Hydraulic transmissivity temperature and flow condition effects and correction formulation for typical drainage products

C.W. Hsieh, J.R. Lai & W.S. Shyu
Department of Civil Engineering, National Pingtung University of Science & Technology, Taiwan

ABSTRACT: The transmissivity flow rate tests were studies for 3 typical geosynthetic drainage products and calibration blocks at 4 different thicknesses and 20°C, 23°C, 27°C, and 30°C test temperatures. The test results indicated that the flow rates (q_w) were greater than 0.3 liter/m-s and in the non-laminar flow condition. In general, the flow rates linearly increased as the test temperature increased. In addition, the flow rates non-linearly increased as the test hydraulic gradient increased for the test conditions. Since the tap water temperature for semi-tropical or tropical regions is generally higher than 23°C or 22°C, this study showed test flow rates were in non-laminar low conditions. A modified temperature and hydraulic gradient correction factor (R_{Ti}) for transmissivity test under non-laminar flow condition was formulized based upon the test results. The revised correction factors were much less than those specified by ASTM and ISO test methods.

Keywords: Ttransmissivity, Drainage, Geosynthetic Geonet.

1 INTRODUCTION

Thick nonwoven needle-punched geotextiles, geonets, drainage geo-composites have considerable void space in their structure, and this space is available for liquid transmission. In-plane flow is an important drainage function for geosynthetic engineering applications. For water flow within geosynthetic products, the variation in geosynthetic product thickness (it compressibility under load) is a major issue. Thus, transmissivity (θ) can be evaluated based upon Darcy's formula, $\theta = q/(i\ W)$, where q is flow rate (m^3/s), i is hydraulic gradient, and W is the specimen width. Besides the liquid flow allowed through the drainage products, the void spaces in it must be sufficiently large. However, the adjacent soil particles should not be carried through the drainage products, leaving unstable soil voids behind (proper soil retention). In addition, the most frequently asked questions "will drainage product eventually clog?" there are guidelines available for noncritical, non-severe cases for selecting appropriate drainage products to provide long-term flow compatibility with the adjacent soils.

The hydraulic transmissivity of a drainage product should be determined only for test that exhibit a linear flow rate per unit width versus gradient relationship, that is, laminar flow. However, non-laminar flow or flow rate greater than 0.3 litter/m-s is commonly measured for geosynthetic drainage products. Main water supply temperature greater than 23°C or 22°C is very typical for tropical or semi-tropical regions. Therefore, it is necessary to study the temperature and flow condition effects on geosynthetic drainage product flow rate at temperatures greater than 23°C.

2 STANDARD TEST METHODS

The scope of ASTM D4716 and ISO 12958 specify the method for determining the constant-head water flow rate per unit width within the plane of a geotextile or geotextile-related product under varying normal compressive stresses. This test is intended primarily as an index test but can be used also as a performance test when the hydraulic gradients and specimen contact surfaces are selected by the user to model anticipated field conditions.

The transmissivity significantly decreases as the normal stress increases. The flow rate per unit width, q_w, can be calculated using the following equation: $q_w = R_t (Q_t / t / W)$, where R_t is temperature correction factor, Q_t is the measured quantity of water collected during the collection time, t is the collection time (s), W is the specimen width. While the hydraulic transmissivity, θ, can be calculated as follows: $\theta = (R_t Q_t L)/ W H$, where L is the specimen length subjected to the normal compressive stress (m), W is the specimen width (m), and H is the difference in total head across the specimen (m). R_t is a function of the test water temperature. However, the correlation equation between R_t and temperature for ASTM and ISO standard methods are slightly different as shown in Table 1. The test temperatures range from 19ºC to 23ºC and 18ºC to 22ºC for ASTM and ISO test methods, respectively. In addition, the ISO test method required the water oxygen content to not exceed 10 mg/kg for water flow rates up to 0.3 litter/m-s. For water flow rates greater than 0.3 litter/m-s test condition, main supply water may be used, and the temperature should be noted and all necessary measures shall be taken to avoid the inclusion of air in the tap water. No temperature correction is required, but the temperature shall be noted and reported. However, it is advisable, should the flow is non-laminar, to work at temperatures as close as possible to 20ºC to minimize the inaccuracies associated with inappropriate correction factors. The test condition for flow rates greater than 0.3 litter/m-s is likely measured for geosynthetic drainage product. Main water supply temperatures greater than 23ºC or 22ºC are typical for tropical or semi-tropical regions. Therefore, it is necessary to study the temperature effect and flow condition effects on geosynthetic drainage product flow rate at temperature greater than 23ºC and in a non-laminar flow condition.

3 TEST MATERIALS AND PROGRAM

Three typical geosynthetic drainage products and various different thicknesses (1 mm, 2 mm, 5 mm and 10 mm) steel calibration blocks at 20ºC, 23ºC, 27ºC, and 30ºC test temperatures were studied, respectively. Low hydraulic gradients of 0.05 and 0.10 were used for calibration block tests. The test chamber width is 300 mm. Hydraulic gradients of 0.1, 0.5 and 1.0 were used for the transmissivity tests of 3 different drainage products. The test normal pressures are 20 kPa, 100 kPa, and 200 kPa. The physical properties of the test prefabricated vertical drain, geonet, geo-core and the calibration blocks are summarized in Table 2. ASTM D4716 standard test method was used in the study.

4 REYNOLDS NUMBER OF LAMINAR FLOW

In laminar flow, the motion of the particles in the fluid is very orderly with particles close to a solid surface moving in straight lines parallel to that surface. Laminar flow is a flow regime characterized by high momentum diffusion and low momentum convection. The dimensionless Reynolds number, Re, is an important parameter in the equations that describe whether fully developed flow conditions lead to laminar or turbulent flow. Laminar flow generally occurs when the fluid is moving slowly or the fluid is very viscous. As the Reynolds number increases, such as by increasing the flow rate of the fluid, the flow will transition from laminar to turbulent flow at a specific range of Reynolds numbers, the laminar-turbulent transition range depending on small disturbance levels in the fluid or imperfections in the flow system. The common example is flow through a pipe, where the Reynolds number is defined as: Re= vDH/ν, where v is mean velocity of the fluid (m/s), DH is the hydraulic diameter (m), ν is the kinematic viscosity (m2/s). Laminar flow occurs when the Reynolds number is below a critical value of approximately 2,040, though the transition range is typically between 1,800 and 2,100. The transmissivity flow test condition is near the parallel plate flow condition. For the parallel plate flow condition, DH = 2(a b)/(a+b), where a is the plate width and b is the distance between two plates. The mean flow velocity v and Re can be calculated based upon the test data. The critical value of Re for parallel plate flow condition is around 1000 (Lien et al., 2011).

5 CALIBRATION BLOCK TRANSMISSVISITY TESTS

Four different calibration block thicknesses were used to verify the flow rates (q_w) and transmissivity test Reynolds numbers (*Re*). The calibration block thicknesses were 1.0 mm, 2.0 mm, 5.0 mm 10.0 mm. Due to large flow rates; a hydraulic gradient of 0.05 is used in the tests. The test temperatures were 20^{o}C, 23^{o}C, 27^{o}C, and 30^{o}C. The flow rates (q_w) in litter/m-s and Reynolds numbers for the test results are shown in Figure 1. It is interesting to find out that only the transmissivity tests with 1.0 mm calibration block conditions show that the Reynolds numbers (*Re*) were less than 1000. These Reynolds numbers (*Re*) indicated that these tests were in laminar flow condition. However, the most and the rest of tests were all under non-laminar flow conditions. As expected, the flow rates increased as the test temperature increased due to the temperature effect on the fluid kinematic viscosity, and the flow rate (q_w) also increased as the calibration block thickness increased. It can also be expected that the Reynolds number (*Re*) is related directly to the change in flow rate (q_w).

6 DRAINAGE PRODUCTS TRANSMISSIVITY TESTS

Three commonly used geosynthetic drainage products, including a prefabricated vertical drain (PVD), a geonet (GN) and a geo-core (GC), were used for the transmissivity tests in this study. As shown in Table 2, the nominal thicknesses of the test PVD, GN and GC are 3.2 mm (with NWGT on both sides), 5.6 mm and 10.6 mm, respectively. Temperature, hydraulic gradient and normal pressure were the test variables. The test temperatures were 20^{o}C, 23^{o}C, 27^{o}C, and 30^{o}C. Hydraulic gradients of 0.1, 0.5 and 1.0 were used. Three different normal pressures of 20 kPa, 100 kPa, and 200 kPa were applied on the test specimens. The test results for the flow rates (q_w) and Reynolds numbers (*Re*) are summarized in Figures 2, 3 and 4, for the PVD, GN and GC, respectively.

Since the test PVD consisted of a thin, less than 3 mm, PVC wave type core material, the Reynolds numbers (*Re*) for the test conditions with hydraulic gradient of 0.1 were less than 1000, indicating that the tests were under laminar flow conditions. However, the remaining tests were conducted under non-laminar flow conditions with Reynolds numbers (*Re*) greater than 1000. The test results also indicated that the flow rates (q_w) were near linearly increased as the temperature increased. In addition, the Reynolds numbers (*Re*) also increased as the temperature increased. However, the rate of increase was higher than that for flow rates (q_w) due to the temperature change.

The influence of normal pressure on the flow rate for each test material was summarized in the Figure 5 for the 3 type products. The flow rates flow rates (q_w) were slightly reduced, around 5% to 10%, as the normal pressure increased. By comparing the test data between the tests with hydraulic gradient of 0.1 and 1.0, the changing of flow rate (q_w) for the condition with hydraulic gradient of 1.0 was also slightly less than that for the condition with hydraulic gradient of 0.1.

The hydraulic gradient effect (i) on the flow rate (q_w) is also summarized in Figure 6 for the test products. The flow rate (q_w) increased as the hydraulic gradient increased (i) in a second order nonlinear relationship for all test products at the test temperatures and normal pressures. As shown in Figure 6(a), the temperature effect on flow rates was more significant for PVD than that for GN and GC as shown in Figures 6(b) and 6(c). Since the GC thickness is greater than GN, and the GN thickness is greater than that of PVD. The thickness effect on the flow rate is clearly shown in Figure 6(d).

7 TRANSMISSIVITY CORRECTION FORMULATION

The transmissivity test results for the tested GN and GC products indicate that non-laminar flow conditions were observed. In addition, the flow rate (qw) increased linearly with the increase in temperature. The flow rate (qw) second-order decreased as the hydraulic gradient ratio (i) increased. In considering the flow rate for the test condition with hydraulic gradient of 0.1 and temperature of 20^{o}C was used as the reference test data. The reference transmissivity values for GN and GC are 0.658 litter/(m-s) and 0.753 litter/(m-s), respectively. Based upon the reference transmissivity values for GN and GC test products, the ratios between those transmissivity values for different test conditions and the reference transmissivity values for the test GN and GC are summarized in the Table 3. However, the temperature and hydraulic gradient ratio correction factors can be calculated by inverting the transmissivity flow rate ratios. The typical correction factor trends for temperature and hydraulic gradient are shown in Figure 7. By combination the temperature and hydraulic gradient ratio effects, a coupling formulation (1.c) is proposed as follows. Based upon the inverted combination correction factors, a regression analysis was conducted and a revised transmissivity correction formulation is shown in equation (1.a) and (1.b). The distribution of the revised correction factor on a three-dimension diagram is shown in Figure 8 for typical drainage products. The revised correction factor is capable for the transmissivity test for temperature varied from 20^{o}C to 30^{o}C, hydraulic gradient ratio varied from 0.1 to 1.0, the flow rate up to 4.0 litter/(m-s).

$$R_t^T\left(T\right)=\frac{1}{q_w^{i01}\left(T\right)}=A_1T+B_1\,,\quad A_1=-0.0043\,,\quad B_1=1.0884 \tag{1.a}$$

$$\begin{aligned}&R_t^i(i)=A_2i^3+B_2i^2+C_2i+D_2\\&\text{where}\quad A_2=-1.9696\,;\,B_2=4.3951\,;\,C_2=-3.4304\,;\,D_2=1.2506\end{aligned} \tag{1.b}$$

$$R_t'\ \left(T,i\right)=\frac{R_t^T\left(T\right)\times R_t^i\left(i\right)}{R_t^T\left(20\right)\times R_t^i\left(0.1\right)} \tag{1.c}$$

8 SUMMARY AND CONCLUSIONS

The hydraulic transmissivity tests on 3 typical geosynthetic drainage products and various steel calibration block thicknesses were studied. The hydraulic transmissivity tests were conducted according to the ASTM D4716 standard test method. Because the main water supply temperature for tropical or semi-tropical regions is normally greater than 23^{o}C, the ambient temperature, hydraulic gradient ratio and normal pressure were the variables used in this study. The test temperatures were 20^{o}C, 23^{o}C, 27^{o}C, and 30^{o}C. Low hydraulic gradients of 0.05 and 0.10 were used for the calibration block tests. Hydraulic gradients of 0.1, 0.5 and 1.0 were used for the transmissivity tests on 3 different drainage products. The normal test pressures were 20 kPa, 100 kPa, and 200 kPa.

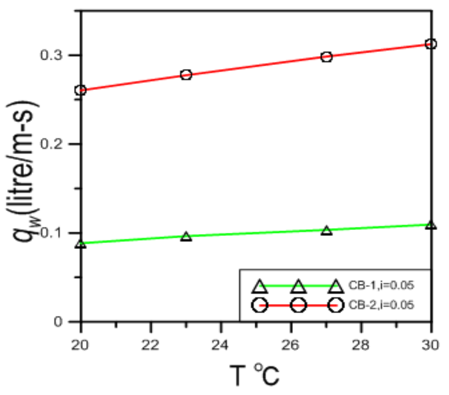
The transmissivity test results for typically used drainage products indicated that non-laminar flow conditions were observed for most test conditions at different temperatures, hydraulic gradients and normal surcharge pressures. This implies that the ASTM D4716 and ISO 12958 test standard assumptions need to be reviewed. The temperature correction factors (Rt) recommended by these international standards were also not applicable for the transmissivity tests of typical drainage products. As expected, the flow rate (qw) increased linearly with the increase in temperature and the flow rate (qw) second-order decreased as the hydraulic gradient ratio (i) increased. Regression analysis was conducted based upon the test results for GN and GC products. The variation in temperature and hydraulic gradient ratio versus the correction factor (RTi) was plotted on a 3-dimensional diagram. A revised combination temperature and hydraulic gradient ratio correction formulation for hydraulic transmissivity for non-laminar flow conditions based upon a regression analysis for the test data is recommended.

Table 1 ASTM and ISO temperature correction factors (Rt) for hydraulic transmissivity test

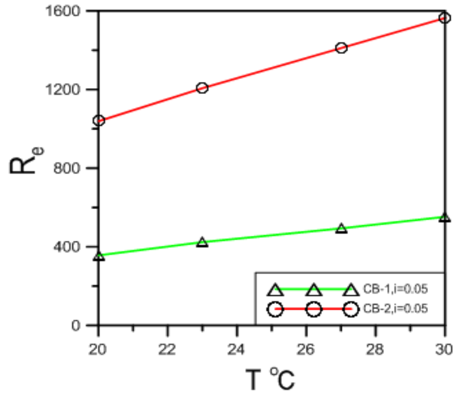
Temperature (℃)	ASTM	ISO
18	------	1.051
19	1.025	1.025
20	1.000	1.001
21	0.976	0.977
22	0.953	0.954
23	0.931	------

Table 2 Physical properties of the test conditions and materials

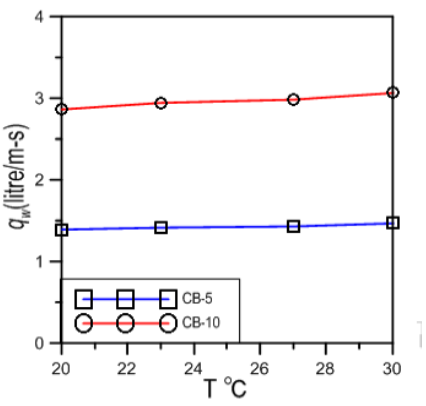
Type	Test method	PVD	GN	GC	CB-1 & CB-2	CB-5 & CB-10
Material	FTIR or X-ray	NWGT & PVC core	PE	PP	Steel	steel
Specific Gravity	ASTM D792	0.89	0.96	--	--	--
Porosity	N.A.	0.73	0.83	0.60	0.83	0.85
Thickness (mm)	ASTM D5199	3.19	5.61	10.59	1.00 & 2.00	5.00 &10.00
Mass (g/m^2)	ASTM D5261	751.50	878.50	1505.20	--	--



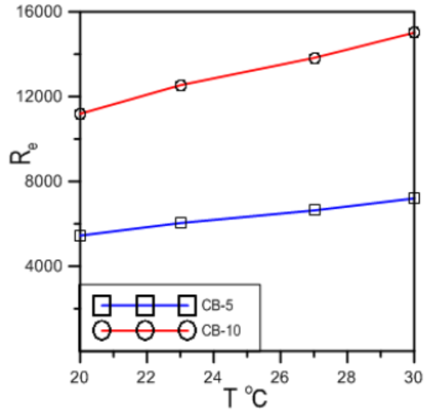
a) q_w for CB thickness =1.0 mm & 2.0 mm



b) Re for CB thickness =1.0 mm & 2.0 mm

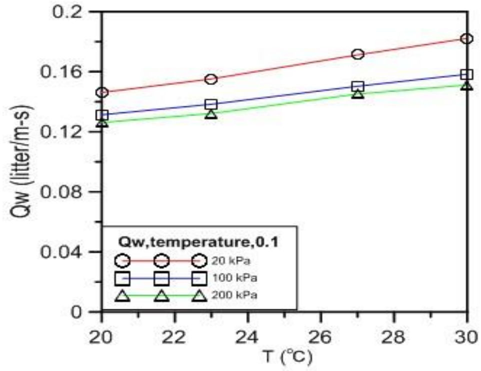


c) q_w for CB thickness =5.0 mm & 10.0 mm

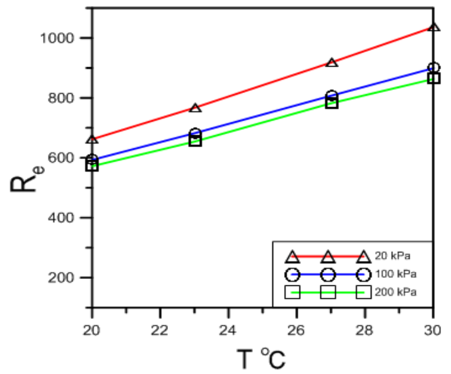


d) Re for CB thickness =5.0 mm & 10.0 mm

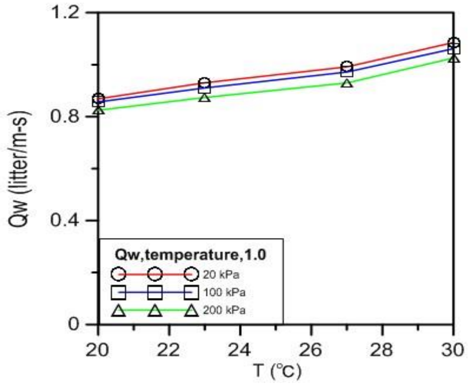
Figure 1 Flow rates q_w (litter/m-s) and Reynolds numbers (Re) for the transmissivity test results for 4 different calibration block thicknesses with hydraulic gradient ratio of 0.05 at different test temperatures



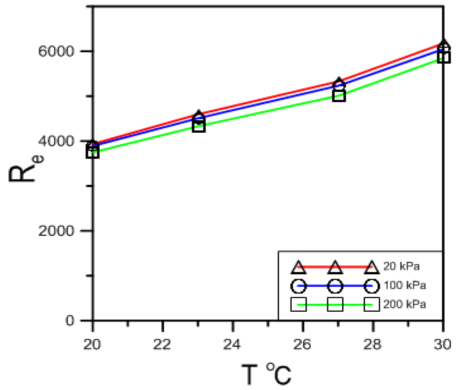
a) q_w for i = 0.1



b) Re for i = 0.1

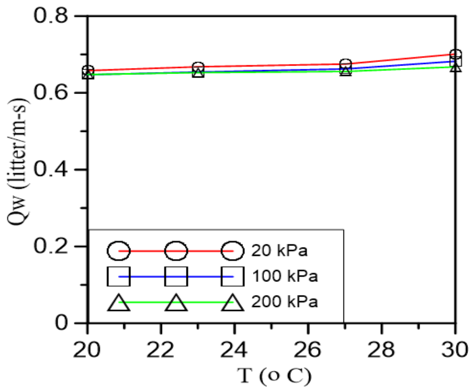


c) q_w for i = 1.0

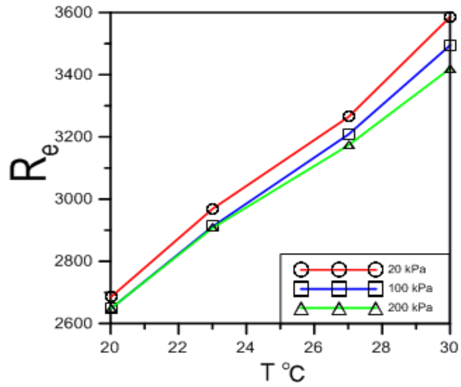


d) Re for i = 1.0

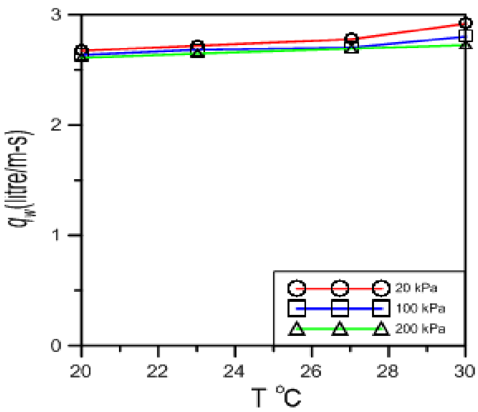
Figure 2 Flow rates (litter/m-s) and Reynolds numbers for the transmissivity test results for a typical prefabricated vertical drain (PVD) with hydraulic gradient ratios of 0.1 & 1.0 at different test temperatures and normal pressures.



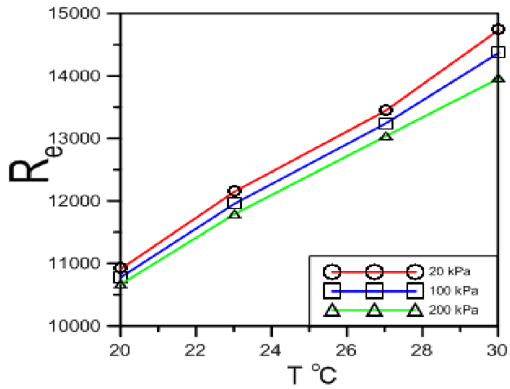
a) q_w for i = 0.1



b) Re for i = 0.1

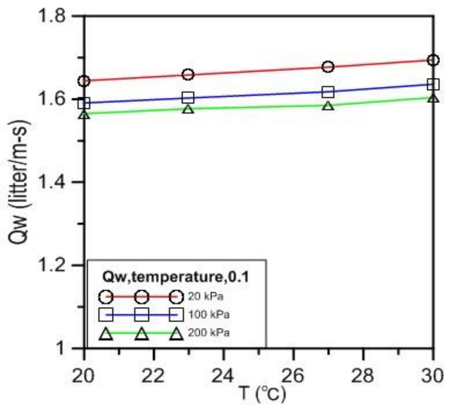


c) q_w for i = 1.0

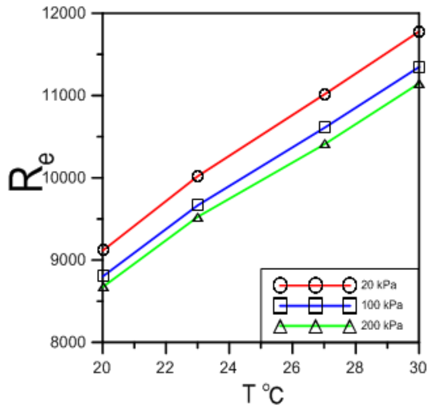


d) Re for i = 1.0

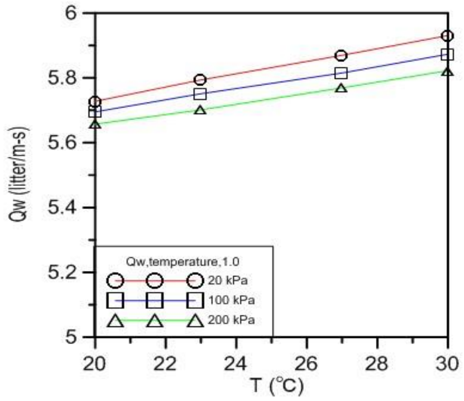
Figure 2 Flow rates (litter/m-s) and Reynolds numbers for the transmissivity test results for a typical geonet (GN) with hydraulic gradient ratios of 0.1 & 1.0 at different test temperatures and normal pressures.



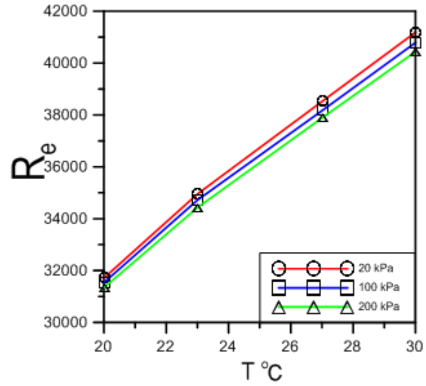
a) q_w for i = 0.1



b) Re for i = 0.1

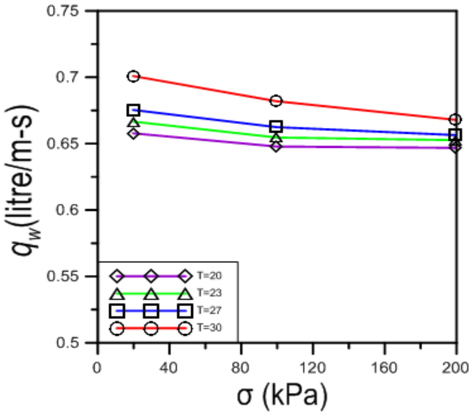


c) q_w for i = 1.0

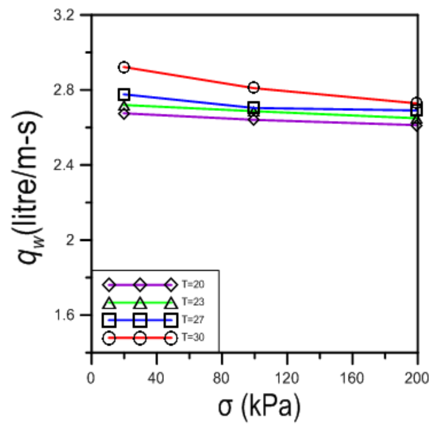


d) Re for i = 1.0

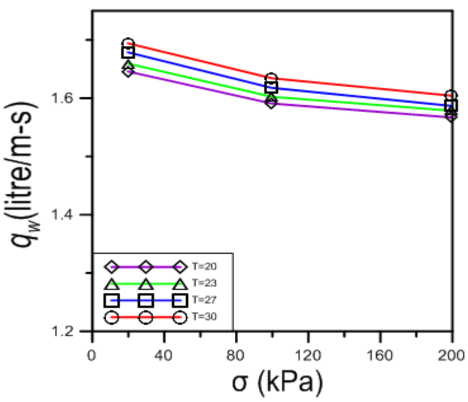
Figure 4 Flow rates (litter/m-s) and Reynolds numbers for the transmissivity test results for a typical geo-core (GC) with hydraulic gradient ratios of 0.1& 1.0 at different test temperatures and normal pressures.



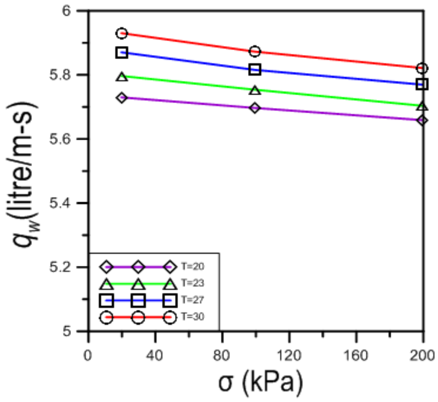
a) q_w for GN with i = 0.1



b) q_w for GN with i = 1.0

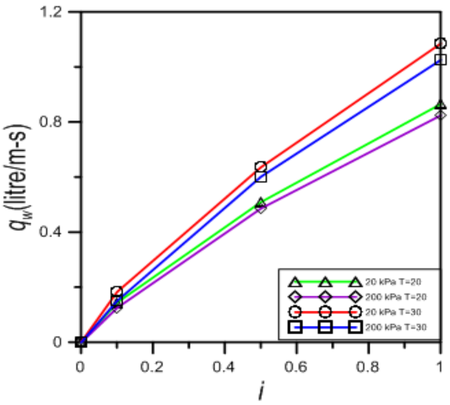


c) q_w for GC with i = 0.1

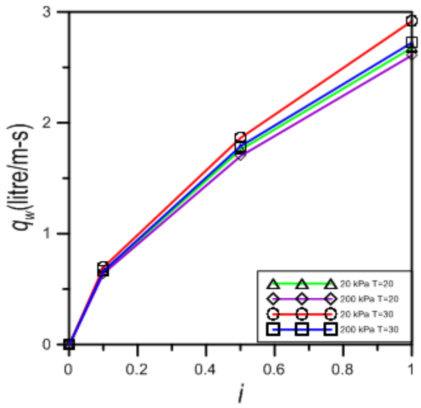


d) q_w for GC with i = 1.0

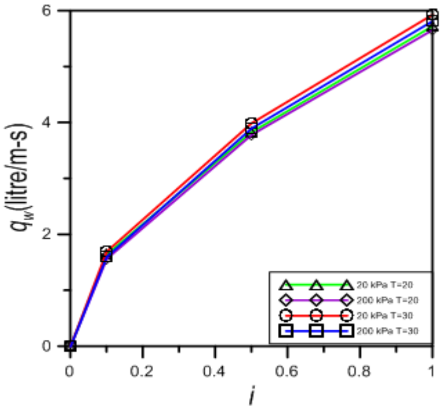
Figure 5 The normal pressure and temperature effects on the flow rates (litter/m-s) for transmissivity tests for three typical drainage products with hydraulic gradient ratios of 0.1, & 1.0.



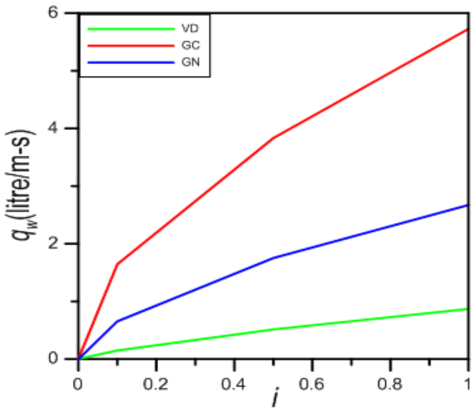
a) q_w for PVD



b) q_w for GN

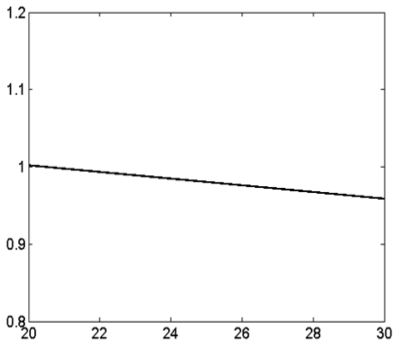


c) q_w for GC

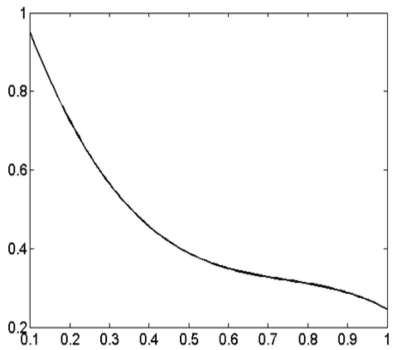


d) q_w for PVD, GN, GC@ 20°C & 20 kPa

Figure 6 The hydraulic gradient effect on the flow rates (litter/m-s) for transmissivity tests for three typical drainage products with different test temperatures and normal pressures.



a) Temperature correction factor at T=20℃



b) Hydraulic gradient ratio correction factor at i = 0.1

Figure 7 Typical variation of temperature and hydraulic gradient ratio correction factors.

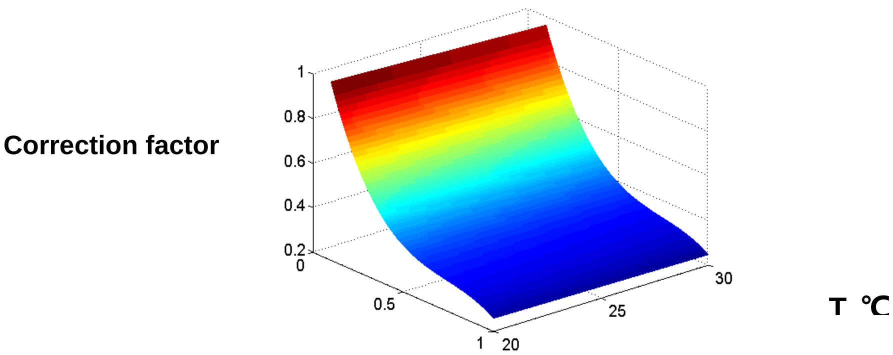


Figure 8 Distribution of the recommended correction formula calculated value on 3-D diagram.

ACKNOWLEDGEMENTS

This study was supported by National Pingtung University of Science and Technology, Taiwan. Mr. Chia-Shin Wu provided great support for the laboratory testing program. The author expresses his sincere appreciation to the Minister of Science and Technology, Taiwan for providing sponsorship to present this paper at this international conference.

REFERENCES

ASTM D4716. Standard Test Method for Determining the (In-Plane) Flow Rate per Unit Width and Hydraulic Transmissivity of a Geosynthetic Using a Constant Head, ASTM International, West Conshohochen, PA, USA.

ISO 12958. Geotextile and geotextile-related products – Determination of water flow capacity in their plane, International Organization for Standardization, Switzerland.

Lien, W.B, Tsao, W.H., and Hu, C.H. (2011). Open Channel Flow, Kao-Li Co., Ltd., Taipei, Taiwan.