the flow of the gas becomes non-laminar. This can be shown in the case of a LFG gradient of 10 (>3), where the correlation factor is calculated to be 19.1 at a water gradient of 0.1.
- An attempt was made to determine the value of the critical Reynolds number of the DGC under study, it was calculated as 200.
- The paper in general agrees with the findings of the previous investigators, however, it adds more insight and understanding to the behavior of the gas flow through a drainage geocomposite that is typically tested for water flow.
- It is a fact that the LFG when generated is at a higher temperature and contains vapor. Further investigation needs to be conducted to study the flow behavior of the mixed fluids.
- Measuring airflow was found to be relatively easy to conduct. Labs and manufacturers are encouraged to perform this testing more frequently on geocomposites used for gas venting layer

REFERENCES

Faure, Y.H., Auvin, G., and Eloy-Giorni 1994. Performance tests and design of geocomposites for drainage of gas, *5th International Conference on Geotextiles, Geomembranes and Related Products,* Singapore, 5-9 September. 1994, pp 833-836.

Koerner, R.M. 1998, *Designing with Geosynthetics*, Prentice Hall Publishing Co., Englewood Cliffs, NJ, 1998.

Richardson, G.N., Zhao, A. 2000. Gas transmission in geocomposite systems, *Geotechnical Fabrics Report,* March 2000, pp 20-23 .

Thiel, R.S. 1998. Design methodology for a gas pressure relief layer below a geomembrane landfill cover to improve slope stability, *Geosynthetics International,* Vol.5, No.6, pp 589-617.