

- $\phi$  = viscoelastic relaxation function ( $\text{Pa}^{-1}$ )
- $\varphi$  = function of strain only in Rabotnov isochrone model ( $\text{N}$  or  $\text{Nm}^{-1}$ )
- $\theta$  = function of time only in Rabotnov isochrone model (dimensionless)
- $\omega_1$  = temperature dependent material parameter ( $\text{N}^{-1}\text{s}^{-1}$ )
- $\omega_2$  = temperature dependent material parameter ( $\text{N}^{-2}\text{s}^{-1}$ )
- $\omega_3$  = temperature dependent material parameter ( $\text{N}^{-3}\text{s}^{-1}$ )
- $\sigma$  = stress ( $\text{Pa}$ )
- $\tau$  = reference time (s)

## Technical Paper by P. Pierson and M. Barroso A "POUCH TEST" FOR CHARACTERIZING GAS PERMEABILITY OF GEOMEMBRANES

**ABSTRACT:** To characterize the gas permeability of seamed or non-seamed geomembranes, laboratory tests were carried out using a new permeability test: the gas permeability pouch test. Circular and rectangular "pouches" made of two pieces of high density polyethylene (HDPE) geomembrane were tested. To study the permeability of the geomembrane itself, the pouch was made of two circular geomembrane sheets welded together (the percentage of the seamed area is negligible compared to the non-seamed area). To study the permeability of the HDPE seams, two rectangular pieces of geomembrane were welded together using the thermal-hot wedge method (where the percentage of the seamed area is predominant). For this test, specimens are pressurized with a gas (e.g., nitrogen, in this case), and immersed either in air or in water. The flow of gas is indicated by a decrease in the pressure inside the pouch. The test results obtained are in agreement with results reported in the literature and show that the gas permeability pouch test can be used to characterize geomembrane permeability, with the advantages of being easy to carry out and allowing the assessment of the seam quality by quantitative measurement of their permeance.

**KEYWORDS:** HDPE geomembrane, Seam, Gas Permeability, Pouch test, Gas flow and permeance.

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## 1 INTRODUCTION

Designers of landfills require the permeability coefficients of geomembranes for different permeants since geomembranes are an active part of a barrier and are in contact with different liquids and gases in service. Several experimental methods and apparatuses have been used to assess the permeability of high density polyethylene (HDPE) geomembranes to gases (Haxo et al. 1984; Haxo 1990; Alter 1962; Pierson 1996), to water (Haxo and Pierson 1991; Eloy-Giorni et al. 1996; Durin 1999), and to organic components (August and Tatzky 1984; Matrecon 1988; Rowe et al. 1996; Sangam and Rowe 2001a, 2001b).

Since flows measured through geomembranes are very small, all permeability tests require a well-defined procedure with highly accurate measurement methods. Certain tests are designed not to quantify the permeability, but to select geomembranes with respect to a maximum accepted flow (for instance, the test method prEN 14150, 2001).

Generally, the flow through a geomembrane is obtained by the difference of concentration in two chambers separated by the tested specimen. The question then arises: is the flow through the seal truly negligible compared to the flow through the specimen? Park (1986) and Koerner and Allen (1997) have pointed out this problem. In addition, as reported in ASTM D 1434, inter-laboratory testing has shown that the flow measurements depend on both the apparatus and on the procedure used. Therefore, since there is no apparent reason for the differences obtained, the non-negligible flow through the seal could be one possible explanation.

Another aspect must be considered: currently, there is no permeability test that can be used to characterize the permeability of geomembrane seams. These vulnerable areas are generally tested only from a mechanical point of view (e.g., shear test and peel test). Nevertheless, the seams must perform as barriers and, therefore, their effectiveness should be assessed in terms of fluid-tightness.

The pouch test (Haxo et al. 1984; Haxo 1990) is a method used to assess the geomembrane permeability to organic liquids (and organic tracer dye); a volume of liquid organic is sealed in a pouch made of two sealed pieces of the geomembrane being tested. The pouch is immersed in deionized water (or in another fluid of known composition, which will be called the "medium" in this study). The permeability is then assessed by transmission rate measurements obtained by recording the changes in weight of the pouch and by chemical analysis of the "medium": the weight change of the pouch is due to the diffusion of organics from inside to outside the pouch.

The test above characterizes the permeability of the geomembrane *and* seams to organic liquids. The seams can be made using field devices and not specific laboratory methods. The seams are then also tested by the pouch test.

Considering that the pouch test does not require sophisticated devices, it would be interesting to apply its principle to assess gas or liquid permeability, leading to the calculation of permeability and permeance coefficients. Such an application of the pouch test has not yet been considered. In fact, the present study is intended to lead to the proposal of a new concept of permeability test: the "gas permeability pouch test".

This paper presents, first, the test principle, and second, the basic equations to evaluate the coefficient of permeability and permeance of the specimens to gas and to

water vapour. Then, it describes the laboratory test methods used for characterizing the gas permeability of the geomembrane itself and the geomembrane seams. Last, it reports and discusses the preliminary test results obtained for high density polyethylene (HDPE) geomembranes.

## 2 TEST PRINCIPLE

In the "gas permeability pouch test", the specimen is pressurized with a gas characterized by an initial pressure,  $P_G(0)$ , and is immersed in a medium (gas or liquid). The flow of gas across the geomembrane is indicated by a decrease in the pressure inside the pouch. Pressure inside the pouch specimen (and outside, if necessary), atmospheric pressure, temperature, volume, and humidity are recorded each time step,  $\delta t$ .

When the medium is a gas (which is the same as the gas inside the specimen but at a lower pressure), it is possible to evaluate the gas flow from the inside to the outside of the specimen (i.e., from the higher gas concentration to the lower gas concentration). The permeability and permeance coefficients for this specific gas can then be estimated. The research can be focused on the study of the geomembrane itself by comparing the results obtained with different gases or different materials. It can also be focused on the seam to determine what is, for instance, the influence of the welding parameters on the permeability of the seamed geomembrane. Depending on the study objective, different pouch shapes have to be made:

- where the percentage of the seamed area is negligible compared to the non-seamed area for studying the geomembrane itself (circular pouches); and
- where the percentage of the seamed area is predominant for studying the seams (rectangular pouches).

When the medium is a liquid (e.g., water), two simultaneous flows must be considered: the gas flow from inside to outside the specimen, and the water vapour flow (or other element if the liquid is not water) from outside to inside the specimen. For each type of pouch, the gas flow can be evaluated if the preceding test (specimen immersed in gas) has already been carried out, assuming that the volume variations of the specimen as well as the gas flow from inside to outside (considering the same gas concentration difference) are the same, whenever the specimen is immersed in gas or in liquid. The water vapour flow (or other element) can then be evaluated and, consequently, the permeability and permeance coefficients to water (or other elements).

## 3 ASSESSING THE PERMEABILITY COEFFICIENTS

### 3.1 Basic Definitions

The concept of permeability in the conventional sense (i.e., according to Darcy's Law) is not applicable to geomembranes, since these are non-porous materials. However, gases and liquids can permeate a geomembrane at a molecular level. The transport of a permeant molecule is usually considered to occur in three steps (Haxo et al. 1984;

Rogers 1985; Mueller et al. 1998): (1) dissolution or absorption of the permeant in the upstream surface of the geomembrane; (2) diffusion of the permeant through the geomembrane under a concentration gradient; and (3) evaporation or desorption of the permeant from the downstream surface of the geomembrane into the ambient medium.

Fick's first law can model the diffusion of penetrant molecules through the geomembrane and can be expressed as follows:

$$f = -D \frac{\partial c}{\partial z} \quad (1)$$

where:  $f$  = permeant mass flux passing through a unit area of the geomembrane surface;  $c_g$  = concentration of the penetrant of interest in the geomembrane;  $D$  = diffusion coefficient;  $z$  = spatial dimension parallel to the direction of diffusion; and  $\partial c_g / \partial z$  = concentration gradient.

To take into account the three steps of the transport process described above, the application of Fick's first law must be extended (Sangam and Rowe 2001a) by considering the equilibrium concentration difference  $\Delta c_f$  of the penetrant molecules in the adjacent fluids, on both sides of the geomembrane, which can be measured contrary to  $\partial c_g / \partial z$  used in Equation 1. Therefore, Equation 1 becomes:

$$f = -\mathcal{L} \frac{\Delta c_f}{L_g} \quad (2)$$

where:  $L_g$  = geomembrane thickness; and  $\mathcal{L}$  = coefficient of permeability ( $\text{m}^2 \text{s}^{-1}$ ). The latter characterizes the mass transfer and depends on  $D$  and on the partitioning coefficient,  $S$ , characterizing absorption and desorption (Henry's law):

$$\mathcal{L} = S D \quad (3)$$

For a gas,  $G$ , Equation 2 can also be written as follows:

$$GTR = -\mathcal{L}' \frac{\Delta P_G}{L_g} \quad (4)$$

where:  $GTR$  = gas transmission rate, which is the mass diffusive flux of gas,  $G$ ; and  $\mathcal{L}'$  = coefficient of permeability expressed in  $\text{mol m}^2 \text{s}^{-1} \text{kg}^{-1}$ . The term  $GTR$  is the terminology used in ASTM D 1434.  $WTR$  will be used to represent the water vapour transmission rate. Equation 2 can also be written as follows by using the partial pressures,  $P$ , of penetrant molecules of gas,  $G$ , in adjacent fluids on both sides of the geomembrane instead of concentrations,  $c_f$ :

$$GTR = -\mathcal{L}'' \frac{\Delta P_G}{L_g} \quad (5)$$

where:  $\Delta P_G$  = partial pressure difference; and  $\mathcal{L}''$  = coefficient of permeability expressed in  $\text{mol s}^{-1} \text{m}^{-1} \text{Pa}^{-1}$ .

Characterizing geomembrane permeability using a coefficient of permeability pre-

sents several drawbacks. First, previous studies on this topic have shown that it may depend on thickness (Haxo et al. 1984; Matrecon 1988; Pierson and Duquenois 2000). Furthermore, it may be difficult to measure the thickness of geomembrane specimens accurately. Last, this coefficient may be confused with the permeability coefficient used for porous media (Darcy's law). Therefore, it is advisable to use the permeance,  $P$ , in  $\text{mol m}^{-2} \text{s}^{-1} \text{Pa}^{-1}$  for characterizing the permeability of the geomembranes. It can be calculated only from  $GTR$  and  $\Delta p$  as follows:

$$P = \frac{\mathcal{L}''}{L_g} = \frac{GTR}{\Delta P_G} \quad (6)$$

To estimate  $GTR$ , it is necessary to know the area of the pouch specimen. However, it can be observed that this area is difficult to estimate accurately. This difficulty comes from nonregular seams and, mainly, from an irregular specimen shape when it is filled with the gas.

In the case of pouches designed for characterizing the geomembrane permeability, where the pouch area is required, a reference area must be measured before filling the pouch with gas and must take into account all potential seam irregularities: this reference area is defined in Section 4.1.

In the case of pouches designed for studying geomembrane seams, there is no reason to express  $GTR$  for the geomembrane area unit, and it is suggested that  $GTR$  be considered as the mole flow rate through the pouch specimen ( $\Delta n / \Delta t$ ) expressed in  $\text{mol s}^{-1}$ , instead of  $\text{mol m}^{-2} \text{s}^{-1}$  leading to a permeance,  $P$ , in  $\text{mol s}^{-1} \text{Pa}^{-1}$  instead of  $\text{mol m}^{-2} \text{s}^{-1} \text{Pa}^{-1}$ . A consequence of such new definitions of  $GTR$  and  $P$  is, if different sealed specimens are to be compared with this method (different materials, different seam parameters), then the pouch must be made using the same procedure. For instance, pouches made using the thermal hot dual wedge method are then well adapted to the study of seam parameters if the seam length is the same.

The following sections present the equations used for estimating the permeance of geomembranes to gas  $G$  (Section 3.2.1: pouch specimens are immersed in air), and to water vapour  $W$  (Section 3.2.2: pouch specimens are immersed in water).

## 3.2 Measurements and Calculations

### 3.2.1 Specimens Immersed in Gas $G$

It should be noted that the calculation of  $P_G$  from Equation 6 is only possible when  $GTR$  and  $\Delta P_G$  are constant, which means when a steady state is achieved. Concerning  $GTR$ , if the mole quantity of gas,  $n_G(t)$ , in the pouch specimen is to be determined each time, it must be calculated when the function  $n_G(t)$  is linear. This was obtained after a reasonable lapse of time during all the experiments conducted (a few days in the case of Figure 4). Therefore, from the precedent definition of  $GTR$ :

$$GTR = \frac{n_G(t + \Delta t) - n_G(t)}{\Delta t} \quad (7)$$

where  $GTR$  is expressed in  $\text{mol s}^{-1}$ ,  $\Delta t$  is the interval of time considered in steady state, and  $n_G(t)$  must be calculated, step-by-step, from the ideal gas law:

$$n_G(t) = \frac{P_G(t)V(t)}{RT} \quad (8)$$

where:  $P_G(t)$  = absolute pressure (relative pressure + atmospheric pressure) measured inside the pouch at time  $t$ ;  $V(t)$  = volume of the specimen at time  $t$ ;  $R$  = Universal Gas Constant, ( $8.3143 \text{ m}^3 \text{ Pa mol}^{-1} \text{ K}^{-1}$ ); and  $T$  = absolute temperature assumed to be constant.

In the case of HDPE geomembranes, after steady state is achieved, the volume variations  $V(t)$  with time are slight; the experimental results obtained in the present research for  $GTR$ , either considering the volume constant or considering the volume variable ( $1.4 \times 10^{-10}$  and  $1.7 \times 10^{-10} \text{ mol s}^{-1}$ , for constant and variable volumes, respectively), indicate that the volume variations during testing were negligible, considering the measurement errors. Therefore,  $V(t)$  is considered here as being constant:  $V(t) = V(0)$ .

In the case of more flexible geomembranes,  $V(t)$  can be estimated after the experiment is conducted with the pouch specimen immersed in water, if the temperature and the difference in pressure are the same.

Therefore, for the HDPE geomembranes in the present study, by combining Equations 7 and 8, it is possible to calculate the gas flow  $GTR$ :

$$GTR = \frac{V(0)}{RT} \frac{P_G(t + \Delta t) - P_G(t)}{\Delta t} \quad (9)$$

Permeance,  $P_G$ , can then be calculated from Equation 6, where  $\Delta P_G$  cannot be considered as a constant, since the gas pressure  $P_G$  in the specimen decreases during the entire test. It is then suggested to calculate  $P_G$  for the mean value  $\bar{P}_G$  during the interval of time  $\Delta t$  (considered for the calculation of  $GTR$ ):

$$\bar{P}_G = \frac{1}{\Delta t} \int P_G(t) dt \quad (10)$$

The mean pressure difference,  $\overline{\Delta P}_G$ , can then be deduced from Equation 11:

$$\overline{\Delta P}_G = \bar{P}_G - P_{Gout} \quad (11)$$

where  $P_{Gout}$  is the gas pressure outside the specimen. This pressure may be the partial pressure of gas  $G$  in the medium if this medium does not consist of pure gas  $G$ . It is the case of the experiment described in Section 4 where gas  $G$  is nitrogen and the medium is air. The atmospheric pressure and the humidity must then be recorded during  $\Delta t$  for the calculation of  $P_{Gout}$  (Appendix A).

The permeance calculated from  $\overline{\Delta P}_G$  is then a mean permeance  $\bar{P}_G$ :

$$\bar{P}_G = \frac{GTR}{\overline{\Delta P}_G} \quad (12)$$

### 3.2.2 Specimens Immersed in Liquid $W$

Regarding the tests carried out with the specimen immersed in water, two simultaneous permeants must be considered. They correspond, respectively, to the migration of gas from inside to outside the specimen ( $GTR'$ ) and to the migration of water (water vapour) from outside to inside the specimen ( $WTR$ ).

**Determining  $GTR'$ :** The gas flow from the inside to the outside of the specimen ( $GTR'$ ) can be calculated from Equation 6, by considering the same specimen but taking into account a new pressure difference  $\Delta P'_G$ , between the two sides of the specimen, different from the  $\Delta P_G$  considered in Section 3.2.1. Thus, from the results of the test carried out in air (giving  $GTR$  corresponding to  $\Delta P_G$ ):

$$GTR' = GTR \frac{\Delta P'_G}{\Delta P_G} \quad (13)$$

If the concentration of gas  $G$  in the medium outside the specimen (which is initially pure liquid  $W$ ) can be considered as negligible (generally the case when the medium volume is much higher than the specimen volume),  $\Delta P'_G$  can be assimilated to the partial pressure  $P_G$  of gas  $G$  in the specimen. Appendix B presents its calculation at each time  $t$ .

**Determining  $WTR$ .** After calculating  $GTR'$ , it is possible to calculate  $n_G(t)$ , step by step, from the definition of  $GTR$  (Equation 7):

$$n_G(t) = n_G(t - \delta t) - GTR' \delta t \quad (14)$$

As the specimen contains  $n_{G+W}(t)$  moles of elements  $G$  and  $W$  at time  $t > 0$ , the application of the ideal gas law gives, assuming that the water temperature is constant:

$$n_{G+W}(t) = \frac{P_{G+W}(t)V(t)}{RT} \quad (15)$$

where  $P_{G+W}(t)$  and  $V(t)$  are the absolute total pressure in the specimen (relative + atmospheric) and the specimen's inner volume, respectively, both measured at time  $t$ .

By combining Equations 14 and 15, it is then possible to calculate, also step by step, the mole quantity  $n_W(t)$  of element  $W$  in the specimen:

$$n_W(t) = n_{G+W}(t) - n_G(t) = \frac{P_{G+W}(t)V(t)}{RT} - (n_G(t - \delta t) - GTR' \delta t) \quad (16)$$

where  $V(t)$  can be considered as a constant in steady-state conditions (Section 3.2.1), in the case of inflexible geomembranes.

If the function  $n_W(t)$  is linear during an acceptable time interval  $\Delta t$  (corresponding to the achievement of steady state), it is possible to deduce the flow  $WTR$  in the same way as  $GTR$ , in Section 3.2.1, has been deduced from Equation 7.



Determining Water Permeance  $P_W$ . The mean permeance,  $\bar{P}_W$ , can then be obtained from WTR as follows:

$$\bar{P}_W = \frac{WTR}{P_{Wout} - \bar{P}_W} \quad (17)$$

In Equation 17,  $P_{Wout}$  is the pressure of liquid outside the specimen (depending on the mean height of liquid above the specimen and on the atmospheric pressure) and  $\bar{P}_W$  is the mean partial pressure of the element,  $W$ , in the specimen during  $\Delta t$ . This pressure can be obtained from the mean absolute pressure in the specimen,  $\bar{P}_{G+W}$  and from the mean partial pressure,  $\bar{P}_G$ :

$$\bar{P}_W = \bar{P}_{G+W} - \bar{P}_G \quad (18)$$

Mean pressures are defined as  $\bar{P}_G$  in Equation 10 from  $p_{G+W}(t)$ , which is measured at each time  $t$ , and from  $p_G(t)$ , which is calculated at each time using Equation B-1 (Appendix B)

## 4 EXPERIMENTAL PROCEDURE

### 4.1 Material and Specimens

As mentioned in Section 2, considering the study objective, two different types of pouches were made using the same type of HDPE geomembrane: Geonap®, provided by Siplast-France, having a density of 0.943 kg/m<sup>3</sup>.

The circular pouch (Figure 1) for studying the geomembrane itself consists of two large sheets welded at the disk extremity (at least 0.6 m in diameter). The circular shape was obtained by a continuous weld made along a precisely drawn line. All irregularities with respect to this line must be estimated in terms of area to allow a precise determination of the initial pouch area. When the weld is made by a machine (the same as used in the field), the seam continuity must be ensured by manual local seam. Compared to other shapes, the circular shape minimizes the number of seam joints and, consequently, the number of potential weak points. The connection between the gas tube and the upper geomembrane was made using two copper washers with the geomembrane sandwiched between them. The two washers were screwed together to compress the geomembrane so as to make an absolute seal. The pouch tested here and presented in Figure 1 was made of two 1.5 mm-thick HDPE geomembrane welded sheets forming a circular pouch, 0.63 m in diameter (total permeation surface: 0.635 m<sup>2</sup>; initial inner volume: 0.04296 m<sup>3</sup>).

The rectangular pouch (Figure 2) for studying HDPE geomembrane seams consists of a true seam made using the thermal hot dual wedge method. The pouch inner volume corresponds to the space left between the two parallel seams. On one extremity of the pouch, the two parallel seams were sealed by fusion. The other extremity was connected to the HDPE gas pipe. The connections between the pipe and the pouch, and

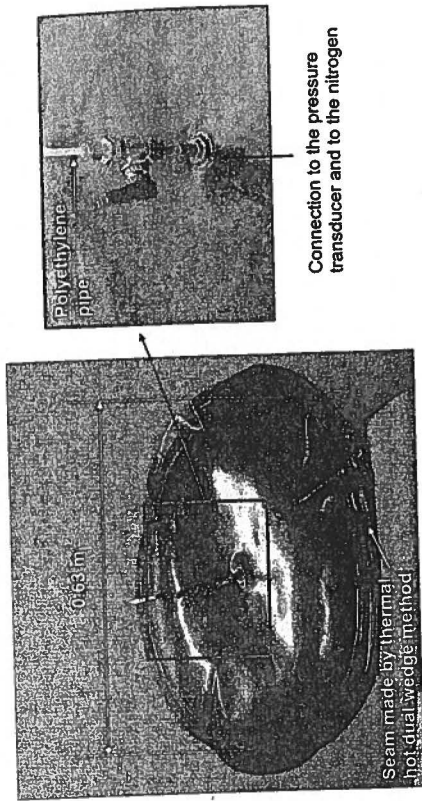


Figure 1. Circular pouch made with HDPE geomembrane 1.5 mm thick.

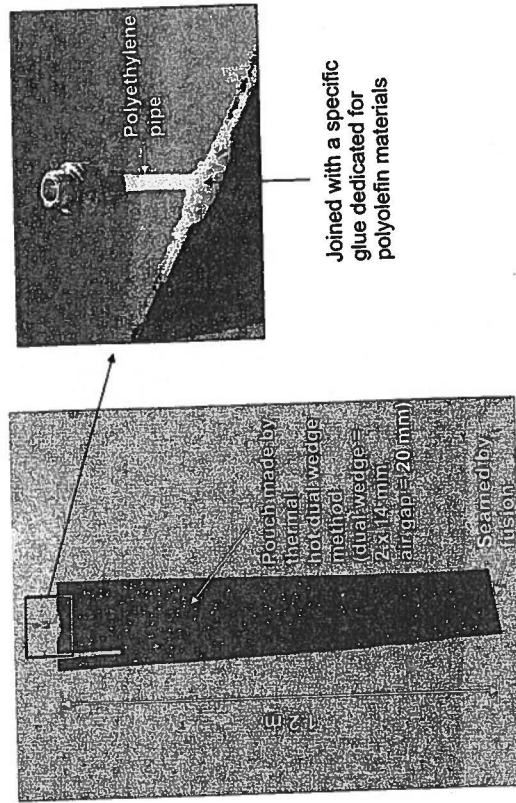


Figure 2. Rectangular pouch made with HDPE geomembrane 2.0 mm thick.

between the two parallel seams, were made using glue that is specifically formulated for polyolefin materials: fusion must be avoided here because of the risks of connection damage and polyethylene flow into the pouch. Figure 2 shows the specimen tested

made with a 2.0 mm thick HDPE geomembrane sealed over a 1.2 m length.

#### 4.2 Apparatus

Laboratory tests were performed using two different experimental assemblies, one for the circular pouch and another for the rectangular pouch. Figure 3 illustrates the corresponding apparatus adapted to rectangular pouches and consists of a permeation cell, a gas bottle, and measuring devices connected to a data acquisition system.

The permeation cell was designed to allow the immersion of each specimen either in air or in water. It consists of two circular stainless steel plates (top and base) and a glass pipe (1.5 m long, inside diameter of 0.186 m) including an agitator for homogenizing the water temperature when filled with water. Measuring devices used for recording the test parameters were connected to the top plate.

The gas bottle was filled with nitrogen. Nitrogen was chosen because it is the main constituent of air, which is used to perform field pressure tests on seams.

The measuring devices used for monitoring all the test parameters are as follows: (i) a pressure transducer for measuring the nitrogen pressure inside the specimen; (ii) sensors for characterizing the ambient air temperature (maintained at  $27.0 \pm 0.1^\circ\text{C}$  using a regulation device), atmospheric pressure, and humidity; and, for the test in water, (iii) a water temperature sensor and a capillary pipe (0.026 m long glass pipe with a 0.00564 m inside diameter) connected to a pressure transducer, for measuring the volume variations of the pouch (transducer readings were converted into height of water in the capillary pipe and then multiplied by the pipe area to obtain the volume change with time).

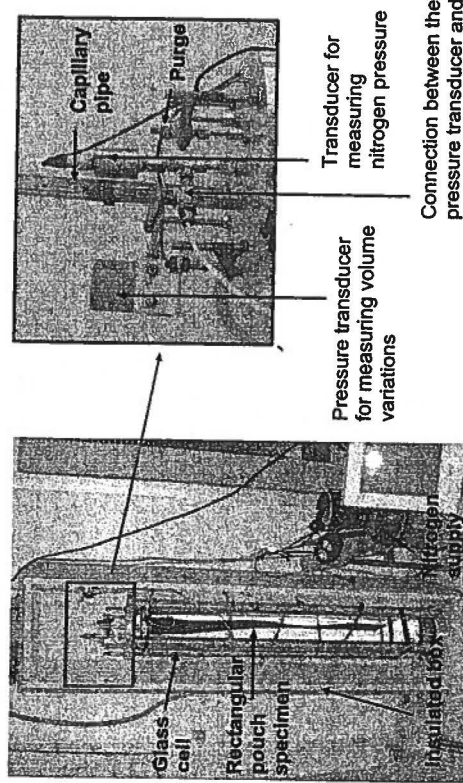


Figure 3. General view of the apparatus for testing rectangular pouches.

The apparatus described above (which was used for testing rectangular pouches) was adapted to test circular pouches by changing the shape of the glass cell to make it large enough to contain the circular pouch specimen.

Tests conducted using the two different types of pouch (circular and rectangular) followed a similar procedure and immersing the specimens either in water or in air.

#### 4.3 Procedure

##### 4.3.1 Test in Water

After the pouch was inserted into the glass cell, which is filled with de-aired water (using a vacuum pump), the water level in the capillary pipe was adjusted and connected to the pressure transducer. All measuring devices were then connected, the ambient air temperature regulation device was activated and, finally, the pouch was pressurized with nitrogen, at a specific pressure. Data were recorded by running a computer application especially developed for this test.

##### 4.3.2 Test in Air

The water temperature sensor and the pressure transducer connected to the capillary pipe were replaced by air humidity and air temperature sensors. The test was then initialized with the same procedure as the test carried out in water.

##### 4.3.3 Initial Volume and Pressure of Gas in the Specimens

Before conducting any test, the initial inner volume,  $V(0)$ , of the pressurized pouch must be determined by assessing the initial pouch volume and by measuring the increase in water height in the cell, before and after pressurization.

Relative pressures of 35 kPa (circular) and 150 kPa (rectangular) were used to pressurize the pouches. The 150 kPa value was selected for having a pressure of the same order of magnitude to the one usually used in field tests. A lower pressure of 35 kPa was chosen for circular pouches because their integrity showed to be affected by higher gas pressures.

## 5 RESULTS AND DISCUSSION

### 5.1 Tests in Air

#### 5.1.1 Circular Specimens

The number of nitrogen moles  $n_{N_2}(t)$  permeating through the circular specimen, which was calculated from  $P_{N_2}(t)$ , using Equation 8, is plotted versus time in Figure 4. Figure 4 shows that the function  $n_{N_2}(t)$  quickly becomes linear, which corresponds to a rapid steady-state achievement.

The nitrogen flow  $GTR$  was calculated from Equation 7:

Table 1. Comparison of the order of magnitude of HDPE geomembrane permeability coefficients to nitrogen.

Reference	Nitrogen permeability, $P''_{N_2}$ ( $\text{mol m}^{-1} \text{s}^{-1} \text{Pa}^{-1}$ )
Park (1986)	$0.8 \times 10^{-15}$
Encyclopedia of Polymer Science and Technology (1964)	$0.4 \times 10^{-15}$
Preliminary tests (non seamed circular specimen), Pierson (1996)	$0.7 \times 10^{-15}$
Present study (circular pouch)	$1.1 \times 10^{-15}$

### 5.1.2 Rectangular Specimens

Figure 5 shows the change over time of the absolute pressure (relative + atmospheric) during the test carried out in air.

The test lasted for 938 hours (39 days). As can be observed in Figure 5, the absolute nitrogen pressure drops by approximately 87 kPa during the test period, corresponding to a 35% decrease.

The number of nitrogen moles,  $n_{N_2}(t)$ , which permeated through the specimen, was calculated from  $P_{N_2}(t)$ , using Equation 8. It is plotted versus time in Figure 6, once the steady state conditions are achieved, i.e., after 660 hours, corresponding to a linear function  $n_{N_2}(t)$ .

Based on Figure 6, the nitrogen flow  $GTR$ , was calculated from Equation 7:

$$GTR = 1.4 \times 10^{-10} \text{ mol s}^{-1}$$

The nitrogen permeance was estimated from Equation 12, for a mean partial pressure difference of 95 kPa:

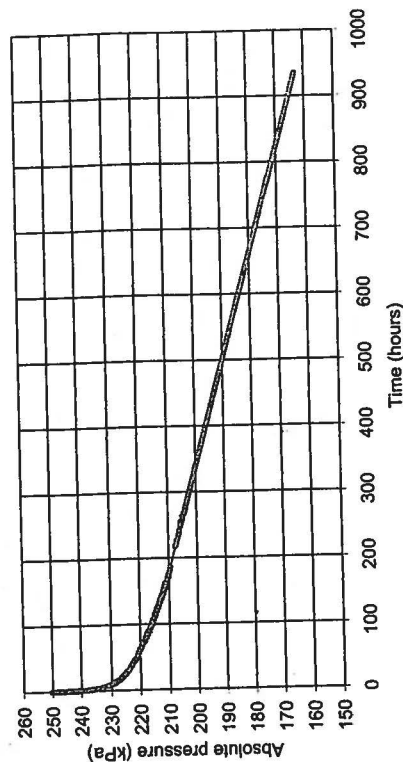


Figure 5. Decrease in the absolute pressure of nitrogen during the test in air.

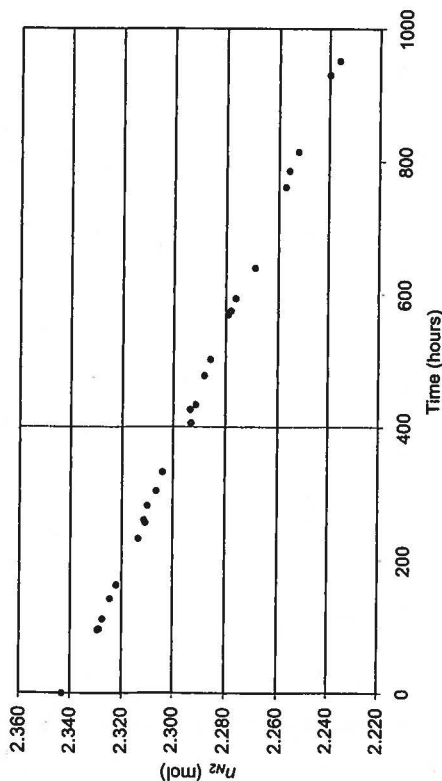


Figure 4. Quantity of nitrogen permeating through the circular pouch specimen.

$$GTR = 4.2 \times 10^{-8} \text{ mol s}^{-1} \text{ m}^{-2}$$

The nitrogen permeance was then determined by Equation 12, for a mean partial pressure difference of 55 kPa:

$$\bar{P}_{N_2} = 7.6 \times 10^{-13} \text{ mol s}^{-1} \text{ Pa}^{-1} \text{ m}^{-2}$$

It would be interesting to compare these results with those reported in the literature, however, due to the different thicknesses of membranes tested, comparisons must be made using the coefficient of permeability, despite the disadvantages reported in Section 3.1 regarding the characterization of geomembrane permeability by the coefficient  $P''$ . The result obtained in the present study for HDPE geomembranes is as follows:

$$P''_{N_2} = 1.1 \times 10^{-15} \text{ mol s}^{-1} \text{ Pa}^{-1} \text{ m}^{-1}$$

This result is compared in Table 1 to earlier findings reported by Park (1986) and by the *Encyclopedia of Polymer Science and Technology* (1964). It is also compared to preliminary test results obtained with non-seamed circular specimens of the same HDPE geomembrane (Pierson 1996). Considering that the coefficient of permeability depends on the thickness, test conditions, type of gas, temperature, and polyethylene quality, the order of magnitude of the coefficient of permeability to nitrogen might be considered consistent with the values presented in literature.

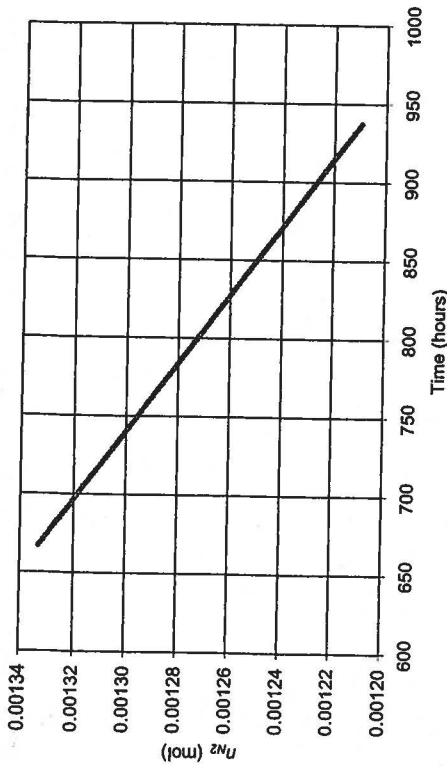


Figure 6. Nitrogen quantity permeating through the rectangular pouch specimen after steady-state is achieved.

$$\bar{P}_{N_2} = 1.5 \times 10^{-15} \text{ mol s}^{-1} \text{ Pa}^{-1}$$

No comparison with other experiments can be made here since a very small geomembrane surface was tested; it should be noted that this test is designed to test geomembrane seams.

## 5.2 Test in Water

### 5.2.1 Circular Specimens

The same circular pouch previously tested in air was immersed in water. Figure 7 shows the results obtained in terms of absolute total pressure in the pouch during 120 days (2,900 hours). As can be seen in Figure 7, the absolute pressure inside the specimen decreases by roughly 3% during the first 30 days of the test, then increases and reaches a value of the same order of magnitude as the initial pressure.

These results are not surprising and are in agreement with the hypothesis considered in Section 3.2. According to this hypothesis, two flows occur simultaneously through the specimen: the nitrogen flow, from the inside to the outside, leading to a decrease in absolute pressure; and the water flow, from the outside to the inside, leading to an increase in absolute pressure.

To calculate the different quantities defined in Section 3.2.2, it is necessary to be sure that the nitrogen moles passing through the geomembrane do not concentrate in the water layer adjacent to the pouch, which would affect the value of the partial pressure outside the specimen. Agitating the water (for temperature homogenization pur-

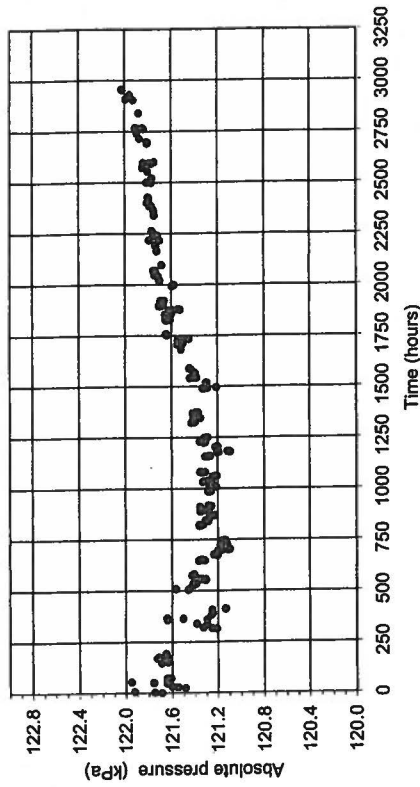


Figure 7. Change with time in the absolute pressure inside the specimen during the test conducted in water (circular specimen).

poses) minimizes this risk. Furthermore, nitrogen diffuses easily in water (diffusion coefficient:  $2.6 \times 10^{-9} \text{ m}^2/\text{s}$  (Reid et al. 1987)), with a Bunsen solubility coefficient equal to 0.01557 (Air Liquide 2002). This coefficient gives the volume of nitrogen that can be dissolved in a unit volume of water. In the experiments conducted for this study, the number of nitrogen molecules that reach the water by crossing the geomembrane and the number of nitrogen molecules that can be dissolved in water are the same order of magnitude. Therefore, no nitrogen bubbles were observed, or could have been observed, in the water.

The number of moles of nitrogen ( $n_{N_2}$ ) and of water ( $n_W$ ) permeating through the specimen was estimated using Equations 14 and 16, respectively. Figure 8 shows the results of these calculations. In Figure 8, the number of moles of nitrogen and water is plotted against time.

It is interesting to observe that  $n_W$  presents a linear variation with time. It confirms that the steady state was achieved as in the test carried out in air, but over a longer period of time.  $WTR$  was obtained similarly to  $GTR$  using Equation 7:

$$WTR = 8.0 \times 10^{-8} \text{ mol s}^{-1} \text{ m}^{-2}$$

The water permeance was then determined by Equation 17, for a mean partial pressure difference of 84 kPa:

$$\bar{P}_W = 9.5 \times 10^{-13} \text{ mol s}^{-1} \text{ Pa}^{-1} \text{ m}^{-2}$$

Similar to the results for nitrogen permeability, the results obtained for HDPE geomembrane permeability to water vapour are compared in Table 2 (using the coef-

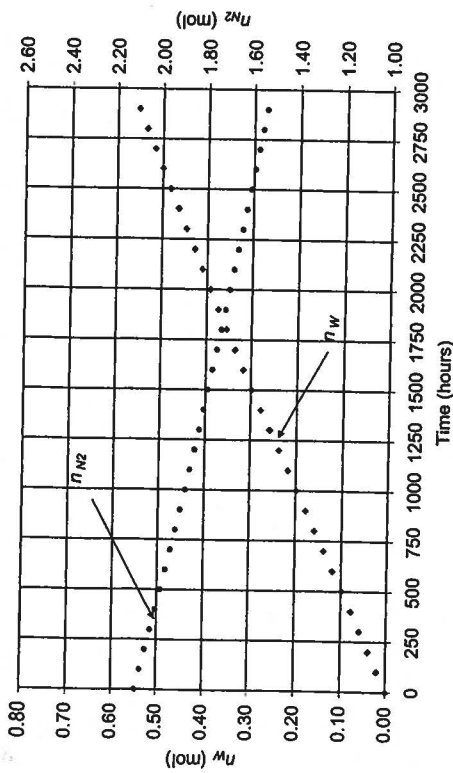


Figure 8. Number of moles of nitrogen,  $n_{N_2}$ , and water,  $n_W$ , permeating through the circular pouch specimen.

efficient  $P_w''$ ) to other reported results (Haxo et al. 1984; Haxo 1990; Rogers 1986) and show an acceptable agreement as with the nitrogen permeability results.

#### 5.2.2 Rectangular Specimens

The same rectangular specimen, previously tested in air, was immersed in water. The absolute pressure versus time is plotted in Figure 9. During the test period (938 hours), the absolute nitrogen pressure decreases approximately 78 kPa, corresponding to a 31% decrease.

In terms of absolute pressure, the results obtained with the test carried out in water and in air show a similar trend. The pressure decreased with time in both tests (recall Figure 5).

The amount of water vapour permeating through the rectangular pouch specimen after the steady-state achievement (which means here after 660 hours) is plotted versus time in Figure 10.

Table 2. Comparison of the order of magnitude of HDPE geomembrane permeability coefficients to water vapour.

Reference	Water vapour permeability, $P_w''$ ( $\text{mol m}^{-1} \text{s}^{-1} \text{Pa}^{-1}$ )
Haxo et al. (1984), Haxo (1990)	$7 \times 10^{-15}$
Rogers (1985)	$8 \times 10^{-15}$
Present study (circular pouch)	$1.4 \times 10^{-15}$

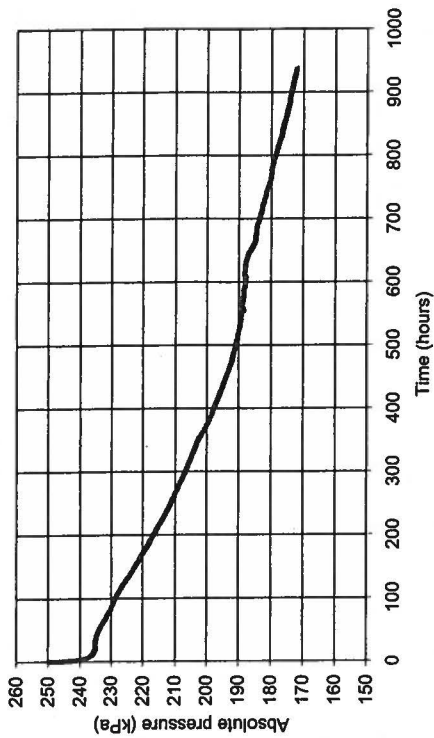


Figure 9. Decrease in the absolute pressure of nitrogen during the test in water (rectangular pouch specimen).

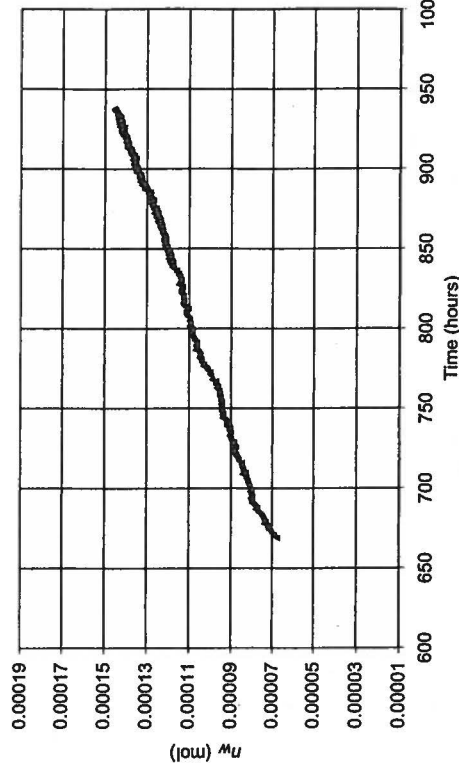


Figure 10. Quantity of water vapour permeating through the rectangular pouch specimen.

Based on Figure 10, the water vapour flow  $WTR$  was determined:

$$WTR = 8.3 \times 10^{-11} \text{ mol s}^{-1}$$



The permeance to water vapour was estimated from Equation 17, for a mean partial pressure difference of 80 kPa:

$$\bar{P}_W = 9.4 \times 10^{-16} \text{ mol s}^{-1} \text{ Pa}^{-1}$$

### 5.3 Discussion

#### 5.3.1 Concerning the Circular Pouch

Experimental results obtained on circular pouches show that it is possible to determine the permeance of HDPE geomembranes to nitrogen and water vapour by the use of the gas permeability pouch test.

These results are consistent with results obtained from different devices devoted to gas permeability measurements. The quantity obtained is the permeance  $P$ , which is the ratio between the gas flow crossing a unit area of a geomembrane and the partial pressure difference across the geomembrane.

Permeance  $P$  is helpful for predicting the leak of different gases (nitrogen can easily be replaced by other gases) through different geomembranes; the gas flow crossing a geomembrane can be easily deduced from  $P$  if the partial pressure difference (or gas concentration difference) on both sides of the geomembrane is known, using the definition of  $P$ . The latter can assess the "gas-tightness" performance of the geomembrane in a landfill, for example, in accordance with the composition of the site biogas.

The gas flow thus obtained is overestimated for two reasons:

- the geomembrane is under tensile stress when the pouch is pressurized;
- the initial pouch area considered as the reference area in the calculation of  $P$  (Section 3.1) is obviously smaller than the one reached once the pouch is pressurized.

This leads to gas flow predictions with a safety coefficient and does not prevent us from comparing different specimens or from studying gas-flow parameters, if the same test procedure is observed.

Permeance  $P$  is also determined from the standard test method ASTM D 1434. Comparisons between the results obtained from both methods (gas permeability pouch test and ASTM D 1434) will be available, as soon as different gases have been considered in the gas permeability pouch test.

It should be observed that results obtained from the gas permeability pouch test may depend on the quality of the pouch seam, in the same way as the results obtained from usual gas permeability tests depend on the quality of the seal, as mentioned in Section 1. The advantages of the gas permeability pouch test over typical gas permeability tests are:

- the possible large size of the specimen (over 0.6 m diameter) made of two sheets of geomembrane, where the seamed portion represents less than 4% of the total geomembrane pouch area;
- the quality of the seam is an important parameter of the gas permeability of flexible membrane liners, i.e., if the pouch is seamed with the same device used in the field,

the gas permeability pouch test results can be considered realistic.

#### 5.3.2 Concerning Rectangular Pouches

Seamed specimens made by the thermal hot dual wedge method have been tested and characterized by a permeance  $P$ . Even if it does not enable the prediction of leaks through geomembrane seams (which mainly occur on site through local defects), the possibility of such measurements represents the main interest of the gas permeability pouch test. Actually, it gives the opportunity of assessing geomembrane seams from the point of view of the imperviousness, based on quantitative criteria. In addition to allowing a study of seam parameters, this test may contribute to correlate permeability and mechanical characteristics: this study is a planned extension of the present work.

It can be observed that seams made by the thermal hot dual wedge method are controlled in the field by a similar method, which is based on pass/failure criteria and which does not allow for a precise characterization of the seam permeability.

Other seaming methods can be tested by the gas permeability pouch test, using seamed pouches where the seamed area predominates the non-seamed area.

#### 5.3.3 Concerning the Test Limits

**Gas Pressure Inside the Pouch.** If the gas pressure inside the pouch is too high, the resulting geomembrane tensile stress near the seam and at weak locations (connections and seam joints) can be too high and the permeability test turns into a mechanical test. All experiments conducted on pouches showed that the maximum relative gas pressure in the pouch is 35 kPa for circular pouches and 150 kPa for rectangular pouches made by the thermal hot dual wedge method. It can be observed that 150 kPa is close to the usual relative air pressure used in the field for quality control of seams made by the thermal hot dual wedge method. Any damage due to pressures in the pouch that are too high can be easily detected by a different pressure decrease with time from the one corresponding to a nondamaged pouch.

**Connections and Geomembrane Thickness.** The connection of the gas pipe to the pouch is a potential weak point and must be carefully done using specific connections and specific types of glue (Figures 1 and 2). Any resulting damage can be easily detected as for the high gas pressures discussed previously.

Nevertheless, such connections require a minimum geomembrane thickness to be effective. For a membrane thickness less than 0.5 mm (which is strictly not recommended in landfill applications), the connections used in the experiments described in this paper may be ineffective. For testing films, this connection problem should be solved and the pouch should probably be tested under a lower gas pressure. Furthermore, as stated in Section 3.1, the geomembrane thickness is difficult to specify with the required accuracy. For example, the thickness variation of geomembranes manufactured from blown film line is known to be  $\pm 0.2$  mm. This confirms the need to test large geomembrane specimens (Section 5.3.1), which better take into account thickness variations, and to use the permeance  $P$  instead of  $P'$ .

*Geomembrane Flexibility.* Only HDPE geomembranes, which are relatively inflexible, were used in the gas permeability pouch tests reported here. Therefore, all experiments showed a negligible volume variation. It is then possible to assess the "gas-tightness" performance of a geomembrane with only one experiment in air. In such a case, the experiment in water is only necessary to characterize the water vapour permeability.

For more flexible geomembranes, both experiments (in air and in water) are required, since the volume variation of the pouch is determined from the level of water (Section 3.2.1).

## 6 CONCLUSIONS

Laboratory tests on gas permeability of HDPE geomembranes were carried out using circular and rectangular pouches. This research attempted to, first, determine the gas permeability of the geomembrane itself using large circular pouch specimens and, second, to assess the quality of the seams according to imperviousness by the use of rectangular pouch specimens where the seamed area is predominantly greater than the non-seamed area.

In the experiments performed with circular pouches consisting of two overlapped HDPE geomembrane sheets, the results obtained are consistent with values reported in the literature for nitrogen and for water vapour, suggesting that the test may be used in the quality control process to assess the gas permeability coefficients of geomembranes. The advantages of this test consist of, on the one hand, being easy to perform in any laboratory and, on the other hand, of having no specific seal (pouches are made by means of welding techniques used on site).

In the experiments performed with rectangular pouches consisting of a true HDPE welded seam using the thermal-hot dual wedge technique, the results showed that the flow rates and the corresponding permeances varied with the penetrant molecules and that this study has taken a step toward defining the quality of geomembrane seams. The gas permeability pouch test appears to be a useful tool to assess the quality of seams by quantitative measurement of the permeance, providing an essential and complementary test to mechanical tests. It may provide the basis for design specifications based on a quantitative permeability criterion.

The approach outlined in this study will be repeated with other geomembrane seams, characterized by different welding parameters, as well as by other seaming methods, in order to understand the specific mechanisms of permeation through the seams and the influence of the parameters that control its quality. This study only considered HDPE geomembranes; however, studies will be carried out to assess other materials.

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## NOTATIONS

Basic SI units are given in parentheses.

$c_f$	=	concentration of penetrant molecules in fluid in contact with geomembrane ( $\text{kg m}^{-3}$ )
$c_g$	=	concentration of diffusing molecules in geomembrane ( $\text{kg m}^{-3}$ )
$D$	=	diffusion coefficient ( $\text{m}^2 \text{s}^{-1}$ )
$f$	=	mass flux of penetrant molecules through geomembrane ( $\text{kg m}^{-2} \text{s}^{-1}$ )
$GTR$	=	gas transmission rate determined for $\Delta p_G$ when specimen is immersed in gas ( $\text{mol m}^{-2} \text{s}^{-1}$ for geomembrane area unit or $\text{mol s}^{-1}$ for pouch specimen)
$GTR'$	=	gas transmission rate determined for $\Delta p'_G$ when specimen is immersed in liquid ( $\text{mol m}^{-2} \text{s}^{-1}$ for geomembrane area unit or $\text{mol s}^{-1}$ for pouch specimen)
$L_g$	=	thickness of geomembrane (m)
$M$	=	gas molar mass (kg)
$M_{air}$	=	air molar mass (kg)
$M_{N_2}$	=	nitrogen molar mass (kg)
$M_{OG}$	=	molar mass of other gases (OG defined in Appendix A) (kg)
$M_W$	=	water molar mass (kg)
$N$	=	gas quantity (mol)
$n$	=	number of moles of specific element (mol)
$n_G$	=	number of moles of gas G (mol)
$n_{G+W}$	=	number of moles of gas G and water W (mol)
$n_{N_2}$	=	number of moles of nitrogen (mol)
$n_{OG}$	=	number of moles of other gases (OG defined in Appendix A) (mol)
$n_W$	=	number of moles of water (mol)
$P$	=	permeance to a specific element ( $\text{mol m}^{-2} \text{s}^{-1} \text{Pa}^{-1}$ for characterizing geomembrane area unit or $\text{mol s}^{-1} \text{Pa}^{-1}$ for characterizing pouch specimen)
$P_G$	=	permeance to gas G ( $\text{mol m}^{-2} \text{s}^{-1} \text{Pa}^{-1}$ for characterizing geomembrane area unit or $\text{mol s}^{-1} \text{Pa}^{-1}$ for characterizing pouch specimen)
$P_W$	=	permeance to water vapour ( $\text{mol m}^{-2} \text{s}^{-1} \text{Pa}^{-1}$ for characterizing geomembrane area unit or $\text{mol s}^{-1} \text{Pa}^{-1}$ for characterizing pouch specimen)
$\bar{P}$	=	mean permeance to specific element determined for time interval $\Delta t$ ( $\text{mol s}^{-1} \text{Pa}^{-1}$ )

$\bar{P}_G$  = mean gas G permeance of pouch specimen determined for time interval  $\Delta t$  ( $\text{mol s}^{-1} \text{Pa}^{-1}$ )  
 $\bar{P}_{N_2}$  = mean nitrogen permeance of pouch specimen determined for time interval  $\Delta t$  ( $\text{mol s}^{-1} \text{Pa}^{-1}$ )  
 $\bar{P}_W$  = mean water vapour permeance of pouch specimen determined for time interval  $\Delta t$  ( $\text{mol s}^{-1} \text{Pa}^{-1}$ )  
 $P$  = coefficient of permeability of geomembrane to a specific element ( $\text{m}^2 \text{s}^{-1}$ )  
 $P'$  = coefficient of permeability to a specific element ( $\text{mol m}^2 \text{s}^{-1} \text{kg}^{-1}$ )  
 $P''$  = coefficient of permeability to a specific element ( $\text{mol s}^{-1} \text{m}^{-1} \text{Pa}^{-1}$ )  
 $P''_{N_2}$  = coefficient of permeability to nitrogen ( $\text{mol s}^{-1} \text{m}^{-1} \text{Pa}^{-1}$ )  
 $P''_W$  = coefficient of permeability to water vapour ( $\text{mol s}^{-1} \text{m}^{-1} \text{Pa}^{-1}$ )  
 $P$  = gas pressure in pouch (total or partial pressure depending on gas composition, monoconstituent or not monoconstituent) (Pa)  
 $P_{atm}$  = atmospheric pressure (Pa)  
 $P_G$  = gas G pressure in pouch (total or partial pressure depending on gas composition, monoconstituent or not) (Pa)  
 $P_{Gout}$  = gas pressure outside pouch specimen (Pa)  
 $P_{G+W}$  = gas and water vapour pressure in pouch (Pa)  
 $P_{N_2}$  = nitrogen pressure in pouch (Pa)  
 $P_{Wout}$  = pressure of liquid outside pouch specimen (Pa)  
 $\bar{P}$  = mean specific gas pressure in pouch during time interval  $\Delta t$  (Pa)  
 $\bar{P}_G$  = mean gas G pressure in pouch during the time interval  $\Delta t$  (Pa)  
 $\bar{P}_{G+W}$  = mean gas and water vapour pressure in pouch during the time interval  $\Delta t$  (Pa)  
 $\bar{P}_W$  = mean water vapour pressure in pouch during the time interval  $\Delta t$  (Pa)  
 $r$  = specific humidity (water vapor, kg; dry air,  $\text{kg}^{-1}$ )  
 $R$  = Universal Gas Constant, 8.3143 ( $\text{m}^3 \text{Pa mol}^{-1} \text{K}^{-1}$ )  
 $S$  = partitioning coefficient (dimensionless)  
 $T$  = absolute temperature (K)  
 $t$  = time (s)  
 $V$  = inner volume of pouch specimen ( $\text{m}^3$ )  
 $WTR$  = water vapour transmission rate ( $\text{mol s}^{-1}$ )

$z$  = spatial dimension parallel to direction of diffusion (m)  
 $\delta t$  = infinitesimal time interval (s)  
 $\Delta c_f$  = concentration difference of penetrant molecule in adjacent fluids on either side of geomembrane ( $\text{kg m}^{-3}$ )  
 $\Delta p_G$  = partial pressure difference of penetrant molecule G in adjacent fluids on both sides of geomembrane for specimen immersed in gas (Pa)  
 $\Delta p'_G$  = partial pressure difference of penetrant molecule G in adjacent fluids on both sides of geomembrane for specimen immersed in liquid (Pa)  
 $\bar{\Delta p}_G$  = mean pressure difference during time interval  $\Delta t$  for specimen immersed in gas (Pa)  
 $\bar{\Delta p}'_G$  = mean pressure difference during time interval  $\Delta t$  for specimen immersed in liquid (Pa)  
 $\Delta n$  = number of moles difference (mol)  
 $\Delta t$  = time interval (s)  
 $\partial c_g / \partial z$  = concentration gradient of diffusing molecules in geomembrane ( $\text{kg m}^{-4}$ )

## APPENDIX A

### CALCULATION OF THE PARTIAL PRESSURE OF NITROGEN OUTSIDE THE SPECIMEN, $P_{Gout}$ , WHEN PLACED IN ATMOSPHERE

The atmosphere consists of nitrogen ( $N_2$ , number of moles:  $n_{N_2}$ ), water vapour ( $W$ , number of moles:  $n_W$ ) and other gases ( $OG$ , number of moles:  $n_{OG}$ ). The partial pressure of nitrogen in ambient air is then:

$$P_{Gout} = \left[ \frac{n_{N_2}}{n_{N_2} + n_W + n_{OG}} \right] P_{atm} \quad (A-1)$$

where  $P_{atm}$  is the atmospheric pressure. Equation A-1 can also be written as follows:

$$P_{Gout} = \frac{P_{atm}}{\left[ \left( \frac{n_W}{n_{N_2} + n_{OG}} \right) \left( \frac{n_{N_2} + n_{OG}}{n_{N_2}} \right) \left( \frac{n_{N_2} + n_{OG}}{n_{N_2}} \right) \right]} \quad (A-2)$$

In Equation A-2, the ratio  $[n_W/(n_{N_2} + n_{OG})]$  can be expressed as a function of the specific humidity  $r$ . This is the ratio of the mass of water vapour on the mass of dry air (nitrogen + other gases), which can be easily obtained from the psychometric chart, when temperature and relative humidity of atmosphere are recorded:

$$r = \left[ \frac{n_W M_W}{(n_{N_2} M_{N_2} + n_{OG} M_{OG})} \right] P_{atm} \quad (A-3)$$

where  $M_W$ ,  $M_{N_2}$ , and  $M_{OG}$  are the molar masses of water, nitrogen and other gases, respectively.

The concept of dry air molar mass  $M_{air}$  is generally used:

$$M_{air} = \frac{n_{N_2} M_{N_2} + n_{OG} M_{OG}}{n_{N_2} + n_{OG}} \quad (A-4)$$

adding to the following by combining Equations A-3 and A-4:

$$\frac{n_W}{n_{N_2} + n_{OG}} = r \frac{M_{air}}{M_W} = 1.61 r \quad (A-5)$$

considering  $M_{air} = 29$  g and  $M_W = 18$  g.

In Equation A-2, the ratio  $[n_W/(n_{N_2} + n_{OG})]$  is equal to  $0.7808$ . By combining equations A-2 and A-5, it is possible to express  $P_{Gout}$  as a function of  $P_{atm}$  and  $r$ :

$$P_{Gout} = \frac{0.7808}{(1 + 1.61r)} P_{atm} \quad (A-6)$$

## APPENDIX B

### CALCULATION OF THE PARTIAL GAS PRESSURE, $P_G(t)$ , IN THE SPECIMEN WHEN IMMersed IN WATER

The partial pressure  $p_G(t)$  depends on the mole quantity  $n_G(t)$  in the specimen. This quantity is determined from the same quantity calculated in the preceding step:  $n_G(t-\delta t)$ , from Equation 14, which implies that  $GTR'$  is known. Since the quantity  $p_G(t)$  is required for the calculation of  $GTR'$  it is necessary to determine  $p_G(t)$  directly from  $n_G(t-\delta t)$ , as follows:

$$p_G(t) = \left[ \frac{n_G(t-\delta t)}{n_{G+W}(t-\delta t)} \right] p_{G+W}(t) \quad (B-1)$$

In Equation B-1,  $p_{G+W}(t)$  is the absolute total pressure measured inside the pouch specimen.  $n_G$  is the mole quantity of gas, G, and  $n_{G+W}$  is the total mole quantity in the specimen (elements G and W). The pressure ratio at time  $t$   $[p_G(t)/p_{G+W}(t)]$  is assumed to be approximately the same as the mole quantity ratio at time  $t-\delta t$ :  $[n_G(t-\delta t)/n_{G+W}(t-\delta t)]$ , which is acceptable if the registering time step  $\delta t$  is small enough. The different steps of calculation are then:

(a) At time  $t = 0$ :

$$n_G(0) = n_{G+W}(0) = \frac{P_{G+W}(0) V}{RT} \quad (B-2)$$

$$n_W(0) = 0 \quad (B-3)$$

$$GTR'(0) = GTR \frac{\Delta p_G(0)}{\Delta p_G} \text{ where } \Delta p_G(0) = p_G(0) = p_{G+W}(0) \quad (B-4)$$

$GTR$  and  $\Delta p_G$  were determined after the experiment where the pouch specimen is immersed in gas G.

(b) At time  $t = \delta t$ :

$$n_G(\delta t) = n_G(0) - GTR'(0) \delta t \quad (B-5)$$

$$n_{G+W}(\delta t) = \frac{P_{G+W}(\delta t) V}{RT} \quad (B-6)$$

$$n_W(\delta t) = [n_{G+W}(\delta t) - n_G(\delta t)] \quad (B-7)$$

$$\Delta p_G(\delta t) = p_G(\delta t) = \frac{n_G(0)}{n_{G+W}(0)} p_{G+W}(\delta t) = p_{G+W}(\delta t) \quad (B-8)$$



**SHEAR STRENGTH PARAMETERS OF SOIL-GEOSYNTHETIC INTERFACES UNDER LOW CONFINING PRESSURE USING A TILTING TABLE**

**ABSTRACT:** Tilting table tests are typically used to determine the friction angle between soils and structures. A procedure is presented to determine both the adhesion and frictional properties of soil-geosynthetic interfaces under very low confining pressures using a tilting table test. A simple tilting table device was developed and a series of tests were conducted on three different types of sand in contact with smooth and textured geomembranes under dry and moist conditions. The study showed the relevance of the proposed procedure and device especially when residual state is concerned.

**KEYWORDS:** Tilting table test, Geosynthetic, Sand, Interface, Shear strength.

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$$GTR'(\delta t) = GTR \frac{\Delta p'_G(\delta t)}{\Delta p_G} \tag{B-9}$$

$$n_G(2\delta t) = n_G(\delta t) - GTR'(\delta t)\delta t \tag{B-10}$$

$$n_{G+W}(2\delta t) = \frac{p_{G+W}(2\delta t) V}{RT} \tag{B-11}$$

$$n_W(2\delta t) = n_{G+W}(2\delta t) - n_G(2\delta t) \tag{B-12}$$

$$\Delta p'_G(2\delta t) = p_G(2\delta t) = \frac{n_G(\delta t)}{n_{G+W}(\delta t)} p_{G+W}(2\delta t) \tag{B-13}$$

$$GTR'(2\delta t) = GTR \frac{\Delta p'_G(2\delta t)}{\Delta p_G} \tag{B-14}$$

(c) At time  $t = 2\delta t$ :