Gas permeability of bentonite barriers:development, construction and testing of a measurement system

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Heraldo Nunes Pitanga
Professor Adjunto IV
Universidade Federal de Viçosa – UFV
Departamento de Engenharia Civil
Viçosa – Minas Gerais – Brasil
heraldo.pitanga@ufv.br

Orencio Monje Vilar
Professor Titular
Universidade de São Paulo - USP
Escola de Engenharia de São Carlos
Departamento de Geotecnia
São Carlos – São Paulo – Brasil
orencio@sc.usp.br

Patrick Pierson
Professeur
Grenoble-Alpes University, CNRS
Laboratory LTHE
Grenoble - France
patrick.pierson@univ-grenoble-alpes.fr

Abstract

This article proposes a testing device to quickly and reliably estimate the gas permeability of bentonite-based clay barriers used in landfill cover systems. The testing methodology is based on a transient gas flow regime that passes through the barrier, therefore not requiring the use of sophisticated equipment that aim to maintain constant differential pressure and measure the gas flow, common requirements for testing methods under a permanent flow regime. To confirm the feasibility of the proposed technique, tests were performed on a pure hydrated bentonite layer, which subsequently encompassed samples of geosynthetic clay liner (GCL) at different moisture contents. Geosynthetic clay liners are often selected as a part of the barrier layer for cover systems in solid waste landfills to prevent infiltration of rainfall and migration of biogas into the atmosphere. The results confirmed the equipment reliability and differentiate the different responses of the gas flow barriers studied, considering their different compositions and different moistures.

Keywords: clay barriers; gas permeability; permeameter.

1. Introduction

The emission into the atmosphere of gases generated in landfills has become a concerning issue in recent years. Carbon dioxide and methane, the main gases resulting from the decomposition of waste, have been recognized for their important contribution to the global warming process (Falzon, 1997; Grantham *et al.*, 1997). With regard to public safety, the most dangerous aspect of gas generation in a landfill is its potential to migrate to adjacent areas and to cause explosions that would result in extensive property damage and loss of life. The incidents in Loscoe, England (Williams and Aitkenhead, 1991), in Skellingsted, Denmark (Kjeldsen and Fisher, 1995) and in Masserano, Italy (Jarre *et al.*, 1997) highlight the importance of controlling the emission of landfill gases.

These explosions can be triggered by the reduction of air pressure in a short time. On the other hand, increasing the air pressure tends to force air into the landfill, thus favoring, for example, dilution of volatile organic compounds (VOCs) in groundwater. A change in the leachate level of waste, water table level or temperature can also lead to differential pressures that lead to the migration of gases. In mining waste containment systems, given the acidification possibility of the leachate from sulfidric waste when in contact with oxygen from the air, the performance of clay barriers in controlling the oxygen flow must be measured for design purposes (Yanful, 1993; Shelp and Yanful, 2000).

In this context, the efficiency of clay barriers in controlling gas emissions is an important issue when designing landfill cover layers. The traditional method of determining the gas permeability of clay barriers essentially involves measuring the gas flow through the barrier under steady-state flow (Didier *et al.*, 2000; Bouazza *et al.*, 2002; Bouazza and Vangpaisal, 2003; Vangpaisal and Bouazza, 2004; Rouf *et al.*, 2016). Although the analysis of the data from the application of this method is simple, the test equipment to ensure and measure this flow regime is generally considered complex and expensive. The measurement of very low permeability values presents special problems for which standard measurement techniques are usually not very practical and hard to implement. In general, under very low permeability, long periods are required for the establishment of the steady state flow.

To overcome these limitations, the transient flow method has emerged as a successful alternative to estimate the hydraulic properties of low permeability materials such as rocks, soils (Haskett *et al.*, 1988; Carles *et al.*, 2007;Barral *et al.*, 2009), concrete (Figg, 1973; Claisse *et al.*, 2003), asphalt coating (Li *et al.*, 2004) and bentonite geocomposite (Mendes *et al.*, 2010; Pitanga *et al.*, 2011).This method is essentially founded on monitoring of system's pressure drop as the gas passes through the permeable barrier. Therefore, compared with the conventional method for measuring permeability in a permanent flow regime, the pressure drop method seems to have advantages such as simplicity, economy and quick results. It is noteworthy that the conventional method considers the permanent flow regime and requires the measurement of the flow through the sample, which is not necessary in the case of the transient method.

Within the context of implementation of these containment barriers and flow diversion in geo-environmental works such as waste containment landfills, this article presents a modified version of the equipment proposed by Pitanga *et al.* (2011), in order to determine the permeability to gas of not only GCLs, but also other clayey barriers with compositions and thicknesses different from those presented by GCLs. The testing device aims to estimate, rapidly and reliably, the gas permeability of these clayey barriers under transient flow regime to evaluate the effect of moisture content on permeability.

2. Material

The gas permeability tests were performed using two samples of GCL (Figure 1): powdered GCL Type A and granular GCL Type B, both manufactured in Brazil. These are two types of needled GCL containing 5.0 kg/m^2 of bentonite that is encapsulated by non-woven geotextiles attached by needling fibers. Gas permeability tests on hydrated bentonite were performed using powdered sodium bentonite from BRASGEL® (Bentonita União Nordeste Ind. e Com. Ltda).

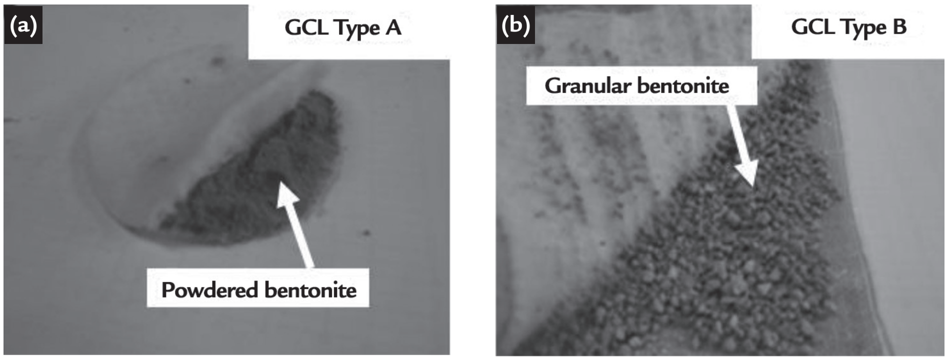


Figure 1
Types of GCL for the gas permeability tests:
(a) GCL Type A (powdered bentonite);
(b) GCL Type B (granular bentonite).

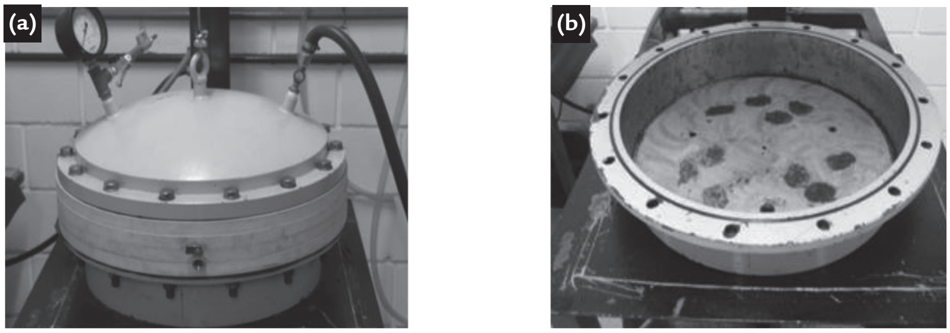
3. Methods

Test equipment

Figure 2 illustrates the test equipment, called *modified transient flow permeameter* (Fig. 2a), for determining the gas permeability of the clay containment barriers and gas flow diversion. This is a modified version of the proposal by Pitanga *et al.* (2011), which originally was solely intended to determine the gas permeability of GCLs under deformation imposed to the center of the test sample. To estimate the gas permeability of other types of clay barriers beyond the GCL, the vertical dimension of the confining chamber of the test sample was increased, enabling tests on thicker samples. Also increased were the diameter of the test sample and the volume of the lower reservoir of gas corresponding to voids of the porous stone. Importantly, the deformation imposed to the sample center was eliminated in this modified version, compared to the original test.

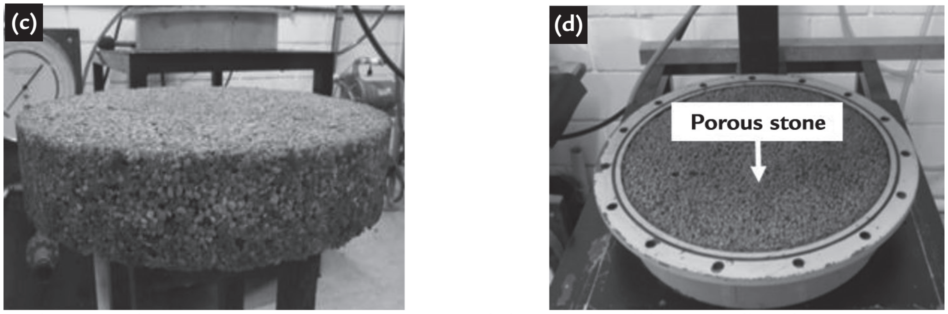
Figure 2 also shows the major components of the test cell. It is a circular metal cell (Fig. 2b) whose inner part is filled with a porous stone 10 cm in height and 50.5cm in diameter (Fig. 2c) casted in the laboratory on the basis of a mixture of gravel and epoxy glue. On the surface of this set (Fig. 2d), a circular sample of the clay barrier is supported, as in the case of hydrated GCL (Fig. 2e). An o-ring and a circular membrane (Fig. 2f) are arranged at the outside of the metal cell to ensure gas tightness of that compartment. An intermediate circular unit (Fig. 2g) on rigid PVC is placed on the o-ring- membrane set and on the edge of the circular GCL sample (sample diameter D = 55 cm). The clay barrier sample contact with the inner wall of the intermediate unit is sealed with bentonite in order to enhance the lateral tightness during the test.

A layer of thin sand is overlaid on the clay barrier sample, filling the interior of the intermediate unit (Fig. 2h). This sand layer both forwards (bottom-up) the gas that passes through the clay barrier, which is initially stored in the lower tank (porous stone), and transmits the normal stress (top-down) to the clay barrier sample placed upon the porous stone. A ball valve disposed on the wall of the intermediate cell allows the gas that permeates the sand reach the external environment, reaching atmospheric pressure. A membrane is overlapped to this sand layer (Fig. 2i) which makes the separation of the sand and the water layer used for application of normal stress. An upper unit consisting of a metal lid (Fig. 2j) is supported on the membrane and the intermediate unit. A set of 15 screws attaches the top, intermediate and bottom units of the test cell, unifying the set (Fig. 2k).



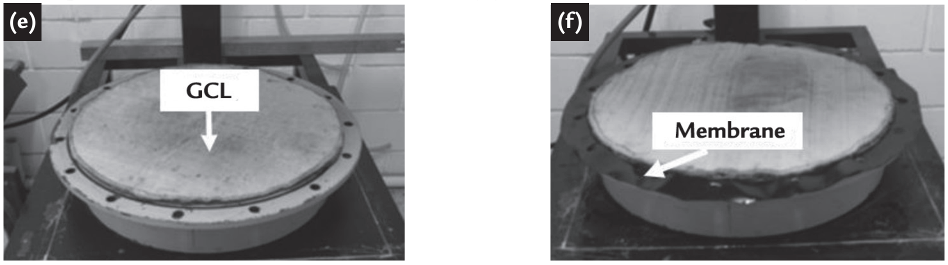
(a) Transient flow permeameter

(b) lower unit of the test cell



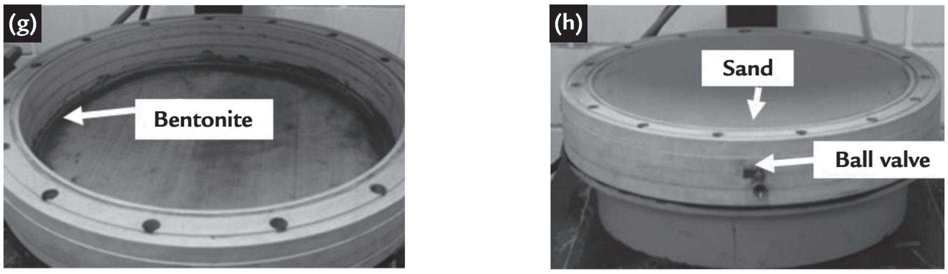
(c) large sized porous stone

(d) lower unit of the test cell and porous stone



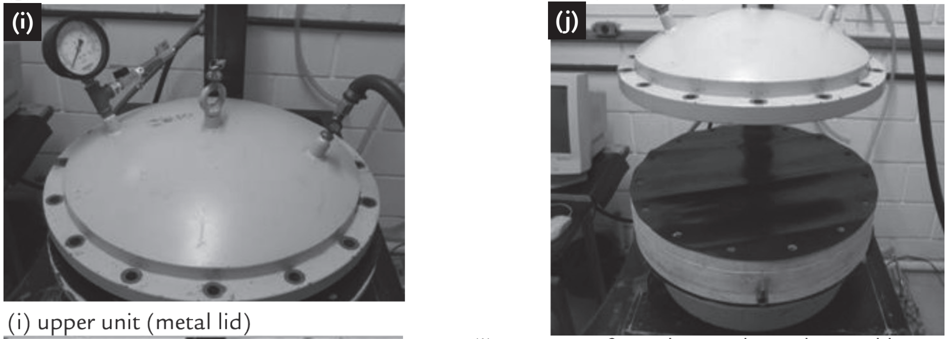
(e) Clay barrier sample

(f) sealing membrane



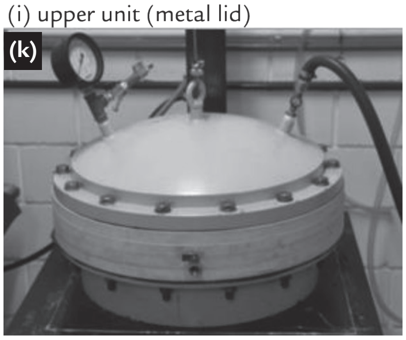
(g) intermediate unit of the test cell

(h) sand layer on clay barrier sample



(i) upper unit (metal lid)

(j) waterproof membrane above the sand layer



(k) fastening screws of the upper, intermediate and lower units

Figure 2
Modified transient flow
permeameter and principal components.

The metal lid is connected to a normal stress application system comprised of a hose connected to a controllable flow motor pump system. The magnitude of the confining pressure is controlled by a valve for pressure relief connected to a manometer on the lid. At the base of the bottom unit, a gas feed tube, a gas pressure transducer and a thermocouple are connected to a valve for pressure relief. The porous stone in the bottom unit that is subjacent to the sample of clay barrier is filled with gas through a supply system connected to a compressed air network. This system is equipped with a pressure gauge and a pressure regulator that allows the control of the gas inlet pressure. A gas pressure transducer is connected at the bottom of the lower unit of the equipment, and therefore has access to the gas that fills the voids of the porous stone and consequently to the pressure exerted by it.

The transducer is connected to a data acquisition and storage system that allows for continuous monitoring of relative gas pressure during its imposition and during the trial via a graphical interface. The acquisition system allows the collection of data at 0.3 second-intervals. A thermocouple is permanently attached to the bottom of the lower cell in order to determine the temperature of the compressed air during the test through a digital thermometer, accurate to 0.1°C. The atmospheric pressure during the test is determined by means of a digital thermo-hygrometric barometer accurate to 0.1 kPa. For the proposed permeameter, gas permeability of the clay barrier sample under transient flow regime is given by (Li *et al*., 2004):

$$k = \frac{-VZ\mu s}{AP_{atm}} \qquad (1)$$

where: V: lower reservoir volume of the transient flow permeameter ($V=6779\ cm^3$);

Z: thickness of the clay barrier sample;

μ: dynamic viscosity of the gas ($\mu=1.77x10^{-5}$ Pa.s);

A: area of the sample cross-section ($A=2003\ cm^2$);

P_{atm}: atmospheric pressure;

s: slope coefficient:

$$\ln\left(c\,\frac{P(t)-P_{atm}}{P(t)+P_{atm}}\right)=st \qquad (2)$$

$$c=\frac{P(0)+P_{atm}}{P(0)-P_{atm}} \qquad (3)$$

P(t): absolute pressure (relative pressure plus atmospheric pressure) of gas in the reservoir at time t;

P(0): absolute pressure of gas in the reservoir at time t=0s.

The gas used in the study corresponded to compressed air ($\mu=1.77x10^{-5}$ Pa.s a $T=20^oC$), because it is a relatively inert gas, with low diffusion in water and volumetric constancy in the application of normal stress. In all tests, the normal stress applied to the samples was 20 kPa, as it is considered representative of the magnitude of the normal stress typically acting on clayey barriers of landfill cover systems (Pitanga *et al*., 2011).

4. Results and discussion

In order to evaluate the ability of the proposed equipment to generate repeatable results from trials performed in the same sample, gas permeability tests were preliminarily conducted on a layer of hydrated bentonite. Hydration of bentonite took place for 10 days, during which it was remoulded successively and manually to standardize its moisture content. Figure 3 illustrates the appearance of bentonite layer after its molding in the test equipment.

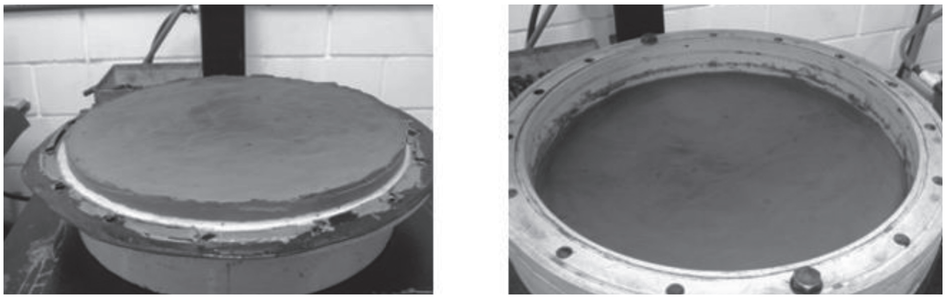


Figure 3
Hydrated bentonite sample molded inside the transient flow permeameter.

Figure 4a shows the curves of the absolute pressure (P_{abs}) over time corresponding to the sequence of 5 trials conducted for the same sample of hydrated bentonite (gravimetric water content w = 232%). In each of the tests in this figure, from the initial relative pressure (P_{rel}) proposed (P_{rel} approximately equal to 5 kPa or P_{abs} approximately equal to 97 kPa), there was a gradual pressure drop, which converges to the value corresponding to relative atmospheric pressure, i.e., $[P(t)-P_{atm}] \rightarrow 0$. A reasonable repeatability of the trials is also confirmed by Figure 4b, where it is possible to observe the overlap of the variation curves of $[P(t)-P_{atm}]$ according to the trial test.

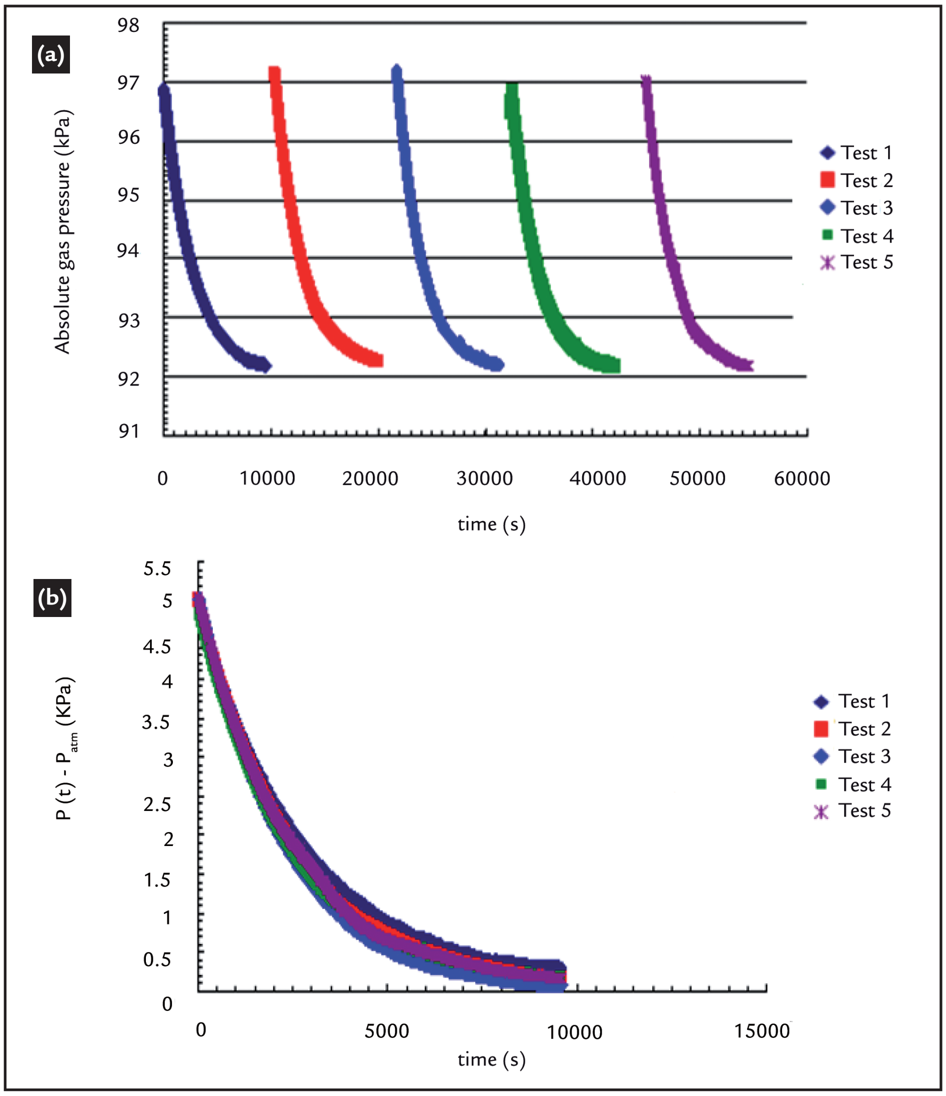


Figure 4
Curves derived from the gas permeability tests under transient flow regime (hydrated bentonite sample with w = 232%): (a) variation in the absolute pressure of the gas over time; (b) pressure drop curve.

Figure 5 shows the variation of the function $\ln[c(P(t)-P_{atm})/(P(t)+P_{atm})]$ over time for 5 tests repeated on the same sample of hydrated bentonite, emphasizing that the s coefficient of Equation 1 corresponds to the slope of the linear portion of the variation curves of this function over time. For the tests performed on the hydrated bentonite sample, Table 1 lists a summary of the parameters required to measure gas permeability through Equation 1 [slope coefficients, atmospheric pressure (P_{atm}), sample thickness (Z)], as well as their values for gas permeability.

The similarity of the gas permeability values determined from repeated tests on the same sample of hydrated bentonite emphasizes the repeatability of the proposed methodology. The average value of the intrinsic permeability corresponding to this sample is 9.10^{-17} m^2, which is compatible with the expected permeability for bentonite under the moisture condition presented by the sample in the trial.

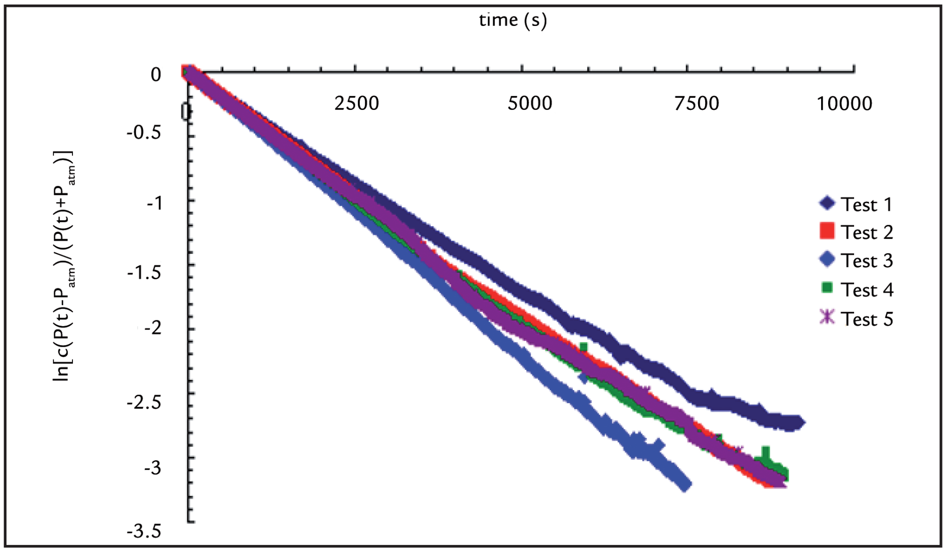


Figure 5
Variation curve of $\ln[c(P(t)-P_{atm})/(P(t)+P_{atm})]$ over time t for hydrated bentonite sample with w = 232%.

Number of the test	P_{atm} (kPa)	Z (mm)	*s* (s^{-1})	*k* (m^2)
1	91.9	37.10	-0.00033	7.98E-17
2	92.1		-0.00037	8.93E-17
3	92.1		-0.00044	1.06E-16
4	92.0		-0.00038	9.18E-17
5	92.0		-0.00038	9.18E-17

Table 1
Summary of parameters required to measure the gas permeability via transient flow method and the permeability derived from tests (sample of hydrated bentonite with w=232%).

After ensuring the reliability of the equipment, the same procedure was adopted for determining the gas permeability of the GCLs considered in this study. For purposes of exemplification, Figure 6a shows the variation in absolute pressure over time corresponding to the sequence of 5 trials conducted for the same sample of hydrated GCL Type A (gravimetric water content w = 112%). This behavior is repetitive and can be regarded as typical, regardless of the type of GCL tested and the moisture content considered. Figure 6b shows the variation of $\ln[c(P(t)-P_{atm})/(P(t)+P_{atm})]$ over time for 5 tests repeated for each sample, and the overlap of curves indicated a reasonable repeatability of the tests.

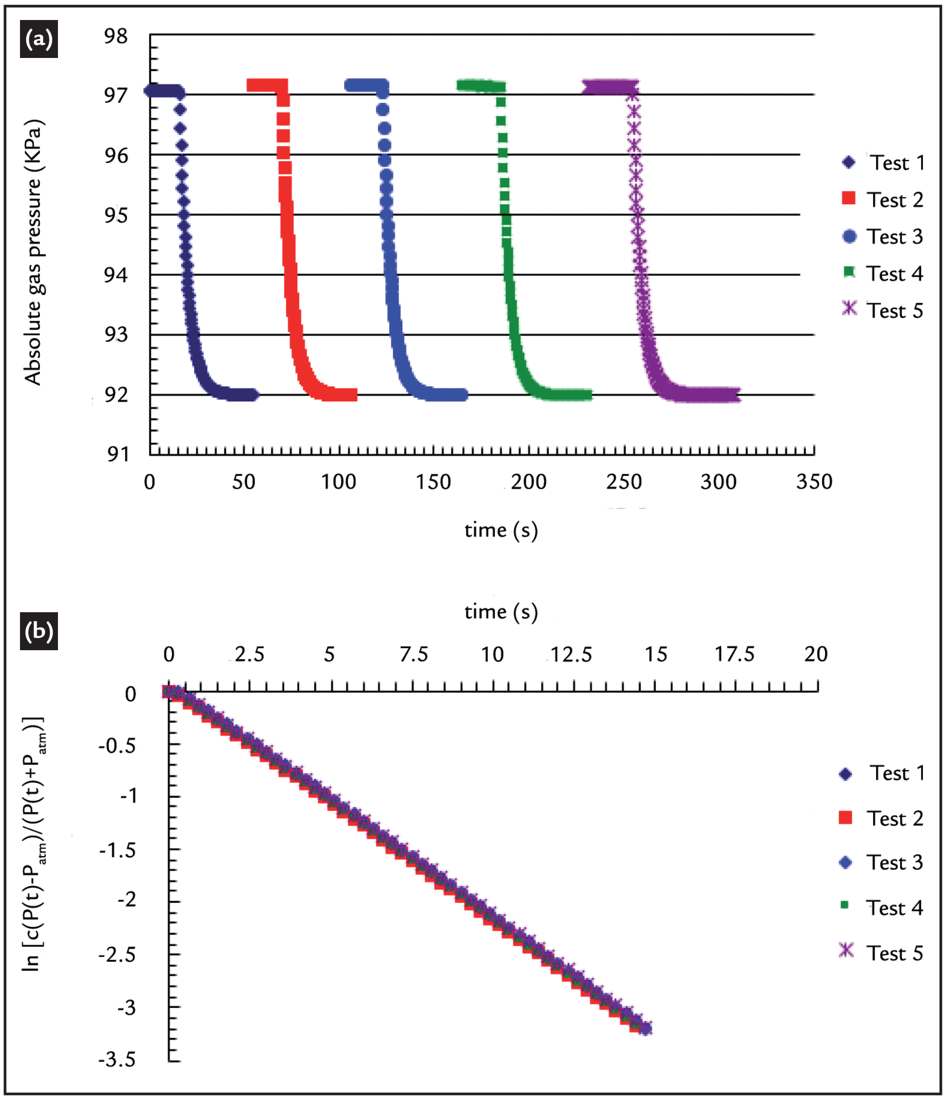


Figure 6
Curves of gas permeability tests under transient flow regime (GCL type A with w = 112%):(a) variation in absolute gas pressure over time; (b) pressure drop curve.

For the tests performed on the sample of GCL Type A with a moisture content w = 112%, Table 2 presents a summary of the parameters necessary to measure the gas permeability using Equation 1 [slope coefficients, atmospheric pressure (P_{atm}), thickness of the GCL sample (Z)], as well as their obtained values for gas permeability. A similar procedure was adopted for the other samples of GCL Type A (powdered bentonite) and GCL Type B (granular bentonite) and the set of all values for permeability to air (average of five tests) obtained for different moisture contents of these samples tested is shown in Figure 7.

Table 2
Summary of parameters required to measure the gas permeability via transient flow method and the permeability derived from tests (sample of GCL type A with w = 112%).

Number of the test	P_{atm} (kPa)	Z (mm)	s (s^{-1})	k (m^2)
1	92.0	10.67	-0.22003	1.52E-14
2	92.0		-0.22002	1.52E-14
3	92.0		-0.22011	1.52E-14
4	92.0		-0.22014	1.52E-14
5	92.0		-0.22015	1.52E-14

From the results presented and considering the moisture content range obtained for samples of GCL Type A (sodium powdered GCL) and GCL Type B (sodium granular GCL), there is a clear reduction trend in intrinsic permeability (k) of GCL to air with the increase of the gravimetric water content. For the tested materials, the magnitude of the air permeability values obtained (10^{-14} m^2) is compatible with that found in literature and the variation of this property appears to be no more than one decimal order of magnitude to the range of moisture levels contemplated by the samples of GCL types.

Comparing the air permeability of the two types of GCL, the GCL Type A has a tendency towards constancy of this property for gravimetric water contents above 85%, while for the GCL Type B, this trend is found for gravimetric water content of more than 145%. For the range of lower moisture content (less than 100%), the sodium powdered GCL is less permeable to the gas than sodium granular GCL, with no significant differences for the range of higher moisture content. Specifically for GCLs, the order of magnitude of values of gas permeability obtained in this study is consistent with the range of variation of this same property (10^{-13} to 10^{-17} m^2) for GCLs tested under conditions similar to the present research, as identified by Pitanga *et al.* (2011).

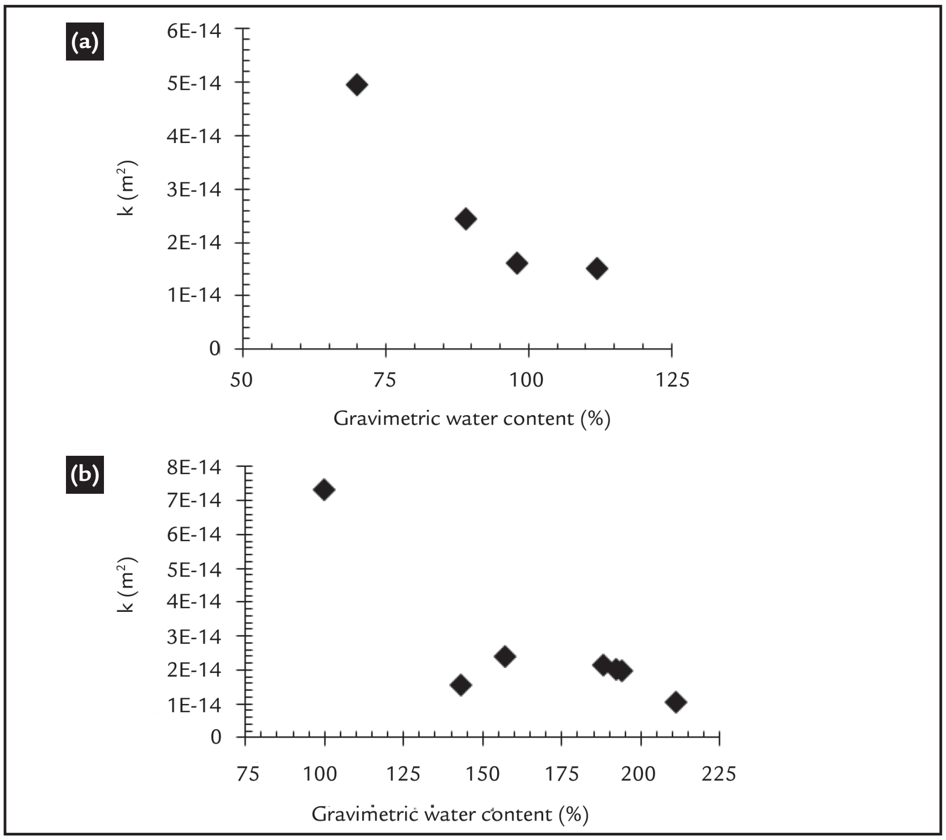


Figure 7
Variation in intrinsic permeability (k) to the air with gravimetric water content of GCL samples under normal stress test of 20 kPa: (a) GCL Type A (powdered bentonite); (b) GCL Type B (granular bentonite).

5. Conclusions

The proposed test technology indicates a reliable determination for the gas permeability of bentonite clay barriers. From the tests carried out, the curves representing the gas pressure drop over time proved to be repeatable for each test sample, as well as the parameters derived therefrom. The tests conducted on the hydrated bentonite and geosynthetic clay liner (GCL) allowed to confirm the reliability of the method and also point to the possibility of extending the use of the equipment in order to determine the gas permeability of other clay barriers distinct from those considered herein.

6. Acknowledgements

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7. References

BARRAL, C., OXARANGO, L., PIERSON, P. Characterizing the gas permeability of natural and synthetic materials. **Transport in Porous Media**, v. 81, n. 2, p. 277-293, 2009.

BOUAZZA, A., VANGPAISAL, T., RAHMAN, F. Gas migration through needle punched Geosynthetic Clay Liners. In: PROCEEDINGSOF THE INTERNATIONAL SYMPOSIUM CLAY GEOSYNTHETIC BARRIERS, 2002, Nuremberg. **Anais**...Lisse: Zanzinger, Koerner, and Gartung, (Eds.). 2002. p. 165–176.

BOUAZZA, A.; VANGPAISAL, T. An apparatus to measure gas permeability of geosynthetic clay liners. **Geotextiles and Geomembranes**, v. 21, n. 2, p. 85–101,2003.

CARLES, P., EGERMANN, P., LENORMAND, R., LOMBARD, J.M. Low permeability measurements using steady-state and transient methods. In: PROCEEDINGS OF THE INTERNATIONAL SYMPOSIUM OF THE SOCIETY OF CORE ANALYSTS, 2007, Calgary. ***Anais***... Calgary: Society of Core Analysis, 2007. p. 1-12.

CLAISSE, P.A., GANJIAN, E., ADHAM, T.A. A Vacuum-Air Permeability Test for in situ Assessment of Cover Concrete. ***Cement and Concrete Research,*** v. 33, n. 1, p. 47-53, 2003.

DIDIER, G., BOUAZZA, A., CAZAUX, D. Gas permeability of geosynthetic clay liners. **Geotextiles and Geomembranes,** v. 18, n. 2-4, p.235–250, 2000.

FALZON, J. Landfill gas: an Australian perspective. In: PROCEEDINGS OF THE SIXTH INTERNATIONAL LANDFFIL SYMPOSIUM, 6, 1997, Cagliari. **Anais**...Cagliari: CISA Environmental Sanitary Engineering Centre, 1997. p. 487-496.

FIGG, J.W. Methods of measuring the air and water permeability of concrete. ***Magazine of Concrete Research,*** v. 25, n. 85, p. 213-219, 1973.

GRANTHAM, G., LATHAM, B., CALLEN, G. Landfill contribution to "greenhouse gas emission". In: PROCEEDINGS OF THE SIXTH INTERNATIONAL LANDFFIL SYMPOSIUM, 6, 1997, Cagliari. **Anais**...Cagliari: CISA Environmental Sanitary Engineering Centre, 1997. p. 17-34.

HASKETT, S.E., NARAHARA, G.M., HOLDITCH, S.A. A method for simultaneous determination of permeability and porosity in low-permeability cores. In: PROCEEDINGS OF ANNUAL TECHNICAL CONFERENCE AND EXHIBITION OF THE SOCIETY PETROLEUM ENGINEERS (SPE), 1988, Houston. ***Anais***... New Orleans: Society of Petroleum Engineers. p. 1-11.

JARRE, P., MEZZALAMA, R., LURIDIANA, A. Lessons to be learned from a fatal landfill gas explosion. In: PROCEEDINGS OF THE SIXTH INTERNATIONAL LANDFFIL SYMPOSIUM, 6, 1997, Cagliari. **Anais**...Cagliari: CISA Environmental Sanitary Engineering Centre, 1997. p. 497-506.

KJELDSEN, P., FISHER, E.V. Landfill gas migration – field investigations at Skellingsted landfill, Denmark. ***Waste Management & Research***, v.13, n. 5, p. 467-484, 1995.

LI, H.; JIAO, J.J., LUK, M. A falling-pressure method for measuring air permeability of asphalt in laboratory. ***Journal of Hydrology***, v. 286, n. 1-4, p. 69-77, 2004.

MENDES, M.J.A., PIERSON, P., TOUZE-FOLTZ, N., MORA, H.; PALMEIRA, E.M. Characterization of permeability to gas of geosynthetic clay liners in unsaturated conditions. ***Geosynthetics International,*** v. 17, n. 5, p. 344-354, 2010.

PITANGA, H.N., PIERSON, P., VILAR, O.M. Measurement of gas permeability in geosyntheticclay liners in transient flow mode. ***Geotechnical Testing Journal,*** v. 34, n. 1, p. 27-36, 2011.

ROUF, M. A., BOUAZZA, A., SINGH, R. M., GATES, W. P., ROWE, R. K. Gas flow unified measurement system for sequential measurement of gas diffusion and gas permeability of partially hydrated geosynthetic clay liners. ***Canadian Geotechnical Journal,***v. 53, n. 6, p. 1000-1012, 2016.

SHELP, M.L., YANFUL, E.K. Oxygen diffusion coefficient of soils at high degrees of saturation. **Geotechnical Testing Journal,** v. 23, n.1, p. 36-44, 2000.

VANGPAISAL, T., BOUAZZA, A. Gas Permeability of Partially Hydrated Geosynthetic Clay Liners. ***Journal of Geotechnical and Geoenvironmental Engineering,*** v. 130, n. 1, p. 93–102,2004.

WILIAMS, G.M., AITKENHEAD, N. Lessons from Loscoe: the uncontrolled migration of landfill gas. ***Quarterly Journal of Engineering Geology and Hydrogeology,*** v. 24, pp. 191-207, 1991.

YANFUL, E.K. Oxygen diffusion through soil covers on sulphidic mine tailings. ***Journal of Geotechnical Engineering,*** v. 119, n.8, p. 1207-1228, 1993.

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