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Gas permeability of geosynthetic clay liners

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Original scientific paper

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Abstract
Geosynthetic clay liners (GCL) are manufactured hydraulic barriers consisting of mineral and geosynthetic components. They belong to a group of geosynthetic products whose primary purpose is to seal and they have been used in many geotechnical and hydrotechnical applications, landfills and liquid waste lagoons for quite a while. They are used in landfill final cover systems to prevent the infiltration of precipitation into the landfill body and the penetration of gases and liquids from the landfill into the atmosphere and environment. Laboratory and field research and observations on regulated landfills have proven the effectiveness of GCL as a barrier for the infiltration of precipitation into the landfill body as well as the drainage of fluid beneath the landfill. Due to the presence of high concentrations of gases in the landfill body, there is a growing interest in determining the efficiency of GCL as a gas barrier. It was not until the last twenty years that the importance of this topic was recognized. In this article, current GCL gas permeability studies, the testing methods and test results of gas permeability in laboratory conditions are described.

Keywords
Geosynthetic clay liners, landfills, gas permeability, gravimetric water content, volumetric water content

1. Introduction

Nowadays, landfills are designed in accordance with the applicable legislation and according to which a landfill's method of construction is chosen. Every landfill is composed of a bottom liner system and a final cover system between which waste is deposited (see **Figure 1**). The final cover system is most often constructed as a combination of soil layers and geosynthetics which work together to perform functions of sealing, drainage, leachate collection and erosion protection. In such complex final cover systems, the most important element is the geosynthetic clay liner. Geosynthetic clay liners (GCL) are artificially produced hydraulic barriers of extremely low permeability. They are composed of an approximately 5 mm thick layer of bentonite clay which is sandwiched between two layers of geotextiles, and in some cases, polymeric geomembranes are also added. GCLs are very commonly used as a sealing layer (barrier) in landfills, while they are frequently used in the final cover systems in combination with polymeric geomembrane in order to prevent the infiltration of precipitation into the landfill body and to prevent the extrusion of liquids and emission of gases from the landfill body into the atmosphere and environment.

The emission of landfill gases into the atmosphere, along with other factors, contributes to the greenhouse effect, which causes long-term climate change and global warming, and in recent years, this has become a growing problem worldwide. Of all the complex components of landfill gases, methane (CH_4) and carbon dioxide (CO_2) have the biggest influence on climate change, and they are both products of the anaerobic decomposition of organic waste (**Lou & Nair, 2009**). In the 1980s, all the negative environmental impacts caused by landfill gas were recognized and so the collection, processing and incineration or transformation to energy began. The intention of each regulated landfill is to collect and use gases that are produced in the landfill body in various ways. It is necessary to continuously process the accumulated gas as well as temporarily store and energetically exploit it after treatment of the gas. Gas which is not appropriately collected can cause many problems and significantly damage the final cover landfill system, which affects the stability of the landfill, the safety of the final cover system and the environment. So today, landfills are being intensively reconstructed, where it is common practice to use a final cover system with geosynthetic clay liners as sealing components that will greatly reduce emissions to minimum values.

2. Theoretical background – transport mechanism

The circulation of gases in porous media such as soil or geosynthetic clay liners are described by the two main

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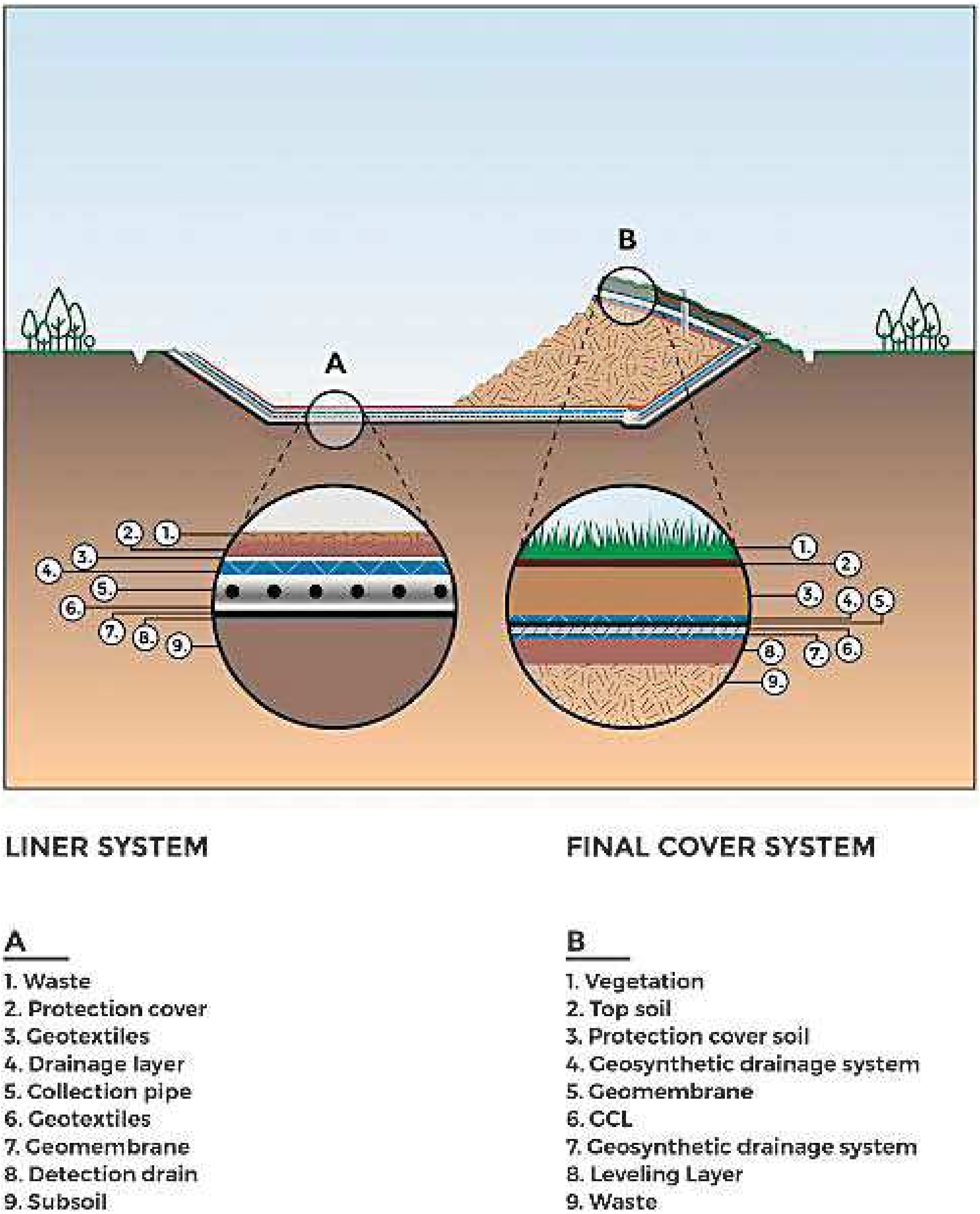

Figure 1. Cross-section of a landfill with liner and final cover system details

transport mechanisms: advection and diffusion. Advection describes the flow rate of gas towards the pressure gradient where the gas travels from areas of high pressure to areas of low pressure. Any sudden change in pressure leads to the migration of gas from landfills. Numerous incidents have been associated with an increase in concentration of methane in landfills. The most famous accident occurred in Loscoe in the UK in the year 1986. The explosion occurred when atmospheric pressure dropped to 2900 Pa (1 atm =101325 Pa) over a period of 7 hours which caused the migration of a substantially larger amount of gas than usual. Through diffusion, gas travels from an area of higher concentration to an area of lower gas concentration. Thus, the gas molecules move as a result of the pressure gradient or the gradient of the gas concentration (**Bouazza & Vangpaisal, 2003**).

Almost all previous gas permeability tests were carried out according to the advection transport mechanism (**Didier et al., 2000, Bouazza & Vangpaisal, 2003, Mendes et al., 2010, Pitanga et al., 2011**). This article will also describe the movement of gases under a pressure gradient i.e. advection. The flow rate of gas through materials of low permeability can be approximated using Darcy's law. The compressibility of gas can be ignored and therefore we can apply boundary conditions corresponding to that assumption. Darcy's law for one dimensional flow Q [m^3/s] of gas in porous media is based on the following equation:

$$Q = -\frac{k}{\mu} A \frac{dP}{dx} \quad (1)$$

where:
k – intrinsic permeability (m^2),
μ – dynamic viscosity of the fluid (Pa·s),
A – cross-sectional area of the porous material (m^2),
dP/dx – pressure gradient (Pa).

When the gas is compressible, the flow rate varies from point to point due to differential pressure. However, it can be assumed that the landfill gases behave as ideal gases and the continuity equation can be represented as follows:

$$\frac{\rho_0 T_0}{P_0} = \frac{\rho T}{P} \quad (2)$$

where:
ρ_0 – gas density under standard pressure P_0 and standard temperature T_0,
ρ – gas density under pressure P and temperature T.

It is also assumed that the rate of mass flow is constant (ρQ = const.) that is, the law of conservation of mass can be applied. In a homogeneous isotropic media under isothermal conditions, stationary flow of gas (dm/dt = 0, m - mass) is assumed.

When measuring gas permeability, due to the compressibility of gas, the volume (density) of gas at the input pressure is not the same volume (density) of gas at the output pressure (which is equal to atmospheric pressure). Thus, it is necessary to consider flow rate in a differential form or otherwise take into account the compressibility of gas. In differential form, changes of flow rate for infinitely small changes in pressure can be mathematically described as:

$$PQdx = -\frac{k}{\mu} APdP \quad (3)$$

where:
k – intrinsic permeability (m^2),
μ – dynamic viscosity of the fluid (Pa·s),A – cross-sectional area of the porous material (m^2),dP – pressure gradient (Pa).

and through the integration of equation (3) subjected to boundary conditions (see **Figure 2**) where $P=P_1$ at x=0 and $P=P_2$ at x=L, the expression becomes:

$$Q_2 = \left(\frac{k}{\mu}\right) A \frac{(P_1^2 - P_2^2)}{2LP_2} \quad (4)$$

The viscosity of a fluid and its density depend on the temperature and so indirectly, the permeability coefficient also depends on temperature. Medium characteristics and pore diameter are also affected by conditions and stress history and so the permeability coefficient will indirectly be affected by the stress state. In fine-grained soils such as bentonite clay, which is an expansive soil where besides the density and viscosity, other

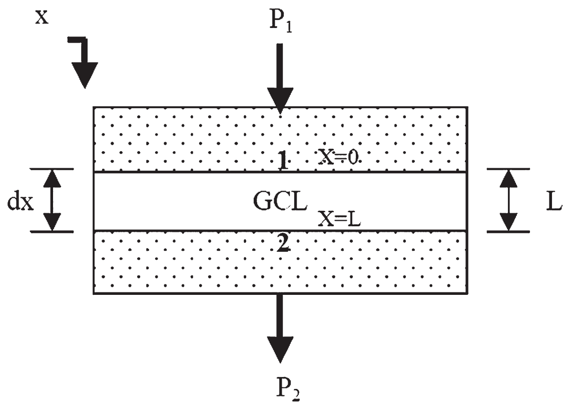

Figure 2. Flow rate of gas through a porous medium (**Bouazza & Vangspaisal, 2003**)

properties of the fluid passing through the media can significantly affect the permeability coefficient as well. These can be chemical and electrical characteristics of the fluid which can cause a change in the particle shape and pore geometry due to expansion, settling or dispersion. In addition, fluid flow can be caused by gradients of electric or chemical potential. **Lu & Likos (2004)** suggest that this phenomenon may lead to significant deviations from Darcy's law while observing the flow through this type of material. The viscosity of the fluid that flows through a medium has a direct effect on the type of flow in a saturated or partially saturated medium. Reynolds number is used as a criterion for the separation of different flow regimes and thus it is a criterion of the applicability of Darcy's law. For flow rate in a porous medium, Reynolds number is defined as:

$$Re = \frac{vd}{\nu} \quad (5)$$

where:
v – Darcy's velocity (m/s),
d – the dominant diameter of pores i.e. the dominant size of pores (m),
ν – kinematic fluid viscosity [m^2/s].

Kinematic viscosity is the ratio of - absolute (or dynamic) viscosity to density - a quantity in which no force is involved. Kinematic viscosity can be obtained by dividing the absolute viscosity of a fluid with the fluid mass density.

$$\nu = \frac{\mu}{\rho} \quad (6)$$

where:
ν – kinematic viscosity (m^2/s),
μ – absolute or dynamic viscosity (N s/m^2),
ρ = density (kg/m^3).

Small values of Reynolds number (less than 10) show that viscosity has a dominant role in the flow of fluid, that the flow is laminar and that Darcy's law applies. Values of Reynolds number greater than 100 indicate that kinetic energy and inertia begin to affect the flow of fluid through a porous medium and the flow most likely becomes turbulent. For Reynolds number values less than 100 and greater than values between 1 and 10, the flow remains laminar but it behaves non-linearly (**Bear, 1972**). In most cases of flow through soil, Reynolds number is less than 1. However, the appearance of larger gradient values may bring flow conditions closer to a nonlinear laminar regime or a turbulent regime.

3. Previous studies of gas permeability

In the 1990s, the use of GCLs in landfills increased, which created an interest for knowledge of all available data regarding the product, i.e. its physical, mechanical and hydraulic characteristics. The hydraulic permeability of GCLs is stressed as a very important characteristic because of the harmful effects of leachate on the surrounding environment. However, the production of high concentrations of gases in landfills has attracted a heightened interest in the assessment of the efficiency of GCLs as gas barriers.

Figueroa & Stegman (1991) conducted a field test on a 0.6 m thick protective layer of soil at a landfill in Germany. Test results show flow rates in the range from 5.2×10^{-6} to 9.6×10^{-5} $m^3/m^2/s$. These tests also demonstrated the impact of drying and differential settlement on the formation of cracks in the cover layer, which significantly affects the rapid flow rates of gas. According to **Daniel (1991)**, theories of gas permeability in the nineties were based on the assumption that gas leakage through a hydrated GCLs is very low. Therefore, gas permeability was rarely studied (according to: **Shan & Yao, 2000**). **Trauger & Lucas (1995)**, measured the flow rate of methane and benzene through GCLs by diffusion. The concentration of methane on the receiving end of the cell was recorded by a chromatograph, and the concentration of benzene was measured using a photoionization detector. Their results show that the gas flow rate through the GCL is very low as long as the gravimetric water content is higher than 90%. These results lead to the conclusion that gas permeability of geosynthetic clay liners depend on their gravimetric water content. Čalogović **et al. (1998)** measured the flow rate of nitrogen through an unsaturated clay in a triaxial cell and specific permeability and the permeability of porous media were determined based on the measured flow rate. Changes in the characteristics of permeability were monitored in clay samples of intermediate to high plasticity. The samples were consolidated in the triaxial cell and then cyclically stressed with increasing amplitudes. Test results indicate a linear dependence of the nitrogen flow rate and differential pressure. After each series of tests, the permeability of porous media is determined in relation to the total consumed energy ΔW which the sample absorbed during the dynamic process.

3.1. Gas permeability of partially hydrated GCLs

In the past fifteen years, tests have been conducted on the gas permeability of GCL samples to gain data on the properties of advective gas flow rate. **Didier et al. (2000)** conducted a series of tests on the gas permeability of partially saturated samples of needle punched geosynthetic clay liners. Testing was conducted in a specially constructed cylindrical cell with an internal diameter of 205 mm which was meant to simulate conditions in the upper layers of the landfill cover. The cell consisted of two chambers to allow the embedding of the GCL sample. The cross-section of the cell is shown in **Figure 3**. The height of the upper chamber was 150 mm while the height of the lower chamber was 100 mm. The diameter of the GCL sample which was embedded into the cell was 250 mm. The lower chamber was filled with sand while the upper chamber was filled with both sand and gravel. Normal pressure was applied by the top cap. The authors tested GCL samples under normal pressures between 20 and 80 kPa. The upper chamber had an opening with a pressure regulator through which compressed nitrogen was supplied to one side of the sample. In the lower chamber there was an outlet port with a flow meter where volumetric flux was monitored. Gas pressure in the lower chamber i.e. the bottom of the sample was equal to atmospheric pressure.

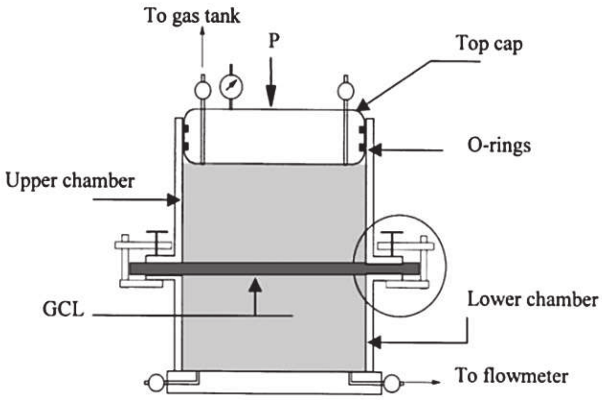

Figure 3. Gas permeability cell (**Didier et al., 2000**)

Samples of somewhat larger dimensions (300 x 300 mm) were hydrated through immersion in de-ionised water prior to testing. Immersion time was from 0.2 to 75 minutes. Afterwards, samples were left to cure for seven days in order to achieve a uniform distribution of gravimetric water content in the GCL during which time, some of the samples were placed under confinement of 20 kPa while others were under zero confinement. After that, the samples were cut to the required dimensions, installed into the cell and left to consolidate. Gas permeability tests were conducted on samples under various pressures and different degrees of gravimetric water content or volumetric water content. The results of these tests indicate, among other things, a substantial change or reduction in the gas permeability of GCL samples as their volumetric water content increases, as shown in **Figure 4**.

In the field of testing gas permeability of GCLs, authors Vangpaisal and Bouazza have distinguished themselves the most, and in collaboration with several authors, they have conducted a number of tests on GCL samples in a cell which they constructed and which has been repeatedly mentioned in some published studies that have since followed. The cell for determining gas permeability is designed to closely simulate conditions around the cover system in a landfill where the GCL is exposed to stress and impact of the surrounding layers. The aluminum cell consists of two separate parts, a base cylinder and an upper cylinder with a piston as shown in **Figure 5**.

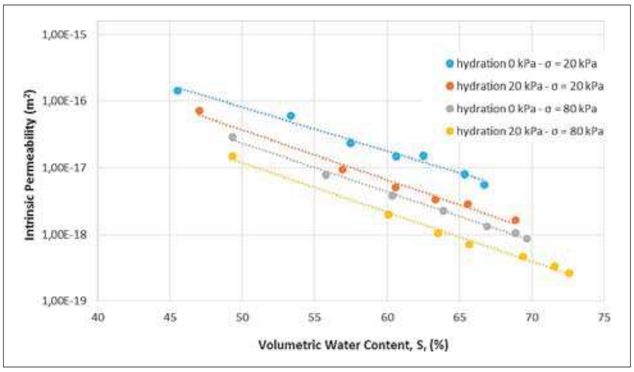

Figure 4. Gas permeability of porous media in relation to the volumetric water content of the GCL sample (**Didier et al., 2000**)

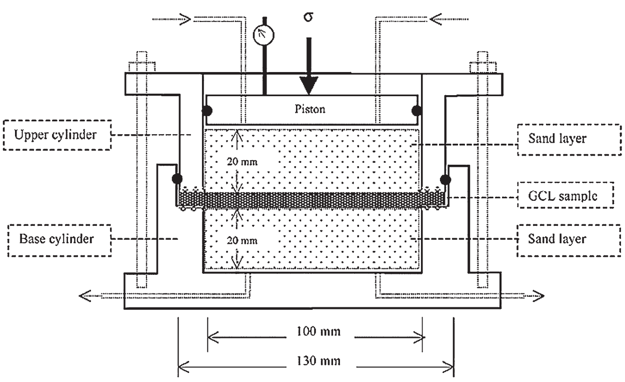

Figure 5. Cross-section of gas permeability cell (**Bouazza & Vangspaisal, 2003**)

The layout for testing gas permeability is shown in **Figure 6**. The basic components of the device are tanks with nitrogen, pressure regulators, a manometer measuring input pressure and a device for measuring the gas flow rate. As a source of gas nitrogen is used because it is relatively inert gas and has a very low solubility in water. All tests are carried out in a room with controlled temperature where the density and viscosity of the gas are considered constant (**Bouazza & Vangspaisal, 2003**).

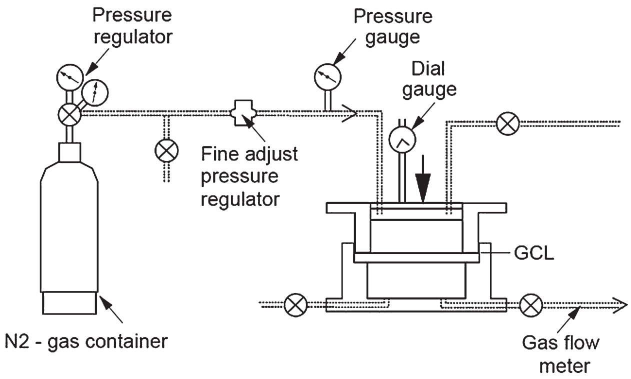

Figure 6. Layout for measuring gas permeability (**Bouazza & Vangspaisal, 2003**)

Vangpaisal et al. (2002) conducted tests on two differently prepared samples under different conditions of gravimetric water content and volumetric water content on the previously described device. The test results showed gas permeability in relation to sample gravimetric water content and the relationship between permeability and the volumetric water content of the samples (see **Figures 7 and 8**).

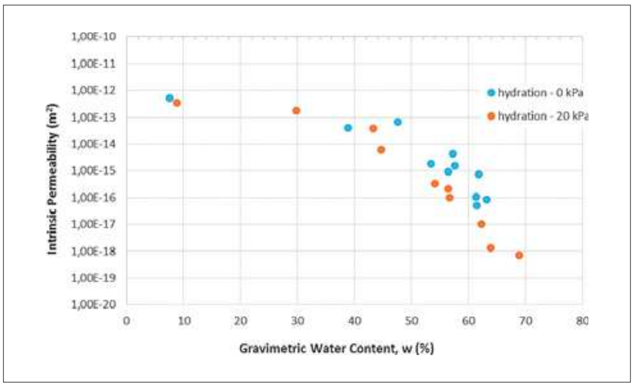

Figure 7. Gas permeability of porous medium in relation to gravimetric water content (**Vangpaisal et al., 2002**)

Figure 7 shows the relationship between gas permeability and gravimetric water content of the sample where it is clear that the gravimetric water content of a sample has a large impact on its gas permeability. The results show that an increase in the gravimetric water content of a sample decreases its gas permeability. It is also evident that a dry sample has a much higher gas permeability than a sample which was hydrated prior to testing. The cause of the greater permeability in dry samples is the space in the pores that was created through drying and thus enabled the easier passage of gas.

Figure 8 shows the relationship between gas permeability and the volumetric water content, and the results show that gas permeability decreases as volumetric water content increases. The influence of hydration methods is also evident: without confinement and under confinement of 20 kPa where the permeability is greater in the first case i.e. when the sample is hydrated under zero confinement. Lowering gas permeability with a confined sample is the result of the reduction of pore space for the passage of gas.

Rouf et al. (2014) conducted a series of tests with different degrees of gravimetric water content, volumetric water content and suction on samples of needle punched geosynthetic clay liners. The results of these tests are described as advective gas flow rate through porous media using Darcy's equation where the flow rate is proportional to the differential pressure.

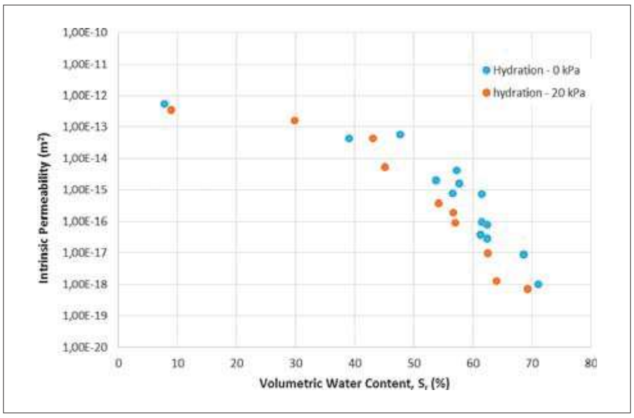

Figure 8. Gas permeability of porous media in relation to volumetric water content (**Vangpaisal et al., 2002**)

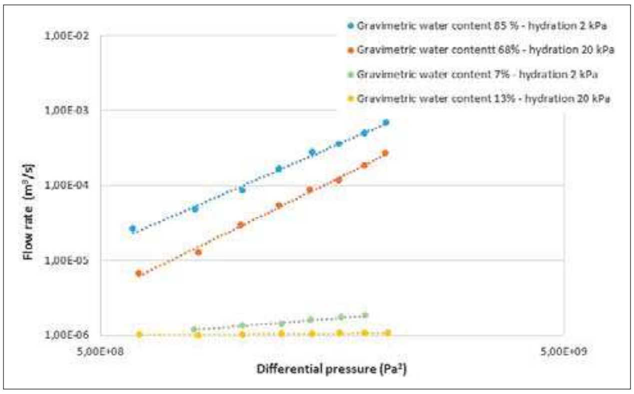

Figure 9. Gas flow rate in relation to differential pressure (**Rouf et al., 2014**)

Figure 9 shows the relationship between gas flow rate and differential pressure in four samples with different gravimetric water content and different stresses during hydration. The results show that gas flow rate has a linear relationship with differential pressure under both low and high gravimetric water content and with two methods of hydration with an initial stress of 2 and 20 kPa on the sample. The linear relationship indicates laminar flow rate during the test. The diagram also shows an increase in the flow rate with an increase in differential pressure in all samples, while under high levels of gravimetric water content, the amount of stress during the hydration of samples also has a major impact on the flow rate.

Measurement of the gas flow rate through GCLs in stationary conditions with the constant head difference method is traditionally most often used to determine the permeability of GCLs today (**Bouazza et al., 2002; Bouazza & Vangpaisal, 2003, 2004; Didier et al., 2000; Vangpaisal & Bouazza, 2004**). However, when samples of the GCL are not completely saturated, or they have low permeability due to high gravimetric water content, a longer period of time is needed to achieve steady flow rate conditions, which can affect the final accuracy of the results because of possible variations in atmospheric pressure. In these situations, the falling head method can be used.

For testing with the falling head method, an aluminum cell with three parts is used, as shown in **Figure 10** (**Mendes et al., 2010; Pitanga et al., 2011**). In the lower part, there is a porous material with a known pore volume. On this material, a GCL sample with a diameter of 380 mm is placed. Above the sample there is a protective layer of geotextile and sand through which normal stress is applied to the sample. In the lower part of the cell, nitrogen gas is introduced through a pressure regulator.

Their work shows the results of repeated tests on samples of GCL with a gravimetric water content of 68%

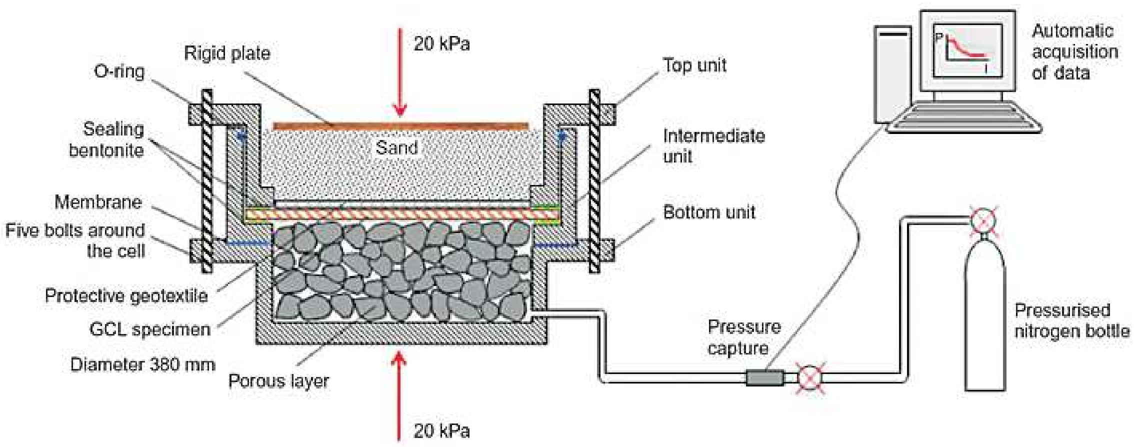

Figure 10. Device for measuring gas permeability using the falling head method (**Mendes et al., 2011**)

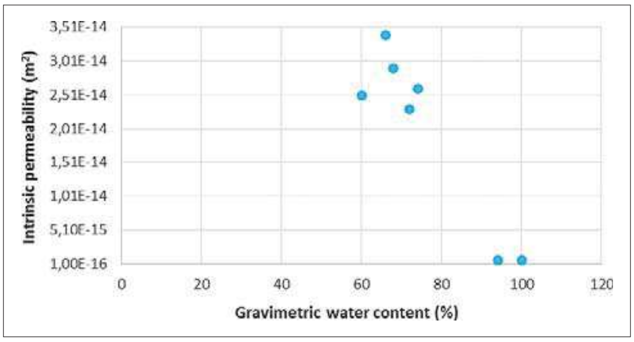

Figure 11. Gas permeability of porous media in relation to the gravimetric water content of samples (**Pitanga et al., 2011**)

and samples of GCL with a gravimetric water content of 100%. The results of these repeated tests were almost the same. Thus, for samples of 68% gravimetric water content, gas permeability of the porous medium was in the range from $2.9 \cdot 10^{-14}$ to $3 \cdot 10^{-14}$ m^2, and for samples of 100% gravimetric water content, gas permeability was in the range from $6.7 \cdot 10^{-16}$ to $6.9 \cdot 10^{-16}$ m^2. Tests were also carried out on the same sample but in the gravimetric water content range from 60 to 100%, and the results are shown in **Figure 11**. As with the previous authors, the diagram shows the trend of a decrease in permeability of porous media with an increase in gravimetric water content in GCL samples.

3.2. The effect of ion exchange, adhesive components of GCL and bentonite granulation in GCL on gas permeability

Bouazza et al. (2006) gave an overview on the influence of hydration - drying and ion exchange on the gas permeability of GCLs. Testing was carried out on samples of needle punched GCL in three series with test liquids of different $CaCl_2$ concentrations. In all three series, the samples were subjected to multiple cycles of hydration - drying prior to their testing of gas permeability. Conditions in which the testing took place showed that alternating hydration - drying cycles have no measurable effect on the gas permeability of GCLs when samples are hydrated with de-ionised water. When the sample is hydrated with a solution of a low concentration of $CaCl_2$, gas permeability was about one order of magnitude higher than that of hydration with de-ionised water. It is obvious that exchanges of Na^+ ions in the bentonite with Ca^{2+} ions present in hydration liquid reduces expansion and the capacity for the self-healing of bentonite components.

Therefore, cracks in bentonite components that are created during the drying phase may not completely heal after rehydration. In that case, the permeability of a dried GCLs which is hydrated with solutions that contain divalent calcium is greater than that of bentonite hydrated with de-ionised water. **Bouazza (2010)** also examined the effect of adhesives used for the production of GCLs. Through a series of tests on various samples of GCLs, he concluded that needle punched GCLs show lower values of gas permeability than glued GCLs. The type of bentonite in the GCLs such as powder or granular form also has an impact on permeability. A hydrated sample in the granular form has a higher permeability than a powdered sample of bentonite. It is assumed that this is caused by the increased pore space between the granules in relation to the pore space of the sample powder, which allows for a higher flow rate of gas.

4. Summary of previous tests results

Gas permeability tests of geosynthetic clay liners (GCL) have been conducted since the beginning of the 1990s to present day by several authors including the most prominent Bouazza and Vangpaisal. From their results, important conclusions related to gas permeability of GCLs can be summarized:

- gas permeability decreases as gravimetric water content and volumetric water content increase
- gas permeability decreases as effective stress increases
- in order to achieve the smallest possible gas permeability of a sample, it must be vertically loaded during the test and hydrated before testing
- gas permeability depends on the form of bentonite (powder or granules) as well as the structure of a GCL (connection method of geotextiles with bentonite - weaving or gluing)
- the gas permeability of dried GCLs which are hydrated with solutions that contain divalent calcium is higher than those of bentonite mats hydrated with de-ionised water.

Table 1 gives an overview of the tests related exclusively to testing the gas permeability of geosynthetic clay liners. In addition to the range of obtained gas permeability, the table includes flow rates, differential pressure, sample preparation methods and type of gas which are used for testing. It is noticeable that the measured values of gas permeability cover a wide range, from $1.2 \cdot 10^{-10}$ to $1.0 \cdot 10^{-18}$ m^2, the flow rate goes from 0.007 to 27 l/min, and differential pressure which was used in testing ranged from 0.5 to 100 kPa. The range of different gravimetric water contents mainly came from sample preparation using the hydration procedure on wet porous media or by immersing them in a container with water. Gas used in testing in most cases is nitrogen.

It is evident in **Table 1** that the measurement of gas permeability is not currently standardized, which results in the application of different procedures of sample preparation and the implementation of testing which ultimately generates such wide ranges of measured values for gas permeability.

Table 1. Literary data on the gas permeability of geosynthetic clay liners

Author	Sample	Gas	Preparation	Gas Permeability [M^2]	Differential Pressure [Kpa]	Flow Rate [L/Min]
Didier et al., 2000	GCL (BF-bentofix iBM-bentomat)	nitrogen	Hydration (immersion) BF from 0.2 to 75 minBM from 1 to 30 min	$7.85 \cdot 10^{-16}$ to $1.00069 \cdot 10^{-16}$ m^2	5 - 40	0.007 – 0.6
Shan & Yao, 2000	GCL (Claymax Bentomat)	air	Hydration (24 hours) drying at 35°C (0-90 days)	0.003 to 0.21 m/s	< 2	0.5 – 27
Vangpaisal et al., 2002	GCL (Bentofix)	nitrogen	Hydration: (immersion) swelling (7 – 10 days) σ = 0 kPa; σ = 20 kPa	$1.0 \cdot 10^{-18}$ to $1.0 \cdot 10^{-11}$ m^2	0.5- 40	-
Bouazza & Vanpaisal, 2003	GCL (Bentofix)	nitrogen	Hydration: immersion (1-120 min) swelling (7 – 10 days) σ = 0 kPa; σ = 20 kPa	$1.0 \cdot 10^{-18}$ to $1.0 \cdot 10^{-12}$ m^2	1 – 40	0.001560 – 2.7
Mendes et al., 2010	GCL	nitrogen	Hydration:immersion (60 – 300 minutes) –swelling (7 days)	$7.9 \cdot 10^{-14}$ to $1.2 \cdot 10^{-10}$ m^2	1 - 100	-
Pitanga et al., 2011	GCL (Bentofix)	nitrogen	Hydration: immersion (5-60 minutes) – swelling (15 days)	$2.5 \cdot 10^{-14}$ to $6.8 \cdot 10^{-16}$ m^2	2.5 – 3.6	-
Rouf et al., 2013	GCL (Elcoseal X2000)	nitrogen	Hydration on a saturated porous sponge swelling in a plastic bag (7-10 days) σ = 2 kPa; σ = 20 kPa	$9 \cdot 10^{-12}$ to $6.5 \cdot 10^{-12}$ m^2	2 – 20	0.006 - 9
Rouf et al., 2014	GCL	nitrogen	Hydration on a saturated porous sponge swelling (7-10 days) σ = 2 kPa; σ = 20 kPa	$1.0 \cdot 10^{-14}$ to $6.0 \cdot 10^{-12}$ m^2	2 – 20	0.051 – 7.56

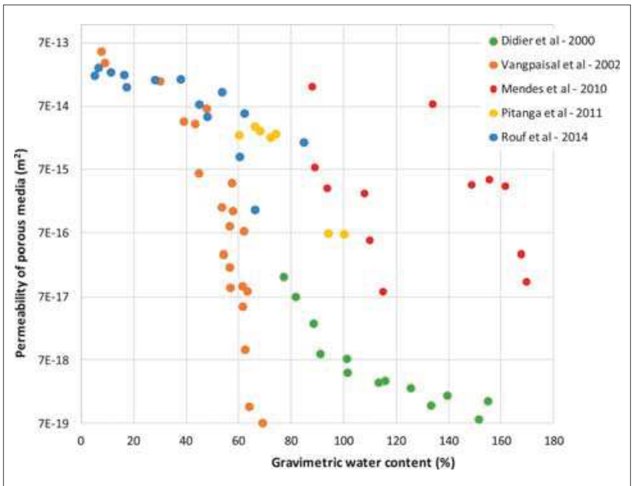

Figure 12. The relationship between gas permeability and gravimetric water content of GCLs

Figure 12 summarizes the collected data of all tests up to present day which were conducted on samples of GCL in a wide range of gravimetric water content. One can observe the impact of an increase in gravimetric water content on a decrease in gas permeability in all tests.

5. Conclusion

The final cover system is one of the most important elements of each modern landfill constructed according to the current state of practice. One of its important tasks is to be a long-lasting barrier that has very low permeability and prevents the passage of gas from landfills. Geosynthetic clay liners have been recognized as a highly effective hydraulic barrier that is easy to install and despite deformation and possible damage, they retain very low water permeability. However, due to the production of large quantities of gases in landfills, there has been a growing interest on information regarding these gas permeability barriers over the past 20 years.

Theories of gas permeability from the nineties were based on assumptions that hydrated GCLs would hardly allow any gases to flow through them. As a result of these conclusions, gas permeability has very rarely been studied. However, significant amounts of gases generated in landfills and large concentrations of their individual components that adversely affect the environment and contribute to the greenhouse effect, created the need to study this phenomenon.

This article shows tests up to present day and their results of testing the gas permeability of geosynthetic clay liners. By reviewing previous tests and their results, it can be concluded that gravimetric water content and volumetric water content have the greatest impact on the gas permeability of samples. However, ambiguity arises in the analysis of these results, in particular in the values of gravimetric water content and volumetric water content of the samples prior to, during and after testing. This points to the need for more tests on different samples with different initial conditions of gravimetric water content and volumetric water content, and their determination during and after the test in order to describe in more detail the behaviour of the sample during the transport of gases. Also, tests should be done on the impact of the flow of gas at a given pressure on the sample and a sample's ability to maintain its initial gravimetric water content even after the gas has flowed through it. Since the observed effect of different stresses during the hydration of the sample on the final result of gas permeability, a greater range of stresses applied during hydration should be tested in order to describe the impact of the stress on gas permeability.

Since the gas permeability parameter is not often studied, this opens a new area of research. In Croatian geotechnical practice GCL is very often used for different purposes, so it is necessary to introduce standardized gas permeability tests. Accordingly, further research will focus on determining the gas permeability of bentonite clay and GCLs.

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