

A non-destructive method for testing non-flexible dual geomembrane seams using gas permeation

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ABSTRACT: A non-destructive test is proposed to control in situ non-flexible geomembrane seams carried out by means of the thermal hot dual wedge method. It consists in pressurising the gap between the two welds by gas injection at a specific pressure and in monitoring the evolution of pressure over time. The migration of gas across the geomembrane is indicated by a decrease in pressure. A permeation parameter (the time constant) can then be estimated under unsteady-state conditions. Experiments were performed outdoors, under variable ambient conditions, to test the feasibility of the method in field conditions as well as in the laboratory, and under controlled ambient conditions to check the validity of the method. The results show that a poor seam from a mechanical point of view is also a poor seam from a permeation point of view. It is also shown that the non-destructive method presented here may be used in situ to test the entire seam. Hence the test is complementary to peel tests, because it reveals poor seams undetectable by the pressurised dual seam method, in pond applications where non-flexible geomembranes are placed.

KEYWORDS: Geosynthetics, Geomembranes, Seams, Hot dual wedge method, Gas permeation

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1. INTRODUCTION

According to Rollin *et al.* (2002), using information collected by Darilek *et al.* (1989), Laine and Darilek (1993), Colucci and Lavagnolo (1995) and Rollin *et al.* (1999), defects in geomembrane seams are the cause of 65% of leaks through uncovered liners of landfills, tanks, basins and ponds. With respect to covered geomembranes, Colucci and Lavagnolo (1995) and Nosko and Touze-Foltz (2000) observed that 6% of leaks are due to seaming failures. It is therefore very important to assess seam quality. This is accomplished by both destructive and non-destructive test methods, as described below.

Shear and peel tests are widely used as destructive seam tests. They are performed to quantify the bond strength and to calibrate seaming machines (Rollin *et al.* 1994; ASTM D 6392; GRI GM 19). The peel test, which evaluates the adhesion strength between two welded geomembranes or between the extruded polymer and the sheets, also provides useful information concerning the

durability of the geomembrane adjacent to the seams (Peggs 1994, 1996). However, such destructive tests provide information only about the limited portion of the seam corresponding to the specimen tested. Furthermore, they require repairs and are time consuming; their frequency must be then optimised. In addition, shear and peel test results have never been correlated with permeation characteristics.

Non destructive seam tests evaluate the seam continuity. They must be carried out on all seams. In order to do this, different methods can be used, such as visual observation, mechanical probe test, pressurised dual seam (double-welded seams: ASTM D 5820), air lance, vacuum box, electrical or ultrasonic methods.

For double-welded seams, the air gap existing between the two welds is pressurised by air injection. The seam is considered acceptable if no air drop on a pressure gauge occurs during a defined period of time (3 to 5 min). This method controls the air permeation of the double wedge and detects only severe defects. It does not give any

quantified information about the real performance of the seam or, consequently, about its long-term performance. It cannot be generally considered as a substitute for mechanical tests. However, Thomas *et al.* (2003) and Stark *et al.* (2004) showed that pressurised air channel evaluation of dual-seamed geomembranes may be used as a substitute for destructive testing when applied to the particular case of thermally bonded PVC geomembrane seams with an air channel. This is possible thanks to a relationship between the welded seam burst strength and the seam peel strength, validated for PVC geomembranes and for a given sheet temperature. This method is interesting because it is not destructive and it tests the whole seam, but it cannot be applied to non-flexible geomembranes, and it concerns only mechanical properties.

An interesting and complementary test to assess seam quality would be a non-destructive test evaluating the permeation performance of the seam by a quantitative measurement. This is proposed in the present study through an adaptation of the permeation pouch test method designed by Pierson and Barroso (2002a, 2002b) and previously called the gas permeability pouch test. This test leads to the determination of the gas permeance of seamed geomembranes in the form of a pouch, with the possibility of characterising the seam as well as the sheet itself, depending on the shape of the pouch. A double hot wedge seam specimen may represent such a pouch and then be characterised by a gas permeance, depending on the seam quality.

Measuring the gas permeance requires the achievement of a 'pseudo steady state', during which the variation of the gas pressure is small enough to be considered as a constant in permeance calculations (corresponding to the mean value). It also requires a controlled ambient temperature, which means that the test must be carried out in the laboratory.

Therefore two questions arise, the answers to which are the objectives of the present study:

- Is it possible to conduct the same test in situ and to characterise the gas permeation of the seam by another parameter, measurable in an unsteady state?
- Are the results obtained from such a test compatible with results obtained from mechanical tests?

As regards the first question, Section 2 focuses on the main principles of the gas permeation pouch test and defines the time constant (the other parameter proposed), measurable in an unsteady state. Section 3 presents time constant results obtained from tests carried out on small- and large-scale specimens, in the laboratory and outdoors (exposed to weather conditions).

With respect to the second question, Section 4 compares the results of the gas permeation pouch test with the results of shear and peel tests.

2. DETERMINING THE TIME CONSTANT FROM A GAS PERMEATION POUCH TEST

Details of the gas permeation pouch test can be found in Pierson and Barroso (2002a, 2002b). Briefly, when adapted to double hot wedge seams, it consists in pressurising the gap between both welds by gas injection at a specific pressure $p(0)$ and in measuring its decrease over time, $p(t)$. If this pressure decrease is not too fast, and if the atmospheric pressure and ambient temperature are constant (corresponding to a specific 'pseudo steady state'), a gas permeance P_G (mol/(s Pa)) can be determined from Equation 1:

$$P_G = \frac{GTR}{\Delta p_G} \quad (1)$$

where GTR (mol/s) is the gas flow through the specimen, obtained from the ideal gas law (if the pouch volume and the ambient temperature are known) and from the variation of pressure over time, and Δp_G (Pa) is the mean partial pressure difference of penetrant molecule G in adjacent gases on both sides of the geomembrane.

It should be noted that the determination of P_G from Equation 1 requires a constant volume of the pouch. Gas permeation tests were also conducted on small-scale HDPE specimens immersed in water, in order to measure the volume of the pouch at each time during the test (Pierson and Barroso 2002a). This volume may change not only because of the gas diffusion, but also because of the possible creep of the specimen. Nevertheless, no volume change could be detected, showing that P_G can be obtained from Equation 1 if the geomembrane tested is non-flexible.

If a gas permeation pouch test is carried out in situ, the variations $p(t)$ will be due not only to the gas diffusion from inside to outside the pouch, but also to the variations in the atmospheric pressure and ambient temperature. Furthermore, in the case of poor seams, the pressure decrease is faster and the 'pseudo steady state' cannot be defined.

Therefore it is impossible to determine the gas permeance P_G of a double hot wedge seam on site, and an 'unsteady state parameter' must be then defined.

From observation of the variations of the absolute pressure inside the specimen, $p(t)$ (see Figures 3, 4 and 5), it is possible to show that, after a delay time t_0 , the following equation may approach the experimental data $p(t)$ with reasonable accuracy:

$$p(t) = p(\infty) + [p(0) - p(\infty)]e^{-t/\tau} \quad (2)$$

where $p(\infty)$ is the absolute final gas pressure in the pouch corresponding to atmospheric pressure (Pa), $p(0)$ is the absolute initial pressure of the gas inside the specimen (Pa), t is the time (hours), and τ is a constant, herein termed the time constant (hours).

It is an exponential law with only one time constant τ , which characterises the pressure decrease of the tested specimen and which may be considered a real permeation

parameter: for a good seam, a long time is necessary to achieve the final steady state (corresponding to atmospheric pressure inside the pouch), leading to a high value of time constant value. In contrast, this final steady state would rapidly be achieved for a poor seam, corresponding to a small value of time constant.

The quantity τ can be easily determined: it is the inverse of the slope of the linear function $\ln Z(t)$, defined as follows and derived from Equation 2 for $t \geq t_0$:

$$\ln Z(t) = \frac{-t}{\tau} \tag{3}$$

where

$$Z(t) = \frac{p(t) - p(\infty)}{p(0) - p(\infty)} \tag{4}$$

Time t_0 is a delay time corresponding to the beginning of the test, during which several time constants should be considered and during which Equation 2 is not valid. It is determined by optimising the coefficient of linear correlation, r^2 , of the function $\ln Z(t)$.

As for the determination of P_G , this method cannot be applied if the pouch volume is not constant, which means again that it concerns only non-flexible geomembranes.

3. EXPERIMENTAL PROCEDURE

The following different tests were carried out:

- tests on small-scale specimens in the laboratory in order both to compare τ values obtained on pouches seamed under different conditions, and to observe the influence of the gas type;
- tests on large-scale specimens in order to determine

the operating conditions of the test on site.

In addition, mechanical tests were carried out to assess the mechanical strength of the seams.

3.1. Tests on small-scale specimens

The description of the test method is more detailed in Pierson and Barroso (2002a, 2002b). Succinctly, these tests were conducted in Lirigm (France) on 1.2 m long pouch specimens made of 2 mm thick HDPE geomembrane. Relevant characteristics of the geomembrane are presented in Table 1. The seam parameters of the pouch specimens are shown in Table 2. No extreme conditions (which should not occur within the limits of a quality control/quality assurance programme) were explored, such as the overheating of the polymer resin. Other tests under different conditions are planned.

The pouches were pressurised with nitrogen (Figure 1) at an initial relative pressure of 150 kPa. The ambient temperature was controlled at $27 \pm 0.1^\circ\text{C}$. One particular specimen was tested with two different gases, nitrogen (N_2) and carbon dioxide (CO_2).

3.2. Tests on large-scale specimens

Two tests were carried out in LNEC (Portugal) on pouches made of the same geomembrane as for the small-scale tests: a 10 m long specimen was tested in an air-conditioned laboratory (air temperature $20 \pm 2^\circ\text{C}$; relative humidity $65 \pm 5\%$), which is herein called the S-LS lab. The other, a 5 m long specimen, was tested outdoors to simulate field conditions. This specimen is herein called S-LS exp (Figure 2). The tests were carried out using nitrogen gas.

Table 1. Characteristics of geomembrane used

Polymer type	Surficial aspect	Thickness (mm) ASTM D 5199	Density (kg/m^3) ISO 1183	Tensile stress at yield (MPa) ASTM D 638
HDPE	Smooth	2.00	0.943	18.6

Table 2. Seaming parameters, time constants and gas permeances measured for small-scale specimens

Specimens		S1	S2	S3	S4	S5	S6	S7
Seam parameters								
Velocity (m/min)		2.5	2.5	2.5	1.8	1.8	1.5	2.5
Temperature ($^\circ\text{C}$)		280	355	355	355	280	280	355
Roller pressure (kN/m^2)		200	200	300	300	300	400	400
Test results								
Time constant (h)	τ_{N_2}	2500	Failed	2500	1700	159	1700	2500
	τ_{CO_2}	–	–	–	–	–	1000	–
Gas permeance per unit of length ($\text{mol}/\text{m s Pa}$)	$P_{\text{N}_2\text{L}}$	1.0×10^{-15}	Failed	1.0×10^{-15}	1.0×10^{-15}	Failed	1.2×10^{-15}	0.8×10^{-15}
	$P_{\text{CO}_2\text{L}}$	–	–	–	–	–	5.7×10^{-15}	–

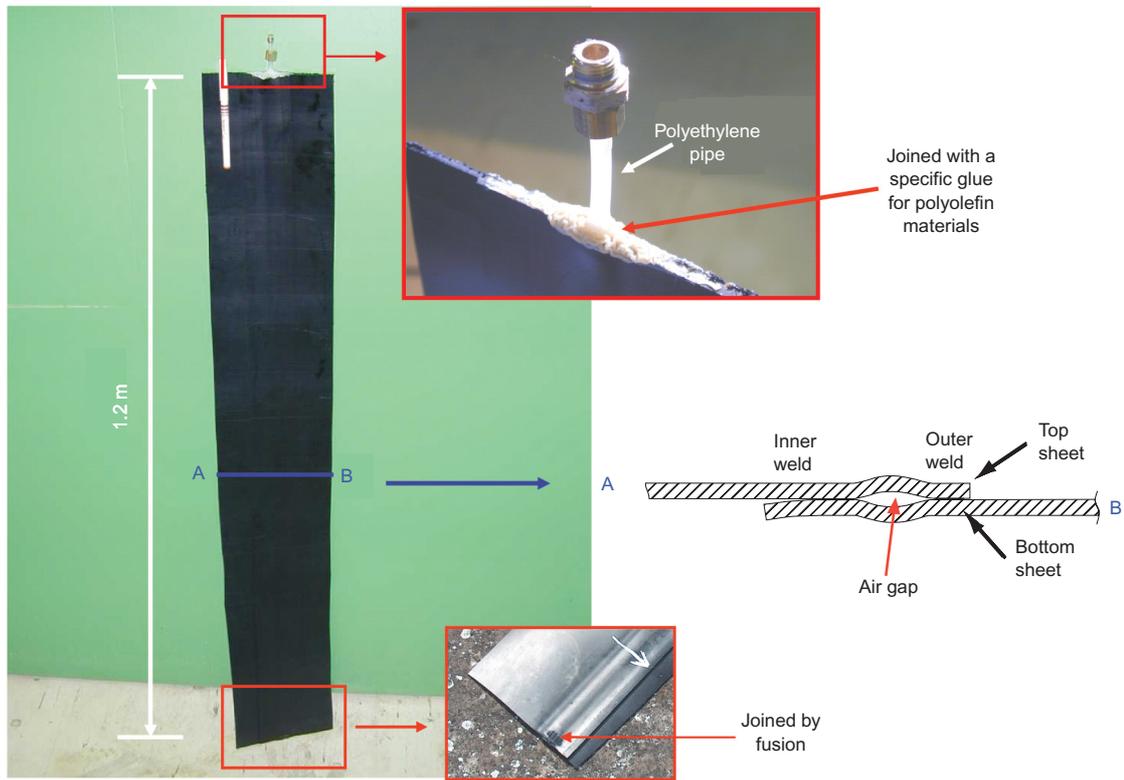


Figure 1. Small-scale pouch specimen made by thermal hot dual wedge method



Figure 2. Large-scale test carried out outdoors (S-LS exp)

3.3. Mechanical tests

From each small-scale specimen, 10 test strip-specimens were cut, using a 25 mm wide die, and were subject to shear

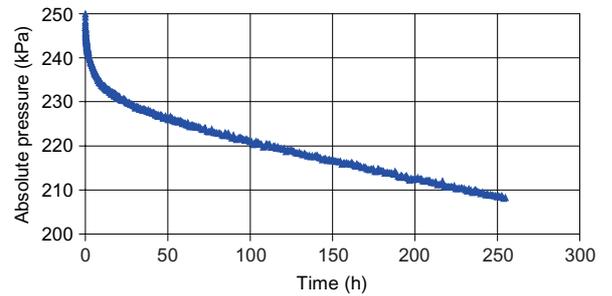


Figure 3. Variation over time of pressure inside small-scale pouch specimen (S4)

and peel tests based on ASTM D 6392 (standard test method for determining the integrity of non-reinforced geomembrane seams produced using thermo-fusion methods).

4. RESULTS

4.1. Tests on small-scale specimens

Figure 3 shows an example of the variations in $p(t)$ for one specimen. The results obtained in terms of time constant (τ_{N_2} or τ_{CO_2}) and gas permeance (P_{N_2L} or P_{CO_2L}) are summarised in Table 2. The gas permeance is here given per specimen length unit ($\text{mol}/(\text{s Pa m})$) for comparison with the results obtained from the large-scale tests. Note that specimen S7 was extracted from the large-scale specimen.

Considering the uncertainties obtained (the uncertainty calculations are detailed in Barroso 2005), the results of Table 2 show that the nitrogen permeance of all the

specimens that did not fail is a constant: $P_{N2L} = 10^{-15} \pm 0.2 \times 10^{-15} \text{ mol}/(\text{m s Pa})$, corresponding to a mean time constant, $\tau_{N2} = 2500 \pm 500 \text{ h}$.

Therefore the different values of τ_{N2} observed in Table 2 are related to uncertainties and not to seaming parameters, which cannot be optimised from quantity τ .

However, it is interesting to observe that specimen S5 failed after 140 test hours, which means that this seam would have not been rejected on site by traditional control based on the pressurised dual seam method. This shows the interest of the gas permeation pouch test, which is more suitable for evaluating seam quality over the long term than the pressurised dual seam method.

Table 2 also shows the influence of the nature of the gas on the results: the same specimen shows a permeance to carbon dioxide ($P_{CO2L} = 5.7 \times 10^{-15} \text{ mol}/(\text{m s Pa})$) that is clearly higher than the permeance to nitrogen ($P_{N2L} = 1.2 \times 10^{-15} \text{ mol}/(\text{m s Pa})$). Also, the time constant for carbon dioxide ($\tau_{CO2} = 1000 \text{ h}$) is clearly lower than the time constant for nitrogen ($\tau_{N2} = 1700 \text{ h}$). The two results are in agreement, corresponding to a higher flux of CO_2 than the flux of N_2 through the same pouch.

4.2. Tests on large-scale specimens

The seaming parameters corresponding to large-scale specimens are the same as those of specimen S7, given in Table 2.

Figures 4 and 5 show respectively the variations of $p(t)$ in an air-conditioned laboratory (S-LS lab) and outdoors (S-LS exp). It can be seen that the large-scale specimen tested in the laboratory presents a similar trend to that of the small-scale specimens. Concerning the specimen tested outdoors, the evolution of the pressure inside the

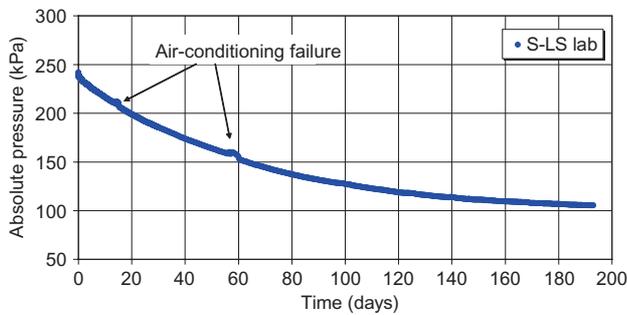


Figure 4. Variation over time of pressure inside large-scale specimen tested in laboratory

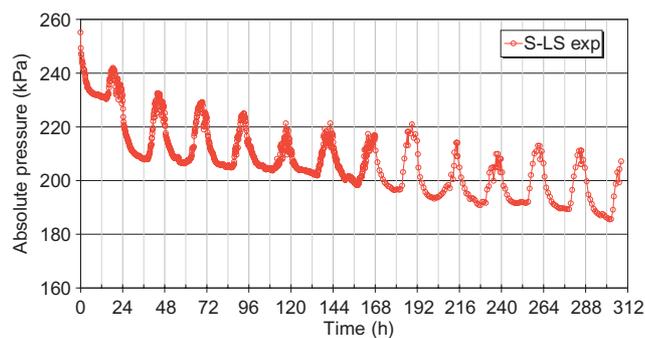


Figure 5. Variation over time of pressure inside large-scale specimen tested outdoors

specimen presents a wave behaviour. This is due not to the migration of gas through the pouch specimen but to the variations of the geomembrane temperature as a result of the important absorption of solar radiations during the day (black product). For instance, as regards the testing time considered here, the difference between the maximum and the minimum geomembrane temperature was estimated at about 45°C , which explains the unsteadiness of the variations of $p(t)$ in Figure 5, and highlights the need to calculate the quantity $Z(t)$ for the same geomembrane temperature, which must be considered here, and not for the ambient temperature.

Thus the values of quantity $\ln Z$ were here calculated each day at a time when the geomembrane temperature was the same. Two different geomembrane temperatures were considered, corresponding to the upper and lower limits calculated based on the solar radiation. For the upper limit, the geomembrane temperature was estimated each day for a solar radiation of about $0.953 \text{ kW}/\text{m}^2$, corresponding to a mean temperature of 62°C . For the lower limit, the geomembrane temperature was estimated for null radiation (night conditions), corresponding to a mean temperature of 17°C . Considering the uncertainties, the same value for the time constant was obtained in both cases ($1700 \pm 400 \text{ h}$).

During the test, it was observed that the influence of atmospheric pressure variations was negligible, compared with the influence of the sheet temperature.

Figure 6 shows the variations $\ln Z(t)$, two days after the beginning of the test (corresponding to the delay time t_0),

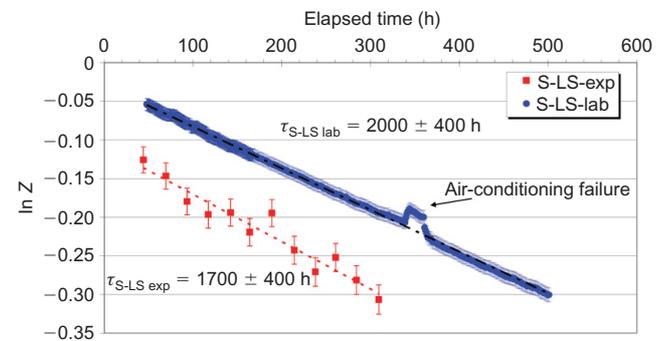


Figure 6. Variation over time of $\ln Z$ for specimen tested in laboratory (S-LS lab) and outdoors (S-LS exp)

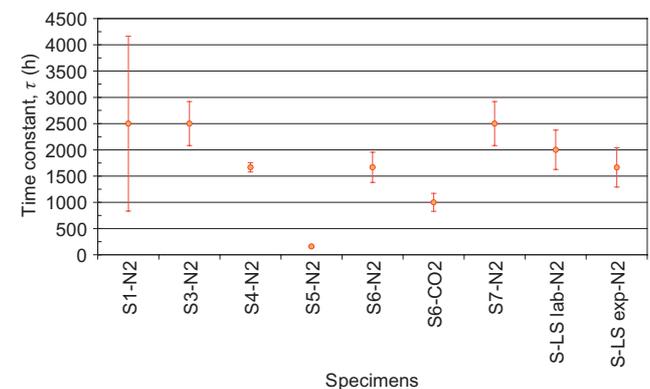


Figure 7. Comparison of time constant results obtained for the various specimens tested

for the tests carried out with the specimen placed in an air-conditioned laboratory and outdoors. For the latter, it includes only the values of $\ln Z(t)$ calculated for one geomembrane temperature (upper limit) for the sake of brevity. Figure 7 compares the time constant values with the small-scale specimen results. Taking into account the uncertainties, all the results are consistent, suggesting that characterisation of the gas permeation of seams by the time constant can be carried out in situ.

Furthermore, in order to confirm the compatibility of results obtained on small- and large-scale specimens, the gas permeance was calculated for the large-scale specimen tested in the laboratory, even if the variation $p(t)$ did not allow a definition of a 'pseudo steady state' (no gas permeance was determined for the exposed specimen because, in addition to the variations $p(t)$, the ambient temperature is too variable). The following value was obtained: $P_{N2L} = 1.2 \pm 0.2 \times 10^{-15}$ mol/(m s Pa). This is in good agreement with the mean gas permeance obtained for small-scale specimens (Section 4.1).

Such results show that it is possible to compare the results obtained on site from the gas permeation pouch test with the results obtained in the laboratory, on a reference specimen, from the same test conducted under the same conditions.

To determine the minimum time required for this test, the time constant was calculated for the large-scale specimen tested outdoors, when considering different time intervals after the 2 day delay time (t_0). Figure 8 shows that a minimum time of 6 days is necessary to obtain a time constant compatible with that calculated at the end of the test (that is, within the uncertainty range).

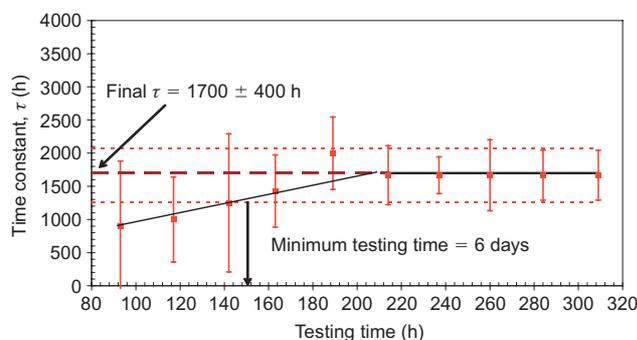


Figure 8. Time constant values calculated for different testing time intervals (specimen tested outdoors with time intervals all considered from $t_0 = 44$ h)

Table 3. Results of mechanical tests

Specimens		S-1	S-2 ^(a)	S-3	S-4	S-5 ^(b)	S-6	S-LS/S-7
Mean peel strength (kN/m)	Inner weld	12.1	9.5	12.7	25.9	3.6	4.5	27.3
	Outer weld	8.3	6.1	11.4	24.3	3.2	9.8	22.9
Mean shear strength (kN/m)		36.9	37.1	37.6	38.1	37.6	38.5	39.5
Acceptance criteria from GRI GM 19		Fail	Fail	Fail	Pass	Fail	Fail	Pass

^(a)Gas permeation pouch test failed a few hours after being pressurised.

^(b)Gas permeation pouch test failed before reaching the pseudo steady state.

5. COMPARISON OF RESULTS FROM MECHANICAL AND GAS PERMEATION TESTS

The results of the mechanical tests are given in Table 3 and compared with acceptance criteria suggested by GRI GM 19, which, for the 2.0 mm HDPE geomembrane seams, specifies that the strength of four out of five specimens tested in peel and shear mode should meet or exceed, respectively, 21 kN/m and 28 kN/m, and the fifth specimen should meet or exceed 80% of the given values.

Table 3 shows that, in contrast to the peel strength values, the shear strength values are very similar for all the specimens tested. This is due to the shear failure, which always occurred in the sheet adjacent to the weld. Therefore shear strength values do not provide useful information about seam bond and will not be considered in the next analysis, which is in agreement with Peggs' recommendations (e.g. Peggs 1994, 1996).

Table 3 also shows that only specimens S4 and S7 should pass according to GRI's acceptance criteria. Therefore specimens S2 and S5, which failed during the gas permeation test, would have not been accepted after the peel test. It is also interesting to observe that specimen S5 gives the worst results during the mechanical and permeation tests, and that specimen S7 gives the best results during the peel test and the permeation test (lowest gas permeance and highest time constant). The mechanical and permeation tests are thus in agreement concerning the extremes.

Nevertheless, it can be seen that some rejected specimens (for example S1 and S3) from the peel test results give similar results during the gas permeation test to those of the accepted specimens (S4 and S7).

Therefore it can be concluded that a seam validated by a peel test is also a good seam from a permeation point of view, with a proved safety margin. This is an important conclusion, which highlights peel test significance.

6. CONCLUSIONS

This study describes a non-destructive test that may be conducted in situ: the gas permeation pouch test. It consists in pressurising the gap between the two seams by gas injection and in recording the gas pressure decrease over time, $p(t)$. The analysis of this function leads to determination of the time constant (τ). Regardless of the length of the seam, a specific material tested with a

specific gas is characterised by a specific time constant, which may be measured in the laboratory for a reference seam. The values of τ measured on site over a week from the gas permeation pouch test can be compared with values from a control seam: they will be even smaller if the seam is poorer.

The objective of this paper was to show the principle, feasibility, and interest of the permeation pouch test. The tests presented here were carried out with pure gases (nitrogen and carbon dioxide) in the laboratory and outdoors. Other gases can be used, such as air.

The permeation pouch test cannot replace mechanical tests, namely the peel test, which proved here to be better adapted for the calibration of seam parameters. Besides the validation of the peel test from a permeation point of view, the results obtained from this work suggest that it is possible to use the gas permeation pouch test in situ to control HDPE dual-seamed geomembranes, with the obvious advantage of it being a non-destructive test method.

In fact, this control is basically similar to the pressurised dual seam method typically used in situ to evaluate the continuity of dual seams, but it reveals poor seams that would have been accepted after a control based only on the pressurised dual seam method. When the seam parameters are optimised, the gas permeation pouch test may also detect small defects on the seam, undetectable by the peel test, except if the test is conducted on the defect location.

The limitations of the gas permeation pouch test on site are as follows:

- It concerns only non-flexible geomembranes. In the case of flexible geomembranes, such as PVC geomembranes, recall that Thomas *et al.* (2003) propose a specific air channel test to be applied to thermally bonded PVC geomembrane seams, which fulfils the specified peel strength.
- The minimum test duration is about six days, which is a long time, unavoidable for a permeation test, but generally unacceptable when the geomembrane must be quickly covered in landfill applications, for example. Therefore the gas permeation pouch test is better suited for pond applications, such as leachate ponds, where no seam defect can be acceptable.

7. ACKNOWLEDGEMENTS

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NOTATIONS

Basic SI units are given in parentheses.

GTR	gas flow through the specimen (mol/s)
P_G	permeance to gas G (mol/(s Pa))
P_{N_2}	permeance to nitrogen (mol/(s Pa))

P_{N_2L}	permeance to nitrogen by unit of seam length (mol/(m s Pa))
P_{CO_2}	permeance to carbon dioxide (mol/(s Pa))
P_{CO_2L}	permeance to carbon dioxide by unit of seam length (mol/(m s Pa))
$p(t)$	absolute gas pressure in the pouch (Pa)
$p(\infty)$	absolute final gas pressure in the pouch corresponding to atmospheric pressure (Pa)
$p(0)$	absolute initial gas pressure in pouch (Pa)
Δp_G	mean partial pressure difference of penetrant molecule G in adjacent gases on the two sides of the geomembrane (Pa)
t	time (s)
t_0	delay time (s)
$Z(t)$	quantity defined by Equation (4) (dimensionless)
τ	time constant (s)
τ_{N_2}	time constant for nitrogen (s)
τ_{CO_2}	time constant for carbon dioxide (s)

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