A test for measuring permeability of geomembranes

S. LAMBERT
Cemagref, Antony Cedex, France

N. TOUZE-FOLTZ
Cemagref, Antony Cedex, France

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ABSTRACT: Geomembrane main functional property is permeability; it thus has to be measured. A method has been developed to estimate watertightness of geomembranes. Co-developed by three laboratories it is now a French standard and has been proposed as a base for an European standard. This paper presents the test method and apparatus that allows to measure very small water flows through geomembranes, ranging from 10^{-7} $m^3m^{-2}d^{-1}$ to 10^{-3} $m^3m^{-2}d^{-1}$. Comments, based on practical knowledge of different PP, HDPE, PVC, EPDM and bituminous geomembranes, are also made to explain limitations of the test. These are due to physical and mechanical reactions of the geomembrane exposed to water and pressure. These mainly influence very low permeability measurements. It appears that, for almost all geomembranes, this test gives accurate values when the flow is greater than 5.10^{-7} $m^3m^{-2}d^{-1}$. For lowest values of flow, a longer test should allow to obtain undisturbed results.

1 INTRODUCTION

Geomembranes are used in long-term applications to act as barriers against fluids in geotechnical and civil engineering projects. They insure, in substitution or in association with traditional materials, like clay or concrete, the watertightness of dams, tunnels, liquid waste pounds, landfills, etc.

Geomembranes definitions always refer to permeability. For instance, European draft terminology on geosynthetics presents geomembranes as very low permeability materials in the form of a manufactured sheet. Besides, the permeability to water is mentioned as a mandatory characteristic for geomembranes by the European mandate M107 that is the reference document for the CE marking of geosynthetics. Other characteristics are mandatory, but permeability must be considered as the main functional property of a geomembrane. The permeability of geomembranes has thus to be measured in a satisfactory way.

The aim of this paper is to present the fundamentals, origin and evolution of the current draft European test method for the measurement of water permeability of geomembranes (TC 189 WI 189067). It thus gives complementary information to this text of draft standard. Transport mechanisms are first recalled. Then, the general method used is presented together with other test methods. Apparatus and testing procedures are detailed, before presenting results. A discussion follows giving answers to many questions concerning the test.

2 RECALL OF TRANSPORT MECHANISMS

Geomembranes are non-porous media. It means that there is no void in the material, but only ‘free-spaces’, which size is in the range of solvent molecule’s size. Due to that, transport in geomembranes occurs at the molecular level; a molecule of solvent, like water for instance, migrates alone in the polymer matrix. This is obviously different from transport in porous media like soils or geotextiles, where voids are much larger than solvent molecules. In this latter case, molecules of solvent are in close contact one with each other as they are driven through the interconnected pore network of the material by the hydraulic pressure gradient.

Both mechanisms may be called permeation and may be characterised by the measurement of permeability. Permeability is a generic term defining the ability of a solid to be penetrated by a fluid; it gives no indication about mechanisms involved. In a porous media, the relevant and precise characteristic is the hydraulic conductivity, for example k for soils, whereas in non-porous media the characteristic is the diffusion coefficient. Hydraulic conductivity and diffusion coefficients respectively refer to porous and non-porous media, and thus to advective and diffusive transport.

Transport through porous media follows Darcy's law, whereas Fick's law (Crank, 1975) governs it a non-porous media. Transport by diffusion is time-dependant: at the beginning the transport is slow and the regime transient, and increases before reaching a permanent regime. The time lag mainly depends on the coefficient of diffusion; the lower the diffusion, the longer the time lag, and thus the longer the time before reaching the permanent regime.

Different driving forces may cause diffusion: concentration, hydraulic or temperature gradients, etc. It has also been shown that diffusion occurs even if there is no gradient; this is called self-diffusion (Eloy-Giorni 1993).

In fact, transport through geomembranes occurs in three steps. The first one consists in the absorption phase, where the solvent molecule gets in the polymer matrix. The second one is the diffusion phase, where the molecule goes from one solution-polymer interface to the other. The third one is the desorption phase, where the molecule of solvent gets out of the polymer matrix. The influence of the three steps must be considered to determine the permeability of a geomembrane, even if the most important one is diffusion through the polymer.

The transport through geomembranes is thus a very complex phenomenon. From a practical point of view, the interesting data is the volume of fluid passing through a geomembrane under certain conditions, without any consideration of its thickness.

The proposed method is based on a hydraulic permeation test aiming at estimating the flux of liquid going through the geomembrane under a hydraulic pressure gradient.

3 METHOD

3.1 *Fluid transport measurements methods*

Various methods were used for estimating geomembrane behaviour towards fluid transport. Great differences in principle and aims exist between these. These differences concern the kind of phenomenon involved or on the kind of result given.

Some tests deal with different kinds of liquids because many fluids may get into contact with geomembranes. Diffusion through geomembranes depends on the nature of the fluid, and thus, water and liquid pollutants containing chemicals have different diffusion coefficient. But, water is preferred because it is the most current and no other fluid is more representative of fields conditions, or more representative of transport phenomena in every types of geomembrane.

Some test methods are only qualitative; the watertightness of the membrane is evaluated thanks to an easy and short test. That's the case with test method prEN 1928 for roof membranes which consists in applying a 60 kPa water pressure on a side of a membrane for a 24 hours period. If moisture appears on the opposite side, then the membrane is declared not watertight. This test only gives an indication on a short-term behaviour.

Other tests give real measurements related to transport through the geomembrane, such as water vapour transmission test ASTM E96-80. But, from an engineering point of view, water hydraulic permeation is far more representative than water vapour permeation.

The test method proposed by Ozsu, Acar (1992) measure hydraulic properties of the geomembrane when exposed to hydraulic gradient of pressure on a 24-h. period of time. This is thought to be too short and test results are not significant of diffusion phenomena (Pelte 1993)

The test aiming at measuring the permeability should then be a long-term hydraulic permeation test performed with liquid water in contact with the geomembrane. Koerner (1986) identified several problems inherent to water hydraulic permeation tests. When conducted with high hydraulic heads, tests resulted in leaks and failed specimens, whereas tests conducted with low hydraulic heads resulted in long test times and evaporation problems.

3.2 *Method developed in France*

A test method was developed taking these points into consideration. It led to the French standard test method NF P 84-515, which is the origin of the current European draft method.

The test consists in applying a constant differential hydraulic pressure between both sides of a geomembrane. It equals 100 kPa, with upstream and downstream pressures respectively equalling 150 kPa and 50 kPa.

The result is expressed in term of flux of water passing through the geomembrane. This flux is calculated from variations of the liquid volume measured during the steady state of transport on both sides of the geomembrane.

Initially, the test method was developed for research purpose. Three public laboratories carried out interesting studies with this method (Duquennoi 1995, Durin, Duquennoi 2000, Eloy-Giorni 1993, Eloy-Giorni et al. 1996). Results concern the method and diffusion phenomena.

The test was therefore two long and too complex to be easily used for regular testing. It was then modified to become the French standard.

The French standard compares the measured flux with a ‘watertightness level’. This conventional level corresponds to a flux of 10^{-4} $m^3.m^{-2}.d^{-1}$ and it is the level of acceptance for geomembrane as ‘very low permeability man made product’. This value was chosen because it is ten times smaller than the flux of water going through a one-meter thick layer of clay of 10^{-9} $m.s^{-1}$ hydraulic conductivity tested in the same hydraulic conditions (10 meter of hydraulic head).

This watertightness criterion was kept for the current European draft.

4 APPARATUS

Two different apparatus were designed simultaneously to develop the test method, one at LIRIGM and the other at Cemagref. Differences concern the volume variations measuring device, and temperature control or measuring. This paper mainly focuses on the second apparatus. Eloy-Giorni et al. (1996) described the other apparatus, using capillary tubes and placed in a thermostatic chamber.

The apparatus is composed of a two-part cell, two volume variations measuring devices and a computer. (fig. 1).

The stainless steel-cell grippes the specimen of geomembrane. In both parts of the cell, two chambers 200 mm ± 1 mm in diameter allow applying a hydraulic gradient through the geomembrane.

At the downstream side of the geomembrane a porous stainless steel disc, allowing liquid transfer, prevents from geomembrane deformation and failure since the upstream pressure is greater than the downstream one.

Both parts of the cell are equipped with outlets for air flushing at the beginning of the test. For the same purpose, it is recommended to place the cell vertically with flushing outlets on top.

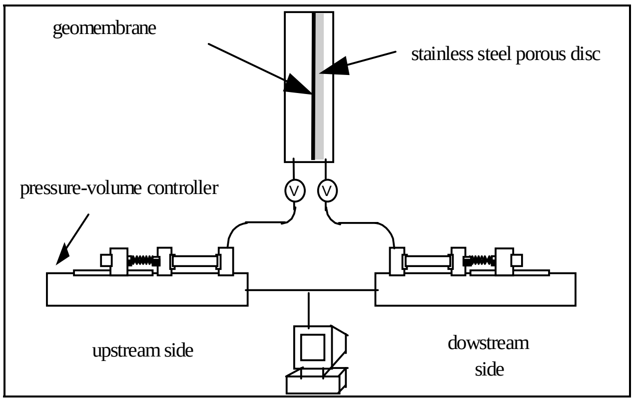

Figure 1. Testing bench

Each chamber, or measuring chamber, is connected to a pressure volume controller. This equipment composed of a cylinder in which a piston slides, is capable of applying a constant pressure (+/- 1 kPa) while measuring volume variations in the corresponding chamber with a 10^{-9} m^3 resolution. Such an apparatus has the advantage of avoiding any evaporation, as it is the case using capillary tubes.

As volume variations are small, measurements may be highly disturbed by even small temperature variations. Four temperature transducers are used to measure the temperature in order to correct volume measurements. They are located on the cell, on the upstream and downstream pressure-volume controllers, and in the air.

5 TESTING PROCEDURE

As mentioned by the standard, there are three stages in the test. Two preparation stages generally precede the test proper.

The main aim of preparation stages is to determine the volume-temperature relationship. During such a stage, the hydraulic gradient between both sides of the geomembrane is small (10 kPa), and one of the chambers is disconnected from its pressure-volume controller. During at least 48 hours volume variations in the other chamber are measured.

The third stage is the test proper generally lasting more than 15 days.

The test results presented were performed with the equipment previously described and not using the ring-shaped control chamber mentioned by the French and European standard.

The geomembrane was placed in the cell dry. The samples were generally not immersed in water before being submitted to test, as it is suggested by the standard.

Watertightness of the settling was obtained by sufficient clamping. Thus no join was necessary, except for bituminous geomembranes for which the clamping strength has to be reduced.

The test duration was limited to 20 days, whatever the results obtained.

6 RESULTS

For five years, all kinds of geomembranes available in France were tested: bituminous, PP, HDPE, EPDM and PVC.

At the beginning of the test volumes vary importantly, and then stabilize; this is a general trend observed on every test. Figure 2 shows volume variations curves obtained during test stage on a PP geomembrane (number 1 in table 1).

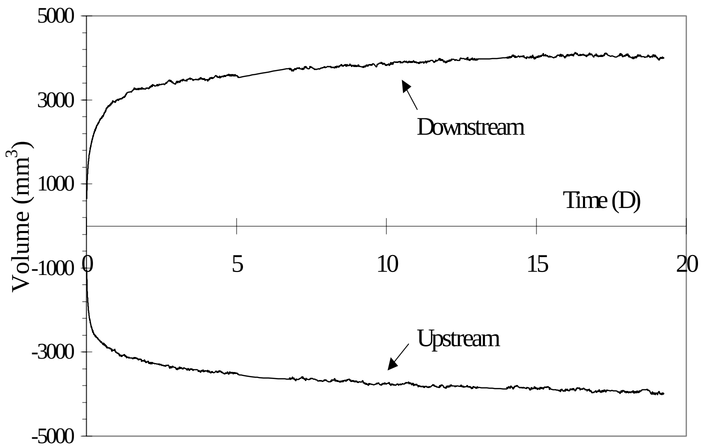

Figure 2. Upstream and downstream volume variations on a PP geomembrane

These data were corrected to eliminate temperature effects. Upstream and downstream curves are symmetrical. Upstream volume decreases and downstream increases in the same way. These results are very good; the curves are relatively symmetrical, and the two values of the flux (upstream and downstream) are equal, what is rarely the case.

Table 1 shows flux calculated from both upstream and downstream measurements obtained on different types of geomembranes, of comparable thickness (1 to 1.5 mm) except for bituminous geomembranes. This table also gives the relative difference between upstream flux and downstream flux.

Both fluxes are rarely equal and differences are sometimes important. It seems that when the upstream flux is higher than $5\ 10^{-7}\ m^3/m^2/d$, then it is higher than downstream one and it is the opposite when both fluxes values are less than $5\ 10^{-7}\ m^3/m^2/d$. This trend is unexplained.

Table 1. Upstream and downstream calculated fluxes on different types of geomembranes

	Kind of geomem-brane	Upstream flux ($m^3/m^2/d$)	Downstream flux ($m^3/m^2/d$)	Relative difference (%)
1	PP	7,9E-07	7,9E-07	0
2	HDPE	1,0E-07	1,9E-07	-47
3	HDPE	1,0E-07	3,0E-07	-67
4	HDPE	1,3E-06	8,0E-07	63
5	HDPE	1,4E-07	7,0E-07	-80
6	HDPE	2,0E-06	8,0E-07	150
7	HDPE	9,0E-07	8,0E-07	13
8	HDPE	7,0E-08	5,0E-08	40
9	PVC	1,8E-07	5,0E-07	-64
10	PVC	9,0E-07	8,3E-07	8
11	EPDM	2,7E-07	6,3E-07	-57
12	Bituminous	1,5E-06	7,0E-07	114
13	Bituminous	5,6E-07	2,3E-07	143
14	Bituminous	4,0E-08	2,0E-07	-80

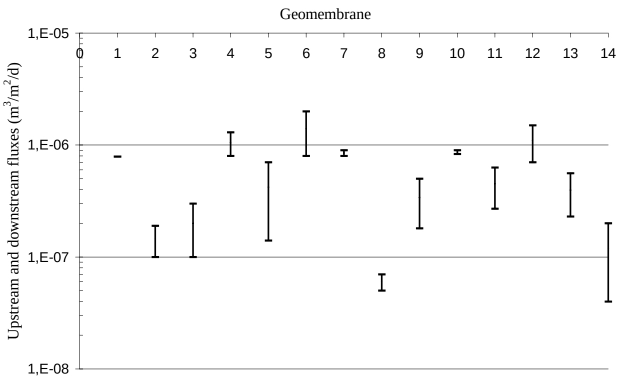

Figure 3. Upstream and downstream flux measurements

Figure 3 presenting both upstream and downstream fluxes on a semi logarithmic curve shows these differences. Due to these differences, results are imprecise. If it is assumed that the real flux passing through the geomembrane is between these two fluxes values, then this figure shows that test generally gives better results when the flux increase.

Fluxes of all the geomembranes tested are largely under the watertightness level. No significant differences appear between the different products. Some HDPE geomembranes have the lowest flux values but some exhibit high values.

In fact, different kind of bituminous geomembranes were tested (modified and oxidized). It appeared that modified bituminous geomembranes are less permeable than oxidized bituminous geomembranes.

It has also been noticed that, on a few geomembranes for which fluxes were very low that the upstream volume after many days stopped decreasing, or increased.

7 DISCUSSION

These results and general background give important information allowing validity insuring and improvement of the test method.

7.1 *Measurement bias*

Transport through geomembranes are very slow and may be disturbed by different uncontrolled mechanical or physical reaction:

- thickness variation of the geomembrane,
- geomembrane deformation due to clamping strength,
- swelling of the geomembrane

These mainly affect measurements at the beginning of the test when volume variations are sometimes 1000 times higher than variations after 2 to 5 days of test; this is not in coherence with diffusion phenomena.
These effects may concern both upstream and downstream measurements or upstream only.
In a smaller range, these may also affect the beginning of calibration stages.

Applying high hydraulic pressures in the cell induces deformations of the apparatus and compression of the geomembrane, which is forced on the porous plate. These variations of dimension are very small but high compared to volume variations due to transport through the geomembrane; thus, they disturb transport volume measurements.

Geomembranes may undergo thickness variations due to the confining hydraulic stress during the first days of test. Table 2 gives the volume variation measured in the upstream cell and induced by geomembrane thickness variation. This only affects upstream measurements that decrease rapidly. Downstream volumes are not affected due to the presence of the porous plate.

For comparison, a flux measurement of 10^{-7} $m^3/m^2/d$ corresponds to a 3 mm^3 daily volume variation measurement. For a flux measurement of 10^{-4} $m^3/m^2/d$, the daily volume variation is 3000 mm^3 per day.

The influence of the geomembrane mechanical response can thus be predominant on first day's volume measurements.

Table 2. Volume variations due to the variations of thickness of a 1 mm initial thickness geomembrane

Thickness variation (%)	Induced volume variation in a 200 mm diameter chamber (mm^3)
0.01	3
0.1	30
1	300
5	1500

Watertightness of the settling is obtained by clamping. Nevertheless, the clamping ring strength is located around the measuring chamber and that may lead to geomembrane deformation affecting measurements. For soft material like PVC and PP, a 'wave' appears very often in the measuring chamber due to that. Thus, it should be necessary to find the appropriate clamping strength leading to the minimum deformation, strength depending on the material. But, such an undesirable effect has only a short-term influence on upstream and downstream measurements. Applying upstream pressure forces the geomembrane on the porous plate, that will finally reach a mechanical equilibrium within a few days. During this period, upstream and downstream volume will vary importantly in opposite directions.

Diffusion leads to a swelling of the geomembrane. As a molecule of solvent gets in the geomembrane the geomembrane volume increases, and its thickness too. For the same reason as for variations of thickness due to compressive creep, even a very small variation may have an important influence on upstream measurements for very low permeability geomembranes. This phenomenon is very slow and thus comparison of daily volume flux with swelling is only indicative. Moreover, this complex aspect should not be considered, as it seems to be relatively negligible and as it still have to be examined. It may explain some increase of upstream volume observed on some very low permeability geomembranes.

7.2 *Leakage*

Leakage due to apparatus or non-perfect watertightness of geomembrane clamping is different from one test to the other due to manipulation. Thus, the leakage can not be predicted. Nevertheless, measuring upstream and downstream volume variations allows detecting leakage. As both chambers are under pressure, a leak can only occur outward of the chamber. As a result, during the test, a leak in the upstream chamber leads to a higher decrease of upstream volume. A leak in the downstream chamber reduces the increase of volume. Considering that no leak can occur from upstream to downstream, a leak will always lead to non-symmetrical volume change rate of both chambers.
Thus, the double measurements method gives guaranty concerning the leakage issue.
Moreover, it seems to be correct to say that, if there is a leak, the real flux value is between the absolute values of both slopes; the highest absolute value being the upstream value and the downstream value being the lowest absolute value.

But leakage is generally observed during calibration stages where transport through the geomembrane is neglected. To confirm any leakage trend observed on a calibration curve, it is possible to plot a curve of the measured volume (i.e. the volume of the chamber of interest) versus the temperature of the chamber. If there is no leak, curve points will move cyclically due to temperature cyclic variations: for a given temperature, a given volume. But, if there is a leak, the volume will decrease, and then the curve will go downward. Figure 4 presents upstream volume variations during upstream calibration stage versus the temperature of the cell. The rounded shape is unexplained, as curve points should theoretically draw a straight line. Nevertheless, it is not due to leakage because after three temperature cycles the same volume is obtained for the same temperature. Such a shape is very current.

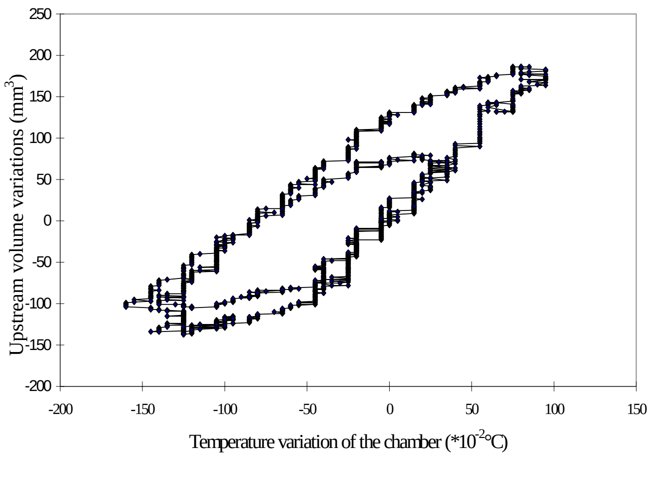

Figure 4. Temperature dependence of upstream volume during calibration stage.

7.3 *Ring-shaped control chamber*

The ring-shaped control chambers, or secondary chambers, mentioned by the two standards were supposed to be used to control measurements. But, these chambers are smaller than the measuring chambers and are also supposed to absorb a part of the geomembrane deformation. These two functions are incompatible; if there is an undesirable effect in this chamber, measurement can not be used to control measurements in the larger measuring chamber.

Tests presented herein and performed without using this chamber showed that leaks can be detected only by volume curves comparison. This tends to show that the ring-shaped control chamber is not necessary.

7.4 *Measurement time*

The measurement time includes a ‘transient regime’ and the period taken into account to calculate the flux. The minimum duration of the measurement time to obtain a precise flux measurements depends on the type of geomembrane.

From an absolutely theoretical point of view, this test is too short for low permeability geomembranes. In fact, in this case, measuring the transport during real steady sate regime would take several months. However, this problem only concern very low permeability geomembranes, i.e. which permeability is around 10^{-7} $m^3/m^2/d$. This value is very low and its precise measurement does not seem to be realistic or necessary for producers or users.
For research purposes, a longer test should provide reliable data.

Moreover, test time should be adapted to permeability. A 15 days of test is not enough for a 10^{-7} $m^3/m^2/d$ flux measurement but is largely enough for 10^{-5} $m^3/m^2/d$ flux measurements. In this latter case, the time necessary to measure accurately the flux may be reduced, but making sure that it is a real steady state flux measurement.

Practically, it may be necessary to reduce the duration of the test when pressure-volume controllers are used. Indeed, available volume is limited, and thus testing time is limited.

7.5 *Temperature effects*

Relative effects of temperature variations on measurements depend on water air content and also on the permeability of the geomembrane. Indeed, these effects are correlated with cell air content; the higher the air content the higher the volume variations for a given temperature change. But, relatively to flux measurements, this change may be negligible or not. Thus, for a 10^{-5} $m^3/m^2/d$ flux measurement the temperature may have no real effect on volume measurements.

The effect of temperature is not only due to air content; the cell and the specimen may react to temperature variations in a significant way for low permeability measurements.

Practically, the necessity of correcting volume readings to take into account temperature variations effects should be evaluated examining curves of measured volumes.

7.6 *Tests limits and tests results significance*

As mentioned previously, effects of undesired phenomena, excepted swelling, are important relatively to flux and firsts hour’s or firsts day’s measurements are not be considered as flux measurements. Moreover, the lower the permeability, the higher the effects of these phenomena.

Both calculated fluxes have to be considered to estimate permeability of the geomembrane. The real flux is between upstream and downstream flux measurement and a safety approach would be to consider the highest value of flux as the real flux through the geomembrane.

The measurability limit of the method, as it is proposed by the draft European standard, seems to be 10^{-7} $m^3/m^2/d$, without any consideration to the volume measurement device accuracy.

Low flux measurements, that is to say about 10^{-7} $m^3/m^2/d$, seems no to be fully satisfactory, and thus, results should only be considered as order of magnitude when values of fluxes are under 10^{-6} $m^3/m^2/d$.

Results presented herein concerning PVC, HDPE and bituminous geomembranes seem to be slightly higher than those presented by Pierson (1994). Nevertheless, tested products are not the same in both studies and strong conclusions may not be drawn. This difference is only a trend that should be explained by the fact that our test is shorter than the test of the mentioned study.

8 CONCLUSION

This test allows determination of permeability of geomembranes, with a method in coherence with expected use of the product; phenomena involved are the one occurring onsite, and the test is a long time test.

Obtained results should only be considered as orders of magnitude when low, that is to say less than 10^{-6} $m^3/m^2/d$. The fact of having such a limit to this test should no be a problem for designers and users because flux value is not a designing characteristic.

Finally, this paper shows that commonly used geomembranes fulfil the watertightness level.

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